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Integrating Building Information Modelling and Extended Reality in the Transportation Infrastructure Industry

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ORIGINAL INNOVATION

Integrating building information modelling (BIM) and extended reality (XR) in the transportation infrastructure industry

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Abstract

Although building information modelling (BIM) has been widely used in the building industry, its usage in infrastructure projects such as bridges has been very challenging. Extended Reality (XR) that simulates a construction project is still considered a new technology in the Architecture, Engineering, and Construction (AEC) industry. This paper investigates the viability of integrating both BIM and XR technologies into transportation infrastructure projects. A fully integrated workflow for introducing different XR, Augmented Reality (AR), and Virtual Reality (VR), and BIM technologies using different software for a case study of El-Merghani bridge, a reinforced concrete girder type bridge, was developed. The models for the bridge included GIS integration and geometric road design according to AASHTO, documentation, shop drawings and quantification were developed for the bridge. A hypothetical time schedule was generated in Oracle Primavera P6 elevating the BIM model to 4-D and developing VR and AR virtual experiences with the capability to investigate, visualize, and present the model in a virtual environment, at a high level of immersion. Additionally, the associated risk reduction for the considered XR technology was assessed using Monte Carlo simulation. The workflow and the detailed 3D models developed for the bridge along with the highly immersive VR and AR experiences have provided an interactive platform for engineers and different stakeholders to monitor the project during the design and construction phases. The risk analysis showed that significant cost savings can be achieved with the utilization of VR and AR technology in bridges construction.

Keywords: Augmented reality, Bridge, Building information model, Extended reality, Virtual reality

1 Introduction

Building Information modelling (BIM) has become widely used in the AEC industry due to its tremendous benefits in recent years. BIM is a process that integrates and visualizes different project data and provides important diverse information on the implemented project which assists project managers in making accurate project decisions (Wei et al. 2021). BIM has the capacity to improve the management and implementation of large-scale construction projects including extremely complicated bridge projects (Wei et al.

2021; Amin et al. 2023; Gupta et al. 2022; Schiavi et al. 2022)]. Digital simulation is crucial in detecting clashes and hence serves as an important way to reduce the overall cost and time of the project (Sacks et al. 2018; Succar 2009)]. Different capturing technologies can be integrated with BIM such as, Laser Scan, image-based photogrammetry, Global Positioning System (GPS), Radio Frequency Identification (RFID), and Quick Response (QR) coding to formulate collective and detailed information about a project (Alizadehsalehi and Yitmen 2016). BIM can have several levels with different n-D models of the project that includes several attributes of the project such as analytical information, cost, time schedule, and energy consumption. This information can be used in Life Cycle Assessment (LCA) study (Röck et al. 2018). For example, adding the time schedule to a three-dimensional (3D) BIM model, which results in a 4D model facilitates material procurement, project management, construction schedule refinements (Alizadehsalehi and Yitmen 2016). Additionally, BIM produces multiple interrelated views of the project eliminating the need for drawing each view individually (Mehmet 2011). Moreover, BIM can develop several design options, which can optimize the design process and provide the owner of the project with the best design option in terms of cost, time and quality. The benefits of BIM are not exclusive to the pre-construction stage only, but they extend to the during and post construction phases. BIM facilitates site planning and mobilization by storing crucial information about site planning and mobilization. It can also be employed by construction managers in planning and plotting access and exit routes, workshop, site materials storage, and machineries which results in better site management. As for post construction, BIM can be used in facility management including scheduling maintenance and monitoring the performance of the devices installed in the structure (Latiffi et al. 2013). Additionally, the interoperability of BIM with industrialized building processes and fabrication of building elements were studied by several researchers. For example, a workflow between BIM modelling and digital fabrication software through modelling, layout planning and geometric detailing in BIM software, changing the model to Industry Foundation Classes format (IFC), which is a standardized digital description of the built environment a commonly known format for data exchange between different BIM software, including buildings and civil infrastructure, usable across a wide range of interfaces. The format was then transformed from IFC to Standard Triangle Language (STL), used for fabrication, Computer Numerical Control (CNC), and 3D printing purposes (He et al. 2021). Nevertheless, this new technology has not been fully implemented in the bridge industry thus far. Bridge stakeholders have come to realize the potential benefits of using BIM in the design and construction of bridges. The need for standardized electronic interchange of data has become very essential throughout the lifecycle of bridges. However, these standards haven't been developed to date (Costin et al. 2021). Most applications of BIM focused on the building industry, however, its implementation in the infrastructure industry is nearly three years behind its full development in building construction (Bae et al. 2016; Bradley et al. 2016; Costin et al. 2018). Several case studies have been conducted in the literature to address the challenges of using BIM in Bridges. (Guo et al. 2022) presented a case study that focuses on interviews with key stakeholders to highlight the main obstacles and solutions of BIM implementation. The research team conducted interviews with 37 professionals from stakeholders of the owner, designers, contractors, and software vendors.

The interviews disclosed four main factors and challenges along with potential solutions for better implementation of BIM.

Furthermore, extended reality (XR) is another technology that is emerging in the AEC sector with the purpose of having real-time interaction among people and information (Arowoiya et al. 2023). The interaction and immersion between engineers, industry professionals, and the data model is facilitated by the XR technology. Video and Audio output are usually used as means for immersion in XR technology. This immersion can potentially be achieved through olfactory and haptic feedback as part of ongoing research in the entertainment industry. The term XR encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies. Better decision making, designs, construction and safety management can be attained by using VR technologies that includes BIM. AR can positively affect the AEC industry in different ways such as, avoiding clashes and hence repetition of work, reducing labour cost and adhering to time schedules (Alizadehsalehi et al. 2020). Using MR also has great advantages in the AEC sector such as, providing information necessary for better decision making, enhancing the sustainability of the project, improving communication between the different parties involved in the project. Alizadehsalehi et al. in 2020 studied a NASA-Mars habitat project, where the researchers developed a BIM-to-VR and BIM-to-MR workflows. Using VR was beneficial in determining the best design option, construction processes, and detecting clashes during the preconstruction stages resulting in more efficient handling of all aspects of the project.

1.1 Objectives and Scope

Despite the significant potential for benefit derived from the utilization of both Building Information Modeling (BIM) and Extended Reality (XR) in the construction industry, the implementation of BIM in the transportation sector, particularly in bridge construction, is not yet a common practice. Moreover, XR implementation in the AEC sector is still limited and can be regarded as a novel technological advancement. The absence of BIM and XR technologies in transportation infrastructure is because BIM was originally designed for vertical structures, optimising cartesian coordinates and other factors such as length, width, and height. However, roads, tunnels, bridges, and airports require the consideration of additional criteria such as horizontal and vertical alignment parameters, stations, and road grade. Moreover, the current BIM software for infrastructure lacks several modelling capabilities and heavily relies on pre-made models for many components, which renders the BIM approach seemingly inefficient and incongruous. Moreover, the application of BIM and XR is still limited as considerable programming and game development skills are still required which typically lacks design engineers. Finally, the additional cost of XR devices is still one of the discouraging factors for applying XR within the construction industry as no return-on-investment study had been presented.

1.1.1 Objectives

The primary aim of this paper is to present a concise workflow for the application of various XR and BIM technologies in the context of bridge construction and to evaluate their effectiveness within the transportation industry. Consequently, the objectives of this paper can be summarized as follows:

- Proposing workflow to introduce different XR technologies for 4D BIM bridges modelling. More specifically, this paper introduces the AR and VR for bridge modelling and assesses the users experience against the developed BIM models.
- Validating the applicability of the proposed workflow through a realistic case study. The assessment of the proposed workflow will be demonstrated through an application for a case study of a reinforced concrete girder-type bridge.
- Assessing the associated risk reduction for the considered XR technology applications.

1.1.2 Scope of work

To achieve the study's goals, various software and hardware were used. GIS and topography data were generated using the Autodesk Infraworks Model Builder tool. Whereas road alignment, grade, and station data were extracted from CAD files then designed in Infraworks to complete the preliminary design. Additionally, Autodesk Inventor was introduced to give more detailing flexibility for complex geometrical elements such as girders, foundations, and piers.

After refining the structural model, Autodesk Revit was used for adding detailed design elements such as adding reinforcement bars to columns, piers, and foundations. Furthermore, Autodesk Revit was used for documentation purposes such as creating shop drawings and quantification schedules. Moreover, Autodesk Navisworks was implemented on the 3D model resulting from the Infraworks and Revit to introduce the fourth dimension, namely time scheduling. The introduction of the time schedule within the BIM model was mainly to aid the designers, contractors, and decision makers to visualize the progress of construction sequence.

2 Methodology

This section presents a brief introduction for the proposed workflow to produce a detailed 4D BIM model and its visualization through different XR technologies (AR and VR). The proposed workflow is to integrate different software to accumulate their associated benefits to provide a comprehensive bridge model accounting for geometric road design, topological data, structural details and the surroundings to visualize the aesthetics of the proposed bridge.

2.1 GIS integration

Transportation projects, such as bridges, are considered longitudinal structures that overpass different obstacles, topological, and geological patterns that are of high importance to designers. As such, integrating bridge design, starting with the preliminary design phase, with the surroundings through GIS system is a vital issue that should be considered. In other words, the preliminary design of the bridge should be incorporated with a georeferenced layout map to provide reliable mode, including the cut and fill quantities, with proper visualization, contextual representation, and proper interactions with surrounding roads, buildings, and different structures. In this context, the topological information can be added either through GIS database or through the actual surveying work.

2.2 Geometric design modelling

Currently used BIM software lack the capabilities of detailed geometric road design, which is considered a key element for infrastructure and transportation projects. As such, an oriented software for the road design is introduced at the early stage of BIM modelling. The recommended software should have the capabilities to account for the road design codes such as horizontal and vertical limits proposed by different code standards (such as the AASHTO, (2020)) (American Association of State Highway and Transportation Officials 2020). Such specialized software will facilitate a dynamic facility for updating the design parameters and the considered stations. The design parameters may include the horizontal alignment parameters (such as the radius, the start point, the end point, and the intersection point) and the vertical alignment parameters (such as the elevation, comfort criteria, entry and exit gradient parameters, radius, and the length of the curve). Moreover, The recommended software should have the capabilities to add further details including the road lanes, median, shoulders, sidewalks, bicycle lanes, asphalt finish, and road decoration hardware (such as light posts, trees, roadblocks, etc).

2.3 Preliminary structural design

After completing the road geometric design, the designer should start the preliminary structural design phase of the suggested bridge based on the proposed stations. The preliminary structural design includes the distribution, shape, and the dimension estimates for the different bridge structural elements including the bridge substructure and superstructure components. This stage is mainly to get a preliminary visualization for the suggested bridge to facilitate the approvals for the proposed structural system. Furthermore, the currently available BIM modelling software is still with limited capabilities for modelling sophisticated shapes that may be proposed within the preliminary design stage. As such, more specialized software can be integrated with the geometric design software to facilitate the generation of more complicated structural components (that can be further implemented as families within the developed 3D model).

2.4 XR application for preliminary design

After compiling the BIM 3D model for the proposed bridge (using the preliminary estimates) with the detailed geometric design within the context of GIS allocation, a visualization for such integration is proposed. This visualization aims to facilitate the process of the preapprovals to commence the full design, documentation, and the project construction planning stages. The proposed visualization can be facilitated with different XR technologies. The XR technologies include AR and VR experiences which can be generated using third party software and plugins such as IrisVR—Prospect, Enscape, Augin, Augmentecture, Unity Engine and many more.

AR plugins usually renders the visible elements in a predefined view to a cloud server with moderate to high level visual effects that are recently presented in the form of accessible QR codes. The generated QR code can be later scanned with a mobile or tablet devices through designated Android/iOS applications. Such AR model can be projected on a flat surface to be investigated.

On the other side, VR is characterized by its capability to visualize the 3D model and its surroundings with high level of rendering. However, to get the whole benefit of the VR technology, designated VR hardware should include sensors such as gyroscope, infrared sensors, and motion detector sensors. These hardware devices are mainly to navigate and annotate in VR model.

2.5 Detailed design modelling

Subsequently, after approving the preliminary design, the project can be distributed among the interdisciplinary designers to commence their detailed design. Although the preliminary model may have some of the projects main data, the detailed design may require higher level of BIM details that may not be accessible through the preliminary modelling software. As such, detailed BIM models of the structural elements needed can be generated using external software and the developed model can be plugged/linked. The current study is based on implementing the proposed framework on Infraworks software which is designated for infrastructure projects. The developed BIM model should include high level of detailing that allows the designers to produce reliable documentation for the project. The developed model should ultimately be composed of designed families to facilitate a robust link to design and documentation software. It worth mentioning that the developed BIM model should meet the minimum requirement for logical parameters for the corresponding family type in Infraworks to be useable in the BIM workflow. After importing the models in Infraworks, the user can replace the preliminary structural elements in the bridge and change all the required parameters accordingly. The imported models should contain the same parameters as the standard ready-made components while preserving editability. After this step, the model can be further developed to produce documentation, VR and AR simulations for the final model.

2.6 Timeline generation and simulation

To make use of the whole visualization package, the 3D developed model can be incorporated with planned construction sequence to introduce a visualization for the fourth dimension which is time. In this context, a TimeLiner tool in Autodesk Navisworks can be used to create the construction activities with their start and end dates, both the actual and the planned dates if applicable. The user can also link data related to material cost, labor cost, total cost, and more using such tool. The TimeLiner tool is considered user friendly since it accepts general files from third-party software exported in the form of.csv format. The user can link a viewport animation and link it to the simulation for presentation purposes. Aside from the mentioned capabilities, the user can manipulate the simulation's duration, intervals, and text that represents information about the simulation. Finally, the user can render the simulation into a video file that gives the decision makers a complete vision about the project timeline visualized in a 3D environment.

2.7 MR application in BIM

Although the AR and VR provide a great visualizing experience, however, both technologies are not visible for site supervision and documentation. Although the AR technology is considered accessible since the model can be visualized through a QR code that can be scanned through a mobile phone or tablet. However, the commonly used AR models lack details that will allow construction engineers to monitor the construction details. Moreover, the AR technology does not allow for annotation which is a vital feature for site engineers for site documentation. The AR technology may be further developed through in-house programming to consider such modelling details. On the other hand, VR technology is considered a great application that can allow the user to navigate and annotate on the 3D model. However, the VR technology is not applicable for site premises as it requires several hardware devices that cannot be installed in the site during construction. On the contrary, MR technologies have proven their efficiency in terms of visualization with accessible hardware (like eyeglasses) mixed with the real site (Cheng et al. 2020) & (Moore and Gheisari 2019)]. The MR technologies have the capabilities to navigate and annotate on the 3D model while moving on the real site. As such, the final developed model can be visualized on different MR technologies to allow the construction site engineers to visualize the design and compare it with the site status. Such technology will facilitate a real-time communication tool between the construction engineers (onsite) and the designers, and stakeholders to visualize the project even with no human contact. Figure 1 summarizes the proposed flowchart for implementation.

3 Case study

This section provides the detailed process and results of applying the developed BIM-to-XR workflow on El-Merghani bridge, starting from developing the geospatial context till documentation, simulation, and visualization of the project.

3.1 GIS and geospatial context of El-Merghani bridge

To create a workspace within a project file in Infraworks, a geospatial extent, boundaries, and information should be defined either manually or using the model builder tool in the software. Due to the inaccessibility of surveying and geospatial data of the project, the model builder tool has been used. Using the link between Esri's ArcGIS and Infraworks, a rectangular boundary has been set around the bridge site with the consideration that the maximum area limit for boundary is 200 km^2. The bridge lies at the intersection of El-Merghani Road and El Orouba Road, two main streets in Cairo, Egypt. Defining the coordinate system in Infraworks is crucial at the stage of project creation since the system cannot be redefined or altered later. The coordinate system used was Ain El Abd-UTM-36N, since UTM 36 North systems provides the highest accuracy and least distortion in coordinates for projects that take place in around the Delta and the Nile Valley. Such details are elaborated within Fig. 2 which depicts the spatial location of El-Marghani bridge.

After specifying the boundaries and the coordinate system, Infraworks analysed the input data in a cloud server, compiled raster images, various GIS data about surrounding objects, and terrain data within the specified boundaries and followed by sending an

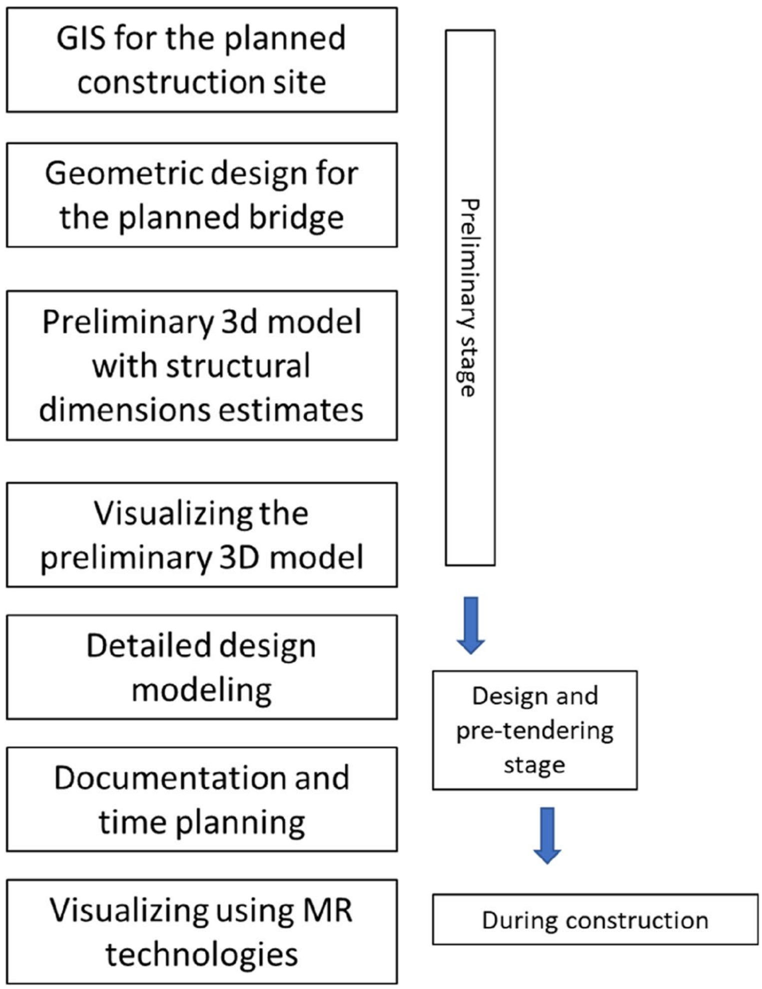


Fig 1. Schematic diagram for the proposed workflow

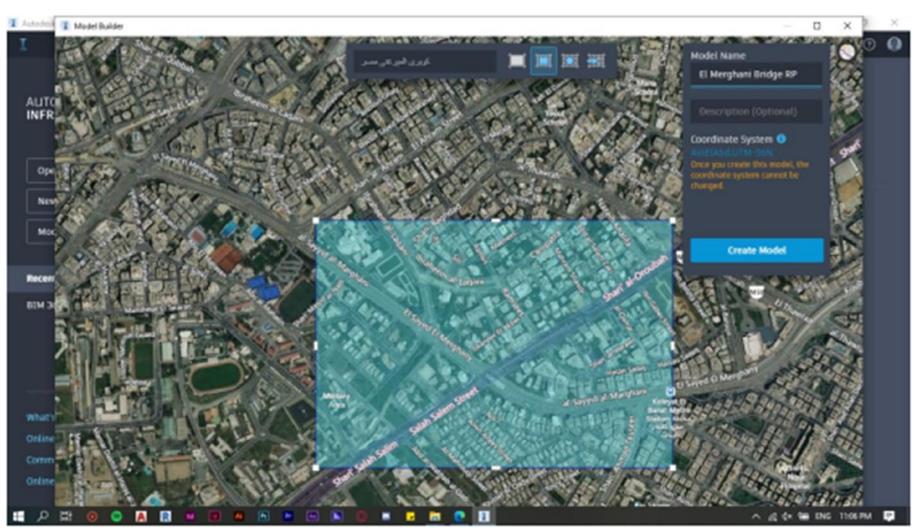


Fig. 2 Spatial location of El Merghani bridge

email notifying that the file is ready for use. The file was downloaded with the.sqlite file extension that could be backed up and manipulated later, though it is not recommended to manipulate Infraworks files as they may get corrupted. Infraworks generated buildings, roads, utilities, bridges, and different structures. El-Merghani bridge was generated as a component model since the project was already finished, yet since the scope of this research revolves around applying the BIM-to-XR workflow on this specific bridge, it was deleted to begin modelling it from scratch. It was also noted that the bridge and other structures were not generated accurately, but that has to do with the fact that these components were generated for the sake of presentation in the first place. The software generated the models and textures for different components using the stock files and textures or using manually downloaded country kits. Country kits contain components that look relevant to the country or the region where the project is taking place, they can also contain structural component families that can be handy when modelling structures like bridges. Some buildings, roads, utilities could be missing or not accurately represented as the GIS data may be outdated. It is strongly recommended to use surveyed data and GIS data as manual inputs for more accurate representation and higher accuracy in quantification of cut and fill of earthworks. However, the automatically generated data was quite satisfactory to serve the objectives of this work. At this stage, changing the component families of the roads and buildings for enhanced presentation was better, non-destructive, than changing it during or after the structural modelling. Where Fig. 3 shows the alignment of El-Marghani bridge within its adjacent neighbourhood.

3.2 Geometric design of the road for El-Merghani bridge

Once the file analysed and prepared by Infraworks was ready for use, the process of geometric design of the road started, which is basically the process of designing the cross sectional slopes, super-elevations, longitudinal profile in terms of vertical slopes and its parameters such as the entry and exit gradients, factor of comfort criteria, curve length, other geometrical parameters and features of the curves, and finally, the horizontal curve

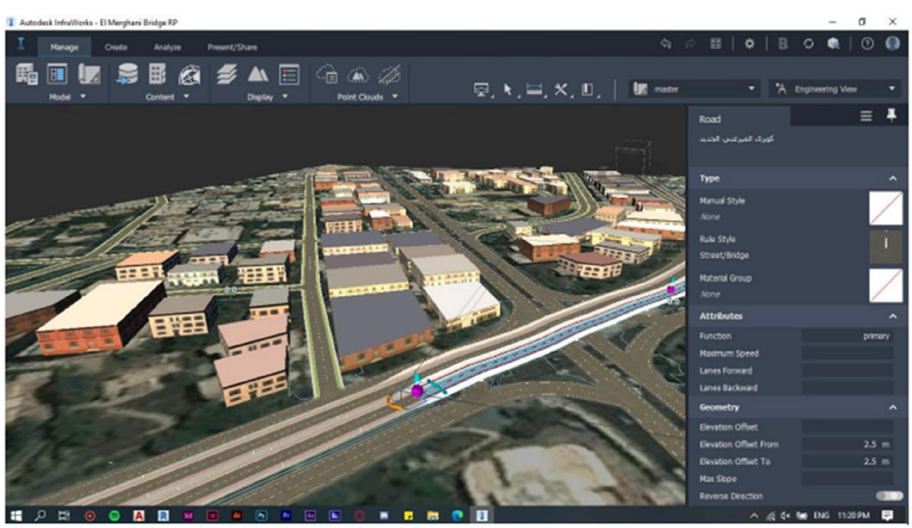


Fig. 3 Alignment for El Merghani bridge

parameters and features of the road. This stage is crucial in terms of properly designing the road for the required design speed, serviceability requirements and criteria, and safety. Infraworks possesses the ability to optimize the curves and super-elevations properly and dynamically in real time while editing parameters according to the inputs given to the software. In this specific case, AASHTO, (2020) was used to design this bridge, which was defined as a code standard for the software along with a design speed of 70 km/h and the road was classified as a collector road. Due to the availability of the geometric design of road schematics and drawings, the accuracy of the road design using Infraworks was tested against the traditional, manual design method. The comparison showed that Infraworks' geometric design was identical to the traditional design method used during the project construction timeframe.

3.3 Preliminary structural design of El-Merghani bridge

To minimize destructive editing, the stage of preliminary structural design of the bridge started after completely finalizing the geometric design of the road. This stage basically consisted of converting the road into a bridge "civil structure", then distribute the structural elements across the bridge according to the conceptual design. The available data was used to accurately locate and distribute piers, abutments, foundations, and girders across the whole longitudinal profile of the project. The number of piers, spacing between them, their correct location from starting point, the girders' thickness, their number, and their spacing within their girder group have all been properly modelled according to the provided data.

At the time this model was developed, the editability of parametric values for the structural elements that Infraworks provided, did not feature any option to edit the existing structural components to fit the project's needs. Infraworks used to offer only three bridge templates with very limited structural components for piers, abutments, girders, and foundations. For the preliminary structural design stage; conceptual design, presentation, and simple projects, modelling via Infraworks should be adequate. However, for further analysis and to achieve the objectives of this research, a 3D modelling software that was compatible with Infraworks had to be used to model the complex elements presented in this project. The tool that was used to further refine the bridge elements was Autodesk Inventor.

3.4 Complex geometrical modelling and detailed structural design of El-Merghani bridge

Autodesk Inventor is a fundamental tool in this project that contained all the tools needed for modelling the bridge structural elements. Autodesk inventor possessed all the sketching capabilities of AutoCAD and 3D modelling to shape and form all the needed 3D shapes. Initially, Autodesk Inventor was used for modelling mechanical parts, just like SolidWorks, but due to the compatibility of Autodesk Inventor's 3D models file extensions with Infraworks, it was included in the BIM-to XR workflow and used to model El-Merghani Bridge's required structural parts. However, recently in 2023 Infraworks was updated to include Revit families compatibility along with the features provided by Autodesk inventor.

According to the drawings and documents provided for this case study, the bridge required building several models: rectangular piers, curved columns, T-section girder, V-section girders, pile caps with piles and abutments. The developed models were then exported to Infraworks to complete the detailed structural design phase. Prior to importing the developed models, Infraworks had to be prepared to receive the imported data and this is accomplished by creating and defining a set of parameters, such as length, width, height, offset, radius and so forth for the different structural elements, within the file. All the parameters whether required or not are editable within Infraworks. In addition to creating and defining the parameters, Autodesk Inventor also requires constraints between all drawn lines and vertices within a sketch for the model to be projected, scaled, and updated dynamically during the detailed structural design stage in Infraworks. The constraints include coincident, collinear, concentric, parallel, perpendicular, horizontal, vertical, tangent, symmetric, and more.

3.4.1 Piles and pile cap

The pile cap was modelled easily using a rectangular sketch, a circular sketch for the piles, array of the piles circular sketch, and dynamic linking between parameters and dimensions. Meanwhile for the abutment, the premade component model of the abutment in Infraworks was satisfactory for this case study. Upon model completion, all the required structural components were imported to Infraworks to replace the preliminary structural elements. Minimal editing in the parameters was required to match the provided design layout, which included modification of foundation dimensions, the number of the piles and the spacing between them, the diameter of piles, dimensions of the column, its layout, skew angle, enabling or disabling compensation for varying depth of girders, enabling, or disabling the curved column feature.

3.4.2 Piers and girders

The pier section was modelled by sketching a simple rectangle sketch, the pier cap consisted of four (4) sketches shaped as a diamond that varied in depth and sidelines slope and finally the cover walls consisted of a rectangle sketch that was placed and constrained by the pier cap model. All sketches had well defined dimensions for dynamic editability and proper logical constraints for better harmony, scalability, and dynamic flexibility for the full extent of usage in bridge projects.

For better dynamic workflow, the curved column was created as an option within the rectangular column Inventor model through a cut extrude in the model using a curve that was controlled by a parameter that is responsible for changing the radius of the curve. The feature to enable the curved column and disable the rectangular column was controlled by a true/false parameter that was linked to a Visual Basic code within the "iLogic" Autodesk Inventor feature. This code's logic works simply through an "if-else" argument that enables the feature when the parameter value is "true" and disables it when "false".

More features were created within the column model file for more accurate and correct representation of the design. The features that have been created comprise the ability of the pier to compensate for elevation difference of pier cap due to varying depth of girders, to compensate for superelevation slopes using "cuts and fills" within the column. These features were represented using "if-else" code arguments as well. Figure 4 shows the typical geometrical prismatic shape of the bridge piers.

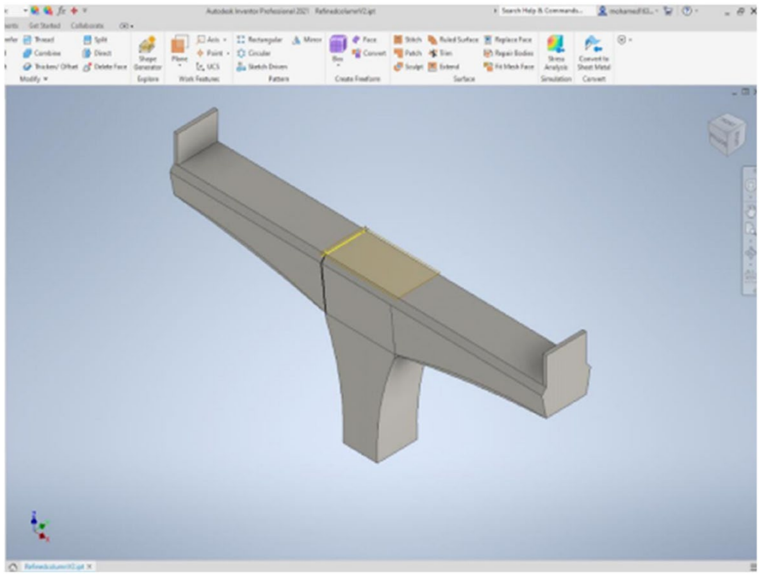


Fig. 4 Typical pier section for El Merghani bridge

Fig. 5. 3D model for El-Merghani bridge

It worth mentioning that the girders were modelled considering one cross section, however, it originally consisted of three different sections (two of which continues for small interval as an architectural requirement). Such modelling approximation was introduced since such variation in the cross section did not affect the girder detailing significantly.

At this stage, the 3D model can capture the complex geometric modelling as shown in Fig. 5. The model at this stage was ready to be imported to Revit for adding the reinforcement details, documentation, visualization, quantification, and timeline simulation.

3.4.3 Reinforcing structural elements in El-Merghani bridge

Upon finalizing the detailed structural design stage, the model was exported to Revit for further refinement, documentation, and quantification, using the Infraworks interoperability plugin in Revit. First, the model had to be published from Infraworks in.imx file extension, then the file was exported to Revit using the "Import Civil Structures" option in the plugin. In case any updates to the structural model is required, the Revit model could be easily updated using the "Check for updates" option. The process of exporting the structure involves converting all the components from Infraworks, whether structural or not, into Revit families, components, generic models. Revit then started extruding, lofting, revolving, and sweeping all the automatically generated sketches from the geometry of the components, which can result in some errors and distortions when generating the model. These errors could be negligible for most applications, yet they might hinder the ability to reinforce some structural elements in the bridge. In the current research, the error appeared while modelling the V shaped girder due to its geometrical complexity as will be discussed shortly.

3.4.4 Substructure reinforcement

In this case study, a girder, a pier, an abutment, three (3) pile caps and piles foundations were selected for reinforcement. For the pile caps, the reinforcement was simple and straightforward; they consisted of U-shaped bars in the X, Y, top and bottom directions, with additional reinforcement in the bottom and shrinkage bars at the sides. For the piles themselves, spiral stirrups and vertical bars were used for reinforcement. All reinforcements were as per the designed diameters, numbers, and spacings. As for the abutment and pier, all reinforcement were modelled accurately without simplifications as shown in Fig. 6.

3.4.5 Superstructure reinforcement

Meanwhile for the girders, only the selected T-section girders were reinforced. The process of reinforcing the T-section girders was not as smooth and easy as the other elements, this has to do with the fact that their cross sections get skewed due to the piers' skewed orientation, yet it was doable. Revit possesses the ability not only to reinforce

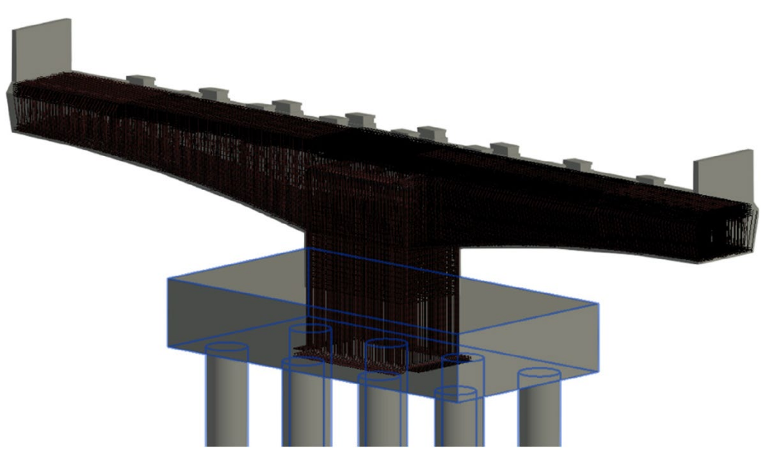


Fig. 6 Substructure reinforcement (focusing on pier and hammer head)

Fig. 7 Typical 3D model for the bridge girder (showing the reinforcement)

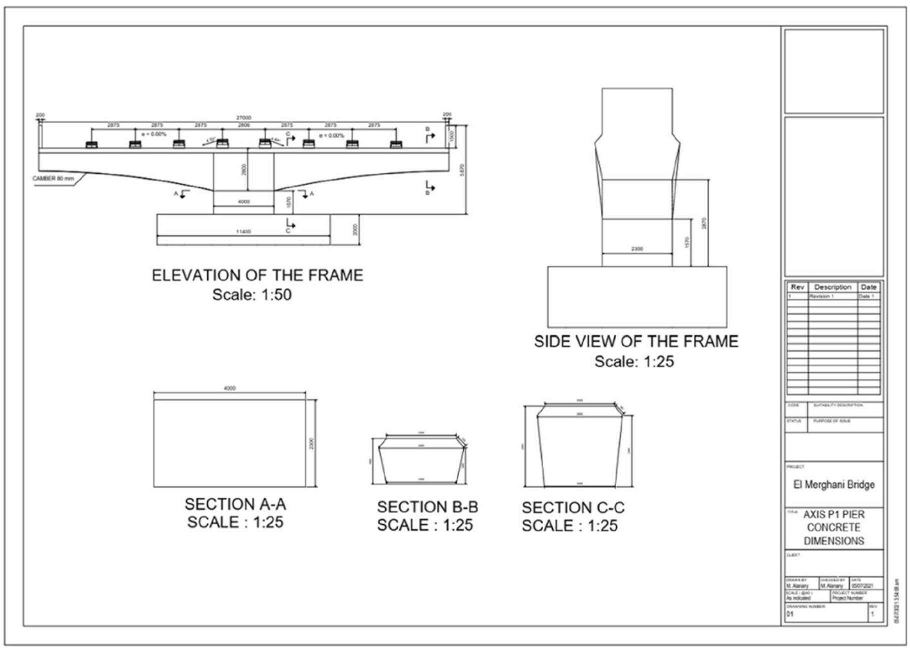


Fig. 8 Typical details drawing for the bridge pier

parallel and perpendicular to the work plane, but also parallel and perpendicular to the concrete cover of the structural element, making rebar placement in the T-section, skewed girders significantly easier. Figure 7 shows the 3D model for the considered girder illustrating its reinforcement.

3.5 Documentation and quantification process for El-Merghani bridge

Once the structural model was converted into a Revit model from the.imx Infraworks format, the structure became compatible with Revit and made use of all the features Revit had to offer for conventional buildings; such as documentation comprised in generating highly detailed drawings for all present structural elements within the model with the availability to update automatically when change is applied, generating detailed schedules and drawings for reinforcement, and generating an accurate, detailed quantity survey report to be used for further applications. In the current study, only eight detailed concrete dimension drawings and a full quantity report were generated. Figure 8 shows the typical form of the generated detailed drawing. Where the title block family for drawings were edited to fit the needs for this project. All plans, views, and layouts were properly oriented, scaled, and dimensioned precisely as modelled. Unlike AutoCAD, where dimensions' text can be edited and the modelled components can be scaled manually, Revit does not allow for manual manipulation of dimensions, scales and geometry since such thing would completely make the BIM dynamic abilities and workflow obsolete.

For the quantification, it was noted that Revit does not provide quantities for road decorations, asphalt layer, and concrete quantities of girders and girder groups. Thus, the road decorations, the asphalt layer, concrete quantities of girders, and the cut and fill quantities were exported and used from Infraworks and the rest of the quantities were exported from Revit. All quantities were then combined in a table comprising all categories.

3.6 Integrating time schedule with El-Merghani bridge model (timeline simulation)

Due to the partial availability of the time schedule data for the project, a hypothetical schedule was generated in Oracle Primavera P6 to be used for the needed simulation. This process elevated the model from 3rd BIM dimension to the 4th BIM dimension. Due to the confidentiality and the inaccessibility of cost data of the project, it was not included in the process, yet the model is ready to be elevated for the 5th BIM dimension at this point. The schedule created was exported to Excel file format to be converted and optimized to be imported to Navisworks as a.csv file.

The Revit model was then exported to Navisworks through Navisworks exporter plugin in Revit. All the features were then presented in Navisworks 3D space and were categorized in the selection tree according to their family types in Revit.

The TimeLiner tool in Navisworks provided the ability to define activities, planned and actual start and finish dates, various cost categories such as labour, equipment, and material costs, progress, and more. Activities could be imported from other scheduling software into Navisworks through.csv file format. The developed schedule was imported and presented in the TimeLiner tool. Moreover, every relevant object in the model was attached to its relevant activity for proper presentation during the simulation of the timeline. For better presentation, a viewpoint animation was created and used in the video of the simulation as shown in Fig. 9.

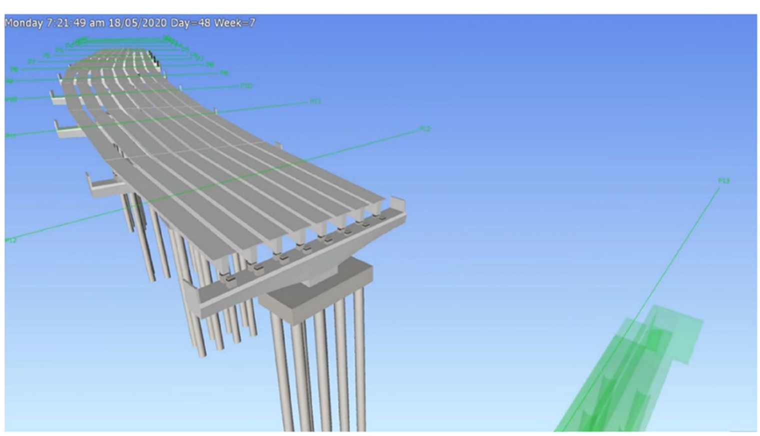


Fig. 9. 4D Snapshot model for El-Marghani bridge

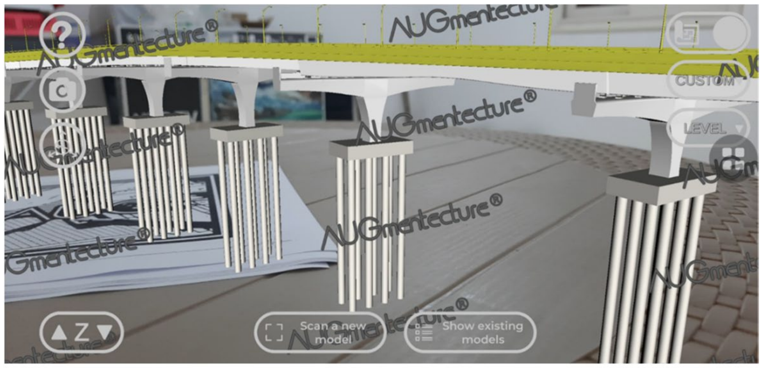
3.7 Developing VR and AR experiences for El-Merghani bridge

To create VR and AR experiences, usually 3rd party plugins need to be used. Among the various options available, IrisVR plugin was used to create the VR experience for this case study. Meanwhile, Augmentecture plugin for Revit was used to create the AR experience. The devices used for the visualization of the VR experience were an Oculus Rift S head mounted display device and a high-end computer. As for the AR experience only an Android mobile phone was used. The Augmentecture AR experience offered capabilities of panning, moving, rotating, taking screenshots, and moving around the object while it was still oriented and placed onto the detected flat surface. VR experience created by IrisVR offered much higher capabilities to investigate the model in comparison to the AR experience, since it offered much higher immersion through the head mounted display than viewing the model on a smartphone. VR also provided a view of the model that is of 1:1 scale, which was highly immersive and realistic. Moreover, VR provided the ability to inspect the parametric values for every object in the model, to use dimensions with both metric and imperial units, to take pictures for reporting and for further issue inspection and tracking, if there were any. Issue tracking was only available through models synced with IrisVR servers. Synced models could be viewed by multiple individuals and interact with each other and the model in real time. IrisVR also allowed for view streaming to the computer's screen, helping in recording the experience and interactivity with other team members. A VR experience was attempted through the Oculus Rift option in Infraworks, yet it appeared very inferior compared to IrisVR. The experience did not feature any parametric data inspection capabilities and was not immersive as the experience was controlled by the keyboard rather than the HMD controllers. Even though AR was not as powerful as VR, yet its power appeared to lie in its portability and ease of use. AR required only a smartphone or a tablet with an application installed, a flat surface, and a QR code of the model to scan. Meanwhile, VR required expensive head mounted display devices, high-end computers, and a lot of cable connections which was not as portable nor as easy to use as AR. The data representation that AR is lacking could be compensated by printed drawings, design notes, and other documents to assist relating the virtual model to data during presentations, design meetings, and progress meetings. Where Fig. 10 a and b shows the AR and VR application for the developed model respectively.

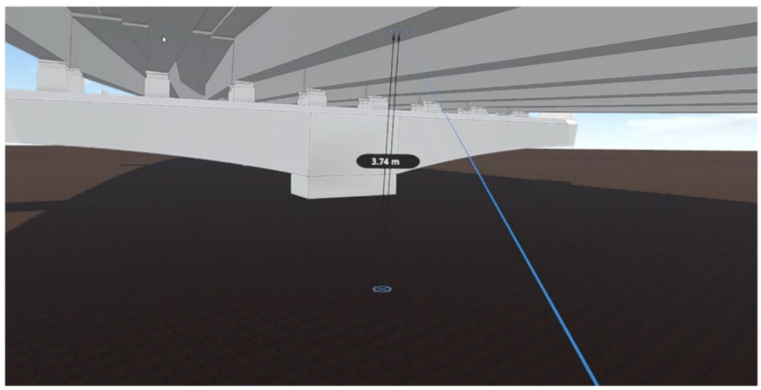
4 Examining potential cost reduction resulting from the utilization of VR and AR technologies on typical bridges construction

The total cost of a construction project typically comprises direct cost, indirect cost, overhead, and markup. The markup part always includes a contingency sum to secure probable risks to a project which usually forms an amount that cannot be underestimated. In this part, the current research aims at examining the potential cost reduction effect due to the change of contingency without the utilization of VR and AR technology against its utilization.

Commonly potential risks affecting bridge construction have been identified from consulting construction bridges practitioners and surveying literature. Seven common risks are identified namely, financial risk, external risk, design risk, management



(a). AR model for El-Marghani bridge



(b). VR model for El-Marghani bridge

Fig. 10 **a**. AR model for El-Marghani bridge. **b**. VR model for El-Marghani bridge

risk, construction risk, contractual risk, and health and safety risk (Choudhry and R. 2019). Qualitative and quantitative risk analyses have been performed on the identified seven potential risks for determining the required contingency to be allocated at a certain level of confidence with and without the utilization of VR and AR during the design and construction phases of a typical bridge construction. Ten experts specialized in bridges construction have been consulted for identifying their expectations regarding the probability and impact of the identified risks on the cost of a bridge construction according to each probable risk. The experts were asked to provide their expectations for probabilities and impacts for each potential risk on a scale from very low to very high. Then the answers were translated into numeric on a scale from 0 to 1 starting by 0.10 to 0.90 (very low takes 0.10, low takes 0.30, medium takes 0.50, high takes 0.70, and very high takes a score of 0.90). Figure 11 represents part of the different number of experts advised with such inputs.

Then the percentage of cost increase is specified in the severity matrix if a risk happened at the different severity levels according to experts' feedback. The weights of the severity matrix are automatically linked to the numbers already generated in the probability/impact matrix as indicated in Fig. 12.

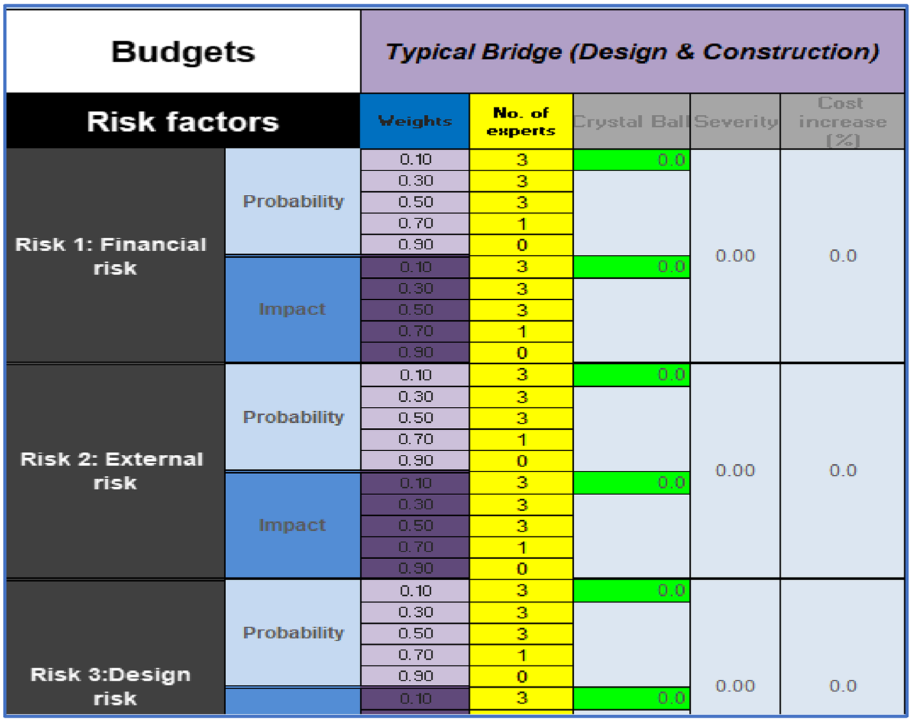


Fig 11. Experts' number data entry

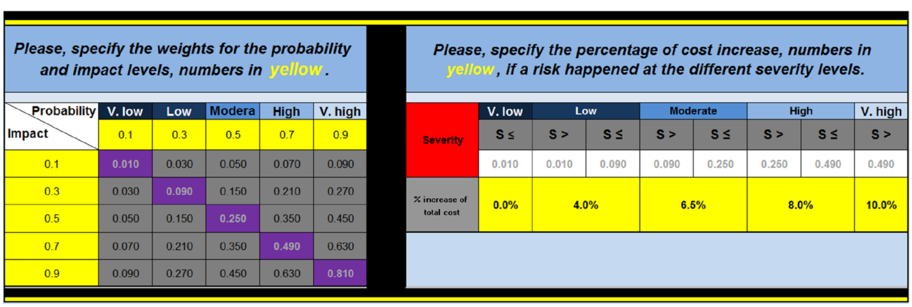
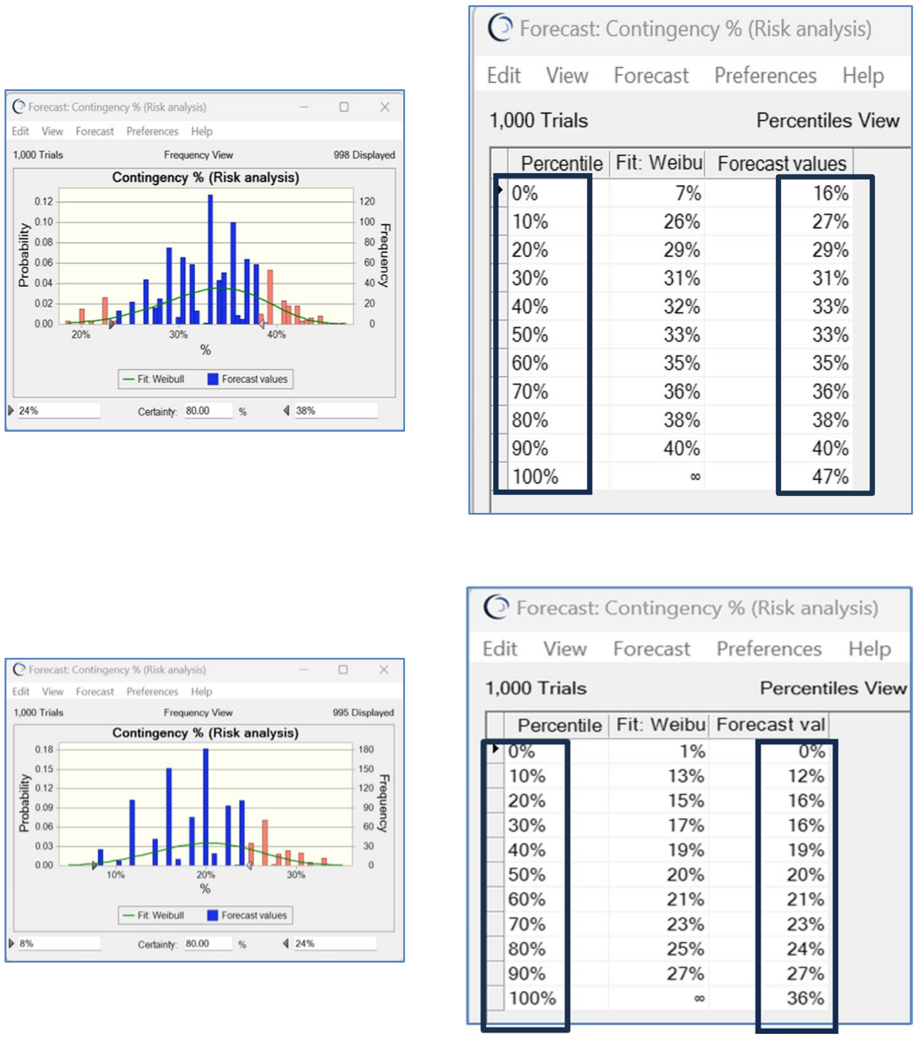


Fig. 12 Preferences for probability-impact and severity-cost increase matrices

Monte Carlo simulation is performed using Crystal Ball software, add-in to Microsoft Excel platform, for the whole assumptions and forecasts defined for risk analysis considering two scenarios, without against with the utilization of VR and AR in bridge construction as shown in Fig. 13. The simulation process helps greatly in minimizing potential biased inputs by some experts as odd data are considered during the process.

By observing the results of the above both scenarios, it can be clearly noticed the great reduction in percentage of contingency against same certainty levels in both scenarios. For example, at 80% certainty of securing risk, the percentage of contingency out of total cost greatly decreased from 38% when excluding the utilization of VR and AR technology to 24% when using it. This examination provides a reasonable encouragement to the utilization of VR and AR technology, and it opens the door for



Percentile	Fit: Weibu	Forecast values
0%	7%	16%
10%	26%	27%
20%	29%	29%
30%	31%	31%
40%	32%	33%
50%	33%	33%
60%	35%	35%
70%	36%	36%
80%	38%	38%
90%	40%	40%
100%	∞	47%

Percentile	Fit: Weibu	Forecast val
0%	1%	0%
10%	13%	12%
20%	15%	16%
30%	17%	16%
40%	19%	19%
50%	20%	20%
60%	21%	21%
70%	23%	23%
80%	25%	24%
90%	27%	27%
100%	∞	36%

Fig. 13 **a** Frequency of certainty level against equivalent percentage of contingency when excluding the utilization of VR and AR in typical bridges construction. **b** Different percentiles (certainty level) against equivalent forecast values (percentage of contingency) when excluding the utilization of VR and AR in typical bridges construction. **c**. Frequency of certainty level against equivalent percentage of contingency when including the utilization of VR and AR in typical bridges construction. **d**. Different percentiles (certainty level) against equivalent forecast values (percentage of contingency) when including the utilization of VR and AR in typical bridges construction

further examinations and considerations of different type of bridges. The overall overview of results shows a great opportunity in cost savings by employing VR and AR technology in bridges construction.

5 Conclusions and recommendations

5.1 Conclusions

The objective of this research was to introduce an innovative workflow for the application of BIM principle till the 4th dimension, which is scheduling and simulation of timeline, along with XR technology for visualization to the construction of typical bridges. Based on the introduced workflow, a combined tools based-model was developed which offers the integration mechanism among different tools such as BIM, XR, GIS, and Primavera P6 for a better management of time and cost of the construction of typical bridges. A real case study of El-Merghani Bridge in Egypt has been used for the verification and evaluation purposes of the introduced integrated model. A highly detailed 3D model was created for the case study featuring all the structural and non-structural elements, along with the highly immersive VR and AR experiences that is expected to benefit the construction practitioners in visualizing the project. The developed integrated model would enable the practitioners to take the proper course of action on issues and design adjustments before beginning the construction phase. It also provides better imagination and visualization to non-technical personnel and stakeholders than the conventional shop drawings and handmade 3D isometric sketches. Both AR and VR technologies are highly beneficial when integrated and used in relevance of the context. AR can be more useful while using it in-situ or for quick demonstrations along with shop drawings where no computer or HMD is accessible. Meanwhile VR is more beneficial for detailed investigation and visualization of BIM parameters for all objects in the model by the design team during design meetings, meetings with professionals and non-professionals for in-depth illustrations and training. XR can help in reducing cost and time resulting from design and construction discrepancies through early clash detection using features such as the issue tracking tool in IrisVR. The developed model also proved high effectiveness of the BIM documentation features as in conventional buildings. Dynamic views will help also in automatic update if any changes to the design of the model occur. Dynamic shop drawings decrease the time needed for submitting shop drawings revisions, and hence project's duration. In addition, BIM to XR workflow benefited the project in the quantification and timeline simulation process.

Quantification for El-Merghani Bridge as a case study has been done using Autodesk Revit and Infraworks. A complete, accurate quantities report has been generated for the project which saves a great amount of time than manual quantification. The room for error in automatic quantification is smaller compared to manual calculations due to lack of calculation error by human factor, yet the accuracy is bound to the level of detail of the model, lack of errors in modelling the components and families, and correctness of parametric inputs. Timeline simulation of El-Merghani Bridge is beneficial for progress reports, progress meetings, planning and scheduling.

Qualitative and quantitative risk analyses showed that the implementation of VR and AR technologies in bridge projects contribute significantly in the reduction of the contingency reserve of these projects, which allows for cost reduction. Overall, the positive results of this research can provide great encouragement for the application of BIM and MR on linear and infrastructure projects likewise typical construction buildings.

5.2 Future Recommendations

To extend the scope of this research, future studies could explore on the following: the benefits of the integration of MR technology in the currently proposed BIM-to-XR framework. Application of the current framework in different infrastructure structures, such as railways, water channels, tunnels, etc. An integration of risk management tool could also be a great addition to the proposed workflow for far better time and cost management of infrastructure projects. An integration of a site inspection tool including a photo recognition tool could also greatly help in time and cost reduction.

Authors' contributions
All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ahmed Alhady, Mohamed Alanany, Yasser Khodeir, Shady Salem and Yosra El Maghraby. The first draft of the manuscript was written by Mohamed Alanany and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data and models generated or used during the study appear in the submitted article.

Declarations

Ethical approval and consent to participate
This study does not contain any studies with human or animal subjects performed by any of the authors.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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