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# DEVELOPING VIP2M: A VIRTUAL ENVIRONMENT FOR PROTOTYPING MOBILE WORK MACHINES

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## 1. Introduction

For most products in mechanical engineering, time-to-market and the understanding of customer needs are major factors in product success today. These goals can be achieved by applying various tools of information and communication technology (ICT) for digital product processes [Pahl et al. 2001]. Computer simulation has finally taken a major role in the entire product process. Furthermore, ICT tools provide the opportunity for users to engage in an organization's innovation process [Di Gangi et al. 2009].

Today, technology costs for creating immersive virtual environments (VEs) have become reasonable. Multi-person VEs, such as walk-in VEs, offer opportunities for companies to collaborate with users in co-creation, which is a process in which consumers take an active role in product design and co-create value together with the company [Prahalad and Ramaswamy 2004]. However, the process of negotiating about customers' needs is difficult, because it requires multiprofessional co-operation, as the participants have different assumptions about the design process and its result. New solutions are needed for supporting users' participation and making use of their own expertise.

Our paper focuses on shaping a VE as a new instrument to facilitate co-creation, and, more specifically, on the practical case of designing the control cabin of a mobile work machine. Machine cabins are complex entities for highly specialized purposes, in forest and mining machines for example. These machines are human-driven and produced in small series. Concurrent engineering is often needed, because typically the machine structure is designed by one engineering team and the control by another team. Designing a control cabin for a mobile machine is challenging in itself, because it necessitates numerous trade-offs between various design qualities, such as visibility, functionality, ergonomics, safety, and industrial design. [Tiainen et al. 2011]

In this paper, we report on a 26-month action research project during which we developed VIP2M, a walk-in VE for prototyping a mobile working machine. Co-creation in this context means that machine operators and machine designers can step in the VIP2M together, "try" driving the machine and operating the functions virtually, and discuss new cabin designs and improvements for the cabin environment. The project was started after discussions with industry partners, who expressed a need for such an environment. We then created and evaluated our VIP2M in two action research cycles.

This paper proceeds as follows: First, we describe what action research is. Then we present details about our particular action research project and its two action research cycles. In the discussion of the research findings, we highlight what can be generalized about creating a virtual prototyping environment for co-creation based on our experience. Finally, we conclude the paper.

## 2. Method: Action research

Action research aims to solve current practical problems while expanding scientific knowledge. Unlike in other research methods, where the researcher seeks to study organizational phenomena to understand them but not to change anything, the action researcher is concerned about contributing to organizational change and simultaneously studying the process [Iversen et al. 2004]. Action research is strongly oriented towards change and collaboration between researchers and practitioners [Baskerville and Wood-Harper 1998], [Davison et al. 2004], whose aim is to capitalize on joint learning within the context of the practitioners' social systems [Susman and Evered 1978], [Baskerville and Myers 2004].

Our research project was multidisciplinary (machine design and information systems science), and its target was to develop a VE for prototyping mobile work machines, which we named VIP2M. The two disciplines involved formed a steady background for the project, design being central in both of them. Our case, focusing on the design of mobile work machines, belongs thus mainly to machine design. From information systems science, we adapted the method of action research that in practice means iterative development and testing [Davison et al. 2004]. Action research is particularly appropriate for the development of system design principles [Iversen et al. 2004].

The purpose of the present study being to explore co-creation by building a VE and to create design objectives for a co-creation system, action research seems highly appropriate for it. Our action research project, which consisted of several sub-projects, involved two Finnish companies, who also partially funded our project, the rest of financing coming from TEKES (The Finnish Funding Agency for Technology and Innovation).

We used a form of action research that is called *collaborative practice research* [e.g., Iversen et al. 2004]. It was developed as a part of a Scandinavian information systems research tradition during the 1980s and 1990s. It aims to understand, to develop support for, and to improve specific professional practices within the participating organizations [Iversen et al. 2004.] In our action research project, researchers and practitioners worked together in all phases of the project. The specific professional practice to be targeted was that of designing new machine models by co-creation.

The epistemological foundation for action research may be positivist, interpretive, or critical in nature. The foundation adopted in our study is interpretive, which menas that it is based on the assumption that knowledge is socially constructed. The results of this study should be seen as ways of making sense of the design of VIP2M.

We conducted an action research project consisting of two study cycles with the following phases [Susman and Evered 1978]:

- *Diagnosing*: Identification of situated problems and their underlying causes. During this phase, researchers and practitioners jointly formulate a working hypothesis to be used in the subsequent phases of the action research cycle.
- *Action planning*: Specifying the actions that improve the situation.
- *Action taking*: Implementation of the action planning phase.
- *Evaluating*: Estimating, with evaluation methods, the quality and efficacy of a design artifact.
- *Specifying learning*: Ongoing process of documenting and summing up the learning outcomes of the action research cycle. These learning outcomes should constitute knowledge contributions to both theory and practice, but they are also recognized as temporary understandings that serve as the starting point for a new cycle of inquiry.

## 3. Two action research cycles

The goal of this action research project was to develop a VE for prototyping mobile work machines, named VIP2M. This section describes our design process, which started in 2009 and included the five phases in two action research cycles completed in the beginning of 2011. A summary of the two action research cycles is presented in Table 1. Next, we go through the phases of both cycles in more detail.

**Table 1. Action research project**

| Cycle 1 (2009) | Cycle 2 (2010–2011) |
|---|---|
| Phase 1. Diagnosing | |
| *Month: 1*<br>Getting insights into the challenges of machine design with virtual design.<br>Starting point: visualizing a static machine model in Cave.<br>Working hypothesis: In traditional design, it is difficult to share ideas, visualize and test them with other stakeholders. Thus, a virtual co-creation system is needed.<br>Data sources: Workshop sessions with machine designers and operators | *Month: 1*<br>Background: Evaluation of participant's behavior in the co-creation system (Cycle 1).<br><br>Working hypothesis: A more immersive environment will increase users' feeling of presence.<br><br>Data sources: Observations of cycle 1 by researchers |
| Phase 2. Action Planning | |
| *Month: 2*<br>In collaboration with practitioners, researchers, and VE technology developers, a co-creation system was designed. | *Month: 2*<br>The objectives for increasing immersion were designed. |
| Phase 3. Action Taking | |
| *Months: 3–9*<br>VIP2M was implemented. It contained:<br>• A motion platform<br>• A 3-wall panoramic view<br>• A driver's seat and control devices<br>• Sounds | Months: 3–10<br>*VIP2M was developed further with:*<br>• A motion platform: filling the pneumatic muscles with oil<br>• Improving the lighting conditions<br>• Using larger, perpendicular walls<br>• Improving the sound environment |
| Phase 4. Evaluation | |
| *Month: 10*<br>User test with 6 machine operators:<br>participant observations, interviews, questionnaires | *Months: 11–12*<br>User test with 25 participants:<br>participant observations, questionnaires |
| Phase 5. Specifying Learning | |
| *Months: 11–12*<br>Main findings: Users get a much more realistic feeling of the machine with the motion platform, but the motion platform swings too much. | *Months: 1–2 (2011)*<br>New findings: In 2D mode, driving is easier than in 3D mode.<br>Users prefer a more immersive environment. All immersion components increase the reality of the experience. |

### 3.1 Cycle 1: First prototype of VIP2M

In the first cycle of our action research project, we built the first version of VIP2M in an immersive environment. The need for VIP2M emerged from the practitoners. The stakeholders taking part in the development process were:

- Researchers of both machine design and information systems science, who planned VIP2M, guided the collaborative design process, planned the user tests, and analyzed their results.
- VE technology developers, who were responsible for building and developing the VE as well as visualizing the virtual models.
- Practitioners, who were employed as professional machine designers and machine operators in companies participating in the project.

*3.1.1 Diagnosing*

The practitioners expressed a need for being able to quickly test different design options and for having a simulation model of the machine to evaluate the effect of the designs on machine appearance and functionality. With this kind of a system, companies would save considerable amounts of time and money in the product design process. Thus we came into a conclusion that a virtual co-creation system is needed.

The starting point for the development of VIP2M was visualizing a machine cabin in an immersive VE, better known as Cave-like VE or, shortly, Cave. For the first draft we put an artificial driver's seat to Cave. The visualization of the machine cabin was done by importing 3D CAD design models into the Virtools visualization software used. This environment is shown in Figure 1. At this point, we could only visualize static models of the machine. The point of view could be changed, so that it was possible to examine the machine either from outside or inside the cabin. There was no possibility for simulation of the machine functions as there were no simulation model or control system of the machine. Still, the first draft was useful in starting the negotiation between practitioners and researchers. By visiting Cave and trying the draft the practitioners got an idea of the possibilities of using virtual prototyping and VE in their own work.

The purpose of the diagnosing phase was to identify the problems associated with visualizing machine models in the Cave-like VE. To achieve this, we organized several workshop sessions with practitioners from the companies we have built virtual machine models for, researchers, and VE technology developers.

In discussions between the researchers and VE technology developers, we identified several issues that needed to be addressed. The Cave-like environment was quite inflexible with regard to both hardware and software modifications. It was also very expensive and required a lot of space, so that, according to practitioners, companies would not be inclined to take such a system in use on their own.

**Figure 1. A static model of a machine cabin with no functionality visualized in Cave**

*3.1.2 Action planning*

In collaboration with the practitioners from the companies involved, we began the design of VIP2M for work machine co-creation. The first phase was defining the design objectives, namely:

*Objective 1: Incorporating 3D CAD models should be straight-forward.*

The practitioners required that they should be able to bring modified models smoothly into the VE for evaluation. The VE technology developers identified the conversion of CAD models as a crucial point in the process.

*Objective 2: The environment should be immersive and have enough space for several persons.*

Machine designers and operators should be able to work together in the VE when evaluating and developing the model.

*Objective 3: VIP2M should be as realistic as possible from the driver's point of view.*

Only then the effect of the model modifications on the actual behaviour of the machine could be reliably examined and evaluated. This objective was opened to three objectives:

a. A physical model of machine operation and functions must be incorporated.
b. The control system of the machine must be authentic.
c. Driving in VIP2M should feel as realistic as possible.

*Objective 4: The cost of the system should be as low as reasonable.*

All of the stakeholders had an interest to spend no more money and resources to the development of the system than necessary.

Based on these design objectives, the development of VIP2M started.

### *3.1.3 Action taking*

The VE technology developers implemented VIP2M with the help of the researchers. The practitioners took part in this development process by pointing out their views on the implementation and providing some of the equipment (a chair and joystick controls). The first prototype of VIP2M is shown in Figure 2. In the implementation of VIP2M, the target was to satisfy the objectives already defined:

*Objective 1* had already been achieved in the Cave-based system, so the VE technology developers could use the same Virtools visualization software for the new environment.

*Objective 2* focuses on the space of VE. For VIP2M, the environment was chosen to consist of three walls, where the 3D image is projected from the back (back-projection). The side walls were placed at a low-pitched angle to generate a panoramic view.

*Objective 3* asks realistic feeling. This was done by creating a motion platform, which was found essential for generating in the user the feeling of actually driving the machine. The VE technology developers designed and created a pneumatic 6-degrees-of-freedom motion platform. Furthermore, an authentic driver's seat, foot pedals and genuine hand control devices were placed on top of the platform (Objective 3b). Sounds of the machine were added to generate a more realistic audio environment (Objective 3c).

*Objective 4* focuses on the costs. Because a Cave-like environment is very costly (which is against the 6th design objective) and building a motion platform on its glass floor would not have been feasible, a more compact but still adequately immersive VE was set as the target.

**Figure 2. The first prototype of VIP2M with a panoramic view and machine functionality**

### *3.1.4 Evaluation*

For evaluating the implemented VIP2M, we conducted user tests with 6 professionals, whose everyday work included designing and testing mining machines. We wanted to examine the

importance of different immersion components to the quality of VIP2M. For this reason, each test user drove with three different VIP2M setups. The first setup contained 2D graphics with no head tracking or motion platform. In the second setup, 3D graphics with head tracking was used. Finally, for the last setup, the motion platform was activated.
The task of the user was to drive into a pile of rocks, fill the bucket with rocks, drive a few hundred meters to the unloading zone, and empty the bucket there. All user tests were recorded with two video cameras so that the user actions could be investigated. Before the test, the users filled a questionnaire about their daily work, their experience on driving mining machines, and what driving a real machine in a mine feels like. After the VIP2M tests, the users completed another questionnaire, this time about VIP2M and the virtual interface. Finally, group discussions were conducted, where each test user had the possibility to discuss the experience with other test users and give final comments about the system. The whole process lasted 3–4 hours for each user. All development ideas and comments about VIP2M from the different information sources (questionnaires, video and audio recordings) were gathered and then analyzed. Comments from the questionnaires were prioritized by the number of test users mentioning each detail.

#### *3.1.5 Specifying learning*

The immersive VE was found very useful. The visibility from the cabin was limited realistically. Observation of the environment is hard in real life, and VIP2M was quite realistic in that regard. In general, it was found that the more immersive the VE is the more realistic the feeling of being in a loader. For example, the use of head tracking allowed the driver to peek outside through the windows as in real life.
The role of the motion platform was particularly interesting. The test users were asked what significant advantages if any the motion platform brought to VIP2M with regard to product development. It was found that while making the simulation experience more realistic the motion platform helps notice things about the development of the machine that could otherwise remain unnoticed. The motion platform allows the users to really immerse themselves in the simulation. This makes the test situation correspond better to actual driving, and the observations about usability aspects under research are more reliably valid also for real working cases. A concrete example is that the motion platform forces the test user to drive slowly in places where the corridor is bumpy. More realistic data can therefore be gathered about e.g. working efficiency.
The users were asked about the biggest differences between driving the VIP2M and a real machine. All of them mentioned that the movement generated by the motion platform was too smooth in certain places. This was due to the large-volume pneumatic muscles used. With the technology employed it was simply not possible to generate fast shaky movements which normally take place for example when driving the bucket to a pile of rocks. The second major point requiring improvement concerned lighting and the visual appearance of the mine. The lights of the simulated loader were not bright enough, making the view even darker than in a real mine. The contrast between lighted and dark areas was too small, making the turns of the corridor hard to perceive. Finally, the sounds of the machine were generally rated as too faint.

### 3.2 Cycle 2: Second prototype of VIP2M

The user tests with professional work machine users were very encouraging with regard to the VIP2M concept. We acquired valuable data for further development of VIP2M. This development constituted cycle 2 of our action research project.

#### *3.2.1 Diagnosing*

Based on cycle 1, it seemed probable, that increasing the immersivity of VIP2M would make it feel more realistic. The practitioners and researchers together came into the conclusion that the motion platform was essential but that it should be modified to reproduce authentic movement of the machine in bumpy corridors, sharp turns, and fast braking situations. From a visual point of view, the excessive darkness of the virtual mine should be addressed. Discussions with the VE technology developers and machine operators revealed that lighting of the simulated machine could be changed to better match real-world conditions.

### *3.2.2 Action planning*

Again, we started to form design objectives for increasing the immersion level of VIP2M. We defined the following objectives for the next development step:

*Objective 1: The motion platform should react faster and without excess swinging motion.*

The pneumatic muscles reacted too slowly and were not capable of reproducing sharp fast movements.

*Objective 2: Lighting of the virtual mine and simulated machine should be as realistic as possible.*

There would be little point for using VIP2M for visibility checking or studying the usability of the control interface if the VE and simulated machine did not appear visually realistic in all ways. Creating more realistic lighting would be the solution here.

*Objective 3: The VE should encompass the user from all visible directions.*

Although the panoramic view of the VE was visually pleasing and impressive, there was room for improvement regarding the immersivity of the system.

*Objective 4: Sounds in VIP2M should be more realistic.*

**Figure 3. The second prototype of VIP2M, which has larger, perpendicular walls**

### *3.2.3 Action taking*

The second prototype of VIP2M shown in Figure 3 was developed to satisfy the objectives defined above:

*Objective 1* was to improve the behaviour of the motion platform. That was done by filling the pneumatic muscles with hydraulic oil. This made the muscles more rigid and able to perform faster movements without abnormal swinging motion.

*Objective 2* focused on lighting. The virtual work machine was equipped with more efficient lights, and the environmental lights in the virtual mine were improved.

*Objective 3* was satisfied by replacing the projection walls in the VE with larger ones, and placed perpendicularly to each other. Instead of seeing a panoramic view, the driver in VIP2M would now be totally immersed in the virtual view.

*Objective 4* was achieved by developing the audio environment by raising the engine sound level and adding sounds that were missing, such as the sound of starting the engine.

*3.2.4 Evaluation*

For evaluating the second VIP2M prototype, we conducted more user tests. The testing procedure was developed from the first cycle with regard to these aspects:

1. The number of test users was increased to 25. In addition, we wanted to have users both with and without experience on driving large machines. The resulting test group consisted of 13 university students, 3 college students, as well as 4 students and 5 teachers from occupational skills improvement training on how to drive large work machines.
2. We also measured some performance metrics of the test runs, namely the number of times the drivers bumped into a wall and the amount of rock they managed to lift and transport.
3. The presence level of the user was measured with a questionnaire. In addition, we asked the users how the immersion components of the VE affected its reality and which VIP2M setup would be the most suitable for training purposes.

The same tasks were used as in the first cycle. To limit the amount of time taken by the testing procedure, each user tested only two different VIP2M setups.

*3.2.5 Specifying learning*

The results of the user tests showed that when two different VIP2M setups are compared, users prefer the more immersive one. All of the immersion components — 3D view, head tracking, and motion platform — increased the reality of the virtual experience. The motion platform has a major influence on how closely VIP2M resembles a real machine. Those test users who had experience on driving large work machines clearly improved their performance with regard to the amount of rock transported, when compared to the inexperienced drivers. In the 2D mode, the drivers bumped into walls clearly less often than with other modes. This underlines the fact that measuring performance alone is not sufficient for estimating the quality of VIP2M.

### 3.3 Needs for further development

To complete the virtual co-creation system, one more cycle will be needed. A major effort then will be the development of the visualization software to fully support co-creation. Changes to the virtual model should be possible to make in real time or at least with just a minimal delay. Only then can machine designers and operators discuss and evaluate different design options and their effects on the usability of the machine. The first step will be the possibility to select different user interface elements in the machine cabin and change their position, orientation, and appearance. All this requires great flexibility from the visualization software. Commercially available software products all have their limitations in this regard. Therefore, it will be essential to create our own visualization software and rendering engine.

At a later stage, implementing some sort of tactile interface would be useful. Generating touch feedback in the user's fingertips when touching the surfaces in the cabin would give the user a better understanding of the cabin dimensions and the effect which the positioning of the user interface elements have for work ergonomics and usability.

Development of the visualization software has already started. To emphasize the potential of the generated VIP2M concept, three researchers who took part in the action research process have formed a company for implementing virtual machine simulators.

## 4. Discussion

Our research objective was to develop design objectives with a system for VIP2M to support the co-creation process of mobile work machines. We conducted an action research project consisting of two action research cycles e.g. [Susman and Evered 1978]. Our results consist of a prototype of VIP2M and the key lessons learned from the design objectives defined.

### 4.1 Theoretical contribution

Prior research on co-creation highlights the importance of systems that support users' and designers' interactions [Prahalad and Ramaswamy 2004],[ Di Gangi et al. 2009]. However, unlike for web-based virtual worlds such as Second Life e.g. [Kohler et al. 2011], there is no prior research concerning immersive walk-in VEs. Our action research project is thus making a contribution towards filling this gap in research. Our study extends earlier work on co-creation by empirically demonstrating how to develop a VE for co-creation.

We can summarize the developed design objectives to the following two key lessons:

- Support presence experience.
- Simulate the functions and design of real-world machines.

The user tests conducted during both action research cycles indicate that supporting the presence experience of the user is very important. Measuring user performance can give information on the usability of VIP2M, but the most important thing is the reality of the driving experience. Users prefer more immersive setups. Thus, increasing the sense of presence generated for the users is worthwhile.

Experienced drivers of large work machines generally have a realistic idea of what using the machine should be and feel like. The movements of the motion platform may make the work task harder for inexperienced users, whereas experienced drivers can take advantage of them and in fact work more efficiently. From the comments of the professional drivers it became clear that the more realistically the machine functions, the better VIP2M suites for product development purposes.

Other kind of theoretical contribution is lessons learnt from the design process of VIP2M. The process constituted action research and helped us to combine general knowledge about co-creation and VEs. The key aspects of the process were to draw upon the literature on co-creation. Our reflections suggest, therefore, that the adapted approach to develop VE for prototyping can be used in other contexts of systems.

### 4.2 Managerial implications

Our paper includes also a managerial implication, namely, that using the latest technological advances can help companies working in the field of machine design and production gain advantage. Comments from the professional drivers who took part in our user tests confirm that a VE such as VIP2M can be extremely useful for product development purposes. When the appearance and functionality of the simulator are realistic enough, machine designers and operators can better discuss and evaluate different designs and their effects on machine usability.

### 4.3 Future research

Further development of VEs such as VIP2M may still need more research on issues concerning the collaborative dimension: design work between users and designers. At least the following issues not covered in this action research project remain to be addressed:

- Fast modifications to machine cabins.
- Sharing the virtual model with VEs in different physical locations.

Currently, converting the 3D CAD models to a format suitable for visualization in a VE takes anything from hours to days, depending on the size and level of detail of the model. It is already possible to make some changes to the virtual model, but to incorporate those changes back to the CAD model is another issue, which will require more work in the future.

It would be useful to be able to share the virtual model with different parties, e.g. company departments or scientific institutions located in different parts of the world. People in different physical locations could then comment and evaluate the same model. Virtual avatars could be used for the persons located elsewhere. Implementing this kind of real time connection and model sharing over the Internet remains a task for the future.

## 5. Concluding remark

Reflecting on our results and the entire 26-month action research project, we argue that the value of our study is in having been able to design and implement VIP2M with relatively low costs, as well as in the key lessons learned from this process. VIP2M can be used to support co-creation process, because the interaction between users and designers happens in a straight-forward manner in a walk-in VE.

As a concluding remark of this design work, we highlight the roles of engineering (machine design) and science (information systems science) in our study. The employed disciplines helped to develop two prototypes of a loader in VIP2M and to evaluate their quality. Another dimension of success was that after the project, a spin-off company for developing simulators was established. Thus, our multidisciplinary action research project managed to be highly relevant to practice.

## References


*Baskerville, R. L., Myers, M. D., "Special Issue on Action Research in Information Systems: Making IS Research Relevant to Practice—Foreword", MIS Quarterly, Vol.28, No.3, 2004, pp. 329-335.*

*Baskerville, R. L., Wood-Harper, A. T., "Diversity in Information Systems Action Research Methods", European Journal of Information Systems, Vol. 7, 1998, pp. 90-107.*

*Davison, R. M., Martinsons, M. G., Kock, N., "Principles of Canonical Action Research", Information Systems Journal, Vol. 14, 2004, pp. 65-86.*

*Di Gangi, P., Wasko, M., "Open Innovation through Online Communities", in Knowledge Management and Organizational Learning, W. R. Kind (ed.), New York: Springer Science+Business Media, 2009, pp. 199-213.*

*Iversen, J. H., Mathiassen, L., Nielsen, P. A., "Managing Risk in Software Process Improvement: An Action Research Approach", MIS Quarterly, Vol. 28, No. 3, 2004, pp. 395-433.*

*Kohler, T, Fueller, J., Matzler, K., Stieger, D., "Co-creation in Virtual Worlds: The Design of the User Experience", MIS Quarterly, Vol. 35, No. 3, 2011, pp. 773-788.*

*Pahl, G., Beitz, W., Schulz, H.-J., Jarecki, U., Wallace, K., Blessing, L., "Engineering Design. A Systematic Approach", Springer, 3rd ed., 2001.*

*Prahalad, C. K., Ramaswamy, V., "Creating Unique Value with Customers", Strategy & Leadership, Vol. 32, No. 3, 2004, pp. 4-9.*

*Susman, G. I., Evered, R. D., "An Assessment of the Scientific Merits of Action Research", Administrative Science Quarterly, Vol. 23, 1978, pp. 582-603.*

*Tiainen, T., Ellman., Kaapu T., "Three Frames for Studying Users in Virtual Environments: Case of Simulated Mobile Machines", Proceedings of the International Symposium on Distributed Simulation and Real Time Applications - DS-RT 2011, Manchester, UK, 2011.*



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