# Visual encoding of a 3D virtual reconstruction's scientific justification: feedback from a proof-of-concept research

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**ABSTRACT**

3D virtual reconstructions have become over the last decades a classical mean to communicate about analysts' visions concerning past stages of development of an edifice or a site. However, they still today remain quite often a one-shot output, neither reusable, nor expressing visually the diversity of the evidence behind the reconstruction. A 3D virtual reconstruction - obtained by means of a synchronic or diachronic study - is a hypothesis, but also a technical work, and ultimately confronts researchers with the challenge of finding a compromise between interpretation and assertions, even within the graphical encoding of a 3D model.

This research is based on a methodological proposal: introducing *justification matrices* that allow to associate to the components of a 3D virtual reconstruction, "indicators" that formalise in a synthetic way an assessment of plausibility. These matrices allow to assign to individual 3D objects or to groups of objects a quantitative evaluation of their plausibility by crossing four criteria: shape, dimensions, existence, and position.

The experiment led to the creation of a proof-of-concept prototype allowing a user to interact in real time with the graphic appearance of each object, represented in a 3D reconstruction, according to the values of its justification matrix. The approach is applied to four phases of the evolution of Marmoutier abbey's hostelry (corresponding to four synchronous states - 12th, 13th, 15th and 18th centuries), and re-uses 3D virtual reconstructions produced several years ago for communication. The paper positions and discusses the three families of issues the research intersects (knowledge modelling, visual encoding and 3D content reuse), presents the case study, details the services offered by the prototype and assesses lessons learned and limitations. The experiment should be seen as an attempt to reason about heritage data sets by drawing on practices from the InfoVis field and is thought of as a call to design and discuss in the scientific community news ways of visualising architectural data, information, and pieces of knowledge.

*Keywords:* Plausibility, uncertainty, 3D virtual reconstructions, Information visualization, HMI, 3D content reuse.

## Introduction

A 3D virtual reconstruction is the result of experts' analyses aiming to propose a plausible spatial arrangement for a building that has changed over time. It is before all the result of an interpretation of available data and information underpinned by 'knowledge' (explicit, tacit, …). Each 3D reconstruction - obtained by means of a synchronic or diachronic study - is a hypothesis.

But a 3D virtual reconstruction is also a technical work, through which assertive geometrical forms have to be chosen in order to represent that spatial arrangement, even if uncertainties were spotted during the interpretation step. Ultimately, from the knowledge and information visualisation standpoint, a 3D virtual reconstruction confronts researchers with the challenge of finding a compromise between interpretation and assertions, even within the graphical encoding of a 3D model (if the model aims to serve analytical purposes).

This research is based on a methodological proposal: introducing *justification matrices* that allow to associate to the components of a 3D virtual reconstruction, "indicators" that formalise in a synthetic way an assessment of plausibility. In other words, these matrices deliver information on the scientific justification of a given spatial arrangement.

The experiment led to the creation of a proof-of-concept prototype allowing a user to interact in real time with the graphic appearance of each object, represented in a 3D reconstruction, according to the values of its justification matrix. The approach is applied to four phases of the evolution of Marmoutier abbey's hostelry (corresponding to four synchronous states - 12th, 13th, 15th and 18th centuries), and re-uses 3D virtual reconstructions produced several years ago (for communication purposes) by the team of archaeologists involved in this experiment.

Several system querying modalities have been experimented in order to better circumscribe the services such a prototype can offer. The prototype is based on a combination of classical and open technologies for the web (RDBMS, JS/CSS/HTML interface, 3D JavaScript library Three.js). It is already operational and available online with free access.

The paper first positions and discusses the three families of issues this research intersects (knowledge modelling, visual encoding and 3D content reuse), then presents the case study the prototype is applied on, before detailing the ways users can interact with the data thanks to the abovementioned prototype. A discussion, an assessment of the research's limitations, and conclusions are provided for in the last section.

## Research background & methods

The need to differentiate, in a 3D model, between attested and assumed elements is not new, far from it. This methodological challenge was already there before the digital era [], and is behind Jean-Claude Gardin's approach (Dallas, 2015), which we will discuss later. For the past 30 years (see Messemer, 2016), the issue has been regularly discussed in the scientific literature, and this in various scientific communities (architecture, history, archaeology, …) both in the form of recommendations and of feedback (Alkhoven, 1993) (Sylvaiou & Patias, 2004) (Pfeiffer et al., 2013) (Morandi & Tremari, 2017).

We have been part of this move for about ten years, with reports of experiments centred on 3D modelling and graphic encoding *per se* or in the form of online 3D information systems, at different scales, scanning different technological solutions (Blaise & Dudek 2002, 2005, 2008). These experiments have led to a collection of 'rules of conduct' inspired by practices in the InfoVis field, now used as a teaching tool (see Appendix 1). The issue remains topical even if it tends to become more marginal under the double effect of an overwhelming presence of 3D data acquisition experiments in the literature, and following on this question the emergence of the still rather vague concept of 'digital twin' – most often viewed as an avatar of the real thing, of an attested thing (and thus an inoperative concept if talking about 3D virtual reconstructions and plausibility). We have chosen to reinvestigate the issue in the context of a wider research programme[1] focusing on methodological aspects such as reproducibility[2], traceability of research workflows, and this along with archaeology colleagues. There are three main reasons for this new attempt:

[1] See the MEMORIA IS platform - http://memoria-dev.gamsau.archi.fr/is/enter.php
[2] An acute question today, and one that obviously needs to be addressed in view of the effort involved in producing 3D reconstructions and the heavy risk of seeing this effort lost very quickly (whether on the technical level - obsolescence of the tools, or on the cognitive level - failure to perpetuate the reasoning mechanisms).

| 90 | - | new technological setups (3D js libraries, Collada 3D file format, etc.), |
| 91 | - | a pre-existing set of 3D models, sort-of dead branch, needing repurposing, and acting as a test bench, |
| 92 | - | finally, the idea that repurposability and interpretability are coming forward as a major part of the |
| 93 | | research agenda in heritage studies at large. |

94     In view of these elements, the result we present should be understood basically as a proof-of-concept
95 experiment, a way to question ourselves on *why not (re)dig a bit further into the question of what a 3D model*
96 *can say, and be used for?*. The experiment is described below by distinguishing three complementary aspects:
97 the knowledge representation problem, the visual encoding choices, and finally the technical approach to the
98 re-use of pre-existing 3D models.

## The knowledge modelling issue

100     What exactly is uncertain when an expert proposes a 3D virtual reconstruction? How to account for the
101 uncertainties associated with a 3D virtual reconstruction in a formal and shareable way, conducive to a
102 comparison within a study case, or between case studies? And what exactly are these uncertainties about?
103 Architectural forms? Their spatial arrangement? Their very existence? Can this notion of uncertainty be
104 formalized in any way other than by an accompanying discourse? On this question, the scientific literature
105 proposes numerous methodological reference points, often discipline-centered, leading to a formalization of
106 uncertainty factors (e.g., Skeels et al. 2010, Zuk et al. 2007, Thomson et al. 2005). In addition, from an
107 archaeological standpoint, how can we exploit the notion of argumentation, present for example in J.C Gardin's
108 logicism (Dallas, *op.cit.*), to make the choices made by an analyst more readable within 3D models?
109     *Uncertainty* is in fact a sort of catchword covering a vast number of situations - analysing different types of
110 uncertainties (and their consequences in terms of decision making) is indeed a research issue by itself, and one
111 that goes far beyond the scope of this paper (see on this issue Blaise & Dudek, 2020).
112     Our contribution introduces a formal model, *justification matrices*, addressing the specific issue of handling
113 *uncertainty* in the task of proposing a 3D virtual reconstructions: we therefore rather use the word *plausibility*,
114 denoting a particular occurrence of *uncertainty*. Justification matrices deliver information on the reason for a
115 proposal present in the 3D model, a proposal that is concretised by given 3D shapes in given positions within
116 the model. It allows to assign individual 3D objects or to groups of objects a quantitative evaluation of their
117 plausibility by crossing 4 criteria: shape, dimensions, existence, and position. This formalism materialises the
118 vision of one analyst, and could potentially allow the materialisation of differences between analyses. It does
119 not constitute an argumentation as such, but it reveals the result of an argumentation. The argumentation
120 itself can naturally be associated with the object as paradata – but this is another discussion, falling outside of
121 the scope of our contribution.
122     Our approach is a methodological questioning that complements the work done by the LAT team on digital
123 architectural models. This team of archaeologists outputted a final publication of a research on the abbey in
124 Marmoutier and used that opportunity to model four synchronic states of this building (12th, 13th, 15th and
125 18th centuries). Emeline Marot and Elisabeth Lorans (LAT) worked with Nicolas Nony (computer graphic
126 designer) to create these 4 models. The restitution of the various elements appearing on the models based on
127 arguments of an analogical, symmetrical, functional order... Many graphic documents were used. If these
128 choices were partly explained in the graphic and textual documentation accompanying the file of the models,
129 nothing allowed to take into account the reliability of these restitutions on the model itself, and thereby to
130 explain the passage between what is observed and what is returned on reconstruction models. The case of the
131 hostelry and its four models appeared to us as an appropriate case study to try and fill this gap.
132     By starting to work on these objects produced by other researchers and with an objective of valorisation,
133 we quickly asked ourselves the question of multiple or at least different uncertainty depending on the
134 architectural objects questioned. Indeed, according to the available evidence we can be certain of the
135 existence of an object without knowing its location, its shape and its dimensions. For example, it may be a
136 fragment of a staircase, the location, shape or dimensions of which are unknown. In other cases, we are certain
137 of the existence of an object for example a buttress whose foundations we were able to observe by excavation
138 attesting its location but its shape and dimensions are not fully known. Thus, it appeared relevant to question
139 the plausibility of each object according to four criteria: its existence, its position, its shape and its dimensions.

It also seemed interesting to question the plausibility not of an object but of a group constituted on the basis of associations of functional, structural, rhythmic order (for example all the bays of the first synchronic state – Figure 1).
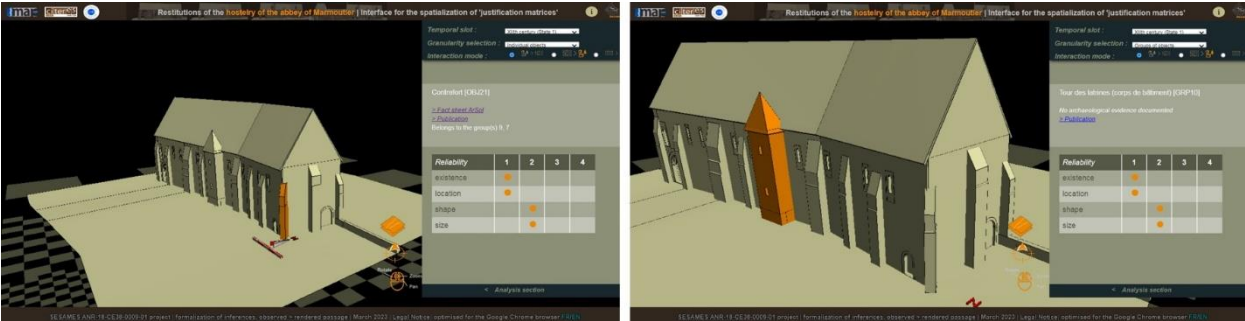


**Figure 1** – Left - plausibility of an individual architectural element (angle buttress), right - plausibility of a group constituted of walls, bays and a covering.

Indeed, the uncertainties applied to each object is not necessarily the same as the one applied to the whole, the whole is not always the sum of the parts! To account for these different situations, we have proposed to synthesize this information in the form of a matrix presenting in line four plausibility criteria (form, dimensions, existence and position) and in column four values.

For each line four values are available, ranging from *1* (highest plausibility) to *3* (least plausible proposal); the value *4* is used to indicate elements for which the plausibility analysis remains to be conducted (Figure 2).

| Plausibility criterions | 1 : "Attested" | 2 : "Likely" | 3 : "Possible" | 4 : "Unassesed" |
|---|---|---|---|---|
| Existence | Presence of the element on the model attested because it still fully or partially elevated in reality | Presence on the model considered as likely on the basis of symmetry patterns, composition arguments, etc. | Presence of the element possible but not grounded on actual remains or documents | Plausibility still unassessed |
| Position | Position of the element in the model attested because it is still fully or partially elevated in reality | Position on the model considered as likely on the basis of symmetry patterns, composition arguments, etc. | Position of the element on the model possible but not grounded on actual remains or documents | Plausibility still unassessed |
| Shape | All the information needed to propose a given 3D shape is available. | Only partial information about the shape of an element is available. | The shape proposed is an expert's vision, not grounded on evidence | Plausibility still unassessed |
| Dimensions | All dimensions of the element or a large majority are known | Some of the dimensions of the element are known | No dimensions are grounded on evidence | Plausibility still unassessed |

**Figure 2** – Verbalisation of the justification matrices' values, showing also value *4* "unassessed" added at implementation time - elements for which the plausibility analysis remains to be conducted.

# The visual encoding issue

A 3D virtual reconstruction is in essence a visual product, in which graphic components are combined. What graphic vocabulary should be proposed, what interaction modalities in the 3D model should be implemented so that the subjective choices behind a restitution hypothesis are legible? How can comparisons between the different components of a 3D model (from the point of view of their relative plausibility) be facilitated? Bertin's graphic semiology (Bertin, 2010.) has spread well beyond its original discipline, geography, and particularly in the field of information visualization. However, it is hard to say there is an equivalent methodological reference point in the field of 3D heritage-related modelling. In that area of concern, after decades of research, practices still tend to privilege realism over semantic encoding, and representations often

165 primarily serve visual communication objectives. At the end of the day, 3D virtual reconstructions often do not
166 really provide services (in terms of scientific added value) commensurate with the effort made.
167     In the proof-of-concept prototype we present once a plausibility evaluation is done - here formalised as
168 *justification matrices*, comes the time when this evaluation has to be encoded visually, some would say
169 *mapped* visually. Representing uncertainties using visual means is nothing like a new issue or practice: for
170 instance Joseph Priestley's *A chart of Biography* is a classic timeline from 1765 that positions in time, using tiny
171 lines running from left to right, the lifeline of more than two thousand famous men (Rosenberg & Crafton
172 2010). When the dates of birth or death of these famous men are ill-know the otherwise continuous line turns
173 dashdotted, thereby intuitively transferring to the reader a sense of *uncertainty*.
174     A wide number of solutions have been tried out before and since the digital age, often in relation with time
175 oriented data with for instance the planning lines visualisation, the chronographs formalism and many others
176 readers can find in (Aigner et al., 2011). Cartographers, geographers or historians have also faced the issue of
177 how to distribute in the space of an objectivised representation - a 2D map - items the exact position of which
178 is not clearly assessed. Depending on the nature of the type of uncertainty to handle solutions can range from
179 the use of glyphs conveying the uncertainty information - through colours or shapes (see for instance Reimer,
180 2010) to clouds of 2D points, polygons or other shapes that localise a *likelyliness area* - area within which the
181 item is supposed to be localised, but that does not match exactly the geometry and position of the item
182 (Davies, 1996).
183     Visual mapping is a task that has been both in cartography and in information visualisation somewhat
184 rationalised with Jacques Bertin's (op.cit) graphic semiology and as part of it his identification of a finite
185 vocabulary of graphic variables. Although written before the digital age, in the context of 2D paper based
186 graphic outputs, his 'methodological frame' can still act as a reference model helping to explain visual
187 encoding strategies.
188     The prototype we have implemented exploits five graphic variables: position, orientation, size, shape and
189 colour. The first four variables are endowed with conveying information about the architectural elements: 3D
190 components distributed somewhere in the 3D space. The plausibility information is conveyed by the fifth
191 variable: colour. Depending on the interaction mode chosen by the user one or several colours are used to
192 represent the plausibility evaluation visually in the 3D space. As will be shown in section Results a more
193 abstract, InfoVis-inspired solution has also been developed that uses the same set of graphic variables. This
194 solution consists of a sort of visual metaphor (Kienreich, 2006), used independently of the 3D space. Obviously
195 our choice of using colour (and *only* colour) to convey the plausibility analysis visually could be debated. Other
196 solutions that go beyond Bertin's original framework and base on specificities of digital platforms (such as
197 interactive texture mapping or translucency) have been tried out but they have not been considered
198 convincing. Translucency, typically, is not easy to handle since shapes tend to get harder to apprehend visually
199 and what is gained in terms of visual differences between the known and the ill known can be lost in terms of
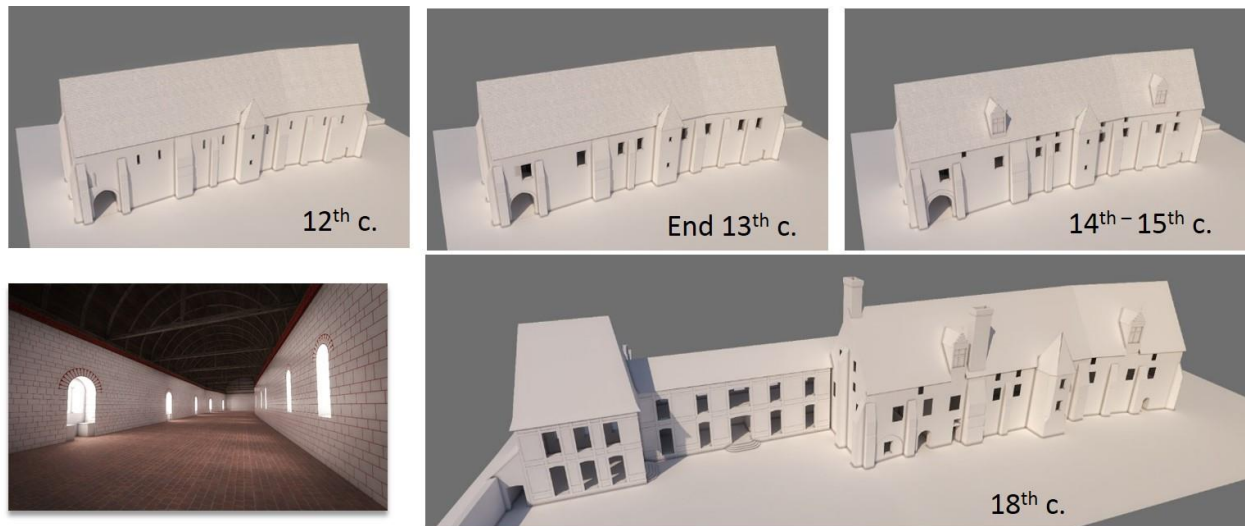200 global understanding of the 3D layout/structure.
201     Our strategy has been to privilege simplicity - as defined by J. Maeda (Maeda, 2006, Schuller, 2009) - as a
202 mean to minimise the learning curve and augment the acceptability of the prototype. The graphic encoding is
203 a simple bichromatic scale, allowing a natural ordering of values, with the grey used to convey information
204 lacks. We do acknowledge though that a thorough and robust evaluation of alternative visual encodings
205 remains to be done: a potential perspective for this work.

## 3D models reuse

207     How can we re-use 3D content for other purposes, in our case 3D virtual reconstructions created primarily
208 for scientific mediation and in a technological context that is obsolete today? This sub-issue can be seen
209 primarily as a purely practical matter concerning technology. But it can also be seen as part of a broad societal
210 movement towards more sustainability and economy of means, a movement that does affect the field of
211 scientific research.
212     This is not a new issue, however, and the emergence of many XML-based formats where the information
213 is detached from the application contexts is proof of this. But developing today such good practices does not
214 necessarily provide practical solutions concerning the reuse of existing 3D content. The interface that we
215 present has been developed to work online thanks to the open source Three.js library, and exploits a
216 systematic repurposing of the original 3D models.

217    The original data we have based on are four polygonal mesh models corresponding to four synchronous
218    states - 12th, 13th, 15th and 18th centuries - in the evolution of the abbey's Hostelry, and available today in
219    the form of OBJ-format saves (Figure 3).
220



221

225    Each of these four models was first divided into significant architectural elements (a wall, a door, a buttress,
226    an alignment of windows, etc.), to which justification matrices were associated (one matrix per element, single
227    object or group of objects). This work was carried out using the Blender software, in editing mode, and
228    consisted of separating and, if necessary, closing each element of the model. Choices had to be made during
229    this step such as the suppression of the internal parts of the models (vaults) insofar as the experiment
230    concerned only the external envelope of the building.
231    Each element was thus given its own geometry, exported in Collada (.dae) format, and corresponding to a
232    justification matrix described in a relational database. The link between the 3D data and the matrices is made
233    dynamically by exploiting correspondence tables (the identifier of an element in the database is used to name
234    the corresponding Collada 3D file). In order to optimise the use of these models in a browser, each state (each
235    synchronous 3D model) is loaded dynamically: only one 3D model is loaded at a time, while the others are
236    removed from memory as they are loaded, a possibility offered by the Collada loader of the Three.js library.
237    The interface allows the selection of elements directly in 3D by the raycasting method - a native function
238    of three.js - which has been adapted to our needs, in particular for the first interaction mode (see *Results*
239    section) which required this direct selection of elements by clicking in the interface.
240    Finally, the interface allows the display or hiding of the ground and of a dimensional grid that the user can
241    move along the horizontal or vertical axis using the keyboard. In addition, symbols with dimensions and
242    orientation (in accordance with archaeological standards) allow the dimensioning and orientation of the
243    model.
244    The method developed had the merit of demonstrating both the feasibility of the 3D models reuse scenario
245    that we had imagined, thus reversing the usual process of research to valorisation, and the rather generic
246    character of this type of web3D interface, reusable with few modifications for other architectural sites.
247    It should obviously not be forgotten that the time needed to segment and partly redraw the 3D models is
248    a constraint, even a limitation, but a limitation to be relativised by comparing it with the time needed to build
249    the original models... a few days versus several weeks per model.

## The case study: Marmoutier's abbey hostelry

250

251     The prototype re-uses the 3D virtual reconstructions of four phases in the evolution of the Marmoutier
252  Abbey hostelry, a site that has been thoroughly studied for years by a team of archaeologist, the UMR 7324
253  CITERES-LAT. The name of Marmoutier is inextricably linked to that of Martin, bishop of Tours from 371 to 397.
254  In fact, during his episcopate he chose this place for his retreat and attracted to him disciples who gave rise to
255  the first or second monastic community of the West.
256     After several centuries of development, this great Benedictine monastery became one of the most
257  important in France. This establishment lasted until the French Revolution, which destroyed most of the
258  buildings in the early 19th century. Archaeological research has been conducted since 2004 under the direction
259  of Elisabeth Lorans of the Archeology and Territories Laboratory (University of Tours - National Center for
260  Scientific Research). These investigations relate both to the spatial organization of the monastery and the
261  architecture of the various buildings that made it up and to the uses of the land that preceded and followed
262  the fifteen centuries of monastic life. It is therefore a question of a global approach to the site and its
263  environment based on the crossing, at different scales of time and space, of all possible sources: archaeological
264  data, written sources, which have existed since the end of the 4th century, and iconographic sources, available
265  since the 17th century.
266     One of the buildings partially spared by the revolutionaries is the monastic hostelry which had the function
267  of welcoming guests of mark of passage in the monastery (Figure 4).
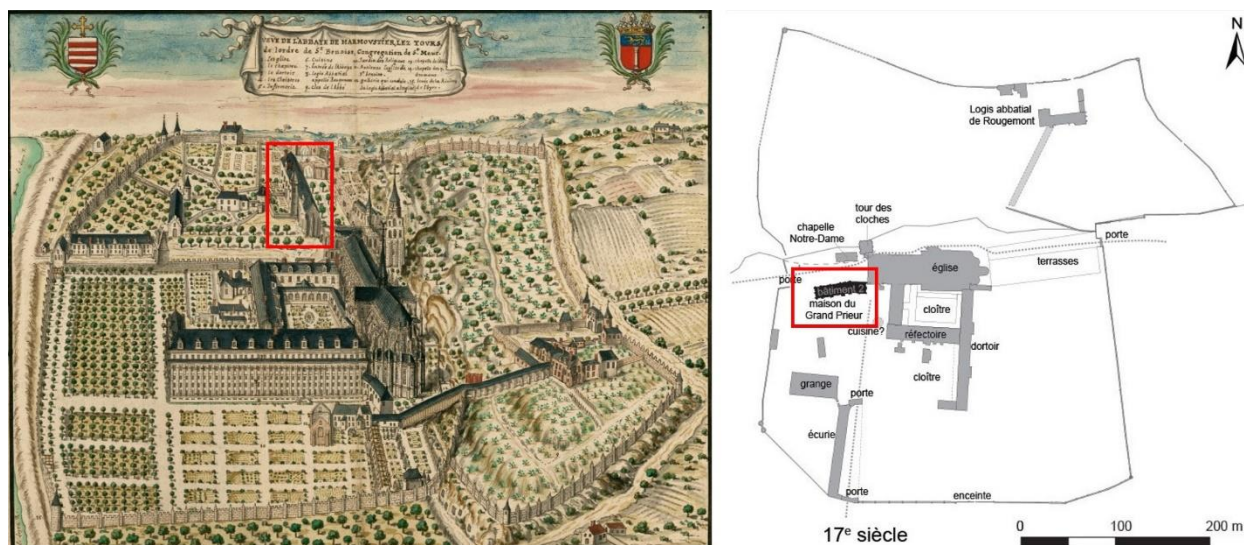
268



269     **Figure 4** – Overall views of the monastery, showing (outlined in red) the position of the hostelry within
270          the site. Left, the monastery before the destruction of the 19th century - Elevated view from Marmoutier
271          Abbey from the east, 1699, Gaignières Collection (BNF VA 407 (1) FT 4-H-183734). Right, Reconstructed
272          plan of the monastery in the 17th century (UMR CNRS/Tours univ 7324 CITERES-LAT).

273     Installed near the main entrance, in order not to interfere with monastic life, a text from the Middle Ages
274  indicates that it was built during the abbey of Hervé de Villepreux (1179-1189).
275     Today preserved on 20m of length, it originally measured 55m, a length known before the excavation by
276  plans of the eighteenth century (Figure 5). A study of the archaeology of the building was conducted on the
277  elevation while the destroyed part was completely excavated from 2006 to 2017.
278
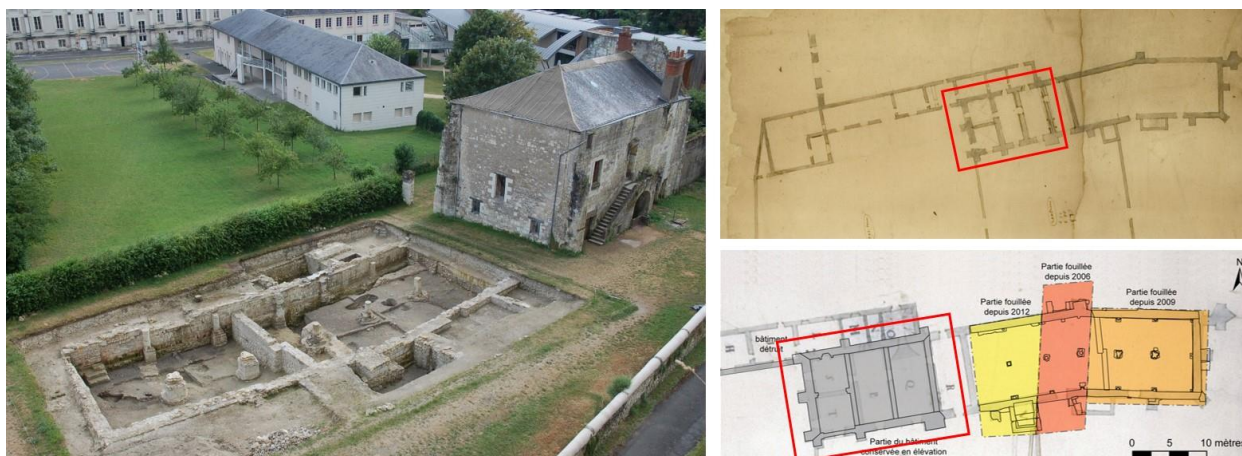
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Several synchronic architectural states of the building were defined:

**State 1**

This building originally had two levels. A vaulted passage located at the western end of the building allowed circulation between the part accessible to lay people, to the north, and the rest of the monastery, reserved for the community and its dependents. This passage was opened by large pointed arches still visible on the facade.

The rest of the ground floor, also vaulted, was used for storage and may have been used as a refectory. The floor, used for lodging, was covered directly by the frame and was lit with bays to the north and south. It had access to latrines installed in a turret.

**State 2**

At the end of the thirteenth or beginning of the fourteenth century, the vault of the ground floor was probably remodeled, the bays of the south façade were enlarged and the whole decoration was redone in false white joints on a yellow background.

**State 3**

In the fifteenth century, the function of hostelry seems abandoned for that of residence of the Grand Prior, one of the main dignitaries of the abbey. This change in assignment required a significant recovery of the building. The available space was increased as the upper level was divided into three. The latrine turret was turned into a staircase to serve these new floors and bays were pierced to illuminate them. The ground floor has been used by craftsmen (forge).

**State 4**

In the eighteenth century, the building underwent a new transformation when the interior ground level was raised. The old doors and windows were thus condemned and the vaults partially destroyed before the deposit of nearly a meter of earth on the entire surface of the ground floor and the installation of a paved floor still preserved to the west of the building. New doors have been created at this level, still visible today. A new wing is built against the north facade of the building. At this time, the vaulted passage, losing its function, was transformed into a living room.

**State 5**

This building does not seem to have been used for a long time, since the Revolution, which intervened shortly after, led to its destruction (no virtual reconstruction was produced for this state). All that remains today is its south wall and the west end, in the street.

Similarly, the eastern two-thirds of *building 2* was levelled in the early 19th century, with the western end used as a dwelling and agricultural dependency in the 19th and 20th centuries. However, the walls of the submerged part were kept in the basement, which allowed, thanks to archaeological research, to restore the chronology of the occupation of this area.

# Results : the online prototype

The basic service expected from our prototype is fairly simple: allow users to interact (through basic clicks on shapes) with architectural elements in the 3D scene so as to retrieve information about their plausibility. But naturally once each architectural element is associated with a justification matrix (concretely here inside an RDBMS) other services can be introduced that will build on the same data set. The prototype proposes three interaction modes exploiting the 3D virtual reconstructions, illustrated in the sub-sections below. In addition, the prototype also introduces an InfoVis-inspired overlay. In that case the focus is put on information patterns at an abstract level: the prototype enables comparing collection of justification matrices corresponding to the various synchronic phases or architectural elements.

**Interaction modes in the 3D environment**

For all three interaction modes building on the 3D environment, users first select one of the reconstructions, corresponding to one of the four synchronic phases of development of the hostelry that the LAT team has modelled. Users will then be empowered with three different means to analyse the plausibility of the reconstructions' components.

*Mode 1 : visualising the matrix corresponding to one architectural element*

The first interaction mode is extremely simple: users select an architectural element in the 3D space and as a result the element's justification matrix is displayed in the right part of the interface (Figure 6). When relevant, links to associated URLs are also available, that can be used to get more detailed archaeological information thanks to online content proposed by the LAT team (the ArSol database factsheet, or the online thorough archaeological publication – covering not only the architecture but also the burial area, craftworks, *etc.*).
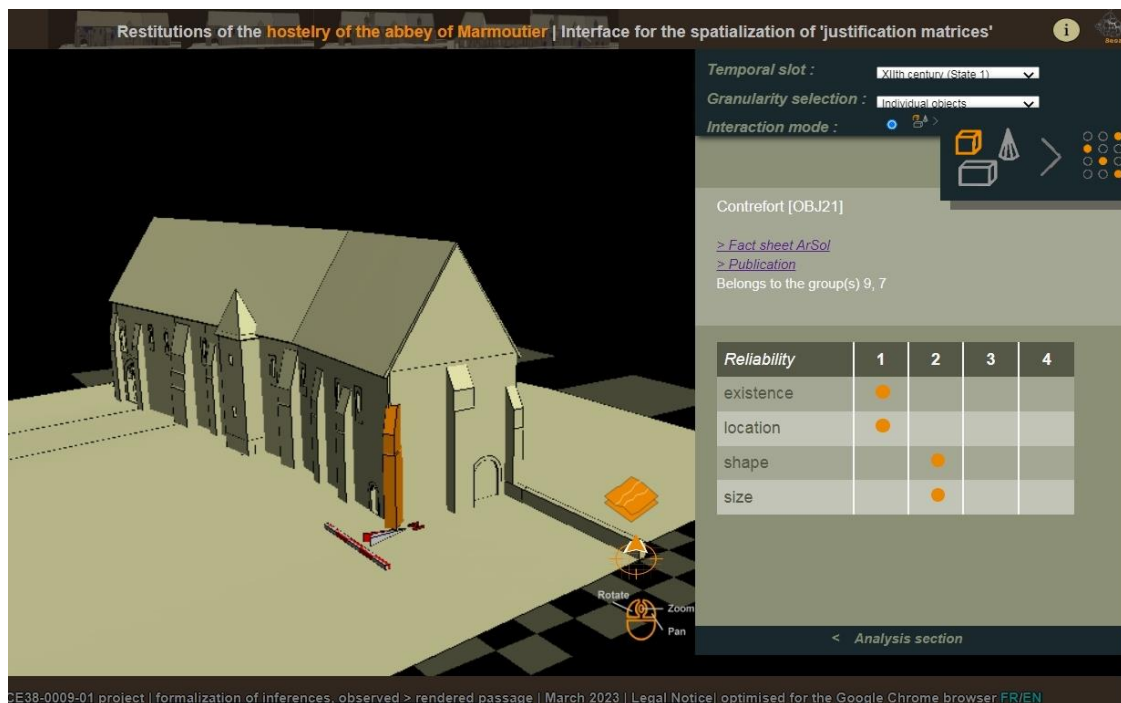


**Figure 6** – *Interaction mode 1*, illustrated on the first synchronic state (13th century). The justification matrix corresponding to the angle buttress highlighted in orange in the 3D scene is displayed in the right part of the interface. The existence and location of this element are fairly well established (remains exist, value *1* for the two first lines of the matrix). Its shape and size are less certain (value *2* for the two last lines of the matrix means likely, but not attested). Two URLs exist for this element that the user can exploit to retrieve further information on it.

349 *Mode 2 : visualising elements corresponding to one matrix*
350    In this mode a user selects a matrix (four values), by choosing values for each plausibility criterion (Figure
351 7). Once it is done, all architectural elements documented with a matrix that corresponds to the selected values
352 are highlighted (orange colour). In other words, this mode allows users to explore the information set starting
353 this time from a selection of plausibility criteria (one value per plausibility criterion) in the matrix, rather than
354 from the 3D scene itself.

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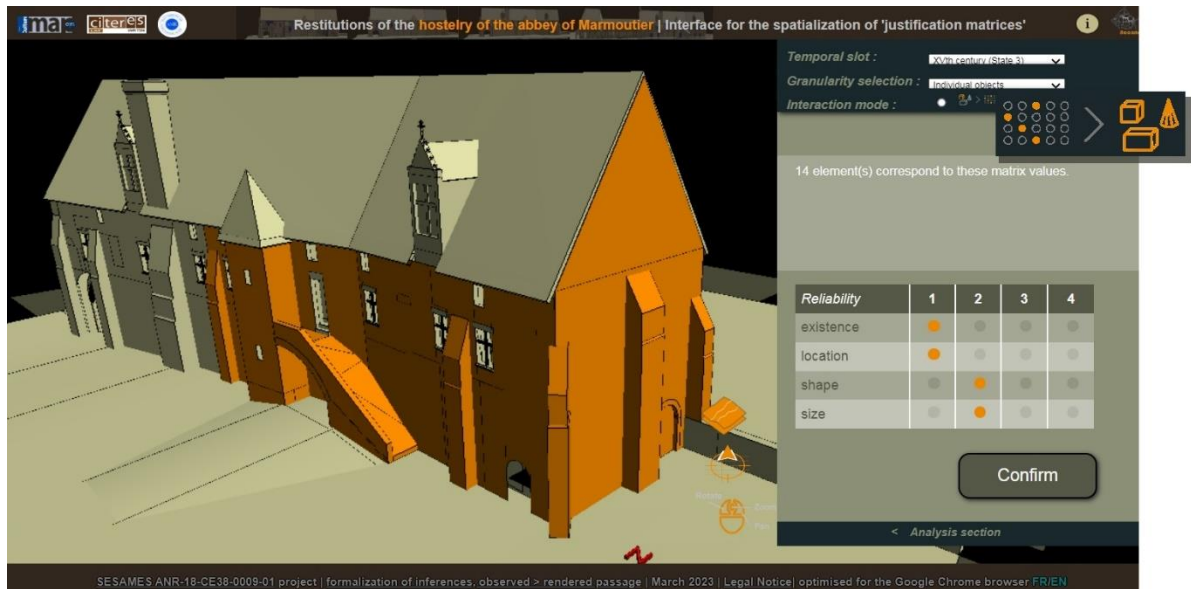


356    **Figure 7** – *Interaction mode 2*, illustrated on the third synchronic state (15th century). All components in
357    the 3D virtual reconstructions with a justification matrix that corresponds to the user's selection (the right
358    part of the interface) are highlighted in orange. Note, the spatial consistency of elements sharing a
359    common justification matrix, and the change of colour for the last part of the building (a part today
360    destroyed, raising more questions in terms of plausibility).

361 *Mode 3 : visualising all plausibility values for one criterion across all architectural elements*
362    The third mode corresponds to a filtering of the plausibility evaluation. A user selects a row of the matrix
363 ("existence" or "shape" criterion for example) and all the architectural components in the 3D model are
364 recoloured according to their plausibility evaluation for this specific criterion (Figure 8).
365



366
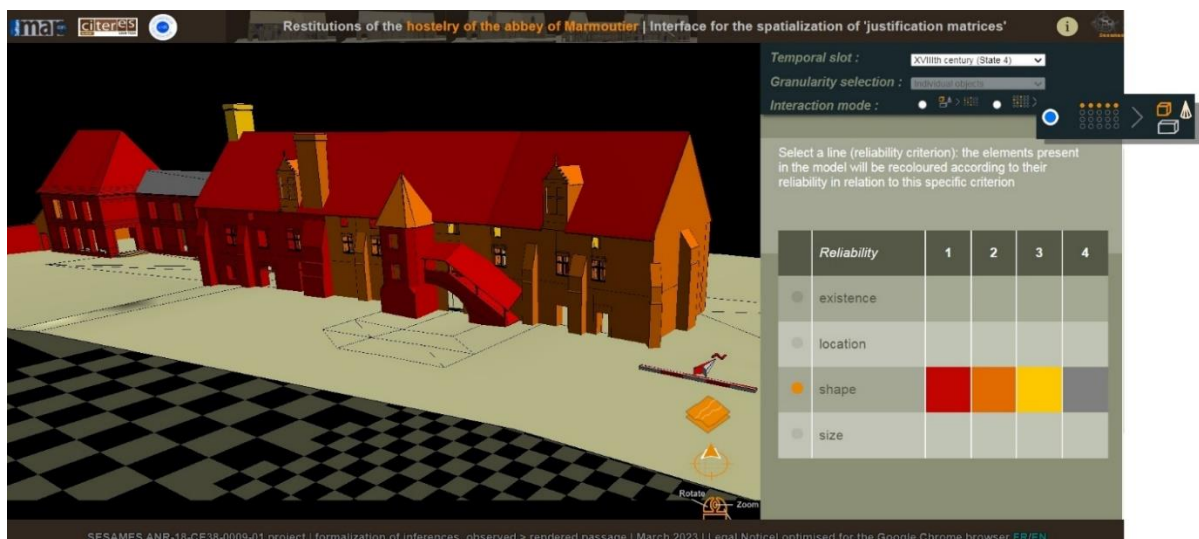
367    **Figure 8** – *Interaction mode 3*, illustrated on the fourth synchronic state (18th century). Each component
368    in the 3D virtual reconstructions is attributed a colour that corresponds to its plausibility in terms of

369    shape. Note the use of the colour 'grey' (value 4) that indicates no evaluation of plausibility of the element
370    has yet been done – a way to assess visually the completion – or not- of the plausibility evaluation effort.

371    **The *information visualisation* layer**
372    The three interaction modes presented herebefore focus on the use of a 3D environment that allows a
373    user to interact with one architectural element, or one matrix, and one synchronic state *at a time*. But what if
374    the user is willing to observe, for instance, the plausibility pattern of buttresses in comparison to this of
375    openings, or differences between synchronic states? As an answer we have implemented a more abstract
376    overlay, building on the concept of 'cumulative matrices'. Cumulative matrices base on the same visual
377    formalism as this used elsewhere in the interface: a grid in which each row corresponds to a plausibility
378    criterion (existence, location, shape, and dimension) and each column corresponds to a plausibility value
379    (attested, likely, possible, unassessed). The visualisation shows in an abstract way values for *collections* of
380    elements, either promoting chronological comparisons across the four synchronic states, or comparisons
381    basing on architectural types. The size of the coloured circles is proportional to the frequency of occurrence of
382    a [criterion, value] pair: the larger the radius of the coloured circles, the more frequently a pair appears (Figure
383    9).
384
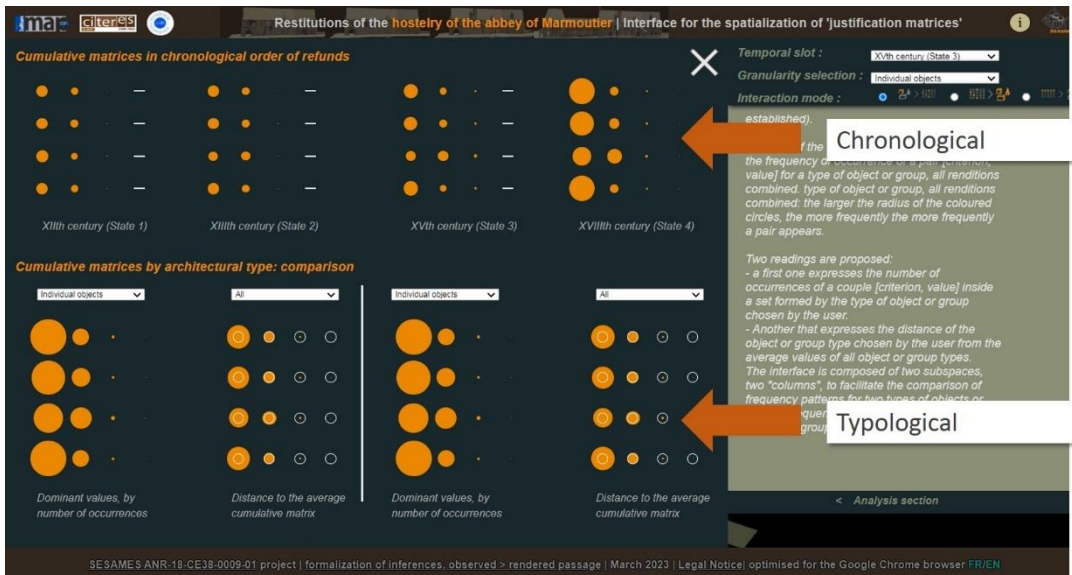


386    **Figure 9** – Visual display of the cumulative matrices, a mean to analyse the collection of objects basing on
387    chronological factors, or typological factors.

388    The top part of the graphics is used to compare values of matrices corresponding to the four synchronic
389    states (values of the matrices of all the architectural elements for a state are cumulated).
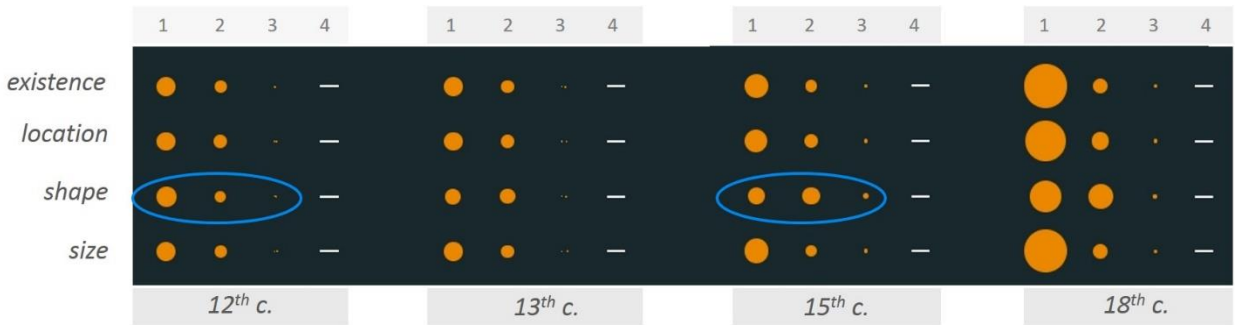


391    **Figure 10** – Cumulative matrices for the four synchronic states – the graphics shows for instance (circled
392    in blue) that for the third synchronic state the plausibility of shapes is lower than for the first synchronic
393    state, a somewhat counter-intuitive finding. The circles for the last synchronic state appear far bigger
394    than for the previous states – this is due to the fact that the edifice was significantly enlarged, and as a

395      result the overall number of architectural element is bigger – and so are the number of [criterion, value]
396      pairs. What is primarily read here are relative proportions, line per line, column per column.

397      The bottom part of Figure 9 is used for one to one comparisons of plausibility patterns corresponding to
398 various architectural types (vaults, arches, doors, buttresses, etc.).
399      The graphics is composed of four visual matrices, two per architectural type. For each architectural type
400 the two matrices correspond to two alternative readings of the plausibility information:
401      - the first (left matrix) expresses the number of occurrences of a [criterion, value] pair inside a set formed
402 by the type chosen by the user. It helps spotting the plausibility pattern for the type chosen by the user.
403      - the second (right matrix) expresses the distance of the architectural type chosen by the user to the mean
404 average value for all types. It helps unveiling specificities in terms of informational pattern for this or that type
405 the user has chosen.



406
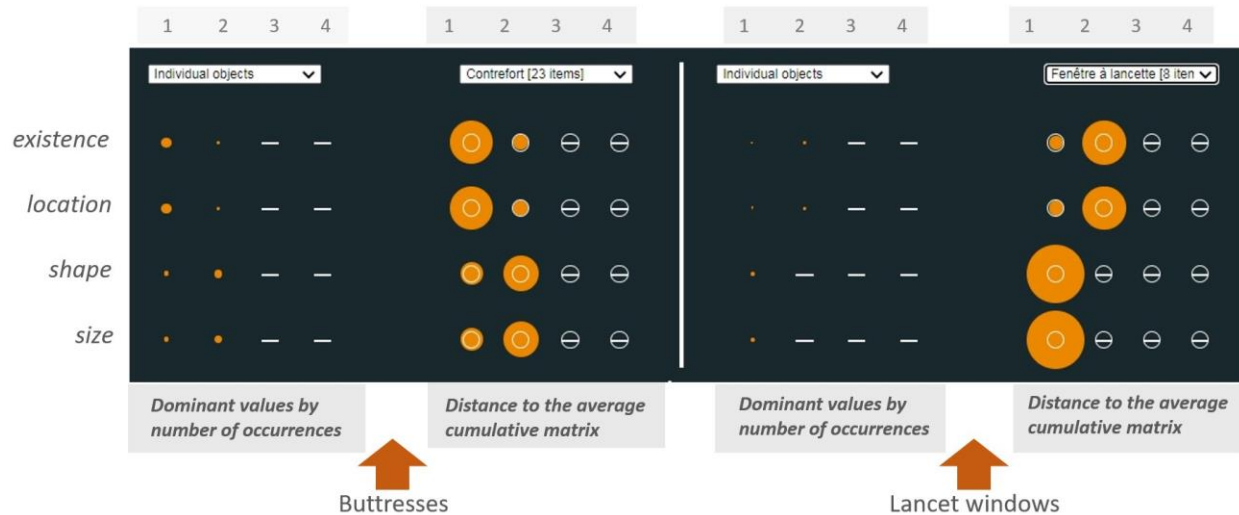
407      **Figure 11** – Cumulative matrices for buttresses (left) and for lancet windows (right). The graphics clearly
408      shows divergent information patterns. The white circles correspond to the mean value of each [criterion,
409      value] pair across the collection of architectural elements. White dashes correspond to [criterion, value]
410      pairs that are never found for the architectural type under scrutiny.

411 **Implementation**
412      The system architecture combines classic components in 3D web development – RDBMS/Php/Massive
413 javascript (three.js). We have been considering the option of developing a so-called responsive interface but
414 remain somewhat undecided on the relevance of this self-imposed development constraint. The issue is not
415 technical, but a matter of readability: does it really make sense to navigate inside a complex 3D monument,
416 with user interactions inside the 3D scene, on six inches screens (average size of mobile phones)? Moving
417 inside or rotating the 3D model in those conditions is workable, but fine grain interactions are not. This aspect
418 of the research remains undigged in, but would be a potential perspective – however falling out of the context
419 of this contribution.

420                          **Discussion, limitations and conclusion**

421      The prototype we present in this contribution has been designed as a tool aimed at distributing in a 3D
422 space, and analysing visually, the scientific justification behind so-called *3D virtual reconstructions*. In this
423 section we first comment on the prototype's current limitations, some of which are significant and justify
424 considering the experiment primarily as a proof of concept. We then conclude on lessons learned, on the
425 relevance of re-examining today the issue, and on what could be done to go further.

426 **Limitations**
427      Our contribution focuses on how to convey visually, in a 3D environment, the ***result*** of an expertise through
428 which 3D architectural elements present in a virtual reconstruction are associated with a formal model

429  expressing their plausibility (justification matrices). It does not address the issue of how to document and
430  model the expert's cognitive process, his/her choices, reasoning paths, decisions concerning a shape and the
431  corresponding matrix. There are ways to do so – starting from Gardin's logicism to today's MEMORIA IS - but
432  commenting on these approaches is beyond the scope of this paper (a key issue though). If sticking to this
433  contribution's core components various significant limitations have to be clearly stated:

434  - The plausibility analysis was carried out *a posteriori* (several years after the creation of the 3D models),
435    and not by the 3D models' creators but by a colleague, who had limited information on why this or
436    that modelling choice was made. What we present is a method, no conclusive results on this specific
437    case should be expected. Significant insights about a specific case would require conducting the
438    plausibility analysis task as the 3D model is created, or at least in direct interaction with the expert
439    that made the key modelling choices.
440  - An in-depth evaluation of the applicability and efficiency of the matrix itself would be needed – this
441    could be done by reapplying the approach to other cases, for instance. Labels and values of the
442    justification matrix as defined in this paper should be seen as a provisional methodological proposal,
443    requiring further debate and experimentation.
444  - The model's discretization is architecture-based: 3D elements present in the reconstruction are
445    consistent from the point of view of the architectural language (a wall, an opening, a buttress) but
446    obviously the reality can be far more complex. Typically sometimes within one consistent architectural
447    element (a wall) there are sub-parts that would call for different plausibility evaluations. As an answer
448    we have introduced a grouping mechanism (alternative granularities) but we acknowledge the
449    solution is at this stage partial.

450  **Lessons learned and conclusions**
451  Shortly said, the experiment results in a number of lessons learned on methodological aspects (real-case
452  evaluation of the matrix formal model) and on technological aspects (interactions in the 3D scene, visual
453  encoding, 3D models reuse with a shift from proprietary 3D format to a web-enabled Javascript-based 3D
454  interface). But due to the above mentioned limitations we do not put forward any assertions concerning the
455  informational patterns that would characterise this particular case study. What we report on in this
456  contribution is a *potential*, backed up by a proof-of-concept experiment (Figure 12). Obviously the approach
457  can only be workable and lead to significant observations and informational patterns on a specific case study
458  if enough is known or remembered about the making of the 3D models (and we mean here the intellectual
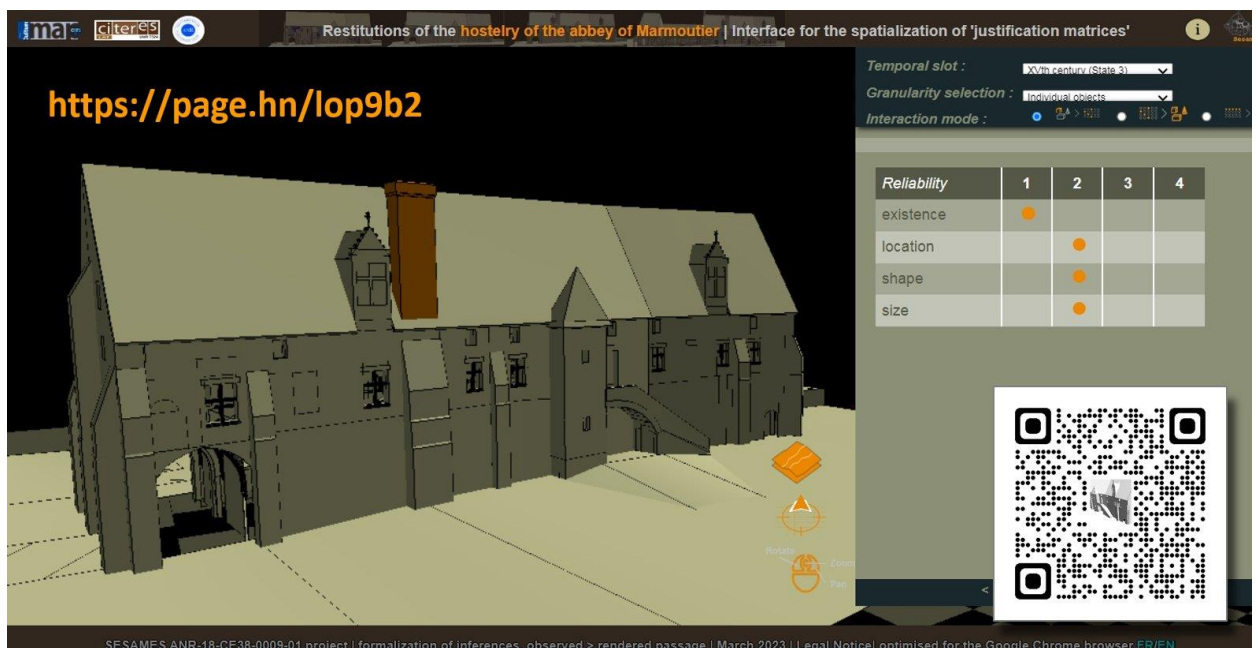459  choices of the expert).

460


461  **Figure 12** – An illustration of the prototype as it stands today, with URL connection links (open access).

462 However we hope such an experiment can act as food for *re*-thinking what type of knowledge can be
463 expressed in a 3D virtual reconstruction. Said differently, we view this experiment as an opportunity to re-
464 question the issue of sensemaking in 3D environments. The result we present materialises a sort of in-between
465 Gardin's demanding approach to documenting 3D models (oriented on decision processes that are conducted
466 in the course of selecting this or that shape, this or that spatial arrangement), and traditional 3D models in
467 which nothing is assessed as far as plausibility, human choices are concerned.

468 More generally, it seems to us that the technology, and the research agenda, may today open an
469 opportunity to reconsider the information spaces connectable to 3D datasets, to enhance the interpretability
470 of 3D scenes, as well as the repurposability of 3D components. The next step is probably to apply the method
471 while producing the 3D models, and in the meantime to collect feedbacks on potential benefits as perceived
472 by users.

473 To conclude, we argue in this paper that besides the most current research topics in and around the
474 architectural heritage (acquiring 3D data, trying to store and share it in FAiR-like ways) providing researchers
475 with means to analyse visually, to reason on (rather than to document) data and information sets is also a key
476 issue (may the focus be put on 3D data or not). The experiment we have conducted is basically a proof-of-
477 concept research, illustrating the fact that 3D datasets  - if talking about a concrete implementation of FAIR
478 principles -should be a repurposable material, *i.e.* content that can be reused to convey or discover new pieces
479 of knowledge, or information patterns (in our case about uncertainty or plausibility). In that sense, our
480 experiment is yet another attempt to reason about heritage data sets by drawing on practices from the InfoVis
481 field. May readers considers the experiment as significant or anecdotal, it definitely is thought of, on our side,
482 as a call to design and discuss in the scientific community news ways of visualising architectural data,
483 information, and pieces of knowledge.

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**Data, scripts, code, and supplementary information availability**

The prototype is available online: https://page.hn/lop9b2

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550                                            **Appendix 1**

551      As mentioned in the core of this paper, questioning the readability of 3D models, in terms of scientific
552  justification, is not a new issue.  Back in 2006, we summed up lessons learned from a series of experiments,
553  in the form a methodological approach called 'informative modelling' including  'rules of conduct' inspired
554  by practices in the InfoVis field (Blaise & Dudek, 2006). A short booklet entitled 'informative modelling: 14
555  rules + one' defines these rules, and is now used as a teaching tool[3]. Definitions were preceded by an
556  introductory text that we naturally will not reproduce exhaustively here, but the following sentences are
557  quite clear about the challenge we faced then, and we still face today:

558      *"In the field of the architectural heritage, computer graphics have become an increasingly popular tool*
559  *for communicating results of historical investigations. Virtual reconstructions are often built in order to let*
560  *a wide public have an idea of how an architectural object may have been like at time t of its evolution. But*
561  *the use of graphics with this sole goal is often discussed in particular on two grounds:*

562      • *a lack of readability - due to the fact that the inferences for the reconstruction are hidden in the*
563          *final result;*

564      • *an appalling level of usefulness for the researchers, who invest time to produce a virtual*
565          *reconstruction, that in the end remains a side-effect of the research process - giving no access to*
566          *deeper information level and limited possibilities of updating.*

567      *In other words, the information-gathering effort made during a process of production of a*
568  *reconstruction, totally evaporates in the final result. […] The basic idea behind informative modelling is that*
569  *the representation of artefacts should not necessarily claim veracity, but should support dynamic*
570  *information retrieval and visualisation. It is concerned with building information-effective graphics through*
571  *which a gain of understanding (not only of the architectural objects themselves, but also of what we really*
572  *know about them) can be achieved."*

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[3] See **www.map.cnrs.fr/BlackWhite/PubSc/book_EN_FR.pdf**

The research we present in this paper definitely is an attempt to address the above challenges, and it seemed to us appropriate in the context of this contribution to list these rules here, as a mean to auto-question the prototype:

1. Each piece of information about the object will be interpreted in order to distribute information among semantic layers called informative scales.

2. The representation of an object will allow the user to retrieve data and information that justify the presence of the object at the time and date the representation shows.

3. The shape given to the object will stem from an interpretation of the data, stating the shape's credibility and making it visible

4. For each object, the representation will show what we know that we ignore, and will not contain unfounded affirmations that would not be justified by relevant data.

5. A theoretical model will describe architectural shapes in a structured way.

6. Objects represented inside 2D/3D models will be instances of the abovementioned theoretical mode.

7. The theoretical model's implementation will allow the reuse, the comparison and the sustainability of the information on the instances.

8. Each concept of the theoretical model will be attached to a given informative scale.

9. 2D/3D model will be the visual answer, displayed thanks to the representation of architectural objects, to a query about our state of knowledge.

10. 2D/3D models will be calculated in real time so as to reflect our current state of knowledge at query time.

11. The appearance given to an object will use a set of graphic codes that should be developed in order to visualise the object's underlying information.

12. The object will be displayed inside 2D/3D models with alternative levels of abstraction depending on both/either the scale and the level of knowledge reached in the investigation process.

13. The investigation process will be implemented as a nonordered process allowing the integration of disjoint sets of information.

14. The level of knowledge reached in the investigation process on a given object will be represented in real time inside 2D/3D models.

15. ***If a 2D/3D model does not produce a gain of insight into the underlying information - it should be considered worthless.***