ON THE SOLIDIFICATION OF POINT CLOUDS FOR BUILDING INFORMATION MODELLING, AUGMENTED AND VIRTUAL REALITY APPLICATIONS IN CONSTRUCTION

Robert Eadie[1*] and Yatchko Ivanov[2]

[1] *Ulster University*
York Str., Belfast, BT 37OQB
e–mail: r.eadie@ulster.ac.uk

[2] *European Polytechnical University*
23, St. St. Kiril and Metodiy Str., 2300 Pernik, Bulgaria
e-mail: yadir_11@abv.bg

Abstract. The Green Agenda has led to less demolition and more retrofitting and extending existing buildings. This has had a knock-on effect as contracts for this type of work now require Autodesk Revit 3D models with Virtual Reality and Augmented Reality. These extra elements using immersive technologies make it easy for clients to envision the changes, aesthetics including colour schemes, impact of lighting, and provide enhanced visualisation on the revised spatial impact of retrofitted and extensions to buildings. This paper looks at the revised workflow required from gathering data using a scanner, through producing a point cloud, solidifying itto bringing solidified elements into Revit as families. It examines user perceptions of five pieces of software used to solidify the models. Furthermore, it examines an alternative uses of 360 degree images gathered by a scanner alongside the point cloud in the production of Augmented Reality tours used for various purposes in Thinglink.

Keywords: Building Information Modelling (BIM), Point Clouds, Augmented Reality, Solidification.

1. BACKGROUND TO AUGMENTED AND VIRTUAL REALITY APPLICATIONS IN CONSTRUCTION

Augmented reality (AR) and Virtual reality (VR) applications have developed at a rapid pace since they were first used around 1987. The earliest of these, VR, is defined as the use of computer modelling and simulation to allowusers to interact with an immersive 3D model, was initially used for gaming (Hamad and Jai, 2022) [1]. This was further developed into the concept

* Corresponding author.

DOI: 10.7546/EngSci.LIX.24.04.01

of Augmented reality and Digital Twins. Furt (2008) provided a generally used definition of Augmented reality as "Augmented reality is a system that enhances the real world by superimposing computer-generated information on top of it" [2]. Kritzinger *et al.* (2018) [3] define "Digital twins ... as virtual counterparts to physical entities". Virtual Reality allows the user to experience an immersive experience using a headset or computer to explore online models. Putting VR and Building Information Modelling (BIM) together has many different uses within the Construction industry [4]: allowing clients to choose colour schemes, look at lighting effects, assess the ambience of the building, it improves communication in the design team, provides enhanced understanding of the impacts through a digital review of the project in VR, thus reducing design errors and increasing buildability prior to the construction stage. Using Digital Twins and further supplementing VR with AR has resulted in further applications within construction and construction education whose practical outworking has not been fully explored. This paper seeks to explore software and applications linking AR, VR, BIM and Digital Twins and examines the workflow from gathering information to how the output is used. An example of a digital twin from a Matterport scanner that can output directly to a BIM model and supplemented via VR tags, produced at one of the authors universities, can be found at this weblink – `https://my.matterport.com/show/?m=LxChsdHD8fE`. However, gathering information from buildings already erected has been traditionally seen as time consuming and awkward. Surveys using taped measurements has led to inaccuracies. Now scanners can remove many of these errors. Examples of these are the Matterport Scanner and the Leica RTC360 Scanner which can produce a digital representation that is accurate to ±20 mm (for the Matterport 3 scanner) and ±1.9 mm over 10 metres and ±2.9 mm over 20 metres with a maximum range of 130 m (for the Leica RTC360 Scanner) [5]

1.1. Gathering information – Coloured Point Clouds

Most newish scanners produce coloured 3D Point Clouds with some linking these to 360-degree photographs. Ulster University invested in a Leica RTC360 3D Laser Scanner. For the purposes of this project, it was used to produce the initial model. The Leica RTC360 3D Laser Scanner produces point clouds at 2 million points per second which contain individual points each with its own spatial coordinates (an X, Y and Z component) and a Red (R), Green (G), and Blue (B) colour for the point. Once multiple points are amalgamated together this can represent objects or spaces. The amalgamed point representation is known as a "point cloud". These objects in a coloured 3D point cloud then

represent the space or as-built structure in a textured 3D model. Thomson (2019) shows that the point clouds are achieved by the scanner and LiDAR (Light detection and ranging) technology and techniques being combined [6]. The operation of the scanner produces many duplicate points. As a result, software provided with the RTC360 device uses a "Statistical Outlier Removal filter" which deletes duplicate points and those inconsistent with other neighbouring points if they are outside the mean distance calculated (Rodríguez *et al*, 2019) [7]. It has its own software for publishing point clouds called Leica Cyclone FIELD 360 [8]. Point Clouds in all industry standard file formats, like LAS, PTS, and E57can be outputted from it. What has not been adequately researched are the packages that use these outputs to clean and solidify these outputs for further use in AR and VR applications.

1.2. Solidifying Scanner Data

As the Point cloud is a series of dots it needs solidified into a mesh object before it can be brought into Building Information Modelling software such as REVIT or AR and VR software applications. For the purposes of this paper solidification can be defined as placing a flat surface between adjacent points to create a solid mesh surface in the shape of the object. There are at least five products that currently proport to carry out this function – Recap Pro from Autodesk [9], MeshLab [10], Bentley iTwin Capture [11], Truevis© "Mesh Import from OBJ Files" which has now been purchased by Autodesk, [12] and RealityCapture [13]. This paper will compare the use of these packages.

Once solidification has taken place the object can be imported into REVIT or other BIM software and also AR and VR applications. For some elements such as walls it is easier and quicker to draw over these in Revit rather than creating a bespoke REVIT family from a point cloud. For bespoke items such as non-standard doors, arched windows and other elements the packages above can be used to solidify elements for family creation.

Family creation is carried out in the following way. Care should be taken to not include brickwork or blockwork surrounding the object. Using the Recap Pro example in Figure 1, the "Scan to Mesh" results in credits being charged to the user. A workflow exporting this to MeshLab at this point results in no money being charged.

1.3. Object markup for Construction and Education purposes

Once a digital twin or 360 degree representation is created either through the process above it can be brought into software for tours or markup. There

Fig. 1. RECAP Pro Example – Object is closen from point cloud, then clipped and clipped area reduced within the software using the Limit Box Function,and then solidified using the "Scan to Mesh" tool. This can then be brought into REVIT as an object

are a number of software packages available to create VR and AR outputs. Two of these are Sketchfab and Thinglink. Thinglink was the one used for this report as it can handle 360-degree images from the Leica RTC 360 Scanner.

2. METHOD

The Leica RTC 360 Scanner was employed around Ulster Universities Belfast Campus (Block BA). Five students were asked carry out the workflow from the raw data, through Point Cloud manipulation to insertion of an element into a Building Information Modelling Software (in this case Autodesk REVIT).

Five different packages for point cloud data were examined on four elements – computer capacity, ease of use, quality of output and cost – and students provided open feedback on these elements apart from the costs. The costs were ascertained from the software websites. This was due to the quality findings as some of the software output quality was linked to cost, therefore a section on costs was added to this report. The weightings for computer capacity were on a 1 to 5 ranking with 1 being the most expensive and 5 being the least. Summing these ranks up indicated the least expensive hardware option. All the students chosen had used the Revit software and where shown how to gather the data for the production of the point cloud from the scanner. Feedback on experience on each of the software packages was written down and collated for this report.

Using the 360 photos that the Leica RTC 360 Scanner produced alongside the point cloud, the students then uploaded these to Thinglink for AR com-

ments and 2D photos to be inserted. Thinglink was then used to produce an AR tour.

3. FINDINGS ON MESH PROGRAMMES

3.1. Computer Capacity

Each of the minimum requirements stated for each package are detailed in Table 1. All the systems ran on Windows 10 and above. As all new systems come with Windows 11 as standard this was not considered an issue. iTwin Capture by Bentley required the highest processing power principally as this had not changed since ContentCapture, a previous version which was not cloud based, followed by Truvis (using the minimum Revit specifications), followed by MeshLab, then Recap Pro and finally Reality Capture. It can be seen from the ranking that Reality Capture minimum requirements require the least expensive hardware overall, followed by Recap Pro in second place, MeshLab and Truvis jointly in third place and finally iTwin Capture requiring the most expensive hardware. If the capacity of the machines available are limited, this should be taken into consideration. The minimum requirements for MeshLab are suggested by users for large files as MeshLab has no published minimum specification.

It should also be noted that Autodesk® ReCap's "Scan to Mesh" tool enables users to create a textured 3D mesh from point cloud data imported into the software [14] and comprehending the large amount of computer resources taken up in producing a mesh from a point cloud, ReCap provides a cloud service rather than an in-app engine. This also removes the computer capability factor from the processing [14].

3.2. Ease of Use and Interoperability

Output from the scanner software can be directly imported into Autodesk® ReCap Pro via "RCS" and "RCP" files. These files are a direct output in point cloud format from the Lieica 360 software. The features are represented by icons on a ribbon and the wide range of features provided need little explanation in providing the transition from imported point cloud data to exported meshed model. Easy removal of "alien" points in the cloud data through clipping and deletion are user intuitive. This clipping and deletion can also temporarily remove irrelevant surrounding geo-spatial data through the "Clip Outside" function. However, this only hides the points keeping the size of the scan, allowing the highlighted area to be reduced or increased through the

Table 1. Comparison of Computer Capacity to run software

Minimum System Specifications	Recap Pro [15]	MeshLab [16]	iTwin Capture [17]	TruvIsRevit plug-in (Revit Specifications) [18]	Reality Capture [19]
Operating System	Microsoft® Windows® 10 (64-bit)	Microsoft® Windows® 10 (64-bit) or iMac version 10.6.8	Microsoft® Windows® XP (64-bit)	Microsoft® Windows®10 or Windows 11 (64-bit)	Microsoft Windows version 7/8/8.1/ 10 (64-bit)
CPU Type	2.0 GHz or faster 64-bit (x64) processor Rank 4	2.8 GHz Intel Core 2 Duo Processor Rank 3	Intel Core I7-4770 Rank 1	Intel® i-Series, Xeon®, or AMD®equivalent 2.5 GHz or Higher.Rank 2	4 CPU cores Rank 5
RAM	4 GB or more RAM Rank 3	4 GB or more RAM Rank 3	32 GB or more RAM Rank 1	8 GB RAM Rank 2	8GB of RAM Rank 2
Display Resolution	1280 x 1024 or higher w/ true colour Rank 1	Not restricted Rank 2	Not restricted Rank 2	1280 x 1024 with true colour Rank 1	Not restricted Rank 2
Graphics Card	OpenGL 3.1 capable graphics device with 256 MB graphics memory Rank 3	NVIDIA GeForce 7300 GT with 256 MB graphics memory Rank 1	Nvidia GeForce GTX 1060 Rank 2	Display adapter capable of 24-bit colour. Rank 5	NVIDIA graphics card with CUDA 3.0+ capabilities and 1GB RAM Rank 4
Browser	Not restricted Rank 2	Not restricted Rank 2	Not restricted Rank 2	Microsoft Internet Explorer 10 (or higher) Rank 1	Not restricted Rank 2
Total Rank	13	11	8	11	15

"Limit Box" function. To minimise the effect of just hiding the points rather than deleting them Autodesk have used the cloud based solution mentioned previously. A removal function that reduces file size by completely removing points outside the limit box extents would be a welcome addition if computer capacity is an issue.

The open source MeshLab software has an issue with import of some of the standard file types. Two of the most commonly used Autodesk file formats are "RCS" and "RCP" and these are not able to be directly imported into MeshLab. MeshLab only imports ".ASC" file types. ASC file types can be created from Recap Pro or free software such as Autoconveeter to be imported to MeshLab. When the object is within MeshLab, in order to get access to the features for mesh conversion another change to a ".mlp" file type, is required. This changes the file from a cloud import to a local working file. However, when trying to export from MeshLab, the "Export Mesh" function offers a enormous variety of file types. This is excellent as these file types readily integrate with Revit and other BIM software. One other drawback is that MeshLab does not offer a significant internal editing tool. Removal of Alien data is clunky and awkward. The students assessing the cloud data found it easier to take the cloud data, imported it into Autodesk® ReCap to remove the alien data before clipping the desired objects and importing to MeshLab to solidify the point clouds into objects. These objects can then be imported into Revit.

iTwin Capture is also limited on the types of files it can import. It only supports ".PTX" and ".E57" file types. Both of these can be directly exported from Leica 360 Cyclone software. However, many consultants with Autodesk Products send files as "RCP" or "RCS" outputs. If using the iTwin Capture software remember to ask the consultant supplying the data to import the "RCP" or "RCS" files to Autodesk ReCap and then using that software to convert them to ".PTX" files for export. The ContextCapture Master software offers a basic but expandable user interface that is easy to follow. The software allows the user to implement a "Project Tree" which is useful in allowing clear identification of where the imported data relates to in each project file. ContextCapture allows the creation of a mesh in three clicks as this is on the main hub menu: firstly, the user selects the project file from the "Project Tree", then clicks "General" from the tab ribbon and then the "New reconstruction" function. A "Production definition" pop-up menu allows definition of the parameters of the output mesh. You can also specify the export file type and save destination on this menu.

iTwin Capture has really good viewing tools providing a snapshot on "3D

View", or the user can launch Acute3D Viewer for a detailed view. This function allows the user to assess the quality of the mesh prior to import into Revit. If required, the model can be loaded into the iTwin Capture Editor to make final alterations to the meshed model before final export. Exporting the file provides many file type variants similar to MeshLab resulting in easy Revit integration. iTwin has now mirrored Autodesk Recap Pro by going to a Cloud Based solution.

Truevis© "Mesh Import from OBJ Files" allows import from OBJ files. OBJ Files are 3D model files. It only works for OBJ files which are not a direct export from the Leica 360 Cyclone scanner software. However, another section of the Leica software can be purchased Cyclone 3DR which allows export to OBJ files. Therefore it requires the "OBJ" files to be converted prior to import through the Revit add-on. Truevis© "Mesh Import from OBJ Files" can be purchased from the Autodesk® App Store, and as a supported plugin integration with REVIT is seamless and access is through the "Add-ins" ribbon. The excellent "Mesh Import Options" provide a way of formatting "Material Name" and "Category" classifications allowing the mesh to enter in to a family with the correct definitions.

Reality capture allows import from the following filetypes: PTX, E57, ZFS and ZFPRJ. It can also importOBJ, FBX, PLY, ABC, GLB, STL, 3MF, DXF, DAE. If importing from OBJ files the same issues as Truevis© "Mesh Import from OBJ Files" exist. However, the main outputs from the scanner in PTX and E57 formats allow point cloud data to be brought in easily. Reality Capture can overlay the 360-degree photos from the scanner on the Point Cloud. Students "took a while" to work out how to manipulate the Alien data in Reality Capture. They found out that the easiest way to do this was create the "reconstruction box"a bit bigger than what they needed, after this they used the " cut by box" tool with fill holes set to "No" and scaled the box to what was needed. Feedback suggested that this was similar to Recap Pro but "*needed more work to get the same result*".

In relation to interoperability and ease of use the students ranked Recap Pro andReality Capture as the two best in this category.

3.3. Cost of Software

The pricing of each of software is provided in order of cost. Firstly, MeshLab stands out in relation to cost as it is a free application released under the GPLv3 license on Windows [10]. The reduction in costs will make up for some of the shortcomings for small practices and education.

Truevis© "Mesh Import from OBJ Files" is currently $50 per seat [20].

Reality Capture used to be a one off fee of 3750 US Dollars but at the time of writing has been reduced in price to 1250 USD before the software moves to an annual subscription. There are also options for pay per use for users who only use the point cloud solidification periodically [13].

The Autodesk®ReCap Pro annual subscription is £390 (Pounds Sterling) and the price of a monthly ReCap Pro subscription is £48. The price of a 3-year ReCap Pro subscription is £1,170. Note also that it is not free for education users [21]. As it is Cloud Based creation of Mesh from Point Clouds the user also need to use Autodesk Credits for conversion. These depend on the density of the mesh. The minimum cost of a job is 1 Cloud Credit (CC)/token. For High quality it costs 1 Cloud Credit/Token per 150 million points processed around 2 Cloud Credits/Tokens total. For medium quality it costs, 1 Cloud Credit/Token per 300 million points processed and finally Low quality, costs 1 Cloud Credit/Token per 600 million points processed. The cost of credits is $300 US Dollars per 100 credits [22].

Lastly iTwin Capture is priced based on where the user is. In the UK the minimum plan is500 Credits / Month is for low use. This equates to 550 US Dollars per month for a small organisation but includes 250 GB of cloud data and 50 GB of reality data storage. This equates to 4 or 5 small scanned projects. As the business grows the pricing increases to 1500 Credits/Month but the price of a credit is reduced to $1.05. This equates to £ 1,575 which includes 1 TB of cloud data and 50 GB of reality data storage [23].

The costs of Autodesk® ReCap Pro and Bentley iTwin Capture as a result are now linked to the output quality of the mesh model. Care should therefore be taken to only apply the Level of Detail (LOD) required in the contract.

3.4. Output Quality

The output mesh quality can be altered in Autodesk® ReCap Pro. The user selects from "Low", "Medium" or "High" quality levels that will alter processing time scale and cloud credit costing. The Freeware MeshLab software for example allows the user toalter the geometric density of the 3D model by reducing or increasing point cloud data without a link to cost.

Autodesk® ReCap Pro guidance [24] suggests the quality level to be used for various scenarios

- Low – The primary focus is the objects main features and less emphasis is placed on minute details. I.e. Walls, roofs and windows.
- Medium – Good quality main features with a reasonable portion of detailing. I.e. Walls, roofs and windows with evident patterns and doors with visible door knobs.

• High – When wanting to preserve any small details within the objects. I.e. Lighting, creasing, reflections and smaller objects that may have only been a blur on the lower quality settings may be visible.

MeshLab quality has no restrictions. After geo-spatial values are determined, using the "Quality Measure and Computations" command on the dropdown menu can automatically provide geometric and topological information. In addition there is also a "Sectioning" tool that creates a view of a cut-through section of the meshed model. The "Remeshing, Simplification and Reconstruction" command allows alteration of the geometric density of a 3D model by reducing or increasing point cloud data where necessary. Implicit surfaces can be created to fill gaps in the model. The Colour Creation and Processing command can be used to edit the RGB values on the point cloud to show what a building would look like painted a different colour.

The iTwin software allows users to automatically generate a high- resolution 3D models using point cloud data, photographs or video files, providing the input data is of high enough quality. Therefore, the data can be collected from any digital camera and from a variety of viewpoints in order to provide iTwin Capture with enough data necessary for to create an accurate model. The quality of the input data can be improved by providing additional input data This removes issues created by lens distortion, focal length, sensor size, and other properties, whether the photo is landscape or portrait, its location and the amount of overlap between the viewpoints. The user can detail the mesh by accessing the "Format/Options" tab during the "Production Definition" function. The detailing options are not as extensive as those within MeshLab but offer more creative control then ReCap.

Reality Capture mesh quality depends on the input quality. Similar to the iTwin Capture software the output quality can be altered after input. The input to the software itself can be supplemented with overlapping photographs to increase the quality of the output. A full suite of tools for editing are also provided.

4. DISCUSSION ON USING THE MESH PROGRAMMES

The hardware/software explored achieved their desired objectives. The Leica RTC360 laser scanner provided point cloud data that could be easily formatted using Leica Cyclone REGISTER 360 software and exported into the manipulation tools. All of the analysed meshing methods was effective in importing the point cloud data, performing the meshsolidification and exporting the result in a format that could be imported to Revit. Each had

their strengths. Autodesk® ReCap was more suitable for meshes of medium sized spaces such as buildings, rooms and components. Due to the lack of output quality restriction, MeshLab was better at creating highly detailed meshed objects or components for smaller elements such as windows. iTwin capture can detail individual components but is more suitable for large buildings, landscapes and infrastructure. Creating BIM families was achievable using Truevis©.

5. USING THE CAMERA OUTPUT FROM THE LEICA RTC360 SCANNER

The Leica RTC 360 Scanner produced 360 photos. In addition, a Ricoh Theta 360 camera was used to show how things were being done. The 360 photo was uploaded and the students marked it up in Thinglink. See `https://www.thinglink.com/card/1489208240209133570`. This link provides examples of a marked up photo. These can be linked together to produce a tour.

6. CONCLUSION

A combination of Building Information Modelling (BIM) and Augmented Reality (AR) together increases the benefits of BIM detailed in Eadie et al (2013) [25]. It allows the new contract conditions being added by both public and private sector clients to be fulfilled. The objectives of the paper were achieved as a workflow was produced that both solidified objects from point clouds and produced 360 images for tours at the same time. Digital objects were created and added to REVIT families from the point clouds. Laser scanning within the construction industry has grown substantially in recent years with a number of large private sector clients insisting on a walkthrough and digital record being produced. It is likely to continue to grow as technological advancements and innovation take place within the BIM space. As retrofitting rather than rebuilding becomes more common, the collection of high quality and accurate data through a Laser Scanner, that can immediately be exported and reworked saves time compared with traditional methods of survey and data collection will become increasingly important.

7. FUTURE WORK

It is hoped that the 2D walkthroughs from Autodesk REVIT which are

output from the software in AVI format can be changed to MP4 format using conversion software and uploaded to Thinglink. Once uploaded to Thinglink AR and VR comments can be added to the walkthrough for teaching purposes.

REFERENCES

[1] A. Hamad and B. Jia, How Virtual Reality Technology Has Changed Our Lives: an Overview of the Current and Potential Applications and Limitations, *International Journal of Environmental Research and Public Health* (2022) **19** (18), 11278, online: http://dx.doi.org/10.3390/ijerph191811278.

[2] B. Furht, Ed., *Encyclopaedia of Multimedia*, Springer Science & Business Media, 2008.

[3] J. Kritzinger, M. Karner et al., Digital Twin in Manufacturing: a Categorical Literature Review and Classification, IFAC-PapersOnLine (2018) **51** (11), 1016–1022, online: https://doi.org/10.1016/j.ifacol.2018.08.474.

[4] M. Johansson and M. Roupé, Real-World Applications Of BIM And Immersive VR In Construction, Automation in Construction (2024) 158, online: http://dx.doi.org/10.1016/j.autcon.2023.105233.

[5] Matterport, Measurement Accuracy in Matterport Spaces, online: https://support.matterport.com/s/article/How-accurate-are-dimensions-inMatterport-Spaces?language=en_US.

[6] C. Thomson, What Are Point Clouds? 5 Easy Facts That Explain Point Clouds (2019) online: https://vercator.com/what-are-point-clouds/.

[7] A. Rodríguez, B. Rodríguez, M. Rodríguez and P. Sánchez, Laser Scanning and Its Applications To Damage Detection And Monitoring In Masonry Structures, in: Long-Term Performance And Durability Of Masonry Structures, Degradation Mechanisms, Health Monitoring And Service Life Design (Eds B. Ghiassi and P. Lourenço), Woodhead Publishing Series In Civil And Structural Engineering, (2019) 265–285, online: http://dx.doi.org/10.1016/B978-0-08-102110-1.00009-1.

[8] Leica, Leica Cyclone FIELD 360, online: https://leicageosystems.com/products/laser-scanners/software/leica-cyclone/leica-cyclonefield-360.

[9] Autodesk, What Is Autodesk ReCap Pro?, online: https://www.autodesk.co.uk/products/recap/overview?term=1YEAR&tab=subscription.

[10] MeshLab, MESHLAB, online: https://www.meshlab.net/.

[11] Bentley, ITwin Capture, online: https://bdn.bentley.com/product/2474#:~:text=ContextCapture%20is%20a%20desktop%20software,XML%20or%20an%20Excel%20file.

[12] Autodesk, Mesh Import From OBJ Files, online: https://apps.autodesk.com/RVT/en/Detail/HelpDoc?appId=7847254631022872970&appLang=en&os=Win64.

[13] RealityCapture, RealityCapture, online: https://www.capturingreality.com/.

[14] AutoDesk, Autodesk adds grading optimisation to Civiil3D, AEC Magazine May–June 2021, online: https://issuu.com/x3dmedia/docs/aec_mayjune21.

[15] Autodesk, System requirements for Autodesk ReCap Pro and ReCap Photo, online: https://www.autodesk.com/support/technical/article/caas/sfdcarticles/sfdcarticles/System-requirements-for-Autodesk-ReCap-Pro-and-ReCap-Photo.html.

[16] Microsoft, MeshLab, online: https://apps.microsoft.com/detail/9n4tl5dxc6c0?hl=en-US&gl=US.

[17] Bentley, iTwin Capture, online: https://www.bentley.com/wp-content/uploads/pds-itwincapture-ltr-en-lr.pdf [last visited April 2024]

[18] Autodesk, System requirements for Revit 2024 products, online: https://www.autodesk.com/support/technical/article/caas/sfdcarticles/sfdcarticles/System-requirements-for-Revit-2024-products.html.

[19] Reality Capture, Datasheet, online: https://www.capturingreality.com/assets/Documents/datasheet_TARASQUE_1.2.pdf.

[20] Truvis, An App brings Meshes into REVIT, online: https://truevis.com/revit-mesh-import/.

[21] Autodesk, Autodesk ReCap Pro: Turn the physical into Digital, online: https://www.autodesk.co.uk/products/recap/overview?term=1-YEAR&tab=subscription.

[22] Autodesk, Manage costs with Cloud Credits online: https://aps.autodesk.com/pricing-cloud-credits#:~:text=Cloud%20Credits%20packs%20start%20at,Take%20advantage%20of%20volume%20pricing&text=Check%20your%20balance%3A%20log%20in%20to%20see%20your%20available%20Cloud%20Credits.

[23] Bentley, Pricing, Available: https://developer.bentley.com/pricing/.

[24] Autodesk, Scan to Mesh Quality Levels, online: https://help.autodesk.com/view/RECAP/ENU/?guid=scan_to_mesh_quality.

[25] R. Eadie, M. Browne, H. Odeyinka, C. McKeown and S. McNiff, BIM Implementation throughout the UK Construction Project Lifecycle: *An Analysis, Automation in Construction* (2013) **36** (December) 145–151, online: https://doi.org/10.1016/j.autcon.2013.09.001.

Received November 11, 2024