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Using Building Information Modelling to map the composition of glass panes in a historic house

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ABSTRACT

Building Information Modelling (BIM) is widely regarded to be potentially useful for the conservation and management of historic buildings. So far, research in this area has mostly concentrated in geometry: surveying, the parametric modelling of building features and the accurate modelling of complex building shapes. But in order to be fully integrated with conservation practice, Building Information Models need to include other types of data. This paper demonstrates a method to introduce and visualise spatially resolved data within a Building Information Model of a historic building. It focuses on the visualisation of the composition of historic glass and the metadata associated with this measurement. The conclusions are, however, extensible to any type of spatially-resolved material information that can inform building management, conservation and interpretation. The software Dynamo is used to add this functionality to a Revit 3D model. The modelling stage requires the creation of shape families for different types of window. This approach is compared with a similar visualisation produced with ArcGIS, a common Geographic Information System (GIS) software. The Dynamo algorithm successfully adds the visualisation capacity to the BIM model, but it is unlikely that this level of customisation is achievable by the average user. There is a need for further development of technological solutions that combine the visualisation capacity of GIS with ability of BIM to link 3D models and numerical data.

1. Introduction

BIM is a process (Bartley, 2017; Gigliarelli et al., 2017; Antonopoulou and Bryan, 2017) – rather than a tool – that has been considerably spreading during the last decade in the architecture and construction field (Azhar et al., 2012; Pocobelli et al., 2018a). It allows to manage the relevant information during the life-cycle of a building, from its conception to its implementation, including management, maintenance and, eventually, restoration (Arayici, 2008; Maxwell, 2014; Brumana et al., 2014). Using BIM technology, it is possible to condense all the information required during building works (Azhar et al., 2012; Arayici, 2008) and to avoid duplications and repetitions (Koehl et al., 2013; Angulo Fornos, 2013), creating what has been called "smart" models (Azhar et al., 2012; Beraldin, 2004). BIM enables the virtual representation of many aspects of a building, including geometry, material properties, environmental parameters, etc. Its usage has been so successful due to its capacity to store all necessary building-related data, as well as endorsing collaboration (Azhar et al., 2012; Arayici, 2008).

Several ways to use BIM in heritage have been proposed, often under the label "Historic Building Information Modelling (HBIM)" (Murphy et al., 2009). The most successful are the inclusion of semantic information (Losciale et al., 2012), with parametric smart object libraries (Murphy et al., 2009). HBIM is commonly intended as process which includes a specific library of parametric smart objects, of historical and heritage content (Oreni, 2013; Barazzetti et al., 2015). Another example is the "Jeddah Historic Building Information Modelling" (JHBIM) library, which is an HBIM extension designed for Old Jeddah built heritage (Baik et al., 2013). Its purpose is to produce a parametric smart object library that can be used both for buildings in Jeddah (specific materials, common material degradations, local construction techniques) and for heritage buildings in general. JHBIM study can help in management performance and in decision-making for conservation interventions (Baik et al., 2014), and demonstrates in practice that BIM technology is possible for heritage buildings. Another possible application of BIM in Heritage is to store useful information for material analysis and conservation. BIM can, in theory, provide a mechanism to

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connect conservation data with a location in a building, which can help interpretation. While this is technically possible, only recently researchers have started to utilise BIM approaches to map damage. Some prominent examples are the mapping of salt efflorescence and other surface pathologies in the Algeciras Market (Bazán et al., 2021), the tracking of crack formation in a castle (Martín-Lerones et al., 2021), and the parametric modelling of a diversity of surface decay mechanisms enabled by Dynamo (Lanzara et al., 2021). The assessment of damage within BIM is sometimes combined with GIS software, such as in the mapping of material pathologies at different buildings of the Forbidden City in Beijing (Qin et al., 2021). Indeed, BIM and GIS offer a natural partnership, allowing information to be mapped at both cartographic and building level (Barazzetti and Roncoroni, 2021). This has resulted in a diversity of research exploring the overlap between these two technologies (Tsilimantou et al., 2020). However, despite the recent surge of interest in mapping of damage and pathologies in BIM, there is still a lack of case studies that develop methods to include quantitative material information in the models. The existing literature demonstrates that areas of building pathologies can be labelled and mapped dynamically. There is, however, scope to develop methods to implement within BIM quantitative assessments of material properties and degradation processes, such as chemical composition, roughness, tensile strength, or any other of the parameters commonly used in heritage science (Pocobelli et al., 2018b). Indeed, there have been very few attempts to insert conservation data into HBIM models. For instance, using a cloud-based Autodesk software, called “Forge”, Bruno and Roncella (2019) have managed to make their model accessible online. Authors (Bruno and Roncella, 2019) create a HBIM model with a tool similar to a plug-in that links the model to an external database, to arrange better heritage-related data management. Afterwards, they upload the model to the cloud, ensuring accessibility through Forge. They have also created a queryable database that can be accessed when needed. Similarly, Autodesk has developed a research project named “Dasher”, which is Internet of Things (IoT) and cloud-based, and allows real-time monitoring of a building based on sensors (Autodesk, 2018). Users, through the BIM model, can access real-time environmental data, such as temperature, light, humidity, etc., and can also plot these parameters. Other attempts to create BIM models specifically for heritage buildings include the work of Empler et al. (Empler, 2018; Calvano et al., 2020; Empler et al., 2018) to document an Italian historic town, which was destroyed by a violent earthquake in 2016. Authors have developed a method based on data fusion to produce informed BIM models with seismic retrofitting information, which method can be used for earthquake prevention.

One of the most popular tools in the HBIM community is Geographic Information System (GIS) (Pocobelli et al., 2021). Its popularity is due to its capability to store geometric information, which can be referenced through coordinates (Dore and Murphy, 2012). Several examples of GIS application into HBIM models exist; for instance, Bruno et al. (2020) have developed a web-based platform that integrates data from both BIM and GIS to display different historic layer. Similarly, Albourae et al. (2017) integrate BIM with GIS and videogame engine technology to display both geometry – through BIM – and non-architectural information through GIS.

These advances should go hand-in-hand with a debate on the required level of detail to successfully support conservation tasks. The technical literature classifies BIM models using two approximate scales: the Level of Detail (LoD) and the Level of Information (LoI). LoD refers to the graphical elements of the model, whilst LoI refers to non-graphical information (Level of Detail for BIM). Specifically, BSI PAS 1192:2–2013 (Standards Institution, 2013) define LoD as “the level of detail should as a minimum represent the space allocation for the product’s access space for maintenance, installation and replacement space in addition to its operational space. For example, the space required to turn on or turn off valves […]” The LoI is defined as “[…] the description of non-graphical content of models at each of the stages” (Standards Institution, 2013). Research is needed in order to identify clearly which LoD and LoI are required for different conservation tasks. In the case of building pathologies, it is likely that decision-making can be successfully supported with relatively low levels of detail, as long as the main features of the degradation problems are captured. In any case, research in this area will only be enabled through the publication of case-studies that report and evaluate the required level of detail.

As this very brief literature review shows, the HBIM field is under active development. There is a tendency to integrate BIM with software from other disciplines, such as GIS. This concept is in perfect agreement with BIM nature, which is by definition, a process of different software able to store, display and analyse all the data related to the specific project.

2. Research aims

The aim of this paper is to demonstrate a method to map quantitative material information within a BIM model. Through a case study, it describes the custom-made technical solutions that are required in order to add relevant quantitative information to a building model. This method is compared with a small-scale GIS approach, in order to contrast BIM with a well-stablished technique of quantitative mapping. This approach is tested with a multivariate dataset of glass composition and its associated metadata. This dataset has generalisable properties that make it analogous to other data typologies of interest. Namely, it is spatially distributed, quantitative, and is associated to certain building features. Therefore, the conclusions are extensible to any spatially distributed material property of any other heritage building.

3. Methods

3.1. The building

Hellens Manor is a Grade II* listed historic brick house constructed in the village of Much Marcle, Herefordshire (Historic England, 2021). The property has undergone several modifications throughout the centuries, but is primarily comprised of Tudor, Jacobean and Georgian Architecture (Interview with Bradley McCreary). From its foundations, it is possible to evince that the first, original structure was built during the 13th century (Interview with Bradley McCreary). Major modifications were made during the 17th and the 18th century, and in 20th century there was a series of important renovations too (Interview with Bradley McCreary). Among the many building features of historical interest, Hellens Manor keeps a large proportion of original historic glass on its window panels. The age of the glass reflects the history of the house, which has caused some windows to be replaced, added in extensions over the years, and conserved in recent times.

3.2. The information

This paper focuses on the dating of the historic glass. The chemical composition of Hellens Manor’s glass panes has been surveyed using a portable X-ray fluorescence (pXRF) spectrometer (Olympus Delta Premium DP-4000 handheld pXRF, with a Delta Rhodium anode X-Ray tube and a Silicon Drift Detector), a technique that offers a relatively low cost and rapid method to identify the composition of inorganic materials. Its use for the dating of glass was developed by Dungworth (2012) in collaboration with English Heritage, given the need for non-destructive analysis of historic glasses.

The dating principle is based in the history of manufacturing methods and raw materials, which can be related to certain metal traces in the glass matrix. An approximate date of manufacture can be obtained with only a few elements: for instance, phosphorus, which is present in "plant ash" glass but disappears after 1835, following the invention of synthetic soda and its introduction to glassmaking, or strontium, the elevated amount of which characterises "kelp" glass (1700–1835). This classification can be further refined knowing the concentrations of manganese, calcium, potassium, and arsenic (Dungworth, 2012).

To interpret this data, it is useful to map concentration and contextualise it within the building. This is particularly important when studying large windows with multiple glass panes, where the spatial distribution of composition can offer clues on the history of the structure, such as the timeline of its construction and subsequent alterations. The compositional typology of each pane visualised on a BIM model facilitates conservation efforts by permitting rapid identification of chemically unstable types of glass, tracking their condition over time, and relating it to factors like cleaning regimes and relative humidity within specific rooms or the window's exposure to dominant winds and rain. In addition, pXRF analysis produces a considerable amount of metadata which is necessary for the correct interpretation of the collected values. The different types of data and metadata are summarised in Table 1. The need for mapping and metadata inclusion makes this information an ideal case study to explore the capabilities of BIM, which can enable the analyst to visualise the measurements in their context.

3.3. The model

3.3.1. BIM

We produced a 3D model of Hellens Manor building using Autodesk Revit, as specified below in Section 4.1. Revit, like all the leading software for BIM, does not offer a default functionality to produce data visualisations integrated in the building model. To include the glass chemical composition in the building model, we used Autodesk Dynamo.

Dynamo is a design computation software that was initially created as a Revit add-on, and today has become a standalone platform (Jezyk, 2017). Dynamo is defined as "A visual programming tool that aims to be accessible to both non-programmers and programmers alike. It gives users the ability to visually script behaviour, define custom pieces of logic, and script using various textual programming languages" (Jezyk, 2017). In practice, Dynamo is a platform to customise the behaviour of

Table 1
Data and metadata used to enable correct interpretation of the XRF model.

	Parameter Name	Data type	Comments
Main Data	Phosphorus content (P)	concentration value in ppm	Measured in triplicate, with an associated standard deviation, and occasional blanks due to instrumental error
	Potassium content (K)		
	Calcium content (Ca)		
	Manganese content (Mn)		
	Arsenic content (As)		
	Strontium content (Sr)		
Metadata	**Reading***	**numerical code**	**Unique identifier of each measurement, produced by the instrument**
	Nozzle	binary (present or absent).	The nozzle is used to keep a constant distance with the analysed surface, but it is not always possible to use it.
	Live Time 1	elapsed time in seconds	Time of exposure to the X-Ray signal of a beam. The time influences the accuracy of the measurement. However, it is occasionally minimised to reduce the total experimental time. While it should be constant in a single survey, it could be changed by different analysts.
	Elapsed Time Total	elapsed time in seconds	As above but referring to the total time of analysis.
	Time	time stamp in seconds	Time of the measurement.

Parameter Name	Data type	Comments
Reading*	**numerical code**	**Unique identifier of each measurement, produced by the instrument**
Window name	Alphanumerical	naming is given according to fieldwork notes and does not correspond to classification naming explained above
Pane name	numerical code	given by the researchers to identify each glass pane
Glass name	numerical code	Given by the researchers to identify each glass element

BIM models. It offers an integration between BIM and other coding languages, therefore opening the door to all types of extensions to the functionality of the software, such as complex calculations and data structures.

Dynamo creates algorithms which main elements are nodes and wires; the former embody operations (numbers, functions, strings, code blocks, etc.) (Jezyk, 2017; Aish and Mendoza, 2016), whilst the latter define relationships between nodes (Jezyk, 2017) and also illustrate data flow (Aish and Mendoza, 2016). The function of each programming node is too detailed to be described here. Rather, an example is shown in Fig. 1, where the Dynamo algorithm of Hellens Manor is depicted. An overview of the whole Dynamo algorithm is provided later.

The bit of Dynamo code shown on Fig. 1 depicts the creation of a list of colours. These colours will be then applied to glasses, according to their content of chemical components. Different colour lists are created for different chemical components; for instance, on Fig. 1, a list of different pink shades is created, which represent different content of potassium. Specifically, light shades represent little content, whilst darker shades display major content. An example of this logic can be seen on Fig. 5 on Section 4.2.1.

3.3.2. GIS data

As part of the analysis of the chemical composition of the window, we also explored an alternative method of visualising the pXRF data through a Geographical Information system (GIS). In this case we used ArcGIS 10.7 (ESRI, 2018), which is a program used extensively for geospatial analysis in heritage management (Conolly and Lake, 2006). It is typically utilised to detail large areas in a 2-dimensional format and is not conventionally used for analyses of this type. However, as it facilitates the collection, processing and visualisation of spatial data, it can be a valuable tool for the analysis and management of information relating to historic buildings (Tobiáš, 2016). It provides a method of database storage, where field measurements can be combined with digitalisations of analog data (e.g. plans and drawings) and other descriptive and metric data (Ciski et al., 2019). More fundamentally, this allows vector drawings to be related to attribute data (and metadata), which can facilitate a better understanding of spatial patterns and relationships. This can then be applied at a landscape, property-wide or building-component (in this case for a window) scale to produce informative thematic maps (Tsilimantou et al., 2020).

An example detailing a single window from the Hellens Manor building is presented in Section 4.2.2. To locate each pXRF sample, a plan of the window was digitised in ArcGIS and a numeric identifier provided for every windowpane. This is then incorporated into a spreadsheet, together with details the sample location code and other descriptive details such as window colour and interpreted phase (Fig. 2).

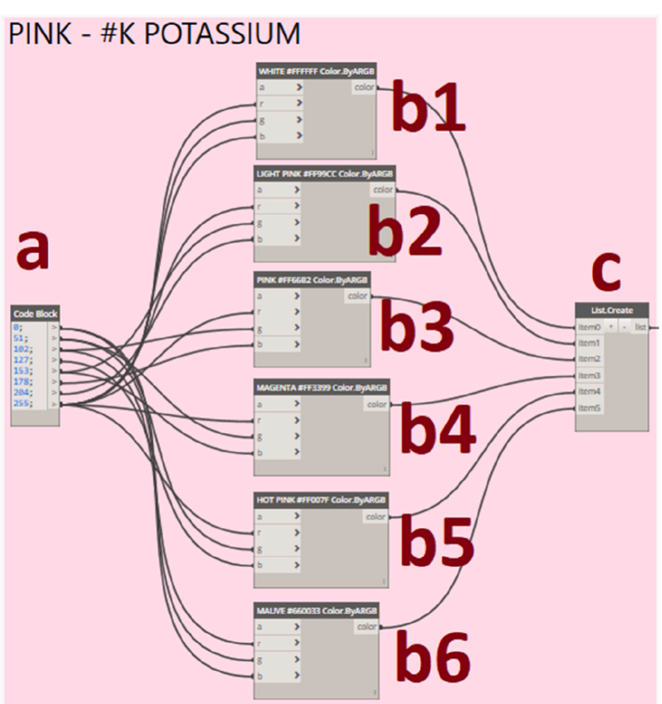


Fig. 1. Creating the potassium colour list - pink. a) “Code Block” node containing RGB numbers; b) b1-b6 create 6 shades of pink through RGB codes; and c) Creates a list of pinks. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Results

4.1. Creating the BIM model

4.1.1. Structure and level of detail

BIM model of Hellens Manor was created using Autodesk Revit. To produce it, we used existing floorplans in pdf format, as well as photographic survey outputs. The result is shown on Fig. 3 below.

Modelling has been performed using existing Revit families for principal building elements, such as walls and floors. Specifically concerning walls, the “Revit Generic Wall” category was chosen,adapting thickness where necessary. Indeed, because Hellens Manor is a historic mansion that has experienced several structural modifications, its building elements are often characterised by irregularities (Historic England, 2021), and therefore manual adjustments are necessary during modelling. During walls creation, a great attention was put to identify windows location, in order to make the next step – windows modelling task – easier.

Afterwards, the model skeleton was completed inserting floors, stairs, doors, and the roof. Fig. 3 shows the finished model, including windows.

This model has a Level of Detail (LoD) of 4, according to Historic England guidelines (Antonopoulou and Bryan, 2017), which is defined as “Sufficiently modelled to identify type and component materials. Accurate dimensions.”. There are LoD above, 5 and 6, which we deemed too detailed for the purposes of our analysis. Namely, the inclusion of construction irregularities is not necessary to support the analysis of the distribution of glass age.

4.1.2. Parametric modelling of the windows

Detailed modelling of LoD 5 was only necessary on the windows. This step was particularly challenging because there are many different window types on the mansion, as shown on Table 2. Their variety precluded the usage of pre-defined shapes or libraries, one of the strengths of BIM.

Windows were modelled using Revit families. These models were based on both photographic survey data, as well as on existing floorplan pdfs. Because of similarities between windows, we chose to model them as families, in order to allow usage of the same family for similar windows thanks to small parametric modifications.

Table 2 shows the identified windows types. It is possible to notice that all windows are based on one same panel, which is then repeated for bigger windows. Additionally, there are 2 variants on the basic panel, based on glass shape, which can be either rectangular or rhomboid. Having modelled the first basic panel, i.e., W3 and W8, all other windows were extended from these two. For instance, W1 is 6-panels window formed by 5 W3s and 1 W8.

4.1.3. Adding material information

The previous section details creation of window skeleton, i.e., frames. As soon as these were modelled, glasses were added as well. Glasses were modelled as single *in-place component*, rather than as part of the window family. This choice was necessary to ensure that each single glass is a smart object, with an attached spreadsheet, and can be

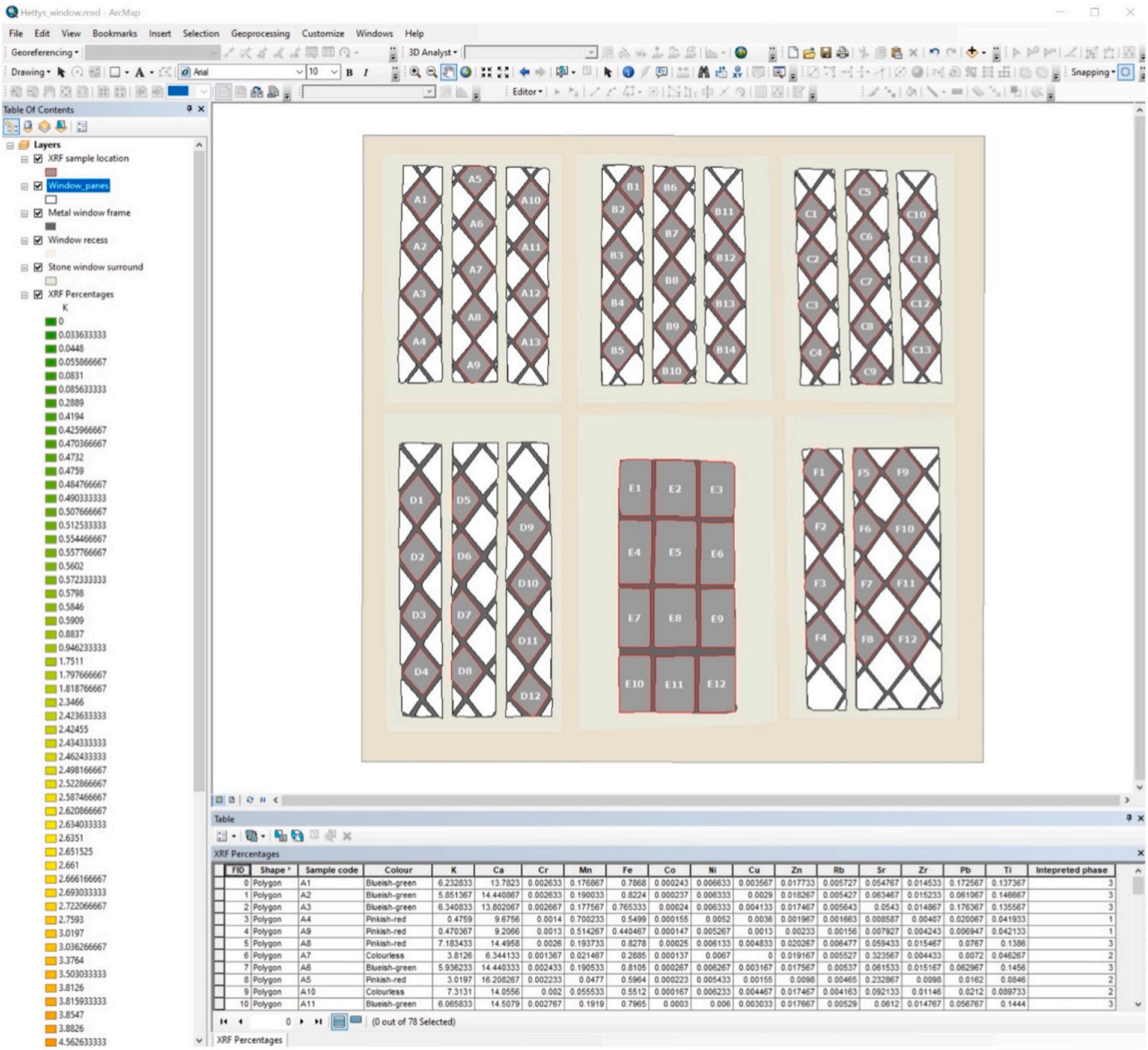


Fig. 2. Example of ArcGIS work environment illustrating relationship between XRF spreadsheet data and vector drawings of the sampled window.

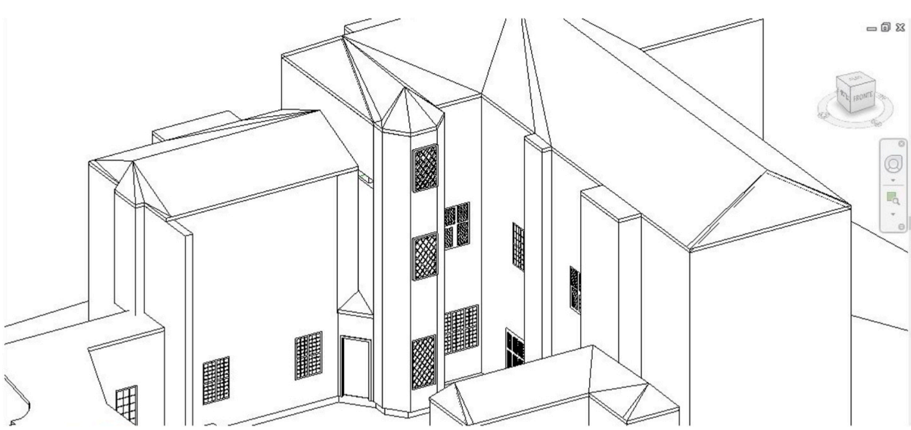
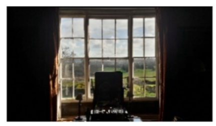
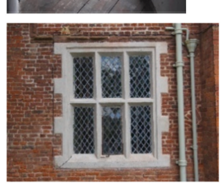
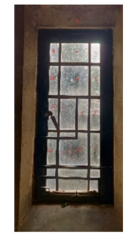


Fig. 3. Hellens Manor BIM model - a 3D view.

Table 2
Hellens Manor BIM model - window types.

Name	No. of Panels	Glass Shape	Image
W1	6 panels	all rhomboid except for bottom centre (rectangular)	
W2	3 panels	all rectangular	
W3	1 panel	all rhomboid	
W4	6 panels	all rectangular	
W5	4 panels	all rectangular	
W6	4 panels	all rectangular	
W7	4 panels	all rhomboid	
W8	1 panel	all rectangular	
W9	6 panels	all rhomboid	
W10	1 panel	all rectangular	

enriched with data when needed. Indeed, this operation was pivotal to make sure that each glass is linked to its specific chemical content data.

Each glass was modelled on the basis of the windows frame in which is contained. Its thickness is of few centimetres in reality, however, for modelling purposes, it was necessary to set the glass thickness to 10 cm. This choice conflicts with the model's LoD 5, however, it was necessary to ensure that is possible to easily select glasses during Schedules creation.

Afterwards, we create Revit Schedules to insert chemical components data (cfr. Section 3.2). Originally designed to provide component identification values, Schedules are the best way to introduce numerical information within Revit. One Schedule was created for each window, where glasses are listed individually in separate rows, as shown on Fig. 4.

4.2. *Visualisation of material information*

4.2.1. *Dynamo and BIM*

The Dynamo algorithm on Hellens Manor has been created on the basis of the existing algorithm produced for the Jewel Tower case study (Pocobelli et al., 2018a, 2019, 2021). Purpose of this algorithm is to display chemical components variance on historic glass. This information is of great interest for conservation purposes, because it enables dating of historic glass. Specifically, knowing historic glass' chemical composition, it is possible to establish its age, and therefore, it is possible to assess whether a specific window is original, or has been replaced during a specific time, etc.

To access chemical components data, users can firstly choose which chemical component they want to visualise. As specified above on Section 3.3.1, different colours have been created to display different chemical components. As soon as this choice has been made, users have simply to connect the chosen colour node to the algorithm, as shown on Fig. 5. The example shown on Fig. 5 exhibits this procedure for Potassium, which correspondent colour list is pink. Here, the pink colour list (Fig. 5, a) is connected to the "ColorRange" node (Fig. 5, b) and to the block of nodes that extracts correspondent data from the relevant Revit Schedule (Fig. 5, c). On Fig. 5, d it is possible to see the result, which highlights a window with different shades of pink on each glass. Darker shades correspond to bigger quantities of the chosen chemical component, whilst lighter shades represent smaller quantities.

Additionally, the Dynamo algorithm enables users to access specific metadata in the BIM model. Indeed, it is possible to visualise Schedules on Revit, where data such as contained on Table 1, can be accessed.

4.2.2. *GIS modelling*

A window on the first floor (W1) was selected for visualisation through GIS as it is of particular historic importance in terms of the narrative of the property. A total of 76 window panes were sampled within this window as detailed in Fig. 2.

A vector drawing of the six panels was digitised from a photograph and each windowpane was assigned a polygon in an arbitrary 2-dimensional coordinate system. These polygons were then related to a

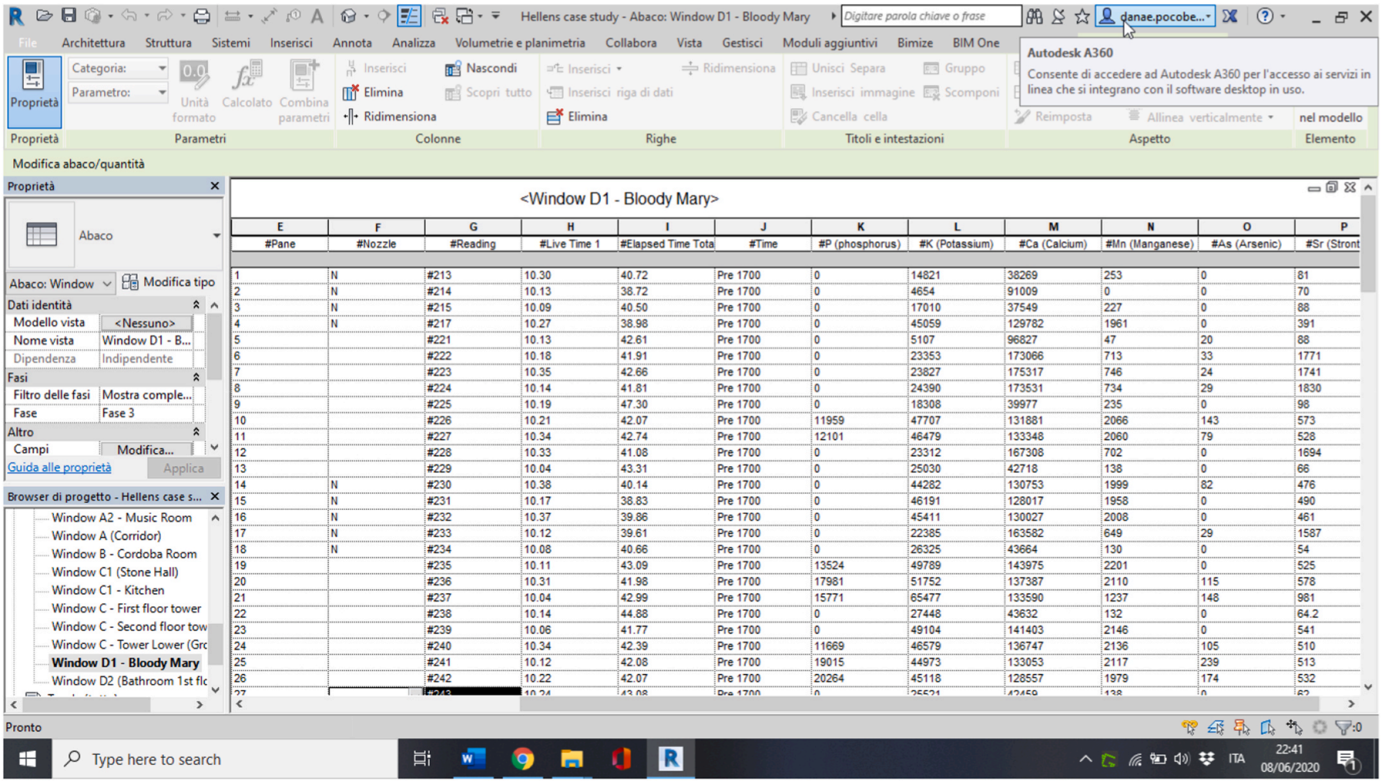


Fig. 4. Hellens Manor BIM modelling: glass schedules.

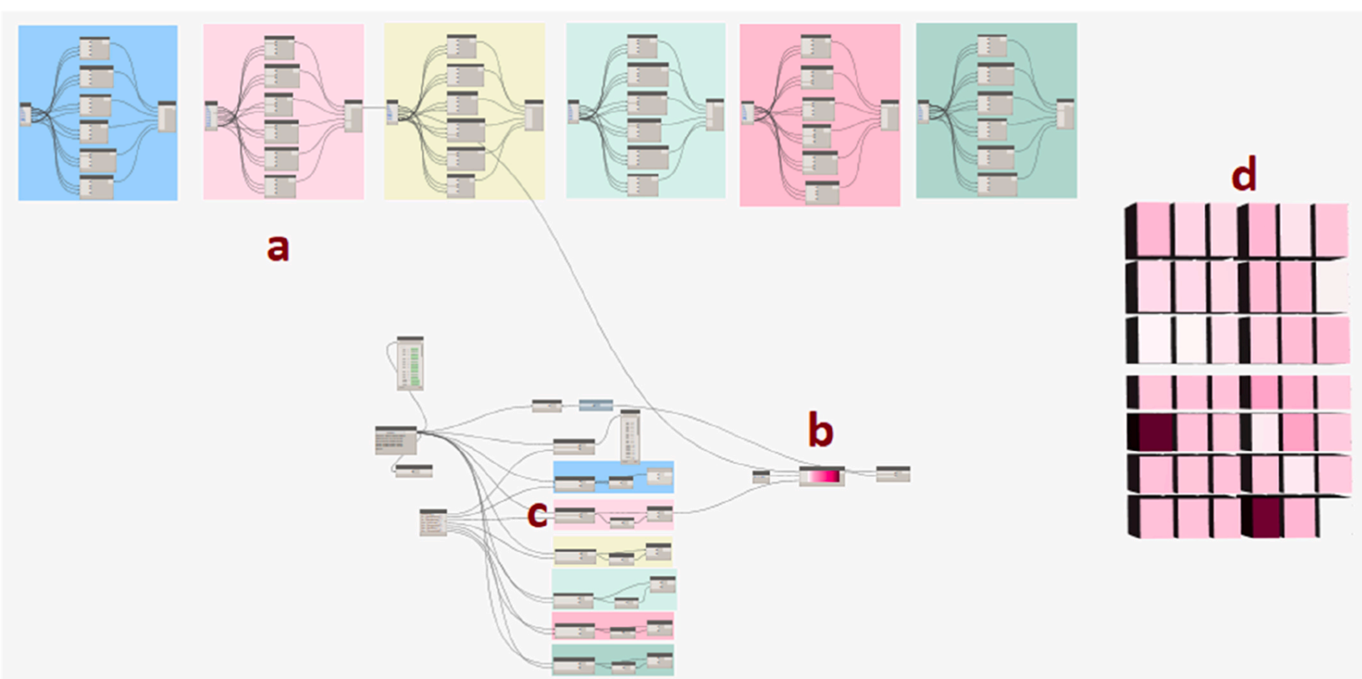


Fig. 5. Application of colours on the first floor bathroom window in Hellens Manor. a) Pink colour list created for Potassium (K); b) "ColourRange" node; c) Extraction of spreadsheet data related to K from relevant Revit schedule; and d) Depiction of K on single glasses – the darker the colour, the higher the concentration of K. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

spreadsheet containing "attributes" of the data and metadata highlighted in Table 1. This enabled the visualisation of the relative proportion of different chemical components of the window glass using a diverging colour ramp (Fig. 6). For each element, green is equal to zero and red represents the maximum value recorded as a percentage, with all other values evenly distributed between them. The advantage of such a display is that different elements can be presented using the same vector layout and attribute table, facilitating a visual comparison of the likely origin of the individual windowpanes.

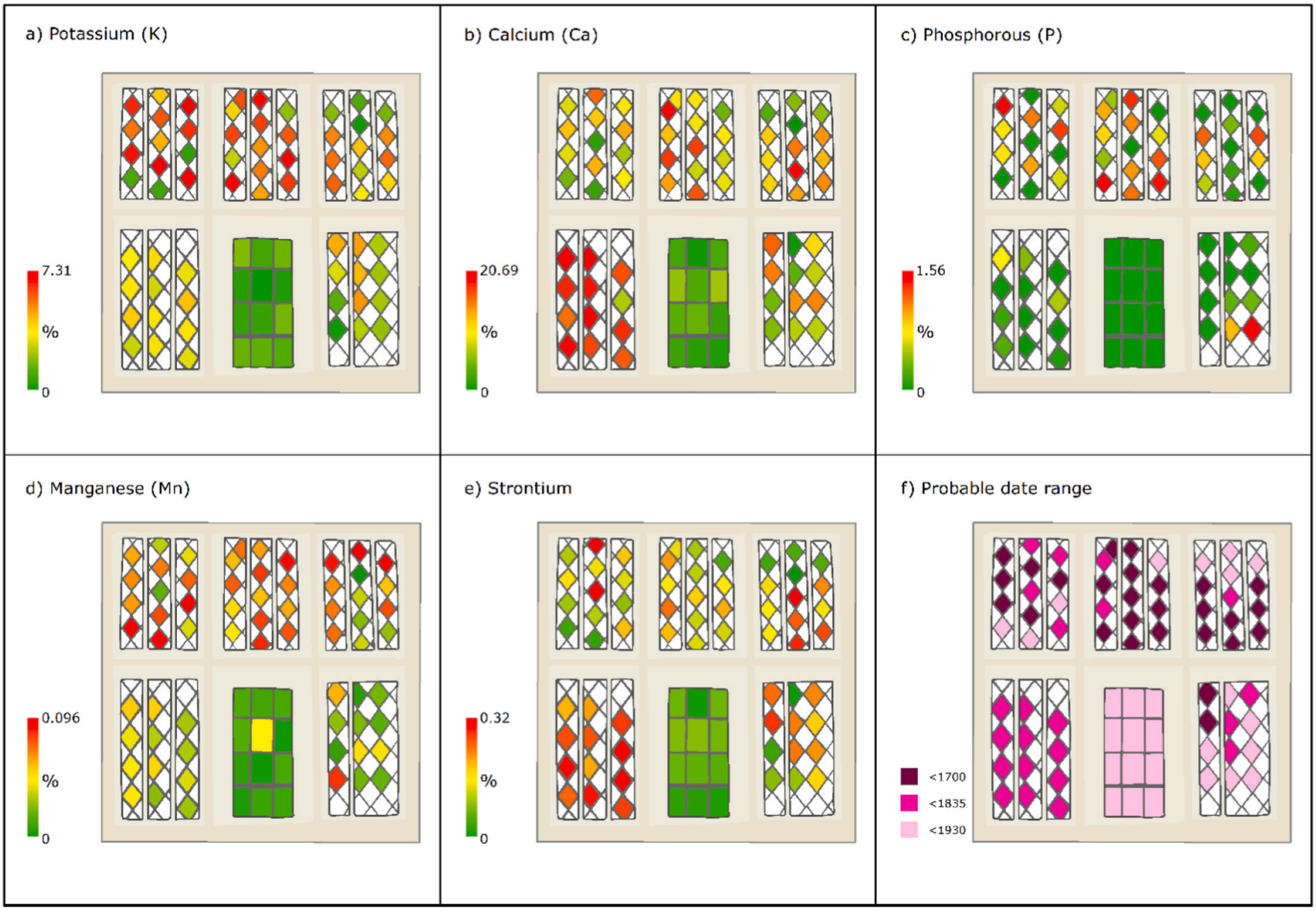


Fig. 6. Relative proportions of select elements from the 1st floor Window in Hetty's room (see W1 in Table 2) displayed with a diverging colour ramp (a–e) and interpretation of the probable date range the analysed windowpanes (f). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Discussion

The two methods used, GIS and BIM, were used outside their main intended functionality. As a result, both methods required some creativity. The main limitation of BIM is that the current leading software packages, including Revit, are not designed to visualise spatially distributed data. Building elements can be linked to data, but by default it can only be seen in numerical form. Programming with Dynamo, which has equivalents for other software packages, gives the user some capacity to increase the functionality of BIM. The algorithm presented here could be used to visualise any spatially distributed quantity in a Revit model. However, it is likely that users will need to customise this algorithm so that it fits the data structures that are relevant to their specific problem. The main barrier to the routine use of algorithms of this type is the steep learning curve, only partially reduced by the inclusion of visual programming strategies.

The main limitation of the GIS reconstruction is that it only provides an isolated 2-dimensional view of a single window. Theoretically, it is possible to scale this up by digitising each window within the property, but rather than an arbitrary spatial reference system, it would be advantageous to maintain geo-referenced coordinates, so that relationships across the whole property can be visualised in situ. However, the 3-dimensional modelling tools of GIS software only permit the construction of relatively simple elements and this is arguably better achieved using CAD or BIM (Centofanti et al., 2012). Nonetheless, as better synergy between BIM and GIS is developed, there is potential to capitalise on the integration these datasets in any future research (Liu et al., 2017).

6. Conclusions

This paper analyses two different methods to depict material data relevant for the interpretation of historic buildings. In summary, BIM is well-suited to the quick creation of a 3D model with sufficient detail to enable interpretation, but the inclusion of information requires a rather complex customisation. GIS is perfectly able to produce visually striking visualisations very close to the actual shape of the windows, but it is constrained to 2D visualisations or very simple 3D models. This case study supports the idea, already suggested by others, that a workflow that incorporates both technologies would be very useful to the building conservation field.

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Author statement

Danae Phaedra Pocobelli: Methodology, Software, Investigation, Presentation, Data Curation, Writing - Original Draft. **Antanas Melinis:** Methodology, Investigation, Data Curation, Writing – Original Draft. **Nicholas Crabb:** Methodology, Investigation, Software, Writing – Original Draft. **Josep Grau-Bové:** Conceptualization, Supervision, Writing – Reviewing & Editing.

Declaration of competing interest

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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