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Review paper
Doi 10.7251/stp2024010130
ISSN 2566-4484

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VIRTUAL PROTOTYPING (VP) IN THE ARCHITECTURAL, ENGINEERING AND CONSTRUCTION INDUSTRY (AECI)

Abstract

Information Technologies are lieders in the fast industrial development. Virtual Prototyping, as relatively young technology, is combination of Virtual Reality and computer technologies with digital prototypes as result. It represents original's true copy in the real world, providing more efficient models' testing, prior construction. With it's implementation in the Construction Industry all the work becomes cheaper, faster, safer, environmentaly friendly and more efficient in comparison to the traditional ones. The paper's primary purpose is brief introduction to modern technologies towards which the future construction industry strives. Description of the basic terms is being followed by the explanation of main characteristics and need for the Virtual Prototyping implementation in the Architectural, Engineering & Construction Industry. Virtual Prototyping tools and real-life applications have been stated as well. At the end, limitations and possible problems are mentioned. Therefore, link between Virtual Prototyping and Architectural, Engineering & Construction Industry is created.

Keywords: Virtual Prototyping, Virtual Reality, Computer Technologies

КРЕИРАЊЕ ВИРТУЕЛНИХ ПРОТОТИПА У АРХИТЕКТОНСКОЈ, ИНЖЕЊЕРСКОЈ И ГРАЂЕВИНСКОЈ ИНДУСТРИЈИ

Сажетак

Информационе технологије су лидери у убрзаном индустријском развоју. Виртуелни прототипи, као релативно млада технологија, представљају комбинацију виртуелне стварности и компјутерских технологија. Представљају копију оригинала пружајући ефикасније тестирање модела. Њиховом имплементацијом у грађевинарству сви послови постају јефтинији, бржи, сигурнији, еколошки прихватљивији и ефикаснији у односу на традиционалне. Сврха овог рада је кратак увод у савремене технологије којима тежи грађевинска индустрија. Након описа основних појмова слиједи објашњење карактеристика и потреба за имплементацијом виртуелног прототипа. Наведени су и алати за виртуелне прототипе и апликације из реалног свијета. На крају су наведена ограничења и могући проблеми. На тај начин створена је веза између виртуелне израде прототипа и архитектонске, инжењерске и грађевинске индустрије.

Кључне ријечи: виртуелни прототипи, виртуелна стварност, компјутерске технологије.

1. INTRODUCTION

Humanity lives in the time when technology is evolving so fast, that people just are not able to keep up with the speed of this development. Today it is common buying a new mobile phone, or even a car, but tomorrow it's becoming unfashionable because on the market is appeared more advanced model of the newer generation. Computers are literally from hour to hour significantly inferior compared to the new ones that are showing up. The rapid technological development has a crucial role in providing a much more comfortable life for all humanity. The technologies that lead to fast development of industry are Information Technologies (IT). It can be said that all other technologies depend on their development.

The construction industry is lagging most other fields in taking advantage of new technologies (Arditiet al. 1997) [2]. Unlike other industries, the implementation of modern technology is going much slower in the Architectural, Engineering & Construction Industry (AECI). Research and development accounts for an embarrassing 0.4% of the annual construction output in the United States (Nicolas & Lemer 1992) [20]. Improving the quality of work and therefore the quality of the final product is highly dependent on availability of possessing resources when performing work. In this study will be pointed attention to the importance of the implementation of computer-advanced technologies in AECI. The focus is, in this case, on Virtual Prototyping (VP). The VP can be a powerful tool for testing and evaluating new products and ideas, decreasing the time to market and reducing product cost (Mujber et al. 2004) [19].

The VP is a relatively new technology, which involves the use of Virtual Reality (VR) and other computer technologies to create digital prototypes (Wang 2002) [31]. Designing different products by using advanced computer software (such is CAD - computer-aided design or CAE - computer-aided engineering) provides designer (for example engineer) possibility to test his model in the virtual world before it goes to production and start usage in the real one, is called VP. The user is making a computer-generated model, in the other words “a digital prototype”, which is in most cases 4D (3D+time), and simulating its behavior in the real world. Observation of its behavior in virtual world can provide designer possibility of improving his idea, redesigning certain characteristics in purpose of bringing it on a higher level of functionality, removing defects, etc. The advantage of VP is that it is giving an opportunity to be tested in much simpler, more efficient and cheaper way, than it would be in the real world.

The other important characteristic is that virtual prototype has to be a true copy of its original in the real world. It also must be more accessible for manipulation and testing than its physical representative. Different challenges project's executors face starting from designs' analyze to the final construction processes, which are easy passed over using Artificial Intelligence (AI) tools. (Elsayed, S., & Radwan, A. 2019) [6] Errors that occur during the testing of the prototype in the physical world as well as the errors that occur during its designing can be quite expensive and complicating for repairing. The main strength of VP is that in much easier, and much more cost-effective way it provides a prototype development while the creator is "playing" with it in the virtual world.

Through several points of this study will be presented main characteristics of VP and illustrated importance for implementing it in AECI, as well as in other industries. Main advantages and disadvantages will be presented as well. The study will propose usage of this approach in the future and will provide examples of the successful implementation so far. As very important segment of study, the limitations and opportunities for improvement will be discussed.

2. KEY FEATURES AND NEED FOR VP

Designing process of certain product includes stages of creation of idea, making the model which is going to be exposed under test and after that production. These processes in the traditional approach can be extremely complicated and expensive. At the moment when the idea was born, designer’s job is to transfer it in physical form, visible to others. This process can certainly be done by making a sketch on paper which is the traditional way, or using various computer software which provides a much simpler approach.

According to (Wang 2002) [31], characteristics of a virtual prototype are:

- A model of a structure or apparatus (or a product);
- Used for testing and evaluate form, design fit, performance, and manufacturability;
- Used for study and training.

Based on Wang's definition, it can be concluded that first required thing is a computer simulation. Most appropriate model presentation is 3D simulation. On a second place is human-product interaction. Characteristics of a model should be effectively viewed, listened, smelled, and touched by a user. All parts of model should be able to tested and evaluated. One of the features of the VP is to enable the transmission of these ideas into materially world in a much simpler and more efficient way for both - the designer and the other. Computer software provides a clearer picture of what the creator intended. Another feature is that the sketch can easily be modified and improved; experiments with design are easy to control. In addition, among the ideas that already exist, VP provides also support from its database by providing additional ideas, giving suggestions etc. Traditional approaches, such is use of sketches on paper, are not able to provide these possibilities. Experimenting with the model using the VP is much simpler and cheaper than experimenting with the ones in real world. Making a "living" model can be a very expensive and time consuming. In addition to debugging and design improvement is much more complicated with the material model to those in the virtual world. The entire process from design to start of production can be repeated many times in purpose of training model in a simple and economical way. Also the presentation of the project interested much more efficient than the traditional method which significantly improves communication.

VP in the AECI provides effective creation, analyze as well as optimization of working schedules. Analysis of constructability is much precise than in traditional way of approach. Considering a large number of parties involved in project, risks curve exponentially grow up. (Bilal, M., & Rahman, I. 2018) [5] Risks during the construction process can be eliminated or put to the minimum. All involved (subcontractors, contractors, investitures) in project can understand much better the scope of it and communicate between each other very precisely. The changes in any stage of project are planned in advance and easier feasible.

A group of researchers from The Hong Kong Polytechnic University and Queensland University of Technology from Australia conduct a survey which clearly shows how implementation of VP in construction industry can significantly improve results in any stage of project development and construction. A Construction VP (CVP) was used in couple of projects in Hong Kong. In research "Construction virtual prototyping: a survey of use; T. Huang, H. Li, H. Guo, N. Chan, S. Kong and G. Chan, M. Skitmore". This questioner survey has been done in 2007 with 28 participants. Their projects used CVP. From 28 participants, a positive response was received from all of them with an accent on visualization and communication. Results showed high potential of VP: Visualization – important for communication and collaboration between all involved in project. CAD 4D reduces 50% of time for explaining designers and 80% of time describing construction operations. Comparing to traditional tools, 4D also provides a more intuitive comprehension of the construction. Testing and verification of functions and performance – integration of geometrical and non-geometrical data, 3D models can carry out extensive and specialized tests and analysis. Collision detection – Software publishers like Autodesk, Bentley Systems, Graphisoft, Vector Works, and Gehry Technologies have this capability. Evaluation of manufacturing and assembly operation – 4D planning allows the analysis of construction schedules prior to the construction phase with advanced tools which support cost management, quantity survey and site layout. Resource modeling and simulation –integration of VP with virtual VR enables user interactions with more realistic 3D models.

Implementing the AI in the AECI offers numerous benefits, including improved project planning and scheduling through predictive analytics, enhanced safety through real-time monitoring and detection of hazards, and increased efficiency in resource allocation and cost management through automated workflows and data-driven decision-making. Additionally, AI-powered systems can optimize construction processes by analyzing vast amounts of data to identify patterns, optimize supply chain management, and enhance collaboration among project stakeholders. (Singh, V., & Loke, S. W, 2020) [25]

According to (Huang et al.) [10] CVP system, which was developed is called DELMIA. It is one of the most powerful VP applications produced by Dassault Systems. The core of DELMIA is a PPRs model that links up with various kind applications – 3D model design, process planning, resources planning, event simulation, 3D visualization, layout planning and VR. The strongest weapon of this approach is visualization and communication. The collaboration efficiency between contractor and sub-contractors is improved around 30% and 30-50% reduction of meeting time. It also provides significantly shorter planning time. In construction implement stage fieldwork is instructed and rework is reduced. CVP approach decreases the workload of project planners. Other important benefit of using this approach in construction industry is much reduced effort in preparing construction documents, as well as close coordination of design and construction work to bring meaningful reductions in the number of personnel and materials.

The result of this study clearly shows through numerical data that implementation of Artificial Intelligence (AI) such is VP is very important for the further advancement of AECI. Any stage of project and construction was very improved using VP as one of main tools to accomplish the work. The AI is becoming inevitable tool in the AECI, revolutionizing the way VP is conducted. AI-powered algorithms offer unfathomable opportunities to rise collaboration among architects, engineers, and construction engineers through the prototyping processes.(Gheisari, M., & Nejat, A 2018), [7] Using the AI, teams can streamline communication, enhance data analysis, and optimize decision-making. The AI techniques can analyze great amounts of complex design data in order to identify potential conflicts or different obstacles, enabling teams to address issues as soon as possible during the prototyping stage. In addition, AI's virtual assistants can facilitate real-time collaboration by providing quick feedbacks, propose design modifications, and facilitating communication among all the parties incorporated in the project's realization. As AI continues to evolve, its integration into VP processes promises to provide higher levels of efficiency, innovations, and collaboration within the AECI. (Shahandashti, S. et al. 2022; Xiao et al. 2018) [27, 30]

3. TYPES OF VP TOOLS IN THE AECI

3.1. BUILDING INFORMATION MODEL (BIM)

BIM is computer-technology, which in digital form presents physical and functional characteristics of building. This concept exists since 1970s. It helps with the decision-making processes during the whole time of designing and building. Also, provides possibility to observe buildings behavior in the future through virtual world and simulations. Recent years, as semantic information modeling, presents one of the most advanced technologies used for improvement of the AECI.

Building Information Modeling (BIM) revolutionizes the construction industry by enabling virtual prototyping, allowing stakeholders to visualize and simulate the entire building lifecycle before construction begins. Through BIM, architects, engineers, and contractors can collaborate more effectively, streamline workflows, reduce errors, and optimize building performance, leading to cost savings and improved project outcomes.(Gu H. et al. 2021) [8]

BIM is usually being combined with the Industry Foundation Classes (IFC). Using BIM designer is able to create a 3D model of building which presents all characteristics of it such are building design, material information, planning details, economics factors, etc. IFC serializes this information and provides communication with other applications related to this. BIM is described as an IT tool, product or process that minimizes waste associated with inefficient information exchange and dramatically improves the construction process.

BIM facilitates the creation of detailed digital representations of buildings, integrating information about design, construction, and operation phases. This enables stakeholders to identify clashes, analyze performance, and make informed decisions early in the project lifecycle, ultimately enhancing efficiency, sustainability, and overall project success. (Hamledari, H., & Eastman, C. M. [9]

However, the lack of agreement between stakeholders pertaining to BIM’s f unction and business value has stifled its implementation (Isikadg et al. 2007) [11] and has confused matters regarding BIM’s impact on construction success measures (Zuppa et al. 2009) [35] are stating three different definitions of BIM. First views BIM as an open standards based information repository for a facilities’ lifecycles. Second one represents BIM as a tool for visualizing and coordinating AECI work and avoiding errors and omissions. The definition explains BIM as a combination of the two and possibility including other factors (Issa & Suermann 2009) [12]. But, there are some other approaches to define BIM such are 3D modeling, interoperability, semantics, clash detection and process integration. Generally BIM remains a complicated to define (Aranda-Mena et al. 2009) [1], which inhibits the collaborative process between stakeholders and makes the measurement of its effectiveness difficult.

BIM is helpful in time and cost estimations, which aid in schedule management for reduced threats of budget and time overruns. The pre-execution visualization feature of BIM enables the construction practitioners in clash detection leading to reduced errors, omissions, and reworks. In addition, visualization in multiple dimensions aids in quality and safety man-agreement with checks on progress of projects.(Raza,M.S. et al. 2023) [24]

BIM can have different applications in AECI such are: visualization 3D, fabrication drawings, code reviews, forensic analysis, facilities management, cost estimating, construction sequencing, conflict, interference and collision detection, etc. Benefits from BIM are: faster and more effective processes, better design, controlled whole-life costs and environmental data, better production quality, automated assembly, better customer service, lifecycle data, etc. Stanford University Center for Integrated Facilities Engineering (CIFE) figures based on 32 major projects using BIM indicates benefits such as (CIFE, 2007): up to 40% elimination of unbudgeted change, cost estimation accuracy within 3%, up to 80% reduction in time taken to generate a cost estimate, a savings of up to 10% of the contract value through clash detections, up to 7% reduction in project time.

One risk related to using BIM is ownership of the BIM data and protection of it through laws. Other is connected to the right to control data entry into the model and responsibility for inaccuracies in it.

As Figure 1 describes, BIM is a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. As a term, BIM has grown tremendously over the years and is now the 'current expression of digital innovation' across the construction industry. It is an intelligent 3D model-based process that usually requires a BIM execution plan for owners, architects, engineers, and contractors or construction professionals to more efficiently plan, design, construct, and manage buildings and infrastructure. [36]

Figure 1. *BIM's purpose [36]*

3.2. COMPUTER AIDED DESIGN (CAD)

Feature-based CAD systems have demonstrated clear potential for creating attractive design environments and facilitating geometric reasoning related to design function, performance evaluation, manufacturing process planning, NC programming and other engineering tasks (Iyer et al. 2006) [13]. CAD is computer software for creation, modification, analysis and optimization of a design. This software simulates behavior of construction and provides clear visualization of structure. It increases productivity, improves quality of product and communications among the members of team by providing a better documentation database.

3D CAD: Three-dimensional drawings of objects who are giving a sense of space are much efficient than 2D drawings because user can have more clear picture of the building for example, as well as feeling and understanding of design and structure.

4D CAD: (Zang et al. 2008) [34] is providing a good example of using 4D in AECI. In his paper "A Framework for Implementing Virtual Prototyping in Construction", he is demonstrating advantage of using VP, as well as difficulties, throe example of residential building in Hong Kong. The main characteristics of using 4D (3D + time) CAD is visual showing of construction site in different stages of building process with possibility of simulating real construction process. Helped with this powerful tool, supervisor can identify errors in process sequence and spatial arrangement. VP integrates 3D CAD, simulation engine, analysis tools and knowledgebase to streamline the whole product design and production process.

Presentation of building components in 3D and construction operations in virtual environment is necessary because it provides possibility that ideas of planners can be captured, communicated and reused. Traditional drawings in 2D are not functional enough. Implementation of VP in AECI is very helpful because constructability data can be evaluated and captured. Engineers can check design efficiency and provide feedback to the designers, using collected data. It allows the discovery of problems in construction early in the designing process which minimizing cost of change. During the construction stage, constructability data can influent on production of a detailed process plan and generation of 3D construction operation instructions for workers. This data can also be used for future 3D maintenance and repairs instruction.

5D CAD: This software is combination of 3D CAD applications with integrated data for schedules (time) and costs (resources) and represents BIM process. Big advantages over simple other programs make 5D CAD the future of the construction industry. It is combining 1D program data, 2D design, 3D building model with an integrated database of information about the building (BIM - Virtual Building), 4D time scheduling (sequencing of construction), and the 5D cost and resources for complete construction. Output from this process can be used after construction for the facility management. This means using the information over the entire life cycle of a building.

3.3. GAMING ENGINES (GE)

Virtual walkthroughs can allow participants to perform design/construction review tasks collaboratively, while locally present, or remotely connected. Collaboration among participants from the initial design stage is important because critical decisions can be made as many and as early as possible to lessen disputes, delays, cost overrun etc.at later stages (Shiratuddin & Thabet 2002) [26]. GE is a system used for designing video games. The characteristic functions are a rendering engine for 2D and 3D graphic models, a physics engine, sound creation engine, scripting and animation, artificial intelligence, networking, memory management, threading, localization support, and a scene graph. GE have possibility to present a realistic virtual environment in real-time. Related to the AECI usage of GE can generate real-time applications in VR that can represent architectural walk- tours, 4D planning and pre-construction planning parts etc. 3D GE is low-cost VR solution with built-in opportunities such are multi-participant capabilities, detection of collision, higher frame rates etc. [29]

GE are providing one very important option more - a better interaction between user and virtual environments. VR is more focused on a graphical section – creating more attractive environment, but whoever works in AECI behind strong graphical part need to have quality efficient control and interaction with the object or its parts that is being designed. GE are providing user possibility to lead avatar throe virtual life/environment. Creating such a feeling of spatial presence can support many geographic application scenarios, such as urban planning or studies on spatial perception, because the experience created by the virtual environment is more similar to the experience created by a real environment. However, the level of immersion of a VR-capable application does not only depend on general VR characteristics, such as a stereoscopic perspective and the tracking on real-world movements. (Keil et al. 2021) [14]

Visualization based on a game engine is more advanced than one on the VR engine base because of several reasons: lower cost, provides more overwhelming results in areas of 3D graphic design and interactivity, needed minimal performance for software and hardware and easy and fast development of functional virtual worlds. Figure 2 is example of successful GE usage in the AECI.

Figure 2. GE sample in the Construction Industry ussage [39]

Some of these engines such are Second Life (Warburton 2009) [32] or Sketch Worlds focus more on fast geometric modeling 3D environment and less on the information modeling. The limitation in these environments is leak of functionality to applications related to AECI. In Sketch Worlds exists possibility to import Orge meshes, which can be used as exportation from AEC applications. However, this is not original information exchange like in AECI.

At the Penn State, a group of engineers is using Immersive Construction (ICon) Lab to experiment with VP (*http://www.joelsolkoff.com/immersive-construction-lab-at-penn-state/sonali-kumar-virtual-reality-modeler-and-designer/*). Sonali Kumar, a graduate research assistant, and John Messner, associate professor of architectural engineering are designing specialized buildings by using a 3D game engine. They managed to develop a life size interactive virtual prototype which is much more economic than physical modeling. Its name is Experience-Based VP Simulator (EBVPS) and functions like a multiplayer video game. A lot of studies have been done where they developed 3D building model and displayed it in the lab. It is similar to 3D movie. Observer has immersion that he is in the space and.

As these researches states, first step is designing a 3D model in Autodesk Revit. After that, they transferred created model to visualization software Autodesk 3DS Max, in which realistic textures were added to the model, and after that to the Unity Game Engine to incorporate interactivity. One of goals is to create a database of standard components that can be used again in some other project.

This team developed a 3D walk through a model of the new Penn State Hershey Children's Hospital. It can help hospital staff as well as patients or visitors to navigate through the building. The idea was to have a decision-making tool for design review, which helps users as well as project team. Design team can communicate more effectively with stakeholders and gather valuable.

3.4. RAPID PROTOTYPING (RP)

Rapid prototyping (RP) is a term, which embraces a range of new technologies for producing accurate parts directly from CAD models in a few hours, with little need for human intervention. This means that designers have the freedom to produce physical models of their drawings more frequently, allowing them to check the assembly and function of the design as well as discussing downstream manufacturing issues with an easy-to-interpret, unambiguous prototype. (Pham et al. 1998) [22] This is technique whose first usage showed up on the market at early '80's for production of different models and prototypes by scaling models of physical parts or installation. During the time that usage becomes much more vide with CAD as a main tool. The purpose is production of prototypes for a short time. These prototypes are being used for further visual analysis and evaluation as well as tools for production. There are various RP systems today on the market.

RP in AECI involves quickly creating scaled models or mock-ups of structures to test design concepts and identify potential issues before full-scale construction begins By rapidly iterating through prototypes, construction teams can refine designs, improve efficiency, and reduce project timelines. (Liu, H.et al 2023; Sun, C. et al. 2022). [16, 28]

In his book, (Noorani 2006) [21] "Rapid prototyping", author states that depending on the materials, this process can be powder based (Selective Laser Sintering - SLS and 3D Printing - 3DP), resin based (Stereo-Lithography Apparatus) or laminated sheet based (Laminated Object Manufacturing - LOM). This technology, however, has some issues related to precision and prototypes quality. Multiple parameters making hard to choose a right combination, in purpose to create an efficient prototype. Integration of this technology with virtual reality creates system, as is VP.

Architects can use this technology for developing models for structure design, which will be useful also for their colleges from construction departments to see more clearly whole project as well as certain parts of it.

3.5. VIRTUAL REALITY (VR) AND MIXED REALITY (MR)

VR is the use of computer graphics systems in combination with various displays and inter face devices to provide the effect of immersion in the interactive 3D computer-generated environment (Pan et al. 2006) [23]. In AECI graphics and information are very important, so practice combination of these two has curtailed significance. VR is computer-simulated environment, which can imitate and simulate physical presence in the real world likewise in imaginary one. It is a computer – generated simulation of the real world, which provides an illusion of participation in a synthetic environment and not a pure observation of the same. This environment is 3D and user is able to look and manipulate with the contest of it. Also, it can be said that VR integrates user with the information.

There are two categories of VR: Desktop (uses PC monitor as an extract-information tool) and Immersive (instead of monitor uses head mounted display unit) VR. Applications of VR in the AECI are in:

- Design: space modeling, interior, lighting, designing of heating ventilation and air conditioning systems, ergonomics and functional requirements, space selling, fire risk assessment, landscaping, etc.
- Construction: site layout and planning, planning and monitoring construction processes, evaluation of construction scenarios, etc.

All data from CAD can be transformed into VR and the process (Whyte et al.) [33]. This is important because users age getting from a 2D architectural drawings 3D models which can be manipulated and simulated like in a real world. The other important characteristic of VR is library-based approach. The database offers different models already designed and especially when it comes to frequently usage of standard parts. Figure 3 demonstrates example of VR projection.

Figure 3. Virtual Reality war simulation (Pan et al. 2006) [23]

(Pan et al.) [23] states, MR in the AECI is used in the later stages of the design process, like are stages in which part of the site is already under construction process. Also, these applications include construction site inspection. Behind that, one more application is project management, specifically for construction progress monitoring. MR visualization can prove a good tool in facility management, building maintenance and renovation and building damage evaluation after disasters.

At Penn State University at the Applied Research Laboratory exists an immersive projection display (four back-projection display screens, stereoscopic and synchronized rendering images, stereo audio and magnetically tracked 3D input devices for creation of VR) system which generates 360 degree, 10'x10'x9' immersive environment. Users can interact with environment and simulate in real-time (Figure 4).

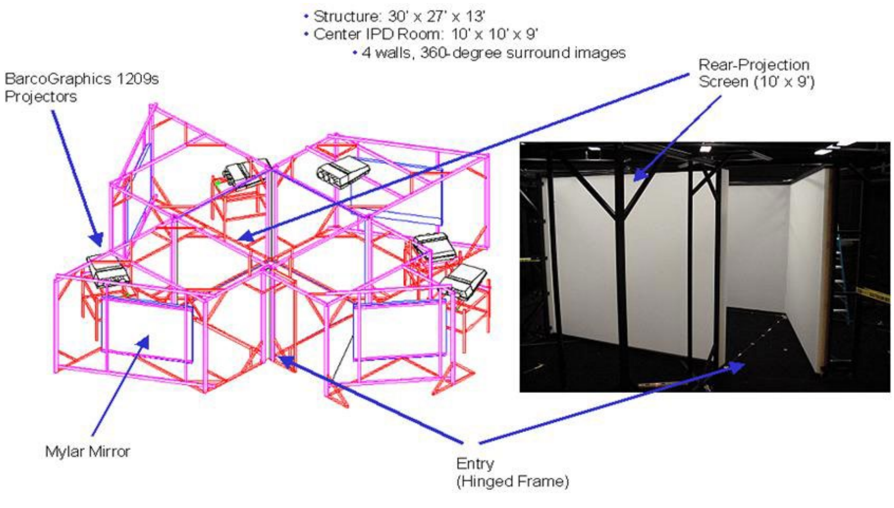

Figure 4. SEAI Projection Display at Penn State Applied Research Lab (Messner et al. 2003) [18]

While there are many benefits from implementing VR into AECI, also some issues can occur as well. One of them is a high price. Using this technology is very expensive because VR facilities are large and provides high-resolution images with also high quality visualization and magnetic tracking features. These display systems can cost over one million U.S. dollars. Other issue is that these facilities have a small footprint. It means that only four to five people can operate. Third problem with using VR is too complicated process of learning how to use it. VR software can be difficult for master the use.

3.6. AUGMENTED REALITY (AR)

AR represents direct or indirect view of real world, whose details are augmented by computer – generated sound, video, graphics or GPS data. The main difference between VR and AR is that the VR presents "copy" of the real world in its virtual representation (simulates it), while AR presents it in a teal-time in a semantic context with environmental elements. AR gives direct interaction between user and world around him and he can manipulate digitally with segments of it. Using AR user can, for example, add virtual objects to the real world elements and create own picture of the real world on the screen.

AR is revolutionizing construction engineering by overlaying digital information onto physical construction sites, enhancing project visualization and coordination. With the AR in construction engineering, stakeholders can experience BIM data in real-time, facilitating better decision-making and collaboration. AR applications in construction engineering allow on-site workers to view 3D models of buildings, infrastructure, and utilities directly within their physical environment, aiding in accurate construction placement and alignment. By integrating BIM models with AR technology, construction teams can identify clashes, verify installations, and troubleshoot issues before they arise, leading to more efficient project delivery. It enhances safety in construction engineering by providing real-time hazard alerts, equipment instructions, and site navigation, minimizing risks and improving worker productivity. Utilizing AR in construction engineering enables remote stakeholders to virtually inspect construction progress, conduct virtual walkthroughs, and provide timely feedback, facilitating smoother project management and communication. The integration of BIM and AR streamlines the construction process, reducing errors, optimizing resource utilization, and ultimately delivering projects on time and within budget. AR applications in construction engineering empower architects, engineers, and contractors to visualize and interact with complex designs, fostering innovation and creativity in project development. AR-enhanced training programs in construction engineering allow workers to simulate construction tasks, practice assembly procedures, and receive real-time feedback, improving skills acquisition and job performance. The marriage of augmented reality and BIM technology holds immense potential to transform the construction industry, driving efficiency, sustainability, and excellence in project execution.(Raza, M. et al. 2023) [24]

As (Azuma 1997) [3] states, three main characteristics of AR are: combination of real and virtual world, interaction in real – time and registration in 3D. The potential of AR is improving architectural construction, inspection, and renovation. AR systems can enable workers on construction site to avoid hidden features (for example electrical wiring). This makes maintenance and renovation operations faster and more efficient, and also reduces the amount of accidental damages. Future versions of AR can guide construction workers through the assembly of actual buildings and improve their work quality. Inspection with AR interfaces may be similarly guided. Work without conventional printed drawings makes job much easier and ensuring that every item is inspected. Example is of the AR potential has been presented at the Figure 5.

Figure 5. Example of AR – a virtual lamp on a real desk [3]

4. APPLICATION OF VP

4.1. OTHER INDUSTRIES

Due to the opportunities provided by VP is widely used in various industries. The significance of this technique is growing rapidly during the time and it can be concluded according to many case studies results that in the near future will be impossible to organize the production of any product without using tools provided by VP software. Design testing in the virtual world prior to its production, as noted above, is much more efficient and cheaper than the traditional method. Aero industry is using this approach for a while. Making real models of tested – subjects in this industry is very expensive. Even a VR technology whose prices a high is worth to use comparing to the models of aircrafts. Also, mimic of some of the conditions in which aircraft will be exposed in a real life, is almost impossible in the real world, so that the simulation in virtual one place almost exactly as in the real and give the necessary results to improve products. For example, aircraft is completely exanimated and tested before it goes to manufacturing. Similar thing is in auto industry.

Virtual prototyping has significance especially in production of expensive products whose testing with real models requires high economical resources. VP has also found its application in the medicine. Future doctors can be trained on virtual models of people or animals that simulate the response of organisms in the same way as in real life.

4.2. IN THE AECI

- Building design and construction: One of the most important industries who provoked development of VP and VR is actually Architectural. Visualization and possibility to immerse them in appropriate design it is gained much clearer understanding of quantitate and qualitative nature of designing space. With VR and VP technologies architects can evaluate proportion and scale using interactive models as well as to simulate different kind of effects. For example, simulation of functionality of fire escapes routes, or anti-fire systems. The other good characteristic and possibility is improved and efficient communication between designers and clients, between ideas and possibilities or opportunities to materialize them.
- Progress monitoring: Visualization and VR technologies can be used for modeling the construction sequence in order to simulate and monitor site progress. This can be successfully accomplished by using a pre-prepared library of building components, which contains 3D graphical images.
- Their related activities are also included and generation of models representing views of the construction sequence in a real time. Control of project progress in a real-time is on a highest level of importance. VP provides to engineers throe visualization efficient supervising of any stage of project with the clear picture of the situation. According to this engineers can remove mistakes, fix errors, planning stages etc. in more accurate and faster way.

- Visual simulation of equipment: As (Li et al. 2012) [15] states, construction equipment is one of the very important factors for successful construction progress. Example can be seen at the Figure 6. Testing of construction machines in virtual world can prevent mistakes like wrong chosen operating machine. Also construction progress supervisors can get familiar with behavior of unknown equipment. This approach can also help with positioning of large and fixed machinery on construction site like cranes or concrete factories etc. Some companies like Leica Geosystems using laser scanners are completing data from real machines, transferring it into a VR world where is possible to manipulate and test certain machine for future usage and manufacturing as well.

Figure 6. Construction machines in virtual world (Lii et al. 2012) [15]

- Facility management: This is area divided into couple of activities such are coordination of space, infrastructure, people and organization. In FM VP can have also crucial role because all these activities can be tested and organize first in virtual and after that in real world. VP enables architects and engineers to simulate and analyze sustainable design features digitally, allowing for the optimization of energy efficiency, material usage, and overall environmental impact before physical construction begins.(Tettey, W. J et al. 2021) [29]
- Demolition and uninstallation of facilities: Demolition and uninstallation buildings can be very dangerous and expensive job (Messner et al. 2012) [17] Facilities can be destroyed first in virtual world where can be recorded exact behavior of different parts of it, so when the real explosion comes almost noting unpredicted can happened. When it's about uninstallation of a, for example, metal structures planning in virtual world can be done and tested the whole process, so everything can be finished in a most economical and safest way.

5. LIMITATIONS AND PROBLEMS' SOLUTIONS

Although VP brings almost unbelievable advantages, it has some limitations. The development and application of VP in the AECI can be complicated because each construction project is unique in term of their conditions, requirements and constraints unlike manufacturing industry where production line is almost constant. One more barrier for implementation of this technology is also that the companies don't want to engage it until they are sure of benefits from that business move. VP technology has lack of a seamless method for data exchange between various tools. The main problem regarding this approach to construction progress is that, even certain amount of time has passed, the cost and highly trained stuff leveling has not moved with significant steps forward.(Bademosi,F.M.& Raja RA.I. 2022) [4]

But, the biggest limitation for fast implementation is economic factor. VP technology is very expensive because of need for sophisticated and advanced software which requires high-prices hardware. For effective usage of VP applications stays its high demand on computing power. The challenge and opportunity to solve this problem is developing business processes and accessible and affordable implementation tools, which includes web-based systems. This will make the power of VR affordable to wide specter of projecting teams and companies.

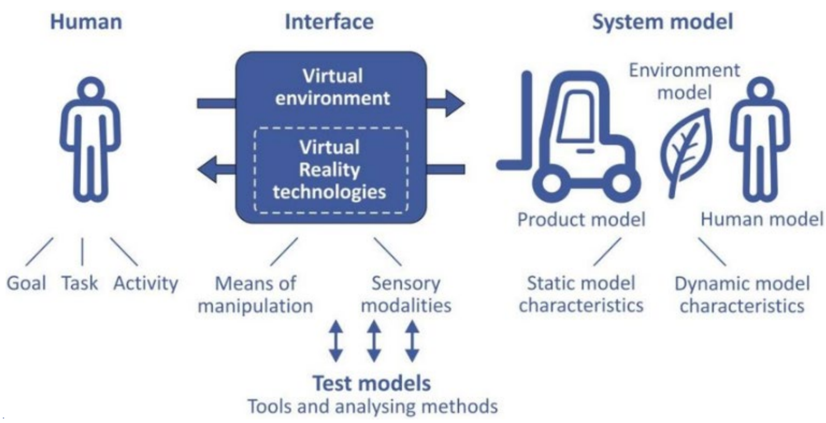

Figure 7. The framework for virtual prototyping in human-machine interaction is a combination of human, interface and system model elements. [37]

Breaking down the models into smaller components and using more advanced modeling techniques can solve the VP models' complexity and large-scale systems. Multiple disciplines integration, which is considering strong collaboration among architects, engineers, contractors, and other parties, is one way ticket to the integration challenges and problems. This might be possible to solve by implementing BIM tools that allow real-time collaboration and seamless integration of different disciplines' models. The VP technologies' cost which requires significant investment in hardware, software, and training is possible to solve "step by step" introducing it to the users, starting with pilot projects and investing in training programs to up skill employees. Regular backups and data auditing can manage managing large amounts of VP data and safe files' storing. Also, providing comprehensive training programs to encourage user adoption will help accelerating future VP implementation in the AECI.

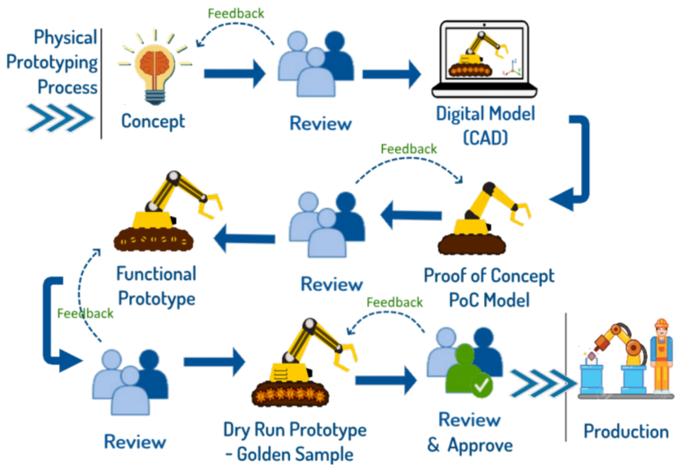

Figure 8. Virtual Prototyping stages. [38]

6. DISCUSSION

The aim of this research is to introduce the reader to the axis of the VP and all the benefits it provides. It is explained through several examples how individual software and techniques function, as well as the specific benefits they provide. Key features and application of Virtual prototyping are stated as well. Also, along with limitations was provided recommendation for solution of problems. However, this is huge area and in one paper could be presented only introduction details.

7. CONCLUSION

VP is providing very powerful tools for improving any stage of design and construction any kind of facilities. Unfortunately, this technique still didn't take part in AECI as it deserves. Problem has economical nature, but in close future should be solved because economical factor is one of the most important on which this technique actually have an influence. Testing models and simulating its behavior in virtual world is much cheaper than in real one and VP is providing exactly that. Also, testing facilities in virtual world prior to the real one has advantages like improving design and functionality, security, etc. Powerful software like VP takes bigger role in other industries than in AEC, and it should be deeper implemented in closest future.

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