A Framework for Virtual Prototyping-Based Design of Operator Support System for Construction Equipment

Vahdatikhaki F., Makarov D., Miller S., Doree A.
University of Twente, the Netherlands
f.vahdatikhaki@utwente.nl

Abstract. Improper design of construction equipment operator support systems can lead to the erosion of operators' trust and ultimately failed adoption. Because keeping the end users in the development process is time-consuming and costly, this is seldom done. To address this issue, a new virtual reality-based framework is proposed in this study. In this framework, designers of the operator guidance system utilize a Virtual Prototyping (VP) platform of the guidance system to receive feedback from the end-users. VP platform allows end-users to have an immersive experience with the front-end system and provide feedback without requiring the designers to make a substantial investment in the design of the back-end structure. This framework is applied to a case of a compaction guidance system. It is demonstrated that VR simulators are able to serve as a technology assessment platform that allows end-users to open transparent and substantive dialogues about the system with the designers.

1 Introduction

In recent years, owing to the rapid development of information technologies, many real-time support systems are developed to help operators of construction equipment improve their performances by allowing them to base their strategies on real data rather than their experiential base (Teizer et al. 2010, Vahdatikhaki and Hammad 2015, Wang and Razavi 2016, Park et al. 2017). These Operator Support Systems (OSSs) deploy sensors and real-time location systems to collect data about the equipment status (Langroodi et al. 2021) and the surroundings of the equipment (Park et al. 2017) and provide the operator with different levels of guidance, e.g., the presence of workers in the blind spot, the best strategy for the next movement, etc. The positive contribution of these systems to the safety, productivity, and quality of construction operations is amply demonstrated in the literature (Lee et al. 2009, Lee et al. 2012, Feng et al. 2015).

The main limitation of the current body of knowledge in equipment operator support systems is that the main focus is usually placed on the technical dimensions of these systems, i.e., methods in which data are collected and translated to relevant information. In doing so, very little attention was paid to the user interface aspect of such systems. This is a major oversight because the successful adaption of these technologies in practice heavily predicates on the acceptance by the operators and without a proper strategy for the Human-Computer Interaction (HCI) of these systems operator acceptance is seldom achieved (Son et al., 2012, Liu et al. 2018).

The HCI-sensitive design of OSS requires the active engagement of operators in the design cycle to ensure that not only operators needs are properly addressed by the system, i.e., from the functional requirements perspective, but also the system does not pose an operational challenge to the operators, in terms of usability and cognitive load. Nevertheless, the user-engaged OSS design in the construction industry is very challenging due to the following reasons: (1) For the users to be able to interact and experiment with OSSs, they need to be exposed to working prototypes of the systems. These working prototype needs to have a certain level of stability and maturity before they can be used for the experimentation; otherwise, the

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operators cannot focus on the usability aspect of the OSS for feedback. However, when the prototypes are developed to this level of maturity, the cost of modifying the system architecture based on the feedback from the end-users is high; (2) Given the high cost of construction equipment, the tight schedule on which equipment operators work, and the strict liability mechanisms, operators are hardly ever willing to compromise the project by pay attention to OSSs, in fear of being held accountable for subpar quality; and (3) Construction operators normally function in a largely intuition-driven and experience-oriented working ecosystem. As such, their interaction with OSSs is usually characterized by the sheer lack of trust in the systems, especially when OSSs are not compatible with operators' intuition.

Virtual Prototyping (VP) has been long applied in other industries and domains to address the above-mentioned issues (Wang 2002, Alberto and Puerta 2007, Kim et al. 2011). To apply the VP concept, a virtual replica of a system/product is developed using virtual reality to allow users to interact with the design artifact safely and securely. While VP has been also used in the construction industry mainly in the building and infrastructure sector (Li et al. 2008, Li et al. 2012) , e.g., through the use of Building Information Modeling (BIM), it has rarely been used for the user-engaged design of construction equipment OSS.

Therefore, this research proposes a framework for the VP-based design of construction equipment OSSs. In this framework, Virtual Reality (VR)-based simulators are used to communicate the design intent and alternatives with the end-users. To this end, a case study of compaction OSS is used to demonstrate the feasibility and effectiveness of the proposed framework. It should be highlighted that the present work is based on the generalization of the previous work of the authors which reported on the specific design issue with respect to compaction OSSs (Makarov et al. 2021). In this research, the result of the same case study is used but from the lens of assessing the feasibility and usefulness of using VP in the design of construction OSSs.

The remainder of this paper is structured as follows. First, the proposed framework is presented. This is then followed by the case study. Finally, the conclusions and future work are presented.

2 Proposed Framework

Figure 1 presents the overview of the proposed framework. As shown in this figure, the framework consists of three main phases, namely, identification of user requirements, development of virtual prototyping platform, and assessment and analysis. These phases need to be followed sequentially in order to gain an insight into the usability, as well as, usefulness aspect of the construction equipment OSSs.

2.1 Identification of User Requirements

The first phase in the proposed framework is largely based on the model-based systems engineering's principle (Madani and Sievers 2018). The first step in the process is to identify the stakeholders of the system. It should be highlighted that given the scope of construction equipment OSSs, the main stakeholders are operators, construction workers, site safety managers, and project managers. Operators are important because they are the direct users of the system; they need to interact with the system, analyze the information, develop strategies and execute them. Therefore, they are the main stakeholder of not only the content but also the interface design of OSSs. Workers play a role because one of the main goals of equipment OSSs is to improve the safety of the construction sites by avoiding collisions with the workers. Thus, although they do not directly interact with the system, the functionality of the system impacts their work environment tremendously. From this perspective, the workers are more concerned with the content of OSSs to make sure information pertinent to their safety is reflected in the systems. The site safety managers also have a stake in these systems because they want to make sure OSSs can contribute effectively to the global safety of the construction site. From this standpoint, the site safety managers adopt a more holistic view towards safety (as compared to workers) and have an interest in the fleet-level and crew-level safety rather than the individual-level performance of the system. Project managers, on the other hand, have yet more global view of OSSs because they expect the system to contribute not only to improved safety but also productivity, cost, and product/process quality. They have a strong impact on the definition of the scope of OSSs to shape them as all-around support systems. Other players can also play a role in setting the requirement of systems, such as client (quality perspective), government (sustainability perspective), etc. It is the role of the system designers to identify the stakeholders and determine to what extent and when they need to be involved in the design and testing of OSSs.

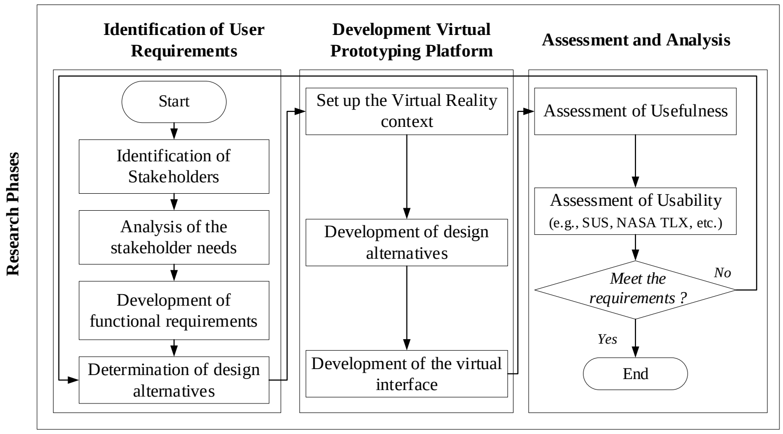


Figure 1: Overview of the proposed framework

Upon the identification of the stakeholders, it is important to identify their needs from the OSS. The identification of the needs can be best done through interviews and workshops with the stakeholders. It is important to note that at this level the needs are required to be expressed in terms of high-level expectations and aspirations (e.g., the system should improve safety).

It is important because a detailed dialogue about the system at this stage may create more confusion as there can be contradictory views of the system among the stakeholders, which can be easily detected if the discussion is kept at the needs level.

The next step in this phase is to identify the functional requirements of the OSS. In this step, the specific features that the OSS needs to deliver to address the needs of the users will be derived by the designer. This includes requirements such as the OSS needs to warn the presence of nearby workers.

Once the functional requirements are set up, the designer needs to develop several different alternatives for the OSSs in terms of how the functional requirements are materialized. This can for instance be about whether the warning against nearby workers is generated in terms of an audio warning, visual warning, or a combination. The designer needs to develop a list of all the alternatives and have them ready for development in the next phase of the framework.

2.2 Development of VP platform

Once the alternative designs are determined, the designer needs to set up the VP platform. VP platform consists of the context, user interface of the OSS, and the VR user interaction, as shown in Figure 2.

Context refers to the overall environment that simulates the condition of the construction site in the VP platform. The previous work of the authors provides a comprehensive description of the context for a realistic VR environment and how it can be generated (Vahdatikhaki et al. 2019). In short, the context includes the geometry of the site, the location, and movement of other equipment/workers, permanent and temporary structures, etc. These elements of the context can be either (1) hypothetical (i.e., built from scratch) or (2) data-driven (i.e., virtual reconstruction of the actual site), as explained by Vahdatikhaki et al. (2019). In doing so, BIM models, publicly available GIS data, LiDAR 3D point clouds, and other 2D and 3D drawings of the construction site can be used to build a realistic context. Also, the tracking data of equipment from past projects, if available, can be deployed to better represent the dynamic aspects of the construction site. Based on the authors' extensive field observations, it is very important to bear in mind that it is very difficult to ask operators (especially with years of experience) to make a distinction between the content and presentation of information in the virtual OSS. The general tendency of the operators is to view the entire system as a single unit. Therefore, incongruities between the actual and virtual context can significantly distract the operators and derail the whole discussion over the OSS usability. Besides, to allow operators to better experience the features of OSS, it is important to build a context that can showcase the full functionality of the OSS design.

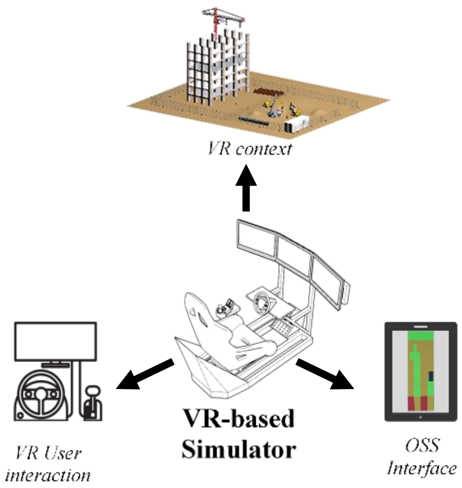


Figure 2: Components of VP for OSS design

Other than the context, the designer needs to determine the VR interaction mechanism. Depending on the type of equipment for which OSS is being designed, a steering wheel, joysticks, and pedals can be used to replicate the cockpit. As for the screen, either a multi-screen monitor setup or a VR headset can be used. While VR headset can offer a better immersive experience, it imposes higher graphical requirements on the system (i.e., to reduce VR sickness) and also pose a technical challenge with respect to tracking and visualizing the hand motions of the operator. For an accurate interaction between the control units and the virtual equipment in the VP platform, it is important to rig the 3D model and capture all the controllable degrees of freedom of the equipment.

Given that the main purpose of developing VP for equipment OSS is to allow end-users to assess the usability of the OSS, it is important to develop the OSS interface as realistic to the design intent as possible. The interface should capture the graphical and audio characteristics of the ultimate design and in general should provide the operator with the pieces of information needed to improve safety, productivity, sustainability, and quality of the operation (depending on the needs determined in Phase 1). Similar to the case of context, the accuracy of the OSS design is vital to have a substantive dialogue with the operators. It is also important to note that other than the Graphical User Interface (GUI) aspect of OSS, it is important to capture the context-system interaction of the OSS as much as possible. In other words, for the user interface to be deemed realistic it should accurately and realistically represent the impact of user decisions, which is manifested in the interaction with the control unit of the VP platform, on the context. Therefore, it is important to make both the interface and context dynamic.

By incorporating the above-mentioned components, the designer should develop different design alternatives in the VP platform.

2.3 Assessment and Analysis

The last stage of the proposed framework is to assess the developed OSS from the usability perspective. To this end, experiment sessions need to be arranged with the potential respondent to allow them to use and interact with the VP platform and compare different alternatives. It would be a good practice to combine new end users with some of the stakeholders who participated in Phase 1. This would allow to assess the extent to which the designed OSS alternatives can globally address the end-users' needs. A statistically significant difference in the assessment by the new and recurring participants can suggest an incomprehensive representation of the end-users' needs.

In essence, the usability of the OSS can be assessed mainly in terms of how easy-to-understand and easy-to-work-with the OSS is. These can be assessed through a number of criteria. System Usability Scale (SUS) is a popular framework that is designed to assess the usability of industrial systems through a set of standard questions (Brooke 1996). Among applications in many domains, SUS is used in the automotive industry for similar purposes (Li et al. 2017).

In addition to SUS, the National Aeronautics and Space Administration's Task Load Index (NASA TLX) method is widely used to gather and assess subjective workload scores based on a weighted average of ratings of six factors: mental demand, physical demand, temporal demand, own performance, effort, and frustration level (Hart 2006). NASA TLX can be used to assess the extent to which OSS cognitively overloads the users. This is an important criterion because construction equipment OSSs are largely designed for application in real-time. Inundation of operators with information in the cockpit can either become counter-productive and distractive or erode the willingness of the operators to use the system in practice.

Table 1 presents the list of usability questions proposed by this research. This list adapted the basic questions from NASA TLX and SUS to make them more specific for construction equipment OSSs. Also, on top of these two well-known questionnaires, several other customized questions can be asked to assess more construction-specific dimensions of OSSs. The users can use the Likert scale to express the extent to which they agree or disagree with each of the statements, where (1) completely disagree, (2) disagree, (3) neutral, (4) agree, (5) completely agree.

On top of these specific questions, the designer needs to investigate the extent to which the developed designs satisfy the needs expressed in Phase 1 of the framework. Therefore, the recurring participants were presented with the list of needs and asked about to what extent they think the developed designs satisfy their needs for the operation. In other words, the usefulness of the developed OSS needs to be assessed separately through the comparison of the functionalities of the OSS with the high-level needs of the operators.

Table 1: Usability assessment of Construction Equipment OSS [adapted from Makarov et al. (2021)]

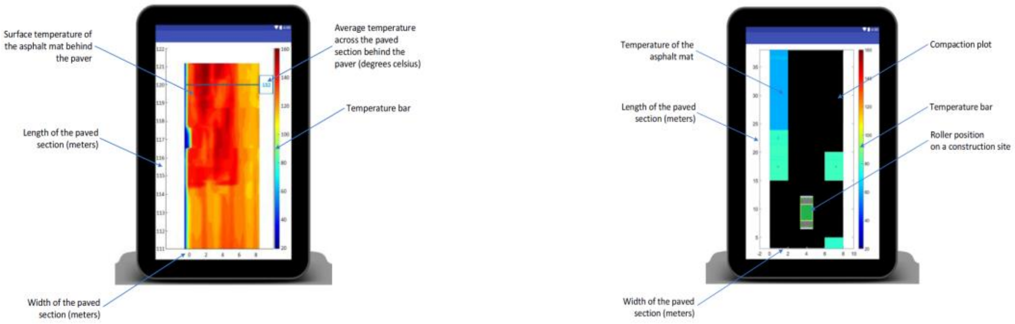
Criteria	Question	Source
Reusable	The provided support encourages you to interact with it frequently	SUS & NASA TLX
Clear	The provided support provides clear information	
Comprehensible	The provided support use understandable visuals	
Easy to use	The provided support provides information that is easy to follow	
Actionable	Looking at the provided information, you know what you need to do	
Non-overloading	The provided support does not overload you with information	
Non-distractive	The provided support provides information in a non-distracting manner	
3D visualization	You would rather have the information in 3D	Customized
Helpful	The provided support helps in the decision making	
Assistive	The provided support helps to find points of attention in the operation	
Instructive	The provided support helps improve your skills	
Informative	The provided support helps improve your knowledge about the operation	
Explicative	The provided support helps see how other operators are working	
Collaborative	The provided support helps collaborate with other operators	
Effective	The provided support helps achieve higher quality operation/final product	
Supportive	The provided support helps make faster decisions about your strategy	
Recommendable	You recommend the use of the system	

3 Implementation and Case study

To assess the feasibility of the proposed framework, the case of compaction OSS for asphalt was used in this study. It is important to mention in the compaction operations, the operators of rollers need to perform a certain number of compaction passes on the hot asphalt at a specific temperature range to ensure effective and efficient compaction of the asphalt. Over/under-compaction or compaction at the temperature above/below the prescribed thresholds increase the chance of not meeting the design density requirements and the chance of premature road failure. That is why it is important to assist the operators of rollers in developing their compaction strategies through the use of compaction OSSs.

In the domain of compaction OSS, the de facto standard for OSSs is based on the provision of descriptive guidance which merely collects real-time temperature and compaction count and presents the results to the operators as contour plots, as shown in Figure 3. This mode of support is however likely to cause cognitive overload. Because operators are expected to analyze two pieces of information concurrently to draw a strategy and this should be done on top of paying regular attention to equipment conditions, other pieces of equipment, and safety.

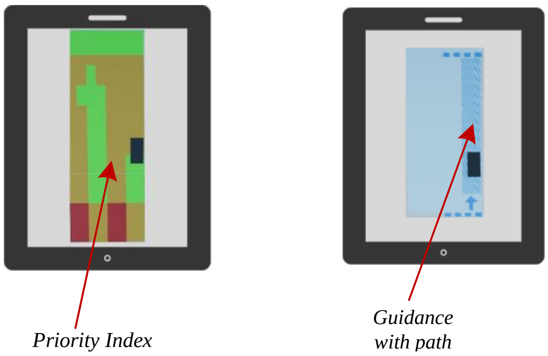
However, based on the lessons learned from the mining and agriculture industries, it seems important for the compaction OSSs to transition to a more prescriptive mode of guidance. In the more prescriptive modes, operators can be provided with more processed information in form of a compaction priority index (Makarov et al. 2019) or a suggested compaction trajectory. At the same time, one can argue that a more prescriptive system can agitate the operators through claiming part of the control of the operation and giving them the impression that their trade is becoming de-professionalized. This can be a serious adoption barrier that may hamper the use of prescriptive systems. Therefore, it seems essential that before the development of compaction OSS is pushed any further, a thorough usability analysis of various alternatives is carried out.



(a) *(b)*

Figure 3: Common representation of (a) temperature and (b) compaction count [adapted from Makarov et al. (2021)]

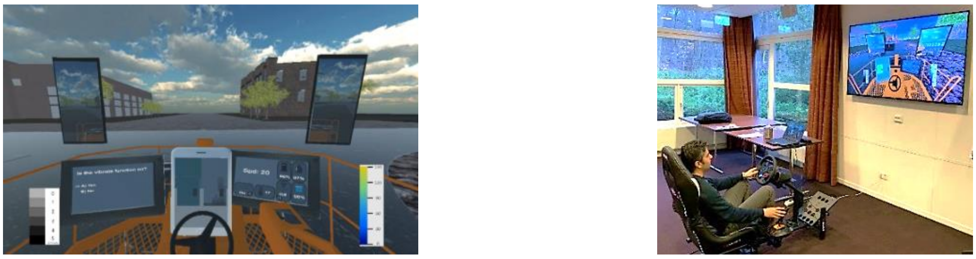
For the above-mentioned reason, the proposed framework was applied. The requirement of the compaction OSS was determined through several informal discussions with the operators and project managers. It is therefore concluded that the main requirements of compaction OSSs are to (1) provide relevant information that can quickly guide the operators as to which part of the asphalt mat needs to be paid more attention at any given time; (2) the provided information should be easy to follow and non-distractive with clear color coding; (3) the placement of the screen in the cockpit should not hamper the normal operation; (4) the provided information should relate to their previous experience or otherwise operators need to be trained for the use of OSS; and (5) the presentation of data on the compaction OSS should follow the industry standard to make sure there are no fundamental differences in how different OSSs should be used. Based on these requirements, three different alternatives were developed for the compaction OSSs. The first type of OSS is similar to the de facto case of the descriptive system presented in Figure 3. The second alternative, which is called semi-guidance, merges the compaction and temperature plots into a compaction priority map as shown in Figure 4(a). Different colors indicate different levels of priority attached to the corresponding parts of the asphalt mat. In the last alternative, which is called guidance compaction OSS, the priority map is further analyzed and processed to recommend a compaction trajectory to the operators, as shown in Figure 4(b). The details of these three alternatives are presented in detail in the previous work of the authors and therefore not repeated here for brevity (Makarov et al. 2021).



(a) *(b)*

Figure 4: (a) semi-guidance and (b) guidance compaction OSSs [adapted from Makarov et al. (2021)]

These three alternatives were developed in a VR scenario that was built in Unity 3D (2022). Figure 5 shows a snapshot of this scenario. The three alternative OSSs were developed inside the scene to enable operators to easily toggle between the three alternatives and experiment with them.



(a) (b)

Figure 5: Developed (a) VR scenario, and (b) hardware

Several workshops with a total of 50 participants were held to assess the usability of different OSSs. The questionnaire presented in Table 1 was used for the assessment. The details of how different OSSs were perceived by the operators are provided in the previous work of the author (Makarov et al. 2021) and because it is out of the scope of the present research, it is excluded from this paper. Instead, this paper focuses more on the evaluation of the suitability of the VP platform for the assessment of equipment OSSs. To this end, a separate questionnaire was prepared and shared with the participant, as shown in Table 2. As shown in this table, this questionnaire is more focused on the suitability of the developed VP platform for the assessment of equipment OSS. Participants were asked to use the 5-point Likert scale to express the extent to which they agree with each of the statements in the questionnaire.

Table 2: Questionnaire about the assessment of PV platform [adapted from Makarov et al. (2021)]

Question	Category
VP is an appropriate medium to evaluate/compare different OSS solutions	Adequate
VP helps you prepare for future work with real machine	Preparative
VP represents scene and equipment realistically	Realistic
VP can be used to explore and evaluate different working scenarios	Work analysis
VP can be used to express your wishes, expectations, and suggestions about OSS	Communication value
VP can be used to test your operational strategy before actual projects	Planning value
VP can be used to assess your skills and progress	Development tracking
Do you recommend using the VP platform to your peers for education?	Education value
Do you recommend using the VP platform for the evaluation of new technologies?	Technology assessment
The VP platform provides sufficient feedback on your performance	Formative
The use of all control elements (wheel, pedals, and buttons) is easy	Easy to use
VP platform can be more realistic with use of additional joysticks & VR goggles	Enhancing Control
VP platform can be more realistic with the use of additional sound accompaniment	Enhancing Audio

3.1 Results

Figure 6 presents the results of the validation. As shown in this chart, the VP platform is found to be adequate for the purpose of assessing different OSSs, with an average score of 3.3. It is also generally appreciated as a platform for the assessment of new technologies in this domain (average score of 3.4). The platform is found to be easy to use (average score of 3.46) and has added value for application as a planning tool before the actual construction operations (average score of 3.5).

Having said that, there are certain applications for which the VP platform was not perceived as suitable, at least in the current shape of the proposal. For instance, the operators found the depth of the feedback provided to them at the end of using the VP platform insufficient (average score of 2.88). Also, although they saw the potential, the details of the developed VP were not deemed sufficient for the use as an educational tool, i.e., training simulator (average score of 2.9). This can be also attributed to the relatively low realism of the simulator (average score of 2.84). This, again, highlights the significance of the point mentioned earlier in Section 2.2 about the importance of having high contextual realism in the VP platform. Part of this low realism was associated with the inadequate control units of the VP platform (average score of 3.8) and also the absence of realistic audio (average score of 3.6).

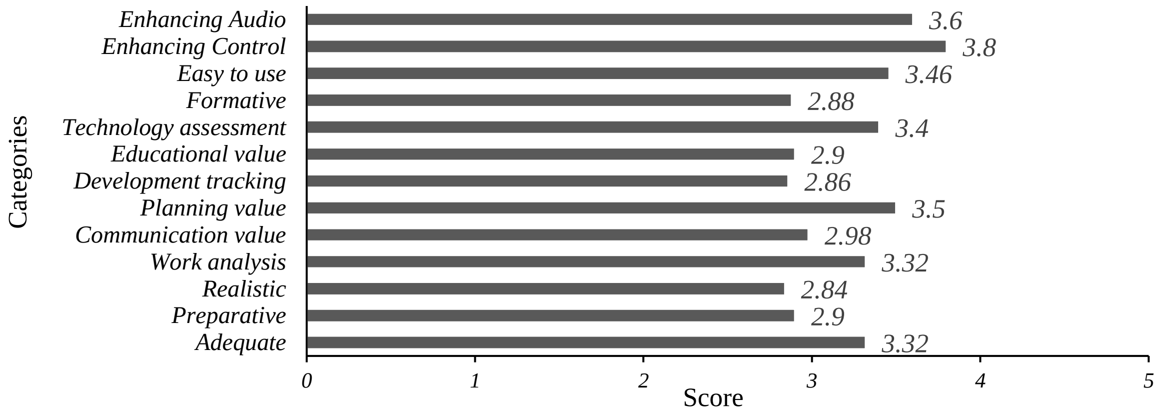


Figure 6: Results of the Assessment of the VP platform

4 Conclusions

The present paper proposed a framework for the use of virtual prototyping for the assessment of various construction equipment operator support systems. The framework starts by exploring the needs of the operators and other stakeholders and proceed to the steps required for the technical development of the VR simulator. In the end, a set of customized questions are proposed to assess the usability of the designed OSS.

Overall, the developed framework is shown to be feasible and useful for the assessment of construction equipment OSSs in a safe and secure environment. Although in the current shape the developed prototype was not deemed ready, overall the VP platform was found to have potentials for applications in the planning, work analysis, and training of construction operations. In general, it is also observed that the VP platform can streamline the design cycle and allow designers to access wider demographics for the testing of their new design concepts. Using the proposed VP platform users can be actively engaged in the design cycle of the equipment OSSs and have their needs and concerns taken into account in the system design at the earlier phases of design.

In the future, the authors would like to focus on the enhanced realism of the VP platform and assess it for other pieces of equipment too. Additionally, by better linking the data from the actual construction projects to the VR environment, the Digital Twin concept can be further extended into the domain of technology assessment and training.

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