APPLYING HERITAGE BUILDING INFORMATION MODELLING (HBIM) TO LOST HERITAGE IN CONFLICT ZONES: AL-HADBA' MINARET IN MOSUL, IRAQ.

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ABSTRACT:

Arguably, the weaponry development during the last century aided in destroying cultural heritage now like never before, this is illustrated in the recent destruction of irreplaceable heritage sites in Syria and Iraq due to conflict. Heritage is often destroyed to demoralise local societies, erase memory, cause extensive economic loss and assert supremacy. Therefore, post-conflict recovery needs to aid in re-establishing damaged heritage as a beacon for cultural and social recovery. Using Heritage Building Information Modelling (HBIM) could provide tools to digitally recover damaged structures. Yet, there is little research on the implementation of HBIM in conflict zones. Thus, this study seeks to apply HBIM workflows to damaged heritage by virtually reconstructing Al-Hadba's minaret, one of Iraq's iconic landmarks, destroyed in 2017 by the "Islamic state". The photogrammetry process used freely available web-based images that were imported into three photogrammetry software: Agisoft Metashape©, Autodesk Recap©, and AliceVision Meshroom to compare crowdsource processing capabilities. The resulting point cloud was scaled using onsite measurements of the minaret's remaining base and imported into Autodesk Revit© to produce a HBIM model. While the process produced comprehensive digital documentation of Al-Hadba', it revealed many challenges confronting digital reconstruction in conflict zones such as lacking documentation, conflict of historical information, crowdsource data constraints, and their effects on the resulting point cloud's quality. The study highlights potential tools to support post-conflict recovery and attempts to present an accessible approach that could be used as a baseline in conflict zones with limited resources to aid in the cultural recovery of valuable heritage sites that represent an irreplaceable part of their community's collective memory.

Figure 1. Al-Hadba' in the past until its destruction (left); an overview of the HBIM process from photogrammetry to model (right).

1. INTRODUCTION

The collective memories, identities, and belongings of communities are deeply connected with their built environment. When the said environment is destroyed due to conflict, great moral and economic losses occur. How could destroyed sites be revived to initiate recovery within affected communities?

Digital reconstructions present a great potential to recover lost heritage. Nevertheless, producing those semantically rich models could demand special equipment and expertise for the data collection, processing, modelling, and managing (Hossain and Yeoh, 2018). These resources could not be available in conflict zones. Thus, there is an urgent need to develop accessible methods to aid in post-conflict cultural recovery using state-of-the-art processes such as Building Information Modelling (BIM).

BIM could be defined as an interdisciplinary set of processes that implements both geometrical and non-geometrical information to produce parametric elements that represent built assets (Argiolas et al., 2022). This paradigm shift of including metadata is crucial for heritage reconstruction as both physical and semantic information play a central role in understanding historic assets.

However, the development of BIM environments and tools is often oriented towards new construction projects with limited support for the complexity of heritage sites (Historic England, 2019). Hence, Murphy et al. (2009) identified Heritage Building Information Modelling (HBIM) as a broader process that combines data acquisition technologies with BIM environments to produce comprehensive heritage models. The spatial data concerning historical assets are collected using modern technologies, such as laser scanning and photogrammetry, and processed to produce point clouds. Those clouds are further developed within BIM environments to produce parametric elements that reflect the geometrical, physical, and historical data of heritage assets (López et al., 2018).

Yet, there is still a limited examination of this concept in reviving affected heritage during armed conflict. Hence, this study seeks to practically apply the HBIM process to a damaged heritage asset: Al-Hadba' minaret in Mosul, Iraq.

Al-Hadba' (or the hunchback) is the minaret for the great Al-Nuri mosque, an iconic site of Mosul city in northern Iraq. It was built between 1170 and 1172 A.D. under the rule of Nur Al-Din, the second ruler of the Zengid Dynasty. Covered in elaborate brickwork, Al-Hadba' is considered a beacon for Mosul's brick minarets architectural style and one of the most prominent structures within the old fabric. Furthermore, it lived as a representation of Mosul's diverse social fabric as it is an Islamic asset built by fine Christian craftsmen.

By the fourteenth century, the minaret started its pronounced tilt and was given the famous nickname. The tilt is considered a result of structural settlement in the soil, other reasons could be the wind and temperature condition of the area (Yousef et al., 2010). The site was renovated by the Safavids in 1511 and dismantled twice in 1864 and 1940s for renovation, but the minaret remained among the few original elements in its medieval form (World Monument Fund, 2018).

Al-Hadba' is an iconic symbol of Mosul and Iraq, it adorns the Iraqi 10,000 dinars banknote and has always identified Mosul's historic low cityscape. The youth of Mosul often refer to themselves as "the sons of Al-Hadba'", it is seen as the icon in many local shops, universities, and organizations. The various tales, sayings, and traditions attached to it illustrate the deep connection a heritage asset could form with its local community. It forms an irreplaceable part of Mosul's identity and memories.

During the Iran-Iraq war, the area was bombed which damaged underground works and increased Al-Hadba's leaning by 40 cm (Asor CHI, 2017). As a result, Fondandel Company was commissioned in 1981 to perform structural maintenance on the minaret. Afterward, Al-Hadba' remained in danger of collapse due to environmental and structural conditions, locals called for maintenance efforts, but no further work was conducted.

With the escalation of armed conflict in Iraq in 2014, the "Islamic State" seized Mosul and occupied the Al-Nuri mosque to assert control over the area. Mosul's residents fled and those who remained were exposed to the destruction of their families, city, and heritage. The fight for Mosul's liberation displaced many and turned much of its heritage into ruins. Eventually, the Islamic State planted explosives on the site which destroyed the minaret's trunk and most of the mosque in 2017 (See Figure 2).

Figure 2. Remains of Al-Nuri Mosque and Al-Hadba' (2021).

In addition to the great suffering of the armed violence Mosul endured, the loss of Al-Nuri mosque, and particularly Al-Hadba' greatly affected Mosul's community, local people often mention that they don't identify Mosul with the leaning minaret adorning its skyline.

As a result, The World Monuments Watch and UNESCO immediately released calls for the reconstruction of the minaret which was finally answered by a collaboration project which started in 2020 between UNESCO, the United Arab Emirates, and Iraq named "Reviving the Spirit of Mosul". Hence, Al-Hadba' was chosen as the subject of this study to contribute to the current reconstruction efforts in restoring the minaret's physical, social, and historic value.

2. PREVIOUS WORK

As there is limited access to scan a lost asset, reconstruction inevitably means imposing hypotheses and judgments during the process. As such, identifying available and reliable resources concerning Al-Hadba' becomes necessary to ensure this judgment is as informed as possible. Thus, a thorough historic search was conducted to gain a deep understanding of the asset's history, status, and significance. Targeted document types include drawings, pictures, scientific research, and archives.

The main challenge here is to communicate the validation process to third parties who could use the model in the future. As such, proper archiving during this process is crucial to assess the sources' validity and provide a clear indication of any interpretation made. A listing of all found sources is produced as a spreadsheet that acts as a resource reference that is quick to set and easy to modify. The categorization process grouped sources similar in nature for comparative analysis purposes. A factual status is given to each source according to its quality and reliability. This allows the introduction of family parameters later in the BIM platform where each element contains metadata that reflects its suitable accuracy.

The materials obtained for this study are all web-based as a paper search was not accessible, these include television programs, documentaries, scientific papers, articles, archival pictures, and a few drawings.

Following maintenance work conducted in 1981 by Fondandel Company, Lizzi and Carnervale (1981) released a technical report describing the geometry and physical qualities of the minaret. This report formed a base for the following scientific literature. Yousef et al., (2010) evaluated the 1981 maintenance work and calculated actual inclination and structural stresses. Abed and Abdullah (2013) monitored and measured the minaret using Topcon Imaging Station. Alomary et al. (2015) studied the visual and urban impact of the minaret on the old fabric.

Yet, there is a great conflict of information found in past research. For example, the minaret height was estimated in significantly different figures ranging from 45m to 65m. UNESCO (2020) identifies the height as 45m in its report "Progress in the reconstruction of the Al-Nuri Mosque complex in Mosul". This number was not agreed with by any scientific paper that measured the minaret. Lizzi and Carnervale 1981 indicated that the minaret's height is 47.25m which Yousef et al. 2010 agree with. While Abed 2013 identified the height as 50m, other non-scientific articles even specified 65m. This information conflict in addition to the loss of the Al-Hadba's trunk which does not allow a proper validation process presented one of the main challenges during this research.

In graphical sources, the ArchNet website offered rare drawings and a rich archive of photos dating back to the 1940s of the site. The documentary "In Mosuli: Al-Hadba' Minaret" which was presented by Wathiq Al-Ghathanfari, a journalist and

anchorman from Mosul, was also useful in providing a rare local view into Al-Hadba', it discusses the local building techniques and less-known stories behind the asset.
This valuable knowledge, in addition to its historical importance, could be used later as educational means to attract the common viewers' attention through storytelling. Thoroughly examining historical knowledge about the minaret further develops understanding and enriches the produced model. As the minaret's trunk is mostly destroyed, the reconstruction is based mostly on record data, geometric measurements were validated using current measurements of the minaret's remaining base. Thus, the tabulation process discussed earlier allows a better understanding of the archive's interpretation and the consequent decision-making process.

3. HBIM PROCESS

Since Al-Hadba's trunk was destroyed with only the damaged base remaining, there is little possibility for another survey to accurately represent the most prominent feature: the tilt. Hence, photogrammetry using crowdsourced photos was the selected method for this case, the results were then validated using onsite measurements of the remaining base which provided a crucial reference to enhance the accuracy of the model produced through crowdsourcing.
Crowdsourcing allows openly available, web-based images which are taken at various times, cameras, and angles to be loaded, adjusted, and processed in suitable software digitally reconstruction assets (Somogyi et al., 2016). This method offers advantages over other technologies (laser scanning for example) such as low cost, portability, ease of use, and the ability to involve the local community to restore ownership over heritage (Dhonju et al, 2018). This is particularly important in cases where heritage was destroyed due to armed violence. Involving the affected community through building capacity could provide economical, and social recovery opportunities.
In damaged heritage cases, crowdsourcing has also been applied for digital recovery. Gruen et al., 2002 reconstructed the Bamiyan Buddha which was destroyed by the Taliban in 2001 using three metric images taken in 1970. Wahbeh et al. (2016) also reconstruct the destroyed Bel Temple in Palmyra using two sets of images (public domain photos and panoramic imagery). The City of Bam case (Kitamoto et al., 2011) combined aerial and terrestrial imagery to produce a reconstruction of the collapsed asset.
Furthermore, the continuously growing body of web-based data along with the availability of powerful devices publicly has transformed crowdsourcing into what Grenshaw 2015 called 'mass photogrammetry'. This concept focuses on public accessibility by providing heritage digitisation approaches accessible to the public (Ch'ng et al, 2019). Many digital platforms are increasingly using this method to provide openly available information such as OpenStreetMap, and Wikimapia.
In addition, there are several projects using crowdsourcing for heritage documentation. Project Rekrei utilises imagery uploaded online by volunteers to generate 3D models, but no results are presented publicly. Other projects such as Heritage together and Curious Travellers also aim to document heritage at risk using images provided by the public.
While this body of work provides evidence of the reliability of crowdsourcing in heritage recovery, there is still little exploration of HBIM's benefits in enhancing crowdsourcing outcomes and presenting heritage data. This study attempts to test the usage of non-metric, generic photos in the context of HBIM process to digitally reconstruct Al-Hadba' (see the process described in Figure 3).

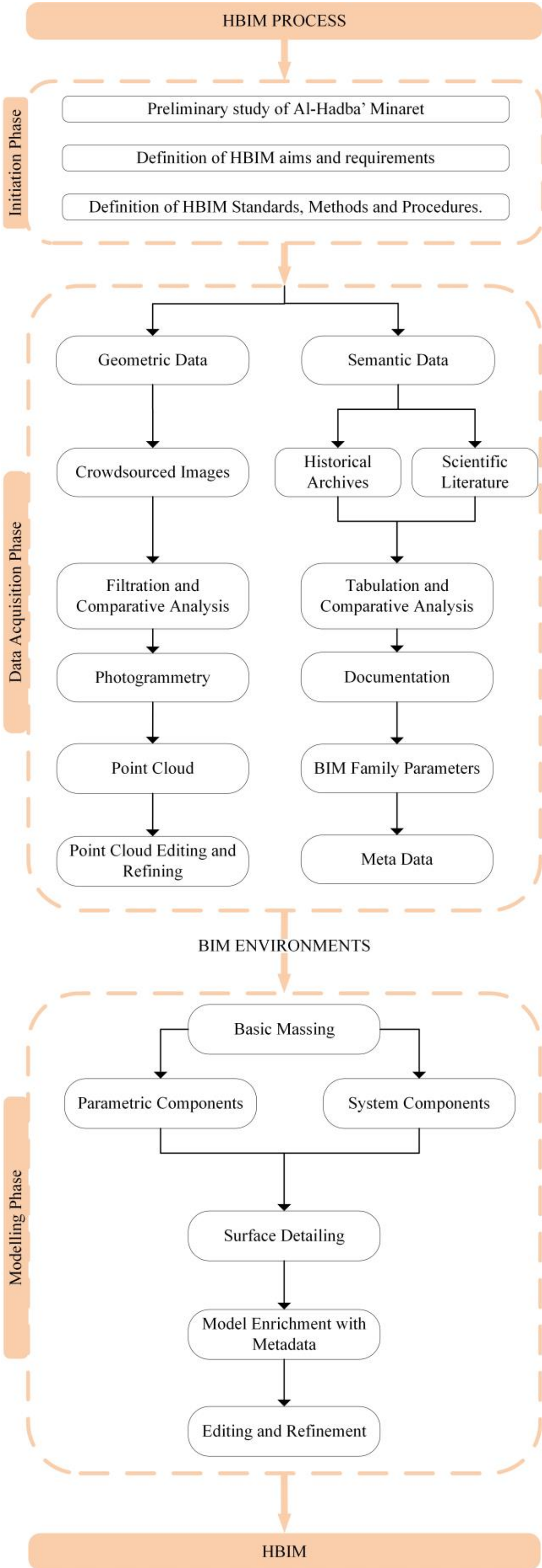

Figure 3. Al-Hadba's HBIM reconstruction process.

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1.1 Data Collection

To reconstruct Al-Hadba', public domain photos from the web provided the main data. The images were collected mainly using the Google search engine in both English and Arabic, reverse image search option was particularly useful in finding untagged images. Images were downloaded from various available websites such as Flickr, Wikimedia, Getty, and social media. The Rekrei website, previously called Project Mosul, was the most useful as it provided high-quality photographs of the minaret with their EXIF data intact. A total of 254 photos were collected including 207 modern images and 47 archive images. In addition, 244 images were terrestrial and 10 were aerial images (see Table 1).

Source	Photos Collected
Google Image	53
Project Rekrei	117
Flickr	3
Getty	20
Wikimedia	14
Archnet	33
Social Media	14

Table 1. Data according to sources.

The images were:

1. Filtered to exclude low quality, redundant, and duplicated images.

2. Categorised to primarily modern and archive which were further subcategorised to aerial and terrestrial.

3. Compared to establish terrestrial and aerial consistent control points (easily identifiable points on the minaret that appear often in the images).

4. Analysed to form family parameters suitable for each element that would be introduced in the HBIM.

Imagery metadata, such as zoom lenses, camera models, and focal length, aids the photogrammetric algorithm in the process of camera calibration. This process defines the camera's interior and exterior orientation to minimise re-projection mistakes between the original and reconstructed image points. In Al-Hadba's case, more than half of the imagery lacked this crucial metadata. Furthermore, the trunk's destruction with limited accessibility to the site complicated the process of verifying the expected outcomes.

Fortunately, Al-Hadba's base survived the attack and remained relatively intact. This enhanced the process significantly as it provided the main accuracy metrics to validate the results. Unfortunately, the site was not available for a photogrammetric scan due to ongoing stabilisation work. As such, the study employed onsite measurements. Several measurements of the base were taken including the upper and lower trapezoidal prism base, ornamentation, height, and the trunk's base diameter. Furthermore, control points established in the data were reflected on the base to define and integrate a coordinate reference system to produce a correctly oriented and scaled model rather than scale it after the reconstruction.
Although not all the images qualified for photogrammetric purposes, they were all employed later for a variety of purposes to enrich the model such as materials, textures, parameters, metadata, historic references, and so on.

1.2 Photogrammetry Process

The data sets were imported into three leading photogrammetry software: Agisoft Metashape©, Autodesk Recap©, and AliceVision Meshroom to compare the resulting clouds. ReCap's fully automated workflow allowed limited manual intervention in the reconstruction process which prevented successful reconstructions. Since most of the case's data were not captured with photogrammetric reconstruction in mind, manual intervention was crucial for the identification and matching of features.
In contrast, Metashape's algorithm offers a variety of alignment and masking tools which allowed masking to exclude unnecessary background and aligning using markers-based alignment. The control points, established in the data processing, were manually placed as 'markers' to guide features recognition and aid the alignment process. A total of 28 markers were added with each photo having at least 7 to ensure proper alignment (see Figure 4). The resulting point cloud is of medium quality and contained 346,879 points.
Lastly, Meshroom was the most successful test as it produced higher quality with much less labour. The resulting cloud contained 475,136 points and offered the most detailed reconstruction of the minaret.

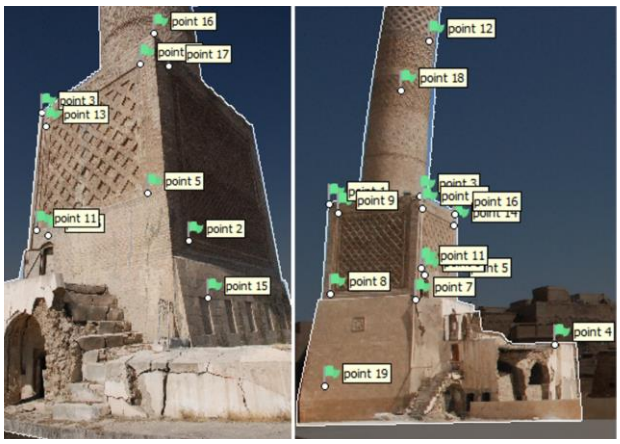

Figure 4. The guided approach in Agisoft Metashape©.

Given the difference in quality, time, and accessibility, the Meshroom point cloud was chosen because it is free, open-source software that provided the highest quality. The point cloud was then filtered, scaled according to on-site measurements of Al-Hadba's remaining base, and exported using AliceVision Meshlab, an open-sourced editing, and processing software for 3D meshes.
The majority of qualified image sets were of high resolution, acceptable focus, and without any previous processing. Nevertheless, the resulting point clouds illustrated the constraints of photography patterns in crowdsourcing. Mainly, the photos covered the south and east elevation of the minaret with little data on the other sides. As a result, many blind spots appeared in the resulting point clouds (see Figure 5). This caused difficulties in the creation of stable geometrical shapes that reflect the minaret. Another challenge was the various environmental conditions appearing across the images. This resulted in significant variations across surfaces and textures in the reconstruction. Obstacles such as trees and people also obscured crucial information, but this was remedied by using masking tools. Despite the challenges, the photogrammetric reconstruction provided a proper base that fulfilled the needs of the modelling stage.

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Figure 5. Metashape's point cloud (left); and Meshroom's point cloud (right).

1.3 Modelling Process

The leading BIM software Revit 2021 was chosen due to key advantages such as linking point clouds directly in the project, available trial periods with the full tool, and phasing tool to link every object to a certain phase. Usually used to distinguish new, existing, and demolished parts in new buildings, phasing could be a powerful tool to label elements and indicate their period, status, and level of accuracy according to the table prepared during the archival research.

As Al-Hadba' is a small structure, there was no need to divide the project into several volumes. One issue is that Revit can only import point clouds in RCP and RCS file format which Meshroom does not support, the solution was to export it as a DXF format using Meshlab and then link it into the project file to form the model base. Since the presence of complicated elements in a BIM file could slow the software's performance significantly, the process was divided into two stages:

1. Setting base building mass by tracing the point cloud.
2. Mass transformation into system and functional families.
3. Detailing and ornamentation.

Although Revit's tools are inherently constrained which presented challenges when modelling Al-Hadba's irregular elements, some tools were particularly useful in modelling the minaret. These include the Conceptual Mass tool which allows modelling irregular geometric elements to be used later as a base for parametric family production, this tool was vital in creating the 7 complex leaning rings of the cylinder trunk. Afterward, system elements such as Walls, floors, and roofs were added by using the Model by Face tool. This method allows construction elements to be added without abiding by the basic constraints introduced by Revit. For example, inclined walls were introduced in the 2021 version, but the software prohibits editing their profile to add the complex geometrical ornamentation of the minaret's base. Nevertheless, using the Conceptual Massing and Model by Face option, the walls could be modelled faithfully to the original form and its ornamentation was added later as a face-based family.

The surface details were challenging as Revit offers little support for such complex patterns, many methods were tested which either resulted in poor results or did not function. Eventually, a method of detailing elements using model-in-place generic families was used to produce surface patterns. However, this method did not work on the cylinder trunk of the minaret as the software was not able to apply the complex patterns to an irregular surface. To reflect the minaret's past view, textures were extracted from the images and were applied as materials to the surfaces to produce as similar to the minaret's actual view as possible. Another negative aspect is the limitation of generic families' property types. Using regular walls allows the introduction of material layers but offers little modelling flexibility. By contrast, using generic families offer great modelling adaptability but little customisation and metadata.

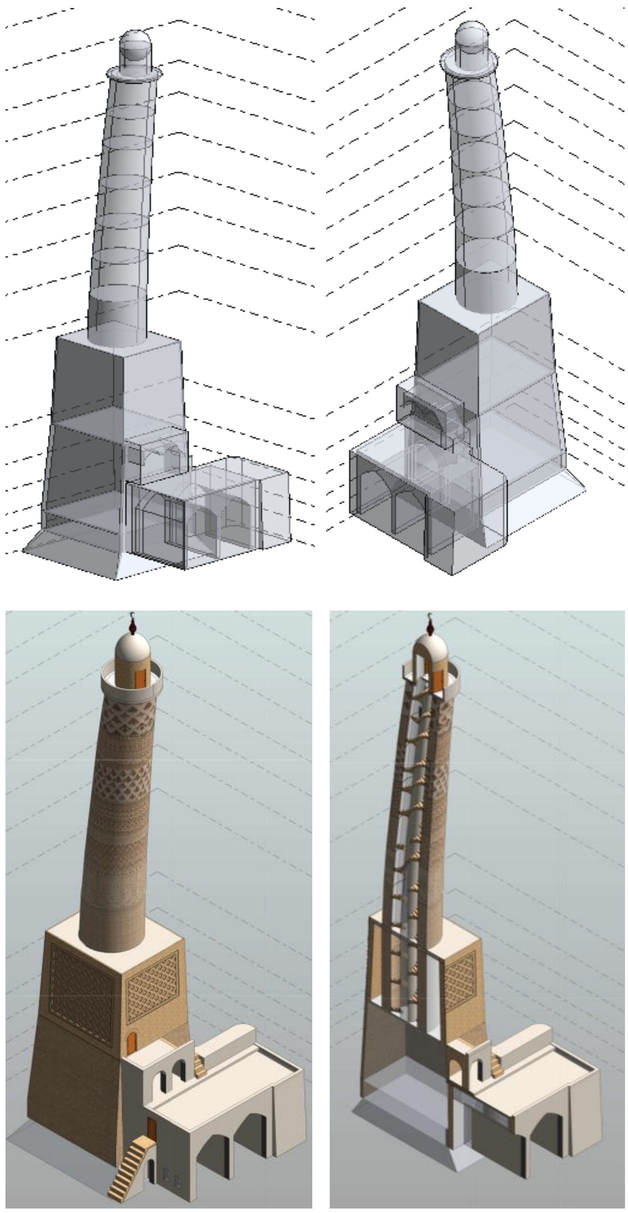

Figure 6. The Base building mass after tracing the point cloud (top); the final HBIM with parametric components and ornamentation (bottom).

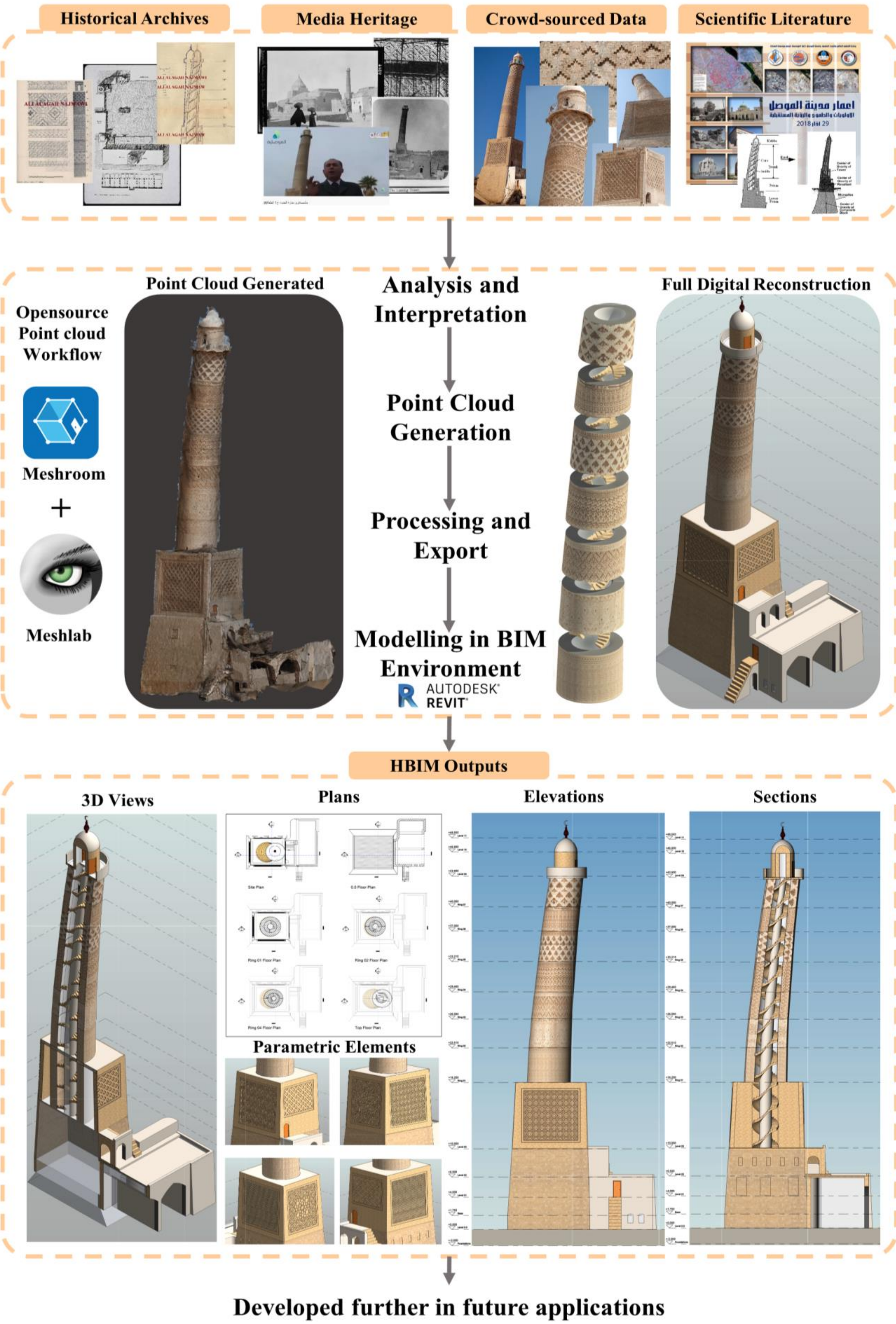

Figure 7. Al-Hadba's 3D reconstruction workflow from crowdsourced photogrammetry to HBIM.

4. DISCUSSION

4.1 Documentation Aspects

Reconstructing damaged heritage often adheres to a certain percentage of speculations, expertise, and informed decisions. In Al-Hadba's case, the main challenge stemmed from the lacking documentation despite the asset's well-known status. This is illustrated in the great discrepancies regarding the minaret's height. Despite the careful review of all available scientific resources to examine their credibility, methods, and year of measurement, it was difficult to form a concrete judgment due to the complete destruction of the minaret's trunk. Fortunately, Al-Hadba's remaining base played an integral role in enhancing the resulting reconstruction. The process of establishing a model reference system through onsite measurements greatly enhanced the accuracy of Al-Hadba's model and aided the study in settling the height dispute. The resulting point cloud highlights the minaret's height during 2012 (the year where most of the images were taken in) as 48.55 meters. The dispute in literature is perhaps due to the continuously increasing leaning of the trunk which changes the height.

the conflict of information illustrated in this case combined with no accessibility to scan the lost parts illustrated the consequences of poor documentation. While this case utilized onsite measurements of the asset's remains, other cases could suffer from complete destruction with little means of validating the results. Hence, developing a proactive documentation approach for cultural heritage should become the prime focus in areas prone to conflict or disasters such as Iraq. This could be done by employing low-cost methodologies, and capacity building to involve people as data collectors using mass photogrammetry. This case illustrated that a single documentation workflow may not breed the desired outcomes. A range of algorithms, both paid and unpaid, were tested and implemented to deliver the aims of the study. Therefore, developing a multidisciplinary approach to documenting cultural heritage at risk becomes a necessity to provide a database that could be relied upon during emergencies. In cases of destruction with a lack of previous documentation, informed judgment is often a component of the HBIM process, this influences the historical validity of the model produced. Thus, a key element in the process is documentation, it is essential to properly document all decisions made to clarify interpretations adopted in historical models.

4.2 Technical Aspects

The usage of crowdsourced photos to produce HBIM models provides a method to preserve and acknowledge destroyed sites, the data is accessible, affordable, and rapidly growing online. Yet, it offered many challenges that were experienced during Al-Hadba's process. The pre-processing filtration could be time-consuming, and the quality of produced models depends on the quality and quantity of available images. Even in the case of Al-Hadba' which is well known in Iraq, the search only resulted in 145 usable images. Moreover, the reconstruction process is affected by the picture-taking habits of people. Usually, the acquisition paths and patterns are key to high-quality photogrammetry reconstruction. However, in cases where people's photos provide the main source of data, acquisition patterns provide a limiting obstacle. Typically, people photograph the most prominent parts of the heritage site, this can be seen in Al-Hadba's case where most of the images were taken from the east with few shots in other directions. This resulted in many blind spots in the point cloud. Moreover, the images were different in quality, proportions, sizes, and time with various overlapping ratios. The results were sufficient for the aims of this study, but if the aim was higher quality, developing a guided 'mass photogrammetry' approach may be a suitable method.

The photogrammetry process illustrated the great benefits of manual intervention and the guided approach in post-conflict reconstruction. The data in Al-Hadba's case came from a diversity of sources. As such, essential requirements such as overlapping, Metadata, and feature recognition were difficult to control and consequently affected the resulting point clouds. Testing different algorithms proved to be useful as each software processed the data sets differently. While this could be time-consuming, it could lead to discovering data processing patterns to inform software choices in future projects.

Importing the point cloud into a BIM platform was a manual and lengthy process because software interoperability is still quite limited from point clouds to BIM environments. This inefficiency could cost a lot of time and resources. Despite HBIM's concept having been under usage for quite some time now, the process of importing point clouds into BIM platforms is still quite manual and time-consuming.

The modelling phase emphasized the BIM environment's limitations in heritage modelling. Al-Hadba's iconic form consists of irregular walls which are heavily oriented with fine Islamic art. Yet, walls in Revit are commonly vertical with constant thickness. Even with some flexibility such as the slanted wall feature, it was still not possible to edit the profile of the wall to add the patterns. As such, walls had to be drawn individually from the pattern which was added as a generic family. Another example is the stairs, Al-Hadba' is leaning and thus the interior stairs are not straight but on the contrary very irregular. There was no option to control the direction of the stairs, this resulted in drawing each floor as regular stairs, converting the drawing into sketches, and modifying them according to the leaning body. A solution to this could be developing custom modelling plug-ins for historical elements that belong to a certain style. In Al-Hadba's case, developing tools that adhere to Mosul's brick minaret style would be beneficial in reconstructing similar minarets as well. Lastly, while the study generated and processed the point cloud in an open-sourced environment (Meshroom and Meshlab), no equivalent was found at the time for an open-source BIM environment. Thus, future research may also focus on the development of such environments.

5. CONCLUSION

This study presented a HBIM practical application for reconstructing damaged heritage in conflict zones based on crowdsourced images. The work focused on implementing low-cost and freely available data acquisition methods to digitally reconstruct Al-Hadba' minaret destroyed in 2017 during armed conflict. The resulting model provides a comprehensive array of information such as construction drawings, perspectives, and metadata. This database could be used in various methods such as visualization, 3D printing, virtual tours, and physical reconstruction. In the future, Al-Hadba's pilot case study will aid more research in developing accessible means of documenting heritage at risk, particularly in conflict zones. Future work aims to further develop and tailor this concept by applying it to other assets. The main aim is to develop a strategic framework to recover heritage in conflict zones with limited resources. The framework should focus on building community capacity, using accessible methods, and most importantly, proactively documenting heritage at risk to aid in post-conflict cultural recovery.

REFERENCES

Abed, R. S., and Abdullah, G. N., 2013. Measurements in Alhadba Minaret Using Robotic Total Station. *Engineering and Technology. Journal*, 31 (5), 910–920. https://www.iasj.net/iasj?func=fulltext&aId=82060 (15 December 2021).

Almosulia Television Channel, 2016. In Mosuli: Al-Hadba' Minaret. https://www.youtube.com/watch?v=5R3PAlKhvyc, (15 December 2021).

Alomary, A. Y., Alqimaqche, N. T., and Alallaf, E. H., 2015. Augmenting the Hadba Minaret Role as A Landmark in the City of Mosul. *Sulaimani Journal for Engineering Sciences*, 2 (2), 45–54. doi.org/10.17656/sjes.10023

Archnet, 2017. Jami' al-Nuri al-Kabir (Mosul). https://www.archnet.org/sites/15592 (15 December 2021).

Argiolas, R., Bagnolo, V., Cera, S., and Cuccu, S., 2022. Virtual environments to communicate built cultural heritage: a hbim based virtual tour, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVI-5/W1-2022, 21–29. https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-21-2022

Asor CHI, 2017. Update: Satellite Imagery Confirms the Destruction of Al-Nuri Al-Kabir Mosque and Al-Hadba Minaret by ISIL. https://www.asor.org/chi/announcements/updates/Satellite-Imagery-Confirms-the-Destruction-of-al-Nuri-al-Kabir-Mosque-and-al-Hadba-Minaret-by-ISIL (4 January 2022)

Ch'ng, E., Cai, S., Zhang, T.E., and Leow, F.-T., 2019, Crowdsourcing 3D cultural heritage: best practice for mass photogrammetry. *Journal of Cultural Heritage Management and Sustainable Development*, 9(1), 24-42. https://doi.org/10.1108/JCHMSD-03-2018-0018

Dhonju, H. K., Xiao, W., Mills, J. P., and Sarhosis, V., 2018. Share Our Cultural Heritage (SOCH): Worldwide 3D Heritage Reconstruction and Visualization via Web and Mobile GIS. *ISPRS International Journal of Geo-Information*, 7, 360. https://doi.org/10.3390/ijgi7090360

Granshaw, S. I., 2015. Imaging Technology 1430-2015: Old Masters to Mass Photogrammetry. *Photogrammetric Record*, 30(151), 255–260. doi: 10.1111/phor.12112

Gruen, A., Remondino, F., and Zhang, L., 2002. Reconstruction of the Great Buddha of Bamiyan, Afghanistan. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 34 (5), 363-368.

Historic England, 2017. BIM for Heritage: Developing a Historic Building Information Model.

Hossain, M. A., and Yeoh, J. K. W., 2018. BIM for Existing Buildings: Potential Opportunities and Barriers. In Proceedings of the IOP Conf. Series: Materials Science and Engineering, 371. doi:10.1088/1757-899X/371/1/012051

Kitamoto, A., Andaroodi, E., Matini, M. R., and Ono, K., 2011. Post-Disaster Reconstruction of Cultural Heritage: Citadel of Bam, Iran. In: Proceedings of IPSJ SIG Computers and the Humanities Symposium, Kyoto, 11-18.

Lizzi, F., and Carnervale, G., 1981. The Static Restoration of the Leaning AL-Hadba Minaret in Mosul (Iraq). In: Proceedings of the 3rd International Symposium on Babylon, Ashor, and Haditha, Baghdad.

López, F. J., Lerones, P. M., Llamas, J., Gómez-García-Bermejo, J., and Zalama, E., 2018. A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technologies and Interaction*, 2(2), 21. https://www.mdpi.com/2414-4088/2/2/21

Murphy, M., McGovern, E., and Pavia, S., 2009. Historic building information modelling (HBIM). *Structural Survey*, 27 (4), 311–327.

Rekrei Project, 2017. Al-Hadba Minaret (al-Noree Grand Mosque). https://rekrei.org/locations/al-hadba-minaret-al-noree-grand-mosque/reconstructions/the-minaret (15 December 2020).

Somogyi, A., Barsi, A., Molnar, B., and Lovas, T., 2016. Crowdsourcing Based 3d Modeling. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B5, 587–590. https://doi.org/10.5194/isprs-archives-XLI-B5-587-2016.

UNESCO, 2018. Revive the Spirit of Mosul. https://en.unesco.org/fieldoffice/baghdad/revivemosul (15 December 2021).

UNESCO, 2020. Progress in the reconstruction of the Al-Nuri mosque complex in Mosul. https://reliefweb.int/sites/reliefweb.int/files/resources/Arabic%20-%20PR%20-%20JSC%20%28002%29.pdf (15 December 2021).

Wahbeh, W., Nebiker, S., and Fangi, G., 2016. Combining Public Domain and Professional Panoramic Imagery for the Accurate and Dense 3D Reconstruction of the Destroyed Bel Temple in Palmyra. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, III–5, 81–88. https://doi.org/10.5194/isprs-annals-III-5-81-2016

World Monuments Fund, 2018. Al-Hadba' Minaret. https://www.wmf.org/project/al-hadba%E2%80%99-minaret (15 December 2021).

Yousef, S. T., Al-gburi, M. A., and Muhammad, M. S., 2010. Study of Maintenance Al Hadba Minaret Monument in Mosul. http://dx.doi.org/10.13140/2.1.3031.0082 (15 December 2021).