



## Virtual Reality-Enhanced Configuration Design of Customized Workplaces: a Case Study of Ship Bridge System

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### ABSTRACT

The paper proposes a design method for the configuration of customized workplaces supported by the use of VR tool. The method allows to consider end-users anthropological features and configuration aspects related to the workplace (e.g. equipment). The adoption of VR technology allows supporting the configuration process, engaging end-users in the final customization. A yachts' ship bridge console is proposed as a case study and a VR-enhanced configuration tool has been developed for the equipment configuration. The adoption of this tool in this specific field shows different advantages such as efficiency in configuration and time saving for the development of workplaces design alternatives. Another benefit of this approach is the automatic generation of an associated BoM and its management through PLM tools.

**Keywords:** VR, Design, Configuration, Anthropological aspects, Ergonomics, Ship bridge system.

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### 1 INTRODUCTION

New market paradigms forces companies offering tailored products to meet customers' demands. A possible way to reduce complexity in the management of different product variants is the use of engineering methods which address the configuration of available solutions, without producing deeply and costly design modifications [5]. Configuration design is defined as a design approach able to develop complex products by using a set of predefined components or components' features [11]. Configuration management allows to create product families and platforms, by assembling modules and components in predefined manners to satisfy a set of requirements and constraints [17]. Product family is a group of related products that share common features, components, and subsystems, and satisfy a variety of market niches [23].

Several methods for configuration design have been investigated in literature as well as their link with computer-aided design technologies [19] [24]. Configuration tools have been developed to aid the engineering tasks during the development of product families and platforms. These tools have been deployed in different industrial contexts with the aim to facilitate the management of complex issues (e.g. components' manufacturability, assemblability of product variants, etc.) [21] [3] [20] [6]. Currently, these tools are consolidated systems in the design and engineering process of industrial products (e.g. automotive, appliances) [8]. The link with 3D CAD systems allowed the development of platform-based products which are considered an efficient way to manage product variants and customizations [1] [12].

Shifting the perspective from product design to the development of more complex systems, such as workspaces and workplaces' equipment, the issue of customization becomes even more complicated. Configuration design of customized workspaces requires a multi-disciplinary approach which includes mechanical design, materials selection, ergonomics, product architecture, etc. [4] [10] [14]. End-users bring at the configuration design level an important knowledge about processes, tasks and potential risks into the development process. This knowledge contributes to both the quality and acceptance of the design solution.

In the last two decades, virtual reality (VR) tools have appeared in the development process of customized product [2] [7]. VR tools allow to design and test virtual prototypes without necessity to build physical prototypes. In particular, these tools have been adopted to include ergonomics factors in the development of specific products (e.g. passenger's vehicles) [13] or to define assembly tasks in specific environments (e.g. plant's control rooms) [9] [18]. In addition, VR systems allow future operators to explore the work environment, in which the workplace and equipment are placed as well as to test tasks and working operations considering the interaction with the equipment and the surrounding environment [10]. However, the literature in this field is mainly focusing in testing ergonomics issues without providing an efficient tool for the customization of products based on the specific needs and features of end-users. Only few examples exist in literature for the configuration of customized workplaces such as bridge control room, cockpits, etc. [15] [16] [22]. Indeed, these workplaces, due to their specific aspects, need to be designed considering tailored characteristics of the end-user, general arrangement of navigation equipment, mechanical/safety features, etc.

The present paper proposes a method for the configuration of customized workplaces (e.g.; control rooms, bridges, cockpits, etc.) by using the mean of virtual reality and considering the anthropological features of the end-users. The approach allows arranging configurable equipment based on specific needs starting with the characteristics of the end-users. By using computer aided design tools, designers are able to combine both workplace configuration and visualization in a 3D environment. The adoption of immersive environments (e.g.; virtual reality) allows supporting the configuration process, engaging end-users in the final customization. A VR-enhanced configuration tool for the configuration of yachts' ship bridge console is proposed as a case study. It allows a fast layout definition of monitors and navigation tools including the reliable validation of their usability by ship owner and/or captain.

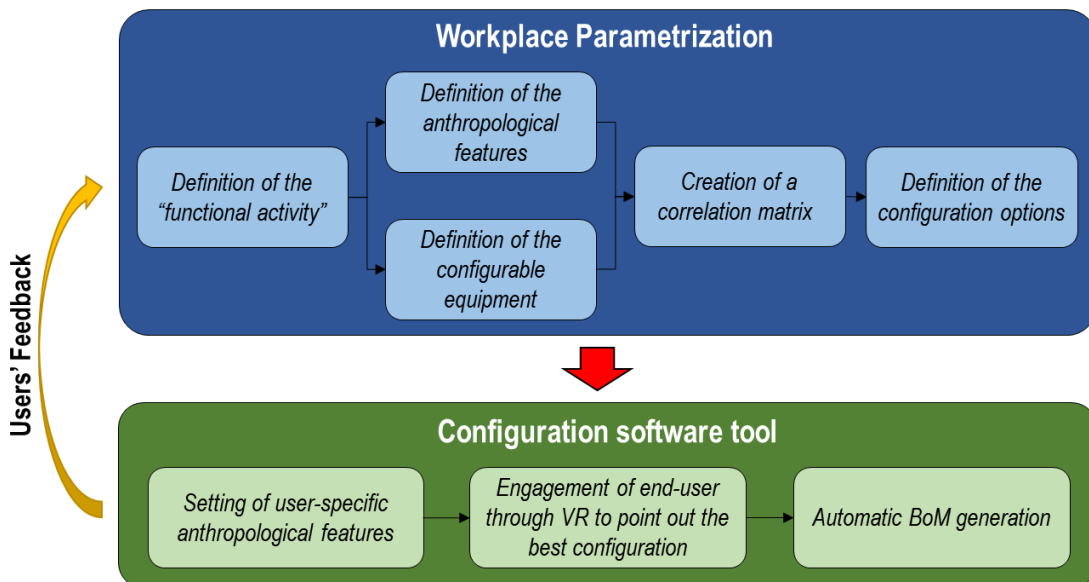
The final goal of this research activity is to include ergonomics and physical aspects as configuration parameters for the development of customized workspaces. The main novelty is related to its application in specific fields (ship bridge design and configuration) which require a high degree of personalization, such as assembly workspaces, control rooms, cockpits, etc.

The rest of the paper is structured as follows: Section 2 presents the VR-based method and tool for customization of workplaces; Section 3 shows the implementation of the configuration tool in the context of motor-yacht bridge system design; Section 4 discusses the results obtained and finally Section 5 presents conclusions and proposals for future work.

## 2 METHOD

The proposed method aims at the definition of immersive environments (VR system) for the configuration of customized workplaces starting from the anthropological features of end-users. The general framework of the method is presented in Figure 1.

The approach has a generic validity in the configuration of customized workplaces and it can be deployed starting from the specific purpose of the environment under analysis (e.g.; cockpit, bridge room, workstation for manual assembly, etc.). The method is grounded in two main modules: the workplace parametrization and the configuration software tool.



**Figure 1:** Proposed method for design configuration of customized workplaces.

### 2.1 Workplace Parametrization

The first module, called “Workplace Parametrization”, allows to identify all the possible items that can be tailored within the workplace, as well as the configuration options which are depending on the anthropological characteristics of a generic end-user. This phase is performed once for each workplace, although the configuration options can be latter modified based on feedbacks coming from the second phase or technological improvements.

The first step of the first module is the “functional activity” definition. The functional activity describes the purpose of the product for which is being designed, and thus the activity that the product should enable to do with safety and comfortably. Two main tasks characterize this step: (i) the definition of the configurable equipment and, (ii) the identification of the anthropological characteristics that should be considered during the design process. These activities can be performed independently, and thus there is not any priority constraint between them. The meaning of configurable equipment is defined as: “each item in the workplace that can be modified during the design phase and replaced with functionally equivalent alternatives that can ensure the fulfilling of the “functional activity”. On the other hand, the anthropological characteristics are all the characteristics of the final user that can affect his/her use experience. Typically, height, weight, size, and other specific features are the most important anthropological characteristic to link with the configurable equipment. Particular diseases can be pointed out to automatically configure the equipment in the workplace, such as color blindness, paraplegia, amelia, etc. In

addition, personal tastes can be considered as one of these characteristics, since several configurations may depend on aesthetics choices and personal preferences.

At the end of these steps, two lists of items are produced: the configurable equipment ( $m$ ) and, the anthropological characteristics ( $n$ ). These two lists are used to create a correlation matrix ( $m \times n$  matrix) that enables to identify the anthropological characteristics that affect each configurable equipment. For each correlation between configurable equipment and anthropological characteristics, it is possible to define a finite number of configuration options, considering technological and dimensional constraints. The number of configuration options may depend on the available technology, available aesthetic alternatives and alternatives of the correlated anthropological characteristic.

## 2.2 Configuration software tool

The second module, called "Configuration software tool" consists in the development of a software tool based on the workplace parametrization previously created. The architecture of the VR-Enhanced configuration system tool is proposed in Figure 2. The tool requires a VR environment, typically a fully immersive system such as CAVE™ (Cave Automatic Virtual Environment). The objects are displayed via 3D rear projector on the active walls of the room and the user, equipped with special helmet/glasses, is able to see the stereoscopic image. The helmet/glasses are also equipped with position trackers to ensure the image changing in front of the user's eyes when he changes his/her position. The use of VR devices (such as joystick, wand or a data glove) enable the person to interact with the virtual objects. All these mentioned items represent the hardware of the system.

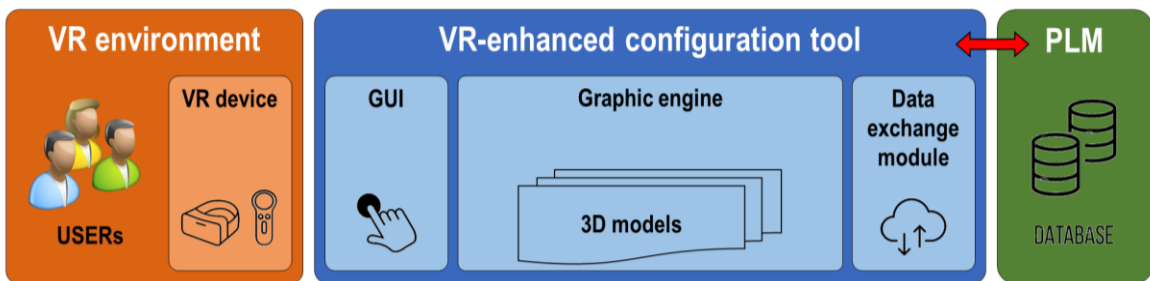


Figure 2: VR-Enhanced Configuration tool architecture.

The software tool is mainly based on three modules: (i) the graphic user interface (GUI), (ii) the graphic engine, and (iii) the data exchange module.

The graphic engine is an integrated development environment (IDE) and it can be considered the core of the system. Commercial IDEs can be adopted for this purpose such as Unity, Dassault Systems 3DVIA Virtools, Quest3D, etc. The graphic engine hosts other tools which are used for different purposes (e.g.; rendering, image processing, sounds, collision detection, scripting, animations, etc.). The graphic engine is the module responsible to create and to host the virtual models of the objects placed in a properly defined environment, ensuring the user experience (interaction and immersion). For example, 3D modeller (e.g. 3DS MAX by Autodesk) can be used to define and to create the workplace equipment.

By using the graphic engine, it is possible to develop the GUI. The GUI requires to be developed considering how the user interact with the tool. Usually, the GUI is built for a fully immersive interaction for this kind of application (by using the VR devices). Sometimes, immersive interaction is coupled with common video interface typically adopted for the anthropological features settings.

The data exchange module is able to exchange files with the company repositories (e.g.; PLM), to store defined configurations and to automatically generate the Bill-of-Materials (BoM). This useful feature allows an easy management of future orders of production.

The interaction of the end-user with the configuration tool consists in different phases. Firstly, the end-user interacts with the system by inputting his/her specific physical characteristics (e.g. height, weight, size). Once that this information is gathered, a preliminary workplace configuration is automatically defined. Secondly, the end-user starts the VR session with the aim to explore and to modify all the items of the workplace based on his/her personal taste. By using the VR devices, the end-user can evaluate all the remaining configuration options including the pre-defined items. If the user is not fully satisfied, his/her feedbacks and suggestions, together with the feedbacks of other users, can be gathered as design knowledge and reused to modify the configuration rules. Finally, when the configuration is completed, the software tool is able to export the necessary information for the generation of the Bill of Materials (BoM).

### 3 CASE STUDY

The method described in the previous section has been adopted for the development of VR-enhanced configuration tool in the field of a motor-yacht bridge system. A yacht is a complex product that is completely customized based on the owner's needs. In particular, some areas (e.g.; accommodation, decks, etc.) are developed following the owner's requirements, and some other technical areas need to be developed to facilitate the work of the crew members.

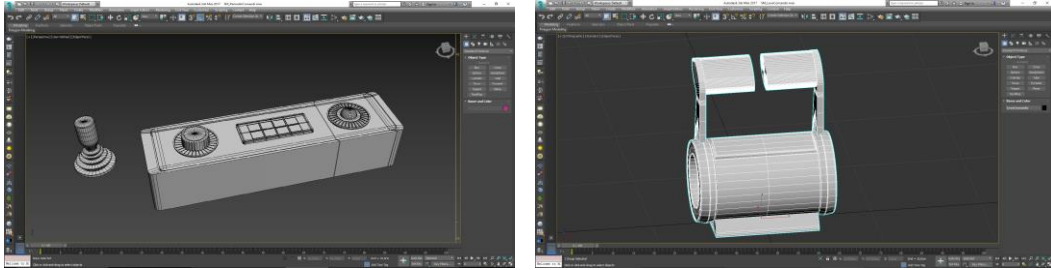
The bridge can be considered the core of the ship and it must be always attended during navigation. The captain is the end-user of the bridge and interacts with the installed equipment. The bridge control system shall guarantee to the captain the full control of the yacht functionalities including safety aspects, in a comfortable and tailored environment.

Based on the developed framework, the first task of the "workplace parametrization" module concerns in the definition of the "functional activity". In this case, the "functional activity" is defined as "the interaction with the navigation equipment for the control and monitoring of a luxury yacht". Following the "functional activity" definition, the two subsequent tasks to perform are: (i) the "definition of the configurable equipment" and, (ii) the "identification of the anthropological features". In the case of ship bridge system, the configurable equipment are the following:

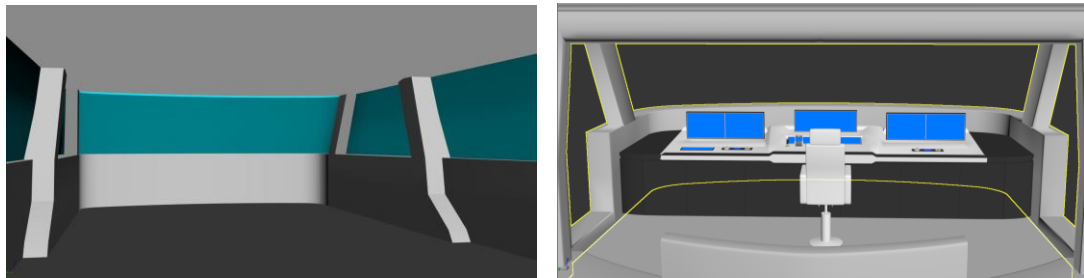
- monitors (position, number, type, rake angle);
- throttle lever (type, position);
- handheld control system devices (type, position);
- chairs (type, number, position) and;
- bridge (material, colour, backlighting colour).

This equipment needs to be modelled with a dedicated CAD tool and then stored in the software repository to be available during the configuration. Two example of 3D models developed for two equipment used in ship bridge system is provided in Figure 3 (respectively the handheld control system devices on left, and the throttle lever on right). The graphic engine used in this example is Unity by Unity Technologies, while 3DS MAX by Autodesk has been used as 3D modeller.

Another important aspect is the evaluation of the surrounding environment, which means the analysis of geometrical constrains for the bridge arrangement. In this specific case study, this task regards the arrangement of ship bridge system inside the bridge room with the aim to identify possible issues related to interference (e.g.; the bridge with the room walls) and the capabilities of the room to host multiple equipment (e.g.; multiple monitors). An example is provided in Figure 4, where the mock-up of the bridge control room is imported in the 3D system and the bridge system with the equipment is arranged.



**Figure 3:** Example of the 3D modelling for configurable items (e.g.; handheld control system devices and throttle lever).



**Figure 4:** Importing of the bridge control room in the 3D system (a) and arrangement of the ship bridge system into the room (b).

Concerning the “identification of the anthropological features”, the following three are identified in the case of a ship bridge system:

- end-user height;
- end-user right/left handed; and
- end-user personal taste.

The combination of configurable equipment with anthropological features allows the “creation of a correlation matrix” which is another task of the method. In the example reported in Table 1 rows represent the configurable equipment with the possible configuration options, while columns represent the anthropological features.

<i>Configurable item/equipment</i>		<i>Anthropological features</i>		
		<i>Height</i>	<i>Right/Left handed</i>	<i>Personal taste</i>
Monitors	Position			X
	Number			X
	Type (typically size)			X
	Rake angle	X		
Throttle lever	Type			X
	Position		X	
Handheld control system	Type			X

devices	Position		X	
Chairs	Type			X
	Number			X
	Position			X
Bridge	Material			X
	Colour			X
	Backlighting colour			X

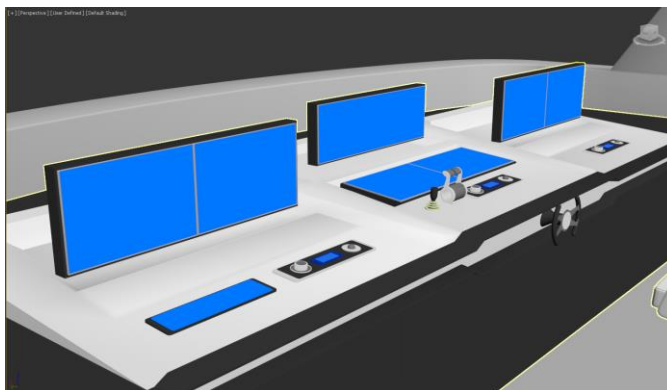
**Table 1:** Correlation matrix between configurable equipment and anthropological features.

For each relation identified through the correlation matrix, the configuration options have been defined considering technical, dimensional and functional constraints. The “definition of the configuration options” is the last task of the workplace parametrization module.

Considering the monitor arrangement for this type of navigation bridge, two sets of monitors are acceptable (Figure 5): the first one in horizontal position ( $0^\circ$ ), and the second one in vertical position ( $90^\circ$ ). A set of monitors may consist of different number of monitors distributed in each position. In addition, for each monitor it is possible to define its type, which means the size and the orientation (portrait or landscape). Concerning monitors’ rake angle, for a matter of simplicity, only the monitors in vertical position can be arranged based on anthropological features. At the end, two possible configurations have been defined:  $90^\circ$  (vertical position) for users lower than 1.75m, and  $105^\circ$  for users taller than 1.75m.

The throttle lever can be selected based on the possible alternatives available in the software repository (commercial items or customized). The throttle lever can be arranged on the left side or on the right side of the steering wheel, depending if the captain is right handed or left handed. As for the throttle lever, the same options are available for the handheld control system devices. In this case, the devices can be arranged on the left side or on the right side of each one of the three monitor’s blocks.

For the bridge, different materials can be selected based on end-user personal taste: (i) satin-finish stainless steel, (ii) leather, (iii) wood and, (iv) carbon fibre-reinforced composite. Only for the leather and wood materials, three different colours are possible: black, blue and red. In addition, it is possible to choose the colour of the bridge backlighting: blue, red and, yellow.



**Figure 5:** Horizontal ( $0^\circ$ ) and vertical ( $90^\circ$ ) position of the monitors in the bridge.

As described above, the 3D model of the bridge and of the equipment have been realized with *3DS MAX* by Autodesk, while *Unity* has been used as graphic engine. The result of this implementation is a software application as presented in Figure 6. This is the result of the “configuration software” module. In particular, the picture highlights a pre-configuration for a left-handed user taller than 1.75m. In this case, the rake angle of the monitors, the throttle level position and the handled control system devices position have been pre-set on the basis of the user anthropometric characteristics. The other configuration options, instead, can be chosen by the user in real time, depending on his/her personal taste.



**Figure 6:** Screenshot of the configuration software.

Concerning the hardware, in the specific case study the system has been implemented in a real scale VR environment which is composed by:

- 3D rear projector on the active wall of the room (Christie Mirage 2000);
- 3D glasses which allow to see the stereoscopic image (Volfono EDGE VR);
- joystick (Xbox controller) which enables the person to interact with the virtual objects.

For the glasses, different models can be adopted in the VR environment. In particular, the proposed CAVE hardware configuration allows the use of glasses/helmet which includes position trackers to ensure the image changing depending on the user point of view.

Once that the configuration is completed, the software allows the user to save a XML file containing a list of all the equipment used in the current configuration. This file can be imported in a product life cycle management tool (PLM) for the automatic handling of orders and for the BoM generation. The 3D file of the selected configurations can be also stored in the PLM as well.

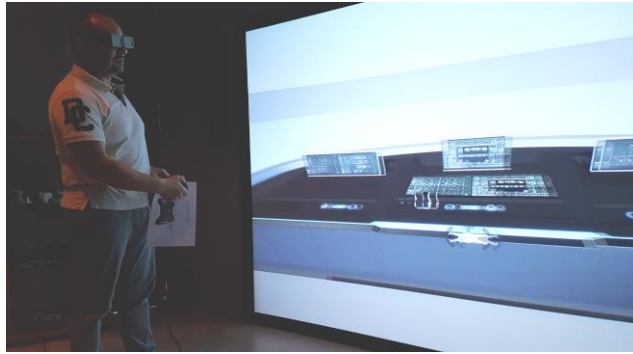
#### **4 MAIN RESULTS OF THE VR-ENHANCED CONFIGURATION TOOL DEPLOYMENT**

The proposed approach and, in particular, the developed VR-Enhanced configuration tool for the ship bridge system has been deployed within a design department of an Italian shipyard and it has been tested for a period of six months. The testing activity involved 14 end-users, mostly captains and owners of motor-yachts. After each working session with the VR-Enhanced configuration tool (duration of approx. 30 min), end-users answered a short questionnaire to verify the effectiveness of the systems during the configuration and to have a rating of several items such as: (A) end-user elicitation and satisfaction, (B) easyness in equipment customization entering antropological features (C) functionalities (e.g. not configurable options). A set of questions for each mentioned characteristic has been developed following the framework proposed by the ISO/IEC 14598 and



ISO 9126 standards for software product quality evaluation. As an example, a picture of the VR testing session is reported in Figure 7. From this picture it is possible to notice the used equipment and how the end-users can interact with the virtual model in a real scale VR environment.

A summary of the survey results is reported here below (Table 2 and Table 3). Survey answers are based on a five-point Likert scale (1 - Strongly disagree; 2 - Disagree; 3 - Neither agree nor disagree; 4 - Agree; 5 - Strongly agree).



**Figure 7:** Example of the VR trial session.

Testing results show that the configuration tool has been generally evaluated positively by the end-users, who declare themselves satisfied by the tool (mean score = 4.0). In particular, highest scores in *Section A* have been reported in questions A5, A6 and A8. End-users highlight that the tool enhances the awareness about the possible workplace customization, that it efficiently supports the configuration tasks and that it is helpful for the purchase management in order to avoid errors, misunderstandings and regrets on aesthetic choices. The lowest score of this section has been observed for the question A3. This result could be expected, since although VR headset have made major improvements during the last few years, many people still suffer from motion sickness when using them. The score obtained is however positive (above 3.0), since motion sickness is limited by the fact that the application is stationary, and during the simulation the user remains seated, and the headset is worn for a limited time.

*Section B* has obtained the best overall score. The configuration tool is indeed quite simple, since the final user only has to input the required anthropometric characteristics and chooses between several configuration options. Most part of each session is spent to decide which option is preferred. Since this decision strictly depends on personal taste, total duration of the tests have shown great variance, with a mean value of each VR session of about 9.5 minutes, a maximum value of 16 minutes and a minimum value of 4.2 minutes.

The simplicity of the tool may have influenced the score obtained in *Section C*, which is the section lowest mean score. In particular, the question C3 obtained a mean score of 2.6, which is the lowest of the entire questionnaire. Not every possible configuration option for the equipment has been in fact inserted in the tool, because of the unavailability of 3D models during the tests. These virtual models unfortunately are not very common in the shipbuilding sector, and the process to reconstruct them can be time consuming. Beside this fact, end-users declared to be satisfied by the workplace parametrization, thus no further modifications have been performed to the choice of configurable equipment, anthropometric characteristics and configuration options.

An additional section (*section D*) of the survey includes also questions related to the anthropological features of the end-users (e.g.; gender, age, height, right/left handed, handicap and years of experience, etc.) and personal remarks about the way to improve the system. This

section has the aim to link the answers of section A, B and C with the personal features of the involved end-user.

<i>Questions</i>	<i>Number of Answers</i>					<i>Mean score</i>
	<i>(1)</i>	<i>(2)</i>	<i>(3)</i>	<i>(4)</i>	<i>(5)</i>	
<b><i>Section A - End-user elicitation and satisfaction</i></b>						
A1 – Did you successfully use the system??	0	0	3	6	5	<b>4,1</b>
A2 – Were you able to control the system and all its features?	0	1	4	4	5	<b>3,9</b>
A3 – Did you feel comfortable during the VR experience?	1	2	6	3	2	<b>3,2</b>
A4 – Did the tool provides a right configuration based on your anthropological features?	0	1	4	6	3	<b>3,8</b>
A5 – Did the tool increases your awareness about the possible workplace customization?	0	0	1	7	6	<b>4,4</b>
A6 – Was the tool more efficient and faster in configuration than a standard practice (e.g.; interviews, co-design session)?	0	0	2	6	6	<b>4,3</b>
A7 – Will you ask for a similar tool for the next configuration?	0	1	5	4	4	<b>3,8</b>
A8 – Do you think that this too will be helpful for the purchase management (e.g.; avoid errors and misunderstandings)?	0	0	3	6	5	<b>4,1</b>
<b><i>Section B - Easiness in equipment customization</i></b>						
B1 – Did you find the user interface easy to use for the equipment customization?	0	0	2	8	4	<b>4,1</b>
B2 – Did you need the help of the assistant during the selection of possible configurations?	0	0	2	10	2	<b>4,0</b>
B3 – Was it easy to configure the monitors?	0	1	3	2	8	<b>4,2</b>
B4 – Was it easy to configure the throttle lever?	0	1	2	3	8	<b>4,3</b>
B5 – Was it easy to configure the handheld control system devices?	0	1	2	3	8	<b>4,3</b>
B6 – Was it easy to configure the chairs?	0	1	2	3	8	<b>4,3</b>
B7 – Was it easy to configure the bridge?	0	0	3	3	8	<b>4,4</b>
B8 – In general, was the configuration easy to perform?	0	1	3	5	5	<b>4,0</b>
<b><i>Section C - Functionalities</i></b>						
C1 – Did the tool provides all the possible configuration based on your personal needs?	1	3	4	4	2	<b>3,2</b>
C2 – Did the tool allows configuring all the equipment necessary for the navigation?	1	1	7	3	2	<b>3,3</b>
C3 – Did the tool allows configuring all the possible options for each equipment?	2	5	4	3	0	<b>2,6</b>

**Table 2:** Survey and results for the testing of the system effectiveness during the configuration.

<i>Sections</i>	<i>Mean score</i>
<i>Section A - End-user elicitation and satisfaction</i>	<b>4.0</b>
<i>Section B - Easyness in equipment customization</i>	<b>4.2</b>
<i>Section C - Functionalities</i>	<b>3.0</b>

**Table 3:** Mean scores for each section.

## 5 CONCLUSIONS

In this study, a methodology for the development of VR tools aimed to the configuration of customized workspaces has been presented. The design of customized workspaces needs the involvement of representative end-users, which may be not familiar with common design tools and documents, such as 2D drawings or CAD models, and thus may be not able to take specific decisions. Configuration tools based on VR technologies can be developed to integrate typical aspects in this context such as ergonomics, anthropological features, personal attitude and taste. Advantages of these systems are shown in terms of product configuration efficiency and time saving for the development of customized workplaces design alternatives. Another relevant benefit of this approach is the automatic generation of an associated BoM and its management through PLM tools. Main limitations of this approach are due to the time required for the creation of the equipment 3D virtual models, which are not always available and must be specifically created.

The application of the proposed approach in a real case study (ship bridge system) indicates that the evaluation methods and representations would be useful to close the gap between designers and end-users avoiding continuous design reviews or even worse post-manufacturing adaptations. In particular, a survey has been conducted among 14 end-users, mostly captains and owners of motor-yachts. The results of the survey proved the perceived usefulness of the developed tool, that resulted to be more efficient in configuring solutions and easier to use than a standard practice tool. Most of the end-users declared that the tool increased their awareness about the possible and acceptable workplace customizations. On the other hand, the user's feedbacks retrieved by the survey highlight few possible improvements of the tool. Some of these concern the possibility to increase the number of possible configurations related to the aesthetical features of the equipment (e.g.; increase the number of materials and colours of the bridge, make available the possibility to choose monitors frame colours or glossy vs. matte display, etc.). Other possible improvements are strictly related to the anthropological characteristics of the end-users and they affect the type (model) of the equipment. In particular, they refer to:

- the possibility to include different models and technologies for the handheld control system (e.g. touch screen systems) and for throttle lever (e.g.; with dedicated panel for speed and rpm);
- the possibility to include equipment provided by different suppliers which have been already developed for person with disability.

Further developments are necessary to fulfil these missing functionalities highlighted by the software tool testing activity. Future work should be focused on the application of the proposed methodology to other case studies, in order to prove its replicability and flexibility in other design contexts where products features, design constraints and end-user's profiles are completely different.

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## REFERENCES

- [1] Azamatov, A.; Lee, J.-W.; Byun, Y.-H.: Comprehensive aircraft configuration design tool for Integrated Product and Process Development, *Advances in Engineering Software* 42(1-2), 2011, 35-49. <https://doi.org/10.1016/j.advensoft.2010.10.016>
- [2] Aromaa, S.; Väänänen, K.: Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design, *Applied Ergonomics*, 56, 2016, 11-18. <https://doi.org/10.1016/j.apergo.2016.02.015>
- [3] Ascheri, A.; Ippolito, M.; Colombo, G.; Furini F.; Atzeni, E.: Automatic configuration of a powertrain assembly line layout based on a KBE approach, *Proc. IEEE Emerging Technology and Factory Automation (ETFA)*, Barcelona, 2014. <https://doi.org/10.1109/ETFA.2014.7005294>
- [4] Berg, L.P.; Vance, J.M.: Industry use of virtual reality in product design and manufacturing: a survey, *Virtual Reality*, 21(1), 2017, 1-17. <https://doi.org/10.1007/s10055-016-0293-9>
- [5] Chandrasegaran, S.K.; Ramani, K.; Sriram, R.D.; Horváth, I.; Bernard, A.; Harik, R.F.; Gao, W.: The evolution, challenges, and future of knowledge representation in product design systems, *Computer-Aided Design*, 45(2), 2013, 204-228. <https://doi.org/10.1016/j.cad.2012.08.006>
- [6] ElMaraghy, H.; Schuh, G.; ElMaraghy, W.; Piller, F.; Schönsleben, P.; Tseng, M.; Bernard, A.: Product variety management, *CIRP Annals* 62(2), 2013, 629-652. <https://doi.org/10.1016/j.cirp.2013.05.007>
- [7] Fan, K.; Murai, A.; Miyata, N.; Sugiura, Y.; Tada, M.: Multi-Embodiment of Digital Humans in Virtual Reality for Assisting Human-Centered Ergonomics Design, *Augmented Human Research*, 2(7), 2017. <https://doi.org/10.1007/s41133-017-0010-6>
- [8] Fellini, R.; Kokkolaras, M.; Michelena, N.; Papalambros, P.; Perez-Duarte, A.; Saitou, K.; Fenyes, P.: A sensitivity-based commonality strategy for family products of mild variation, with application to automotive body structures, *Structural and Multidisciplinary Optimization*, 27(1-2), 2004, 89-96. <https://doi.org/10.1007/s00158-003-0356-x>
- [9] Gatto, L.B.S.; Mól, A.C.A.; Luquetti dos Santos, I.J.A.; Jorge, C.A.F.; Legey, A.P.: Virtual simulation of a nuclear power plant's control room as a tool for ergonomic evaluation, *Progress in Nuclear Energy* 64, 2013, 8-15. <https://doi.org/10.1016/j.pnucene.2012.11.006>
- [10] Grajewski, D.; Górski, F.; Zawadzki, P.; Hamrol, A.: Application of Virtual Reality Techniques in Design of Ergonomic Manufacturing Workplaces, *Procedia Computer Science* 25, 2013, 289-301. <https://doi.org/10.1016/j.procs.2013.11.035>
- [11] Haug, A.; Hvam, L.; Mortensen, N.H.: Definition and evaluation of product configurator development strategies, *Computers in Industry*, 63(5), 2012, 471-481. <https://doi.org/10.1016/j.compind.2012.02.001>
- [12] Jiao, J.; Simpson, T.W.; Siddique, Z.: Product family design and platform-based product development: a state-of-the-art review, *Journal of Intelligent Manufacturing*, 18(1), 2007, 5-29. <https://doi.org/10.1007/s10845-007-0003-2>
- [13] Lawson, G.; Herriotts, P.; Malcolm, L.; Gabrecht, K.; Hermawati, S.: The use of virtual reality and physical tools in the development and validation of ease of entry and exit in passenger

- vehicles, *Applied Ergonomics*, 48, 2015, 240-251.  
<https://doi.org/10.1016/j.apergo.2014.12.007>
- [14] Marconi, M.; Germani, M.; Favi, C; Raffaelli, R.: CAD feature recognition as a means to prevent ergonomics issues during manual assembly tasks, *Computer-Aided Design and Applications*, 15(5), 2018, 734-746. <https://doi.org/10.1080/16864360.2018.1441240>
- [15] Nordby, K.; Børresen, S.; Gernez, E.: Efficient Use of Virtual and Mixed Reality in Conceptual Design of Maritime Work Places, *Proceedings of the 15th International Conference on Computer and IT Applications in the Maritime Industries*, Lecce, 2015.
- [16] Österman, C.; Berlin, C.; Bligård, L.O.: Involving users in a ship bridge re-design process using scenarios and mock-up models, *International Journal of Industrial Ergonomics*, 53, 2016, 236-244. <https://doi.org/10.1016/j.ergon.2016.02.008>
- [17] Pakkanen, J.; Juuti, T.; Lehtonen, T.: Brownfield Process: A method for modular product family development aiming for product configuration, *Design Studies*, 45(B), 2016, 210-241. <https://doi.org/10.1016/j.destud.2016.04.004>
- [18] Pontonnier, C.; Dumont, G.; Samani, A.; Madeleine, P.; Badawi, M.: Designing and evaluating a workstation in real and virtual environment: toward virtual reality based ergonomic design sessions, *Journal on Multimodal User Interfaces*, 8(2), 2013, 199-208. <https://doi.org/10.1007/s12193-013-0138-8>
- [19] Raffaelli, R.; Mengoni, M.; Germani, M.: Improving the link between computer-assisted design and configuration tools for the design of mechanical products, *AIEDAM*, 27(1), 2013, 51-64. <https://doi.org/10.1017/S0890060412000388>
- [20] Salvador, F.; Chandrasekaran, A.; Sohail, T.: Product configuration, ambidexterity and firm performance in the context of industrial equipment manufacturing, *Journal of Operations Management*, 32, 2014, 138-153. <https://doi.org/10.1016/j.jom.2014.02.001>
- [21] Song, I.; Shimada, K.: Sketch-based Computer-Aided Design Tool for Configuration Design of Automobile Instrument Panel, *Computer-Aided Design and Applications*, 6(5), 2009, 585-594. <https://doi.org/10.3722/cadaps.2009.585-594>
- [22] Wang, L.; Xiang, W.; He, X.; Sun, X.; Yu, J.; Zhou, L.; Sun, G.: The virtual evaluation of the Ergonomics layout in Aircraft cockpit, *IEEE 10th International Conference on Computer-Aided Industrial Design & Conceptual Design*, Wenzhou, 2009. <https://doi.org/10.1109/CAIDCD.2009.5375353>
- [23] Zha, X.F.; Sriram, R.D.: Platform-based product design and development: A knowledge-intensive support approach, *Knowledge-Based Systems*, 19(7), 2006, 524-543. <https://doi.org/10.1016/j.knosys.2006.04.004>
- [24] Zhang, L. L.: Product configuration: a review of the state-of-the-art and future research, *International Journal of Production Research*, 52(21), 2014, 6381-6398. <https://doi.org/10.1080/00207543.2014.942012>