Redefining Customer Co-Design for Individualized Products Using Virtual Reality

Neufestlegung des Customer-Co-Designs für individualisierte Produkte mittels Virtual Reality

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Abstract — This paper aims to summarize and systematize author's ideas and experimental results obtained so far in course of his long research work on the application of Virtual Reality (VR) for enhancing and extending Customer Co-Design in context of developing individualized product variants. It explains the Customer Co-Design paradigm, identifies the points of useful involvement of different VR technologies in the process of creating individualized products, discusses their benefits and limitations and presents case studies from completed research projects with the author's participation supplemented by updated information and practical comments on technical details.

Zusammenfassung — Das Ziel dieses Artikels ist es, die Ideen und experimentellen Ergebnisse des Autors, die er im Rahmen seiner langjährigen Forschung zur Anwendung von Virtual Reality (VR) zur Erweiterung des Customer-Co-Design im Kontext Entwicklung individualisierter Produktvarianten erhalten hat, zusammenzufassen und zu systematisieren. Der Artikel erläutert das Customer Co-Design-Paradigma, identifiziert die Punkte, an denen verschiedene VR-Technologien sinnvoll in den Prozess der Erstellung individualisierter Produkte einbezogen werden können, diskutiert deren Vorteile und Begrenzungen und legt Fallstudien aus unter Mitwirkung des Autors abgeschlossenen Forschungsprojekten vor, die durch aktualisierte Informationen und praktische Kommentare zu technischen Details ergänzt sind.

I. CUSTOMER CO-DESIGN METHODOLOGY

Nowadays the trend for developing products precisely according to specific requirements of the individual customers (a customer centric process) is already a common practice for a lot of producing companies. In order to be successful and competitive they, regardless of their scale or specialization, have to seek diverse innovative ways to adapt their products to satisfy the individual needs of each customer while keeping the costs at the mass production level. One of the possible approaches to do so is known as *Customer Co-Design* (or as *Design-by-the-Customer*). In the context of the product development, it refers to a process in which end customers are allowed to express their specific requirements and carry out a mapping process to the physical domain of the product [1].

The Customer Co-Design for development of new products comprises two stages: *(i) Customers' Needs Identification and Structuring* and *(ii) Product Design* [2] as depicted on Fig. 1.

During the first stage customers' needs acquisition and structuring, in terms of determination of product attributes and their possible values, are performed. The aim here is to develop a product platform which is a set of items, subsystems and interfaces to form a common structure from which a stream of derivative products can be efficiently developed and produced as explained by [3]. At the end of first stage so-called *Product Family Architecture (PFA)* is evolved. It defines how a product shall be arranged from physical items and how these physical items shall interact with each other. According to [2] the PFA consists of three elements: *(i) item base of common and shared items among the different product variants, (ii) differentiation enablers that differentiate the product variants and {iii) a configuration mechanism as a set of rules that define the generation of the product variants*.

During the second phase the customers interactively design (i.e., configure) their individualized product variants. To do so they are presented a product configurator. The customers can select possible values of a set of product attributes in an iterative process. In such a case the customers are not just passive buyers, they more likely act as proactive *"co-designers"* of a product variant which is "*tailored"* especially for them. That could be observed as a two-way continuous exploration and interaction between the product (its respective producer) and the customer in which the customer's needs are systematically identified, processed, prioritized and translated in engineering requirements on which base the individualized product shall be materialized. At the end of the second stage of the process a product design alternative (individualized product) is presented to the respective customer for fine tuning and final design review.

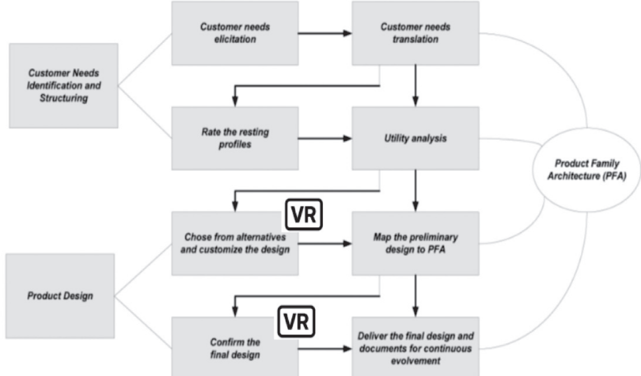

Fig. 1. Customer Product Co-Design process according to [2] with points of potential involvement of VR

The Customer Co-Design paradigm brings a lot of benefits for both the producer (of the product) and the customer which could be summarized extending the presented in [4] as follows: *(i) a better starting product configuration through direct use of customer needs, (ii) supporting the product design through creativity and expertise of its potential customers (iii) reducing product development time, cost and efforts, (iv) changing the customer attitude toward a new product*. As a consequence, the traditional cycle of *"Design – Make – Sell"* is replaced by new one *"Design – Sell – Make"*. The customers *"design"* product by themselves precisely according their specific requirements, buy it, and only then send the order to be produced.

II. Virtual Reality as Enabler of Customer Co-Design for Individualized Products

The Virtual Reality (VR) is an exciting and contemporary emerging area of computer graphics which can support communication and collaboration within product design stage. It belongs to the group of so called "exponential technologies" due to the rate of its growth and penetration in everyday life. According to the experts VR shall be a key technology of the next decade and shall disrupt the work routines in many domains leading to convergence of different information media (e.g., Metaverse). There are a lot of definitions of VR. Technically it could be referred to "a high-end user-computer interface that involves a real-time simulation and interactions through multiple sensorial channels" [5], based on so called 3 "I's": (i) Immersion, (ii) Interaction, and (iii) Imagination. The syncretic effect brought by VR when all these three elements are combined in a seamless experience gives user a sense of immersion and presence into some sort of a virtual space. That space can model physically existing reality, or be something entirely fictitious. An altered sense of immersion in VR applications typically use of stereographic visualization. Further VR applications are interactive. Users should be able to explore a virtual space to gain a greater understanding of their surroundings and collect experience on early design stages. A number of special input devices are available for VR applications, from head position trackers to data gloves, which can provide a high level of interaction between user and environment. VR has proven to be an effective tool for helping engineers to evaluate product designs [6]. Using VR enables everyone on a design team to understand underlying ideas better, leading to more informed and meaningful decision making. The reason for this is as simple as obvious: the possibility of a 1:1 representation of complex 3D interactive structures allows a realistic viewing and evaluation of products or objects which do not yet actually exist in the physical realm. Furthermore VR *(i) reduces the number of physical product prototypes needed; (ii) improves the overall product quality through frontloading of information on early development stages; (iii) improves the communication flow and collaboration; (v) streams up the design process;* and *(vi) reduces cost and time to market.* Because of all these the different types of VR (non-immersive VR, immersive VR, Augmented Reality, Mixed Reality) are being increasingly integrated into the product lifecycle and used for different tasks as reported for example in [7], [8], [9].

The Virtual Reality provides an environment which enables a proactive participation of customers in defining their own needs and requirements as well as an interactive multimodal validation of the properties of the configured products. With VR the customers are allowed to carry out more efficient mapping of their functional requirements into the physical domain and then they are able not only to observe or simulate they individual "creation", but also to perceive it through multiple sensory channels (e.g., visual, audible and tactile). All this suggests that VR is very promising as technology for implementation and enhancement of the Customer Co-Design approach for the case of development of individualized products. According to [10] where a considerable and representative number of sources reporting VR applications in design has been analyzed, VR has a good potential as a facilitator of participatory design activities.

On the ground of the performed analysis and practical experience two points, where involvement of VR into the Product Design stage of the Customer Co-Design process makes sense, have been identified as shown on Fig.1: *(i) Product configuration* and *(ii) Design Review (Validation)*. The specific tasks and the different VR technologies used are explained below on example of case studies.

III. Virtual Reality for Product Configuration

The product configuration is referred to a process of selecting different product attributes and their values and combining them into a final configuration (i.e., product variant). The product configurators are defined respectively as software tools that are used for performing diverse activities in an act of manufacturer-to-customer interaction [11]. The configurators perform various tasks and contain much more than calculating algorithms. They check the specification of individual product configurations for completeness and consistency. Additional functionalities such as price and delivery time calculation etc. may be provided.

Regardless of the fact that the study conducted on information sources has found out numerous reports of 3D, visual and web-based configurator applications (e.g., cars [12], e-commerce products [13], diverse [14], the use of VR for product configuration is not that common with only a few reports (e.g., [15] immersive configurator for conceptual design, [16] VR based personalization of smart products). This fact shows that the topic is still not enough studied and worthy of attention, especially in context of Customer Co-Design.

A. *Non-Immersive VR Product Configuration*

Technically, the non-immersive VR is an alternative form of VR which is often overlooked because it is a part of everyday life. It also places the user in a 3D environment, however the interaction with that environment is on a conventional Desktop PC using a monitor, a keyboard and a mouse. Another significant difference to the Immersive VR is the fact that the user remains aware of and is able to control his/her physical environment. Much of the technology that support both VR types is same or at least similar (e.g., 3D models, interaction, lighting, shading, etc.) as described in [17].

One of the possible ways for direct involvement of the customer within virtual product development process is the use of 3D websites. 3D model of the product over Internet enhances communication and collaboration between the customers and the producer located in geographically dispersed places. The customer can select some of the product features and their correspondent parameters using a virtual model of the product manipulating it using the standard web controls. In general, a virtual product model contains data that are used to render a 3D digital world in which the customer could navigate in real-time and interact with the objects located therein. Regardless of his/her geographical location the user of the configurator could *"explore"* the virtual product in a 3D virtual space from different angles and with different resolutions and is able to interact with the product, to trigger animations or simulations showing product dynamic behavior such as assembly or disassembly sequence, working operations etc.

The websites containing VR functionality are two types: *(i) sites that display interactive 3D models directly embedded into web pages* and *(ii) sites that are based on a 3D virtual environment which is displayed via plug-in inside the web browser*.

In the first case, the primary information structure and user's interaction methods are still based on the hypermedia model, with the additional possibility of inspecting 3D objects. In the second case, the primary information structure is a 3D space, within which users move and perform various actions. Technologies for implementation of 3D Web sites are based on the commonly used technical and architectural solutions typical for the "conventional" web. The content, represented in a proper format, is stored on a server, requested by a client, through HTTP, and displayed by a browser, or by a plug-in for a web browser. 3D content can be integrated with other kinds of multimedia content such as images, sound, videos. For implementation of 3D Web two open ISO standards are used: VRML and X3D. There are also many other (non-standardized) technologies for 3D on the web. Recently wide use finds the WebGL software library related to graphic based on OpenGL. It allows the user to incorporate a 3D graphic directly in the browser. WebVR is an Internet based web technology which provides support for virtual reality devices (e.g., Oculus Rift, HTC Vive) [18].

In order to test the technological feasibility and integration options of non-immersive VR functionality intended for a direct involvement of customers in the development of individualized product variants an experimental prototype of a web-based, non-immersive VR configurator on the base of *DriveSets* product family was implemented. *DriveSets* have been designed as a scalable and a "self-evolving" parametric range of electric driven linear positioning and handling systems for industrial and laboratory automation, built with OEM components as shown on Fig. 2. A detailed explanation of the *DriveSets* product family concept is given in [19].

This configurator represents a wizard, in which a set of product attributes and their possible values are presented for selection and modification by the "co-designing customer". It renders a simplified (in term of low LOD and lack of textures) 3D representation of a product variant in the web browser, animates the system operation and allows changes of the structure and key parameters (e.g., dimensions, travel of axes etc.) as shown on Fig. 3. The configurator provides some typical VR interactions (e.g., rotating, aligning, flying etc. The proposed solution is slick and simple. It uses XML descriptions of the configured product variants for generation of a X3D files that are visualized directly in the web browser. DOM scene interface connection provides dynamic display of and interaction with data. The calculation algorithm is implemented as a C++ application. It communicates through TCP/IP socket technology with the configurator DB and the PHP application which generates HTML pages based on predefined templates and are served by APACHE web server. Details about the implementation can be obtained from [20].

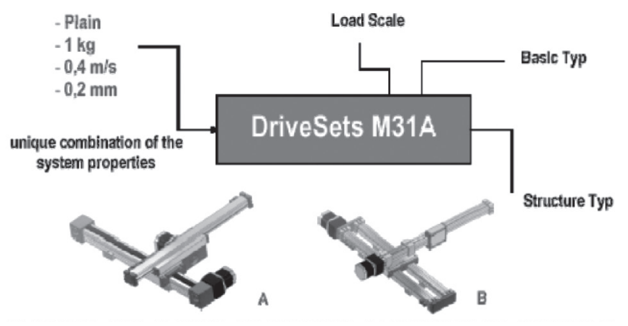

Fig.2. Example for a product variant of DriveSet positioning and handling system with respective key system parameter set and product family number

At this research stage the described experimental implementation of a non-immersive product configurator has fulfilled its purpose for studying technological feasibility, user interaction, working flow and an educated guess can be made that use of non-immersive VR facilitates and simplifies process of product configuration leveraging involvement of customers as co-designer of their own unique product variants. With attachment of additional functional information, it could be expected that it shall be possible to develop an advanced X3D based product model for more sophisticated VR representation and for extending the configuration features. Further development here could include implementation of additional algorithms, automatic validation checks of configured product variant, optimization loop etc.

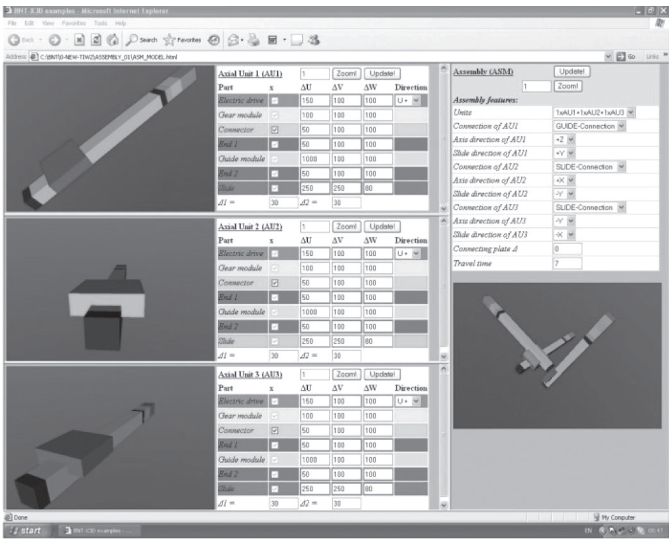

Fig.3. User interface of the experimental implementation of a non-immersive VR product configurator

B. *Immersive VR Product Configurator Using HMD*

Head-mounted display (HMD) is a display device worn over the user's head as could be seen on Fig. 4. It features a display in front of the eyes that stream data, images and other information. Besides that, HMD may feature position tracking and stereo sound, providing a high level of immersion. There are many types of HMDs for various purposes with different characteristics starting with the very simple cardboard box and ending with sophisticated wireless devices [21].

The HMD VR as a concept and implementation is definitely not new, but in the last years there is a growing attention to HMDs end-user devices for immersive presentation of Virtual Reality. This is mainly due to the investments in the sector from some major companies (e.g., Facebook, Alphabet, Sony etc.) and the introducing on the market of a third wave of new, affordable devices of different featuring acceptable and high-end performance characteristics. However, the main focus for practical use of these HMDs is limited to gaming, social VR, entertainment, showcasing and other similar topics. Engineering applications, in particular related to the product customization such as in [22] are not commonly reported as stated in [10]. Most probably the reason for that is related to the performance characteristics of the available devices which are still not optimal and there is a long way before reaching the required maturity. The performed analysis shows however that HMDs have a significant potential to become a valuable tool for supporting engineers in performing their routines and decision making and for bringing new dimensions to the application of traditional CAD and CAE. In this term, the exploration of the specifics of the HMD interaction and user interfaces is of a significant importance.

For the purpose of this case study for testing the usability and UX of HMD VR, a simple VR-based product configurator application for a dummy product has been implemented. It was adopted that the product, subject of the configuration process, constitutes an assembly built from multiple subassemblies and/or single parts presented in different variations (instances). The configurator provides two main roles for the participants in the process: *Engineer (administrator)* and *Customer (user)*. The *Engineer* prepares the *Product (a modular assembly)* and creates a hierarchy of objects. Each object (assembly, subassembly, single part) has its own different properties that can be handled. Beside other, the Engineer can configure the compatibility between the objects to enable implementation of real-world scenarios. The Customer configures the Product based on the object hierarchy defined by the Engineer, handles it in the VR environment and finally stores the configuration. The configuration process can be restarted or performed multiple times. Thus, different configurations can be created, tested and compared. This provides better user experience, improved configurations and satisfaction. The tasks of the Engineer and the Customer require different interactions and user interfaces. Therefore, the configurator is divided in two sub-applications, which communicate through the standard JSON format.

The main part of the Product Configurator is presented by the application, which provides a Virtual Reality environment accessed with a Head-Mounted-Displays (HMD) and interacted through a hand tracking system (Leap Motion). In this environment, the user can look in arbitrary direction, move and resize the configured assembly object, change its properties (e.g., color, shape, etc.) and undo and redo previous operations. The test scenario is intended to be performed in a suitable virtual environment (e.g., room). The customer interaction is performed with "virtual hands" as shown on Fig.4. They react on every movement of the user's hands and fingers and repeat it in the VR environment. Using gestures, the user can easily handle the configured object, change its size and perform zoom-in and zoom-out. A user menu is integrated in one of the virtual hands and provides access to variety of options and functions. In order to maintain the cognitive load at acceptable level the interaction paradigm and visual interface have to be simple as recommended in [23]. Full details about the implementation and integration of this testing configurator can be found in [24].

Fig. 4. Testing the immersive product configuration using HMD

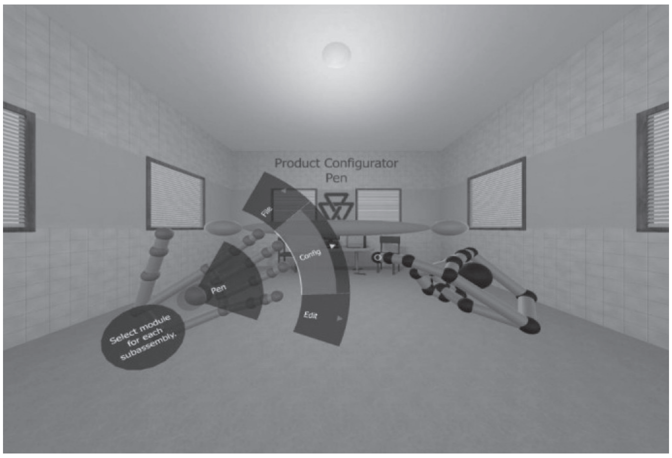

Fig. 5. User interface of the immersive VR product configurator featuring "virtual hands" avatar and functional menu

A simplified usability study of the product configurator has been performed based on a predefined testing procedure to evaluate the proposed interaction paradigm and UX as shown on Fig. 5. 16 participants took part in the testing with equal count of males and females. The participants of age 18 - 24 years (students) prevail. In the performed study, every respondent should configure his/her individualized variant of a simple dummy product. At the beginning the purpose of the study has been explained to the respondent. After that, he/she receives instructions about the way of use of the configurator and the virtual hands mechanics is explained. Each participant has put on the HMD by himself/herself and has performed multiple tasks. Upon completion of the testing procedure the first impressions have been registered through a personal interview upon and then the user should complete a usability questionnaire with 20 questions.

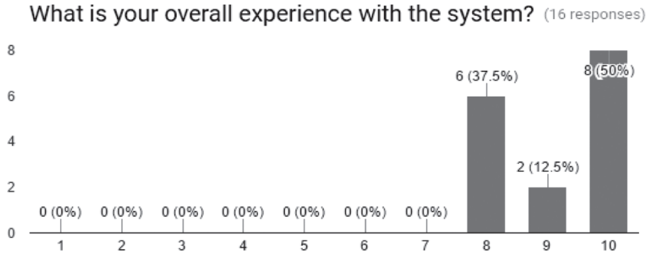

Fig. 6. Evaluation of the of the overall user experience from the use of the immersive HMD based product configurator, 10 presents the best possible

The most of the respondents report positive experience with configurator as shown on Fig. 6. Half of them is completely satisfied with it. One of the most important issues related to the Virtual Reality is the physical comfort of the user. Manifestation of some of these symptoms with different extent are reported from five of the participants, mostly a general discomfort. Only in one case the symptoms persisted after termination of the test procedure.

It was found that the resolution of the HMD has a significant effect on the quality of the user experience. The experiment has been performed using an Oculus Rift HMD of low fidelity. For most of the participants the text in the VR environment has been hard to read and this has hindered the interaction with the application. Nearly two-thirds of the participants has liked the control with the virtual hands. The rest has reported some difficulties in interaction which has been overcame after a short learning period. According to the majority of the users the menu is well structured and organized, but not far from perfect. Due to too many options which it provides is regarded as difficult. One possible solution of this issue shall be the use of voice commands or gestures (related to additional tracking sensors). where is stated that HMDs are not optimal suited for such type of applications in the validation experiment the overall evaluation is good what is contradiction with the statement in [10] that HMDs are not optimal for such types of tasks. That motivates for future development of the immersive VR configurator. Most probably the negative aspects were not due to the product configurator itself, but from the performance characteristics of the used hardware. The technology is improving continuously and therefore it may be expected that the low resolution, latency and related discomfort or sickness symptoms shall be not an issue very soon.

IV. VR FOR DESIGN REVIEW AND VALIDATION

The design review is a milestone within the product development process. It evaluates a specific design to provide feedback on whether or not it meets a definite set of initial criteria and requirements and is feasible to implement. The main goal of the design review is to check and identify any errors and potential issues, to propose solutions for them and to optimize the overall final design. For the Customer Co-Design a design review is essential to ensure that the product variant design configured by the customer (not expert user) within a defined PFA (individualized product) is checked and approved by a competent user (producer of the product in the role of an expert) prior to release its “materialization”.

On the grounds of a thorough analyses of significant number of information sources on the VR usage in Engineering design [25] finds out that a lot of researchers tried in the past few years to integrate the VR into design evaluation. Examples for real-world applications of VR for design review are presented for example in [26], [27], [28].

According to [29] VR technology may contribute to a better understanding of geometrical properties (dimensions, spatial arrangement, topology etc.) as the designs can be viewed in full scale and in a way that would otherwise be impossible and allows to identify issues which are difficult to see on a flat screen presentation in case of conventional design review techniques and tools. Besides that, a specific product variant can be imported into an immersive environment that mimics the native environment in which this product is used. This enables participants involved in the process to get frontloading related to the product properties and behavior and to perform a deeper exploration of the potential problems.

A. *Final Confirmation of Configured Product Variant Using Immersive CAVE VR*

According to the Customer Co-Design process depicted on Fig. 1 upon the completion of the configuration the newly evolved product variant has to be approved for production. For this purpose, a CAD model of the product variant has to be reviewed using VR.

The Cave Automatic Virtual Environment (CAVE) is a projection-based virtual reality space of three to six walls. This technology is rather old (since 1992) and good known, see [30]. However, the CAVE technology is especially suitable for performing design reviews. From one hand it brings a full-immersive experience, and from the other the users always remain aware of and is able to control the physical environment like in non-immersive VR. That is very important for making the right decisions. Due to this fact CAVE VR has been chosen to support the final confirmation of the configured product variants within Customer Co-Design.

The simplified design review pipeline using VR comprises four stages: *(i) CAD model creation, (ii) CAD model virtualization, (iii) "Putting life"* and *(iv) Immersive experiencing* as shown on Fig. 7. At the beginning (1st stage) the 3D models (assets) are created with the industry standard 3D modelling software applications (e.g., CATIA, SolidWorks, Creo etc.). Within 2nd stage these assets are prepared for integration in a virtual scene. The assets are either converted in an appropriate exchange format (e.g., VRML. STEP etc.). In this case problems may eventually appear due to information loses. The model can also be imported directly within a VR scene graph editing or VR publishing applications, this requires respective plug-ins. This process of CAD model virtualization is described in details in [31]. NuGraf program is a good option for conversion due to its unique ability to import, render and optimize 3D data from literally all known 3D file formats and is used here as middleware. In the 3rd stage the virtual models are brought to life. They are enriched with semantics and meta data. Interactivity is added by application of behavior scripts or direct programming. The elements of the virtual scene are spatially and temporally organized in dynamical virtual environments (worlds) comprising of scenes and levels. Further the special interface devices (e.g., "space-mouse", "flying-stick", "magic wand" etc.) are defined that shall be used for exploration of the so created virtual world. Additional sensory channels such as 3D sound pictures or haptic feedback can be added as well. All this could be mate either with a specialized software (e.g., Unity) or directly in the VR rendering application, if it has authoring functionality (e.g., Poly VR or Covise). The design review itself is performed in the 4th phase. The virtualized CAD models and their virtual environment are rendered on CAVE VR (stereoscopic projection system) facility and are ready to be experienced by the user to complete final confirmation. Recently Dassault Systems has provided a new functionality in its 3D Experience platform for direct VR visualization of CAD data created on it. A final review of a newly evolved product variant based on above mentioned *DriveSet* product family within a validation experiment in the CAVE environment at IMI - KIT is shown on Fig. 8. This pipeline remains the same when a deep immersive VR using HMD has been chosen as visual output. If so, the user is excluded from the physical environment and that may affect and bias the decision making with a negative effect.

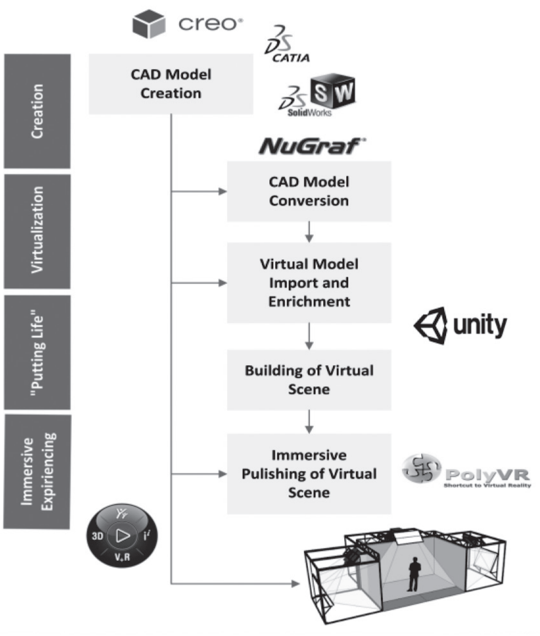

Fig. 7. Design review pipeline using Virtual Reality

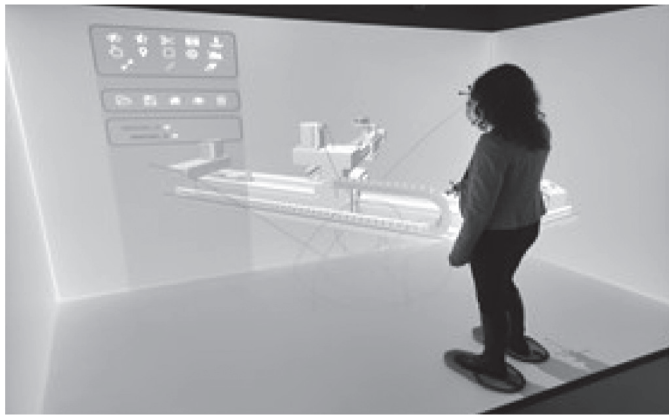

Fig. 8. Final confirmation in CAVE environment using Poly VR, a full-scale scene authoring system for engineering applications It combines common virtual reality features like clustering, tracking and scene graph operations with advanced features, physics engine, simulation

V. Conclusion and Outlook

Customer Co-Design is a product design approach used nowadays as a common practice by several producing companies in order to adapt their products to satisfy the individual needs of each customer while keeping the costs at the mass production level. It benefits mainly from the *creativity and expertise of potential customers who are* involved at predefined points in the product development process. This guarantees a precise identification of the specific customer's requirements in every single case, reducing the time for development, number of design iterations, cost and efforts. It also changes customer attitude toward the product perceived now as a fully individualized product. Combining the Customer Co-Design with the power of VR technology redefines and enhances the process bringing new functionalities and possibilities for both, Customer and Producer, and ensuring successful outcome. Two points of useful application of VR technologies in Customer Co-Design workflow have been identified: configuration of product features and confirmation of evolved product variants.

On the grounds of experimental implementations and validation experiments it was found that immersive and non-immersive product configurators are technologically feasible using a mix of software techniques and hardware. Presently end user devices (i.e., displays and interaction devices) have still not reached technological maturity and their performance should be improved in order to provide better UX and to be widely used for the immersive VR product configurating tasks in the practice. The market of VR gear is highly dynamic. New devices appear all the time and they should be tested in order to find the right hardware setup. User interactions and workflow have been assessed as satisfying, however far from optimal and require fine tuning based on large scale study of the user preferences. It makes sense to consider implementation of "self-adjusting" virtual environment for the configurator which can adapts itself to the individual characteristics of the user. A pipeline for immersive design review of four stages was proposed. It uses CAD model of a product variant which is virtualized and enriched with semantics and behavior and published as immersive virtual scene in immersive CAVE facility. The CAVE technology combines a full-immersive experience with user's ability to stay always aware of the physical environment in order not to bias decision making. In the next step this pipeline has to be automated.

As further research it will be exciting to study implications of use of AI-enabled VR for product configuration and the possibilities for integration of Customer Co-Design process directly in one of the emerging VR platforms such as Metaverse.

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