INTERNATIONAL DESIGN CONFERENCE - DESIGN 2006
Dubrovnik - Croatia, May 15 - 18, 2006.

DESIGN 2006

A METHODOLOGY FOR VR SYSTEMS BENCHMARKING IN THE INDUSTRIAL DESIGN PROCESS

M. Mengoni, M. Germani, R. Onori and F. Pavani

Keywords: industrial design, design review, virtual reality

1. Introduction

The majority of Virtual Reality (VR) applications developed today are either specific products oriented, not flexible enough to be implemented in every industrial design process, or are marketing presentation oriented. Despite the promise and the development activity of over two decades, there has been a considerable lack of real-world applications. The issues regarding the deployment of VR in everyday work contexts revolve around the practical difficulties: setting up special and costly hardware, requiring special teams of developers and maintenance staff, but also providing the high-level tools that will support users in their complex tasks and can succeed in establishing a collaborative VR work environment amongst individuals of different disciplines.
Experienced practitioners in the field of VR have indicated that to work effectively in a Virtual Environment (VE), the application content must include the ability to access or change environmental/system/meta parameters, create and manipulate particular objects, perform analyses, and export changes to permanent storage. While the current state of VE development has advanced its techniques to support these tasks, the company staff rarely decides to implement the VR technology to achieve complex real world tasks within its design workflow as it difficulty succeeds in measuring the effective benefits connected with the use of the VR systems. Among all the activities that can be developed in the VE, the Design Review (DR) has been identified to be the best process during the styling product development to test the real applicability of these systems.
In this context the adoption of VR systems, designed and customized on the need of the specific company, can be accepted if it is possible to quantify the achievable benefits in terms of time, quality and cost. Our research focuses on how these benefits can be objectively measured. A benchmarking program and related metrics to explore advantages and disadvantages connected with the new design technology have been studied. The main goals of the benchmarking, hence, are both to measure the performance of the VE-based design review processes using a VE by meaningful test cases and to define the VR tools possible improvements to optimise the design review process.

2. Research context and scope

In industry, VR has proven to be an effective tool for helping workers evaluate product designs. In 1999, BMW explored the capability of virtual reality for verifying assembly and maintenance processes [Gomes de Sa, 1998]. They tested the VR potentialities to reduce the number of physical mock-ups, to improve overall product quality, and to obtain quick answers in an intuitive way during the conceptual phase of a product. This successful example of VR application in the industrial field shows that it can effectively represent a solution to several product design needs. Another recent example of the use of VR systems for industrial design applications is reported in Weiss [Weiss 2005]:

he describes how a passive stereoscopy projection system can support the design process of a refrigerator. He presents a solution dedicated exclusively to product visualisation and neglects the way that can support the process iterations during to design review activities. Application of virtual reality technology provides not only a tool for product analysis, it also offers opportunities for intended users to synthesise design information themselves. A scenario-based product design process supported by VR systems for industrial design applications is described in [Tideman 2005]. It can be an approach to embody the VR systems within a structured design process. However, as reported in [Whyte 2001], there is no one single approach to VR application, but rather a set of related strategies and models that are mainly used at the later stages of the design process. Instead we believe that most advantages can be achieved along all the design workflow, especially along the first phases.
From a technological point of view, there are various VR implementations and these can be classified broadly into three categories depending on the sophistication of the technologies being used: desktop systems, semi-immersive and fully immersive systems [Burdea 2003].
Each category can be ranked by the sense of immersion or degree of presence it provides. Presence is generally believed to be the product of several parameters including level of interactivity, image complexity, stereoscopic view and the update rate of the display.
Non-immersive systems are the least immersive implementation of VR techniques. Using the desktop system, the virtual environment is viewed through a portal or window by utilising a standard high resolution monitor. These systems are of little use where the perception of scale is an important factor and many are considered not to be VR by most workers.
A semi-immersive system will comprise of a relatively high performance graphics computing system which can be coupled with a large screen monitor or large screen projector system or multiple television projection systems. They can be provided images that are of a far greater resolution than Head Mounted Displays (HMDs) and in addition, they offer a simultaneous experience of the virtual space on a high visual scale screen. An alternative to HDMs, that offer the most direct fully immersive experience of VE, is the systems provided with CAVE-like (Cave Automatic Virtual Environment) surround projectors and panoramic projectors. They require theatre like large space that can be spherical or flat. If multiple wall projection display surrounds the viewer the projection technology realizes a CAVE. The projection systems can be classified in front projection, whose disadvantage is that the volume of projectors obstructs the image on screen, and in rear projection systems. The immersion in the visual space can be realized by projecting monoscopic or stereoscopic computer graphics onto the display screens. The latest can be both active and passive according to the depth of sensation they provides and to the possibility to experience the object space simultaneously with other users. The visual sensation and the haptic feedback can be improved by implementing the system with special tracking devices [Brooks 1999]. The systems using a monoscopic visualization can be regarded as the lowest cost VR immersive solution which can be used for many applications.
Most of these systems have been implemented within research laboratories, while there has been a poor penetration in the industrial world. The interviewed industries that have just implemented the VR technology, suggested that the main difficulties connected with the use of VE are:

1. the mistrust of the technical staff to replace the traditional design techniques by innovative ones that shift the real word product space to virtual environments;
2. the lack of objective tools and methods to evaluate the real benefits achieved by the implementation of the VR within the design workflow in terms of time to market and design costs;
3. the awareness of the lacking use of the VR systems for the design activities instead of marketing purposes.

As in literature lacks a rigorous methodology to evaluate the performances of the VR systems use within an industrial design process, our research scopes are both to supply a scientific methodology to objectively evaluate the benefits generated using specific VR technology within a particular product development phase to managers and engineering operators, and to identify the design phases where its use can effectively upgrade the traditional design practices.

Our idea is to define metrics to measure the performance of the design process deployed by VR systems. A preliminary metrics list an a way to realise the related benchmarking program have been described in the present work.
In order to test the real applicability of our results we have experienced the Virtual Prototyping in a company leader in the wellness products whose project's requirements consist in a customised system based on a low cost semi-immersive technology designed around the company's products features.

3. Industrial design process and actors

Design is an activity that is rarely performed and completed by any one individually. From a design perspective, complex design problems generally require more knowledge than any one single person possesses because the knowledge that is relevant to a problem, is usually distributed among stakeholders. As the engineering world adopts methods such as concurrent engineering, designers are being required to collaborate with customers, marketing people, manufacturing engineers, suppliers, distributors, end-of-life personnel, and all other stakeholders that are likely to be affected by the evolving design process. One immediate benefit of this type of collaborative work is the coming together of participants with heterogeneous skills, who, on sharing their knowledge, skills, expertise and insight, create what is known as distributed cognition. The collaboration of individuals with different insights, tacit knowledge and expertise generally results in the generation of new insights, new ideas and new artifacts. Therefore, cooperative multidisciplinary design teams dispersed across the enterprise have to be supported and, the management of distributed information and knowledge has to be facilitated within what is known as a distributed design environment. VEs can be a valid tool to support the collaborative process around the virtual model of the new product.
An industrial design process can be seen as executing a series of design goals to arrive an acceptable solution. The design tasks are often defined by the industry's needs in the early design phases. The goals the product must achieve are related to style, manufacturing technology and budget. Based on objectives a set of important design constraints and product requirements are listed in the *product brief* given to the designers.
Designers sketch to explore design solutions and communicate with others. The act of drawing helps designers to see and understand the forms they work with. They tend to make extensive use of sketching in the first form generation (ideation) phase. Thanks to the wide development of CAS/CAID tools nowadays designers usually interpret and transform the 2D geometries into a 3D product model in order to represent the complex aesthetic shapes.
Analysing the typical product workflow of our industrial partner (figure 1), we synthesize three critical phases in the design process:

1. the first step, called 1° check point, when the company's decision making group analyses different design solutions and chooses which one better answers to the requirements expressed in the *product brief.* The presentation of a digitally modelled object usually comprises not only the 3D model itself, but also photorealistic images rendered from the model and several sketches. The design models are abstract, conceptual and lacking in technological and manufacturing information.
2. The second phase is characterized by iterative *Design Reviews* (DRs) on the physical prototype in order to define the product form coherently with functions, ergonomics and technological components. This phase can be considered the first collaborative moment between specialists with different abilities whose viewpoints generally conflict. It's generally time consuming. The full scale physical mock-up, realized by sculpturing clay or milling wood or chalk, is continuously modified according to the suggestions of the technical committee. These materials are usually different from which the final product will be manufactured. The DRs activities addressed to the aesthetic and functional product's assessment can be summarized in: sketching on the physical mock up, evaluating different materials and colours, different product additional functions, analysing ergonomics and product dimensions.
3. The third phase consists in a set of engineering design reviews that take place within the company's technical department. The aim of the design activities is to engineer the product

form. In the mechanical engineering definition the physical prototype is replaced by the CAD model that can be subjected to all kinds of geometrical and functional simulations (structural and manufacturing simulations, assembly/disassembly verifications…) In this field many efforts are made to achieve a compromise between form and function.

As the design review process needs of physical prototypes, time to market stretches and there can be the loss of the product quality due to the difficulty to assure the correspondence between the design intent, the preliminary brief requirements and the manufactured product model.

Virtual Prototyping (VP) is quickly becoming an interesting tool for product development: it allows to integrate different viewpoints in the product common space, to manage product complexity, to increase the number of product variants without realizing several physical mock-ups and finally to reduce product development time and costs.

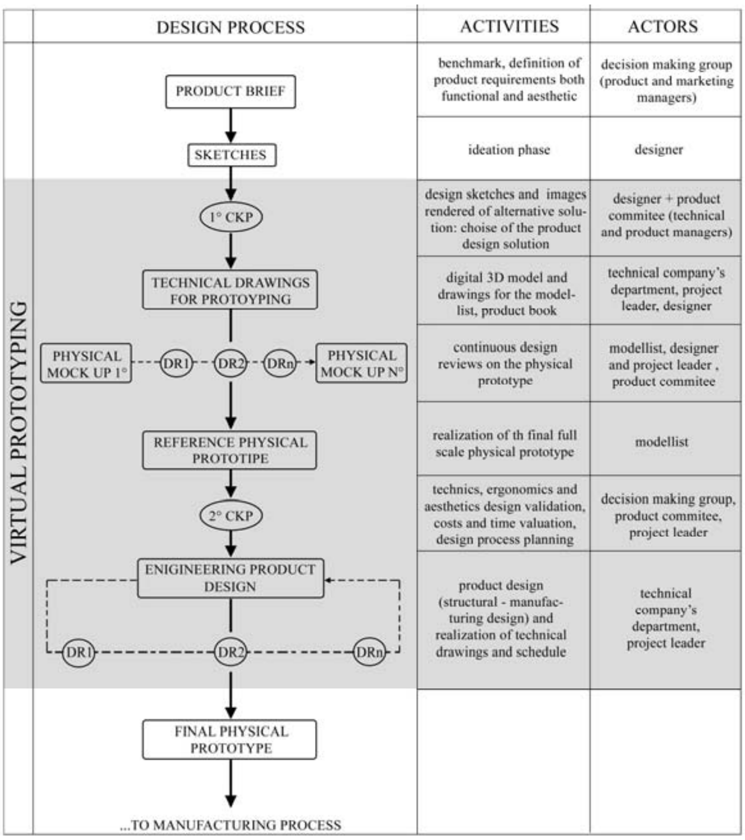

Figure 1. Industrial design process flowchart using VR systems

There seems to be two different understandings of what exactly VP is: the "computer graphics" and the "mechanical engineering" point of view.

In the computer graphics definition of VP is the application of virtual reality for prototyping physical mock-ups (PMUs). The VR system simulates and renders all characteristics relevant to the particular context as precise and realistic as possible in an immersive environment. In the mechanical engineering definition of VP the idea is to replace physical mock-ups by software prototypes in order to shorten time to market and product design cost. [Gomez de Sa, 1998].

$$VP \subset VR \qquad (1)$$

In the first decision making phase (1°CKP) and in the following design reviews, VP systems can be used to evaluate alternative design solutions. Virtual Prototyping offers some advantages such as the possibility to assess the full scale product in different virtual environments, with alternative product additional functions, with different colours and materials and to modify the shape in real time by using haptic devices. It creates a sort of virtual framework for collaborative design due to the fact that all the actors, involved in the design process, look at the model from the same viewpoint and can interact in the product model common space by annotating suggestions and technical references on it, otherwise the traditional design reviews that generally take place on paper. Furthermore it allows to store all the design process activities, recording documents, images, models showed in different working sessions in order to compare, analyse and plan the design developments, despite of the physical prototype is continuously modified during the design process.
As in the first design reviews virtual prototyping tools are used for functional and aesthetical evaluations and for exploring alternative design solutions, in the following engineering developments they are useful to integrate different abilities of the specialists involved and to show in a full scale product model both structural, ergonomic and manufacturing simulations. VP can implement the Digital Mock Up (DMU) strategy. One of the most important aspects of VP application is that several engineers can work together. At any time each of them has to know exactly about what the others are talking.

4. Metrics for industrial design process evaluation

In industry, benchmarking is an accepted technique used to identify the strengths and weaknesses of a wide range of processes, procedures, and operations associated with the company business. Benchmarking [AA.VV. 1995] typically searches for the best practices, thus leading to superior performance. Metrics are quantitative estimates of product and process performances and they can be a tool for developing the benchmarking program.
The measuring task must be performed since new effects and factors (e.g. new technologies, new staff, new product typologies, etc.) will be included in the design review phase. The design processes and benchmarking results only differ from the traditional practices in the introduction of VE.

4.1 Metrics to measure the performance of design activities

In order to quantify design process improvements by means of VP technology over successive benchmarks, performance measures are essential. A list of metrics have to be established to evaluate what are essentially subjective attributes such as usability, users satisfaction of the new technology, tools integration, non-recurring cost and process/product improvements.
We distinguish between *product* metrics, gathered in two main high-level groups: product quality and product cost, which measure product properties such as dependability and manufacturing iterations, that can be improved by DMUs simulations, and *process* metrics, which measure the advantages connected with the use of the VP tools during the whole design workflow (table 1).
As the first ones are too difficult to be measured for they allow to evaluate the product augmented quality in terms of costs and manufacturing iterations only after the consolidated implementation of the VR in the company workflow, in our preliminary VP applications benchmarking we focus on the definition and measuring of the *process* metrics that rapidly let to monitor the DR activities.
The *process* metrics can be classified into three categories: design cycle (from the 1° CKP to the engineering design reviews activities), design review process (that is a sub-class of the first but we have highlighted for its basic relevance to the process analysis), product development process that comprises all the activities that can be further accomplished by the VE (design planning, marketing, trade fair organization designing, decision making group meetings, teleconference moments, etc.)
Each metric is related to a certain unit, specified as part of its definition. We explain in more detail the less intuitive.

1. *number of design phases* = it allows to measure the reduction of the cycle design time;

2. *digital components reuse* = it quantifies the degree of VP ideation's potentialities in the definition of customized products. It can be measured by the percentage of the components, materials or additional functions presence in different models of the same line of products.
3. In the traditional practice the designer difficulty experiments different materials, colours, additional functions (e.g. taps, jets, headrests etc.) because collecting materials, adapting functions to a physical prototype are time consuming activities. The VR systems allow to test different design alternatives by easily selecting aesthetic features from a database of models and finishing maps.
4. *hardware and software reuse* = it measures the degree of VP integration in all the phases of design cycle. It can be measured by the times the VE is used for activities (as video conferences, modelling tasks, simulation analysis, project managing meetings, etc.) that are very different from DRs;
5. *software specification* = it measures the degree of software integration in terms of different tools useful for VP activities.
6. users satisfaction, easy to use, hardware and software usability = they assess the VP impact in the design review sessions.
7. *physical prototypes* = it measures the number of physical prototypes realized along the product development.
8. *workflow activities* = it is the number of the workflow activities that take place in the VP room; it measures the degree of VE flexibility for different product development objectives;
9. *manufacturing iterations* = it allows to know the efficiency of DMU simulations to predict the real behaviour of a product.

Table 1. Main and supporting metrics

Metrics			Typical Units
Process	Design Cycle	Process step time	hours
		Number of design phases	number
		Digital components reuse	percentage
		Hardware reuse	percentage
		Software reuse	percentage
		documentation	person-hours
		Software specification	number
	Design Review Process	Users satisfaction	words
		System hardware usability	
		System software usability	
		Physical prototypes	number
	Product Development Process	Workflow activities	number
		Time to repair	minutes
Product	Product quality	Correspondence to brief requirements	number
		Manufacturing iterations	number
		Dependability	number
	Product cost	Manufacturing	person-hours
		Testing	person-hours
		Maintenance	person-hours

4.2 Methodologies to analyse the design process performance

Once defined the metrics and the related units it's necessary to compute each of them by analysing the whole workflow activities deployed by the VE. We have identified two different analysis protocols to quantify the values of design metrics: the first is based on the Diary Study, [Dorst 2001], and the second is based on the Video Interaction Analysis (VIA) described by Jordan [Jordan 1995].

There have been continuing difficulties with getting access to study engineers and designers at work. The diary study is adopted to elicit information about design cycle activities in terms of either qualitative and quantitative data or a mixture (date, time, documents format, VP users…). The diary is an electronic paper based form as a MS word form. In order not to be intrusive by interviewing the VP system's users, the diary study provides a format that can be immediately filled in real time by the researchers observing the activities or by the users themselves. Unlike Culley's diary study's approach based on questionnaires [Cully 2005] to report design activities, our proposal is focused on a structured data collection where only a simple list of information is required instead of free text. (table 2). The aim of the diary is not only to share parameters values but also to structure documents for the following working sessions.

Table 2. Design Cycle information elicited in the information need component of the diary

number	date	VP users	Type of activity	Product models	Format files	File names	time
free text	free text	free text	free text	free text	checkbox	checkbox	free text

Among the methods that can be applied to evaluate users interaction and experiences in the VEs, as we are interested in understanding the moment-to-moment interactions with media, VIA is chosen to capture the interactions. A video camera positioned in the virtual room can capture the dynamics of the work sessions and the complexity of interactions, can record the human activities such as talks, nonverbal interactions, the use of artefacts and technologies and the immediate workplace context available for repeated viewing and analysis. Therefore we can assess the real usability, easy to use and users satisfaction of the new technology. This kind of analysis allows the researchers not only to measure process metrics, in terms of technology usability and of collaboration, but also to define the technology features that could be improved according to the users behaviours. In VIA research technique a team of researchers view segments of tapes selected by the primary investigator and identify design practices, problems related to the immersive technology and resources for their solution (table 3).

Table 3. Virtual design activities' report by VIA

Date	Time	Transcript (tape number)
00/00/00	00:00	Verbal communications' transcription

The tables described above are compiled to check design activities with and without VP system in order to evaluate the real advantages of the new technology by using the metrics measurement.

5. The case study

For Teuco Guzzini S.p.a., the industrial partner of this research work, the Department of Mechanics in collaboration with the technical company's department developed a semi-immersive Virtual Prototyping system for the evaluation of the aesthetic aspects, the ergonomic aspects and the functionalities of new industrial design products both in the first styling phases and in the following engineering developments. The VE consists of a DLP projector with high luminescence and a rear projection on a diffuser plate (3x2,5 m) made of special Fresnel lens that intensify the main light source. The special form of prisms allows the display to be much more efficient at collecting and directing the light rays in order to improve the image projected quality. Thanks to the low cost hardware technology adopted, to the software reuse and advantages connected with immersive environments , the system is a good compromise between costs and benefits. Since September 2005 the Virtual Prototyping system has been integrated in the company's design workflow.

During the present research program experimental phase, University researchers are continuously monitoring the design activities that take place in the virtual room by applying the Diary Study method and the VIA technique.

The industrial design product models displayed in the virtual environments are showers, whirlpool bathtubs, equipped columns, steam saunas and multifunction and fitness corners.

All the products are the result of a set of aesthetical and technological features such as wood facings, glass panels, plastic shells of shower columns and bathtubs, typically in the colours of white and blue, and the line of taps and additional functions. Although they belong to products for giving deep

sensations of well-being and bodily experiences, they are different in size, shape, materials, manufacturing processes, technological components and additional functions as aromatherapy, chromo therapy and ultrasound massage.
The Virtual Prototyping Room has been built to supply the product's visualization and simulation during the DRs.

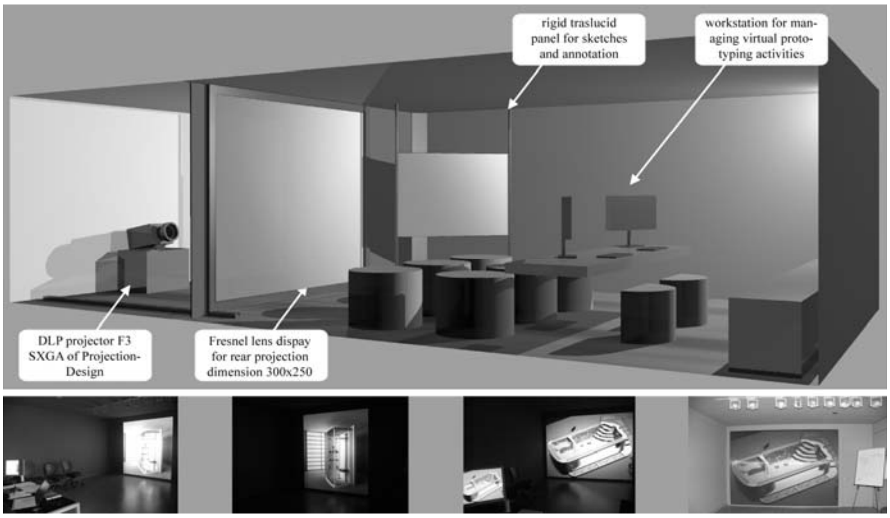

Figure 2. Virtual Reality system implemented in Teuco Guzzini S.p.a.

5.1 Initial observations: design activity

As we are developing the benchmarking program on the whole design workflow, our work is mainly focused on the study of the design review activity with the support of virtual prototyping tools. The study was undertaken during two months of design activity on three different wellness products design: the sport spa, the "asym" shower and the re-styling of an old shower.
During the design review activities the full scale prototypes were showed as rendered models images with and without different product scenes to evaluate the aesthetic impact, as animations of mechanic components, as images of structural and manufacturing analysis of the DMUs.
Besides images captured from the models, the virtual room is used to display predefined products presentations, technical schedule and design process planning. During the course of the designing a researcher records all the activities by diary study and VIA technique in order to estimate *product and process* metrics.
The Diary Study was structured as a table to be filled during the different working sessions in the virtual room (an example is reported in table 4).

Table 4. Diary study of 2 working session in VP room

session	date	VP room users	Type of activity	Product	Format files	File names	time
1	03/10/05	technical company's department, project leader	engineerin g DR	sport spa	.prt, .asm, .doc, .jpg	comp_asm.prt, sportspaver5.asm, images3.jpg, proj_plan.doc	3 h
2	06/10/05	designer, product committee	1° CKP meeting	asym shower	.jpg, .avi, .igs, .pdf, .xls, .doc	scen2_asym.avi, mat_comp.pdf, asym2.jpg, sol1_taps.jpg, briefasym.doc	2 h 30 m

The tables are then separately analysed for each product in order to compile the main and supporting metrics.
Table 5 shows an example of the diary study's elaboration for measuring the design cycle metrics (process step time, number of design phases) the DR process metrics (physical prototypes) and the product development process metrics (workflow activities).

Table 5. Example of diary study elaboration

product name	working session	time	number	physical prototype
ASYM SHOWER	1° check point	3 h 30 min	1	0
	design review	2 h	5	0
		1 h		
		1 h 30 min		
		1 h		
		2 h		
	2° check point	1 h	2	0
		30 min		
	engineering design review	1 h	7	1
		2 h 30 min		
		3 h 30 min		
		1 h		
		3 h		
		2 h		
		1 h		
TOTAL		21 h	15	1

The VIA technique results are not yet available because the experimental activity is still in progress, and it requires an amount of tapes to give a detailed response.

5.2 Results discussion

Analysing the VIA and Diary Study reports, we have preliminary noted that DR activities both on physical and virtual prototypes, have a number of similar settings and interaction styles: presenting, querying, discussion, revolving, referring to model or sketch directly by physically touch the screen, analysing the model proportions, changing the viewpoint. Furthermore in VE the users can evaluate different product solution by simply replacing different taps, colour and materials on the same 3D model, by sketching on the images rendered from the model to understand size, by comparing different product alternatives developed in previous working sessions. A detailed analysis of the interaction reveals that the semi immersive system is not intrusive: the users are more concentrated on the projected images and animations than on the technology itself, they can discuss about form and function without changing their viewpoint, they can recall previous product models and compare them (figure 3) The main difficulties expressed are related to the impossibility both to virtually sketch on the same image and to move, rotate, scale the object model simultaneously.

6. Conclusions and future developments

Being highly innovative, virtual reality environments require dedicated decision making processes to be evaluated in terms of cost/benefits. Therefore, the need for appropriate benchmarking methodologies is imperative. The proposed *process* metrics form a sound basis to objectively measure the advantages connected with the implementation of the virtual technology in the design workflow. It is proposed to use both diary study protocol and VIA technique for metrics measuring.
Future work will be focused on a wide meaningful collection of data for the validation of the proposed methodology. The benchmarking results will be used for the upgrade of the VP technology with dedicated real time software and for better quantifying advantages and disadvantages connected with the implementation of the VP in the design process flowchart.

Figure 3. The Asym shower history's comparison

References

AA.VV., "Continuous improvement. Benchmarking", Tool & Manufacturing Engineers Handbook 4th Ed., SME, chapter 7, vol 7, 1995

Brooks, F., "What's Real About Virtual Reality?" in Computer Graphics and Applications, November/December,1999, pp 16-27.

Burdea, G.C., Coiffet, P., "Virtual Reality technology", Wiley-Interscience, 2003.

Culley, S., Darlington, M., Liu, S., McMahon, C., wild, P.J., "A diary study in the engineering domain", in the Proceeding of the Studiying Designers'05, Aix en Provence, France, October, 2005, pp 181-195.

Dorst, K., Hendriks, D., "The role of the design context: in practice and in design methodology", Lloyd P. and Christiaans H. (eds), Designing in context, Delft University of Technolog, 18-20th December, 2001.

Gomes de Sa A., Zachmann G., "Integrating Virtual Reality for Virtual Prototyping", in CD-ROM Proceedings of ASME DECT 1998.

Jordan, B., Henderson, A.., "Interaction Analysis: Foundations and Practice", The Journal of the Learning Sciences, 4, 1995, pp.39-103.

Tideman M., Van der Voort M., Van Houten F.J.A.M., "A scenario based method for product design", in Proceedings of the 15th International CIRP design seminar, Shangai, China 2005, pp.31-40.

Weiss Z., Weiss E., Konieczny, R., Kasica M., Kowalski M., "Some experiences with virtual technique implementation in household product development", in CD-ROM Proceedings of Virtual Concept,Biarritz 2005.

Whyte J., "Business drivers for the use of Virtual Reality in the construction sector", in Proceedings of AVR II and CONVR 2001, Goteborg 2001, pp.99-105.

Maura Mengoni, Ph.D student
Polytechnic University of Marche, Department of Mechanics
Via Brecce Bianche, Ancona, Italy
Tel.: +39-712204797
Fax.: +39-712204801
Email: m.mengoni@univpm.it
URL: http:// www.dipmec.univpm.it