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).

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

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

The knowledge modelling issue

What exactly is uncertain when an expert proposes a 3D virtual reconstruction? How to account for the uncertainties associated with a 3D virtual reconstruction in a formal and shareable way, conducive to a comparison within a study case, or between case studies? And what exactly are these uncertainties about? Architectural forms? Their spatial arrangement? Their very existence? Can this notion of uncertainty be formalized in any way other than by an accompanying discourse? On this question, the scientific literature proposes numerous methodological reference points, often discipline-centered, leading to a formalization of uncertainty factors (e.g., Skeels et al. 2010, Zuk et al. 2007, Thomson et al. 2005). In addition, from an archaeological standpoint, how can we exploit the notion of argumentation, present for example in J.C Gardin's logicism (Dallas, *op.cit.*), to make the choices made by an analyst more readable within 3D models?

Uncertainty is in fact a sort of catchword covering a vast number of situations - analysing different types of uncertainties (and their consequences in terms of decision making) is indeed a research issue by itself, and one that goes far beyond the scope of this paper (see on this issue Blaise & Dudek, 2020).

Our contribution introduces a formal model, *justification matrices*, addressing the specific issue of handling *uncertainty* in the task of proposing a 3D virtual reconstructions: we therefore rather use the word *plausibility*, denoting a particular occurrence of *uncertainty*. Justification matrices deliver information on the reason for a proposal present in the 3D model, a proposal that is concretised by given 3D shapes in given positions within the model. It allows to assign individual 3D objects or to groups of objects a quantitative evaluation of their plausibility by crossing 4 criteria: shape, dimensions, existence, and position. This formalism materialises the vision of one analyst, and could potentially allow the materialisation of differences between analyses. It does not constitute an argumentation as such, but it reveals the result of an argumentation. The argumentation itself can naturally be associated with the object as paradata – but this is another discussion, falling outside of the scope of our contribution.

Our approach is a methodological questioning that complements the work done by the LAT team on digital architectural models. This team of archaeologists outputted a final publication of a research on the abbey in Marmoutier and used that opportunity to model four synchronic states of this building (12th, 13th, 15th and 18th centuries). Emeline Marot and Elisabeth Lorans (LAT) worked with Nicolas Nony (computer graphic designer) to create these 4 models. The restitution of the various elements appearing on the models based on arguments of an analogical, symmetrical, functional order... Many graphic documents were used. If these choices were partly explained in the graphic and textual documentation accompanying the file of the models, nothing allowed to take into account the reliability of these restitutions on the model itself, and thereby to explain the passage between what is observed and what is returned on reconstruction models. The case of the hostelry and its four models appeared to us as an appropriate case study to try and fill this gap.

By starting to work on these objects produced by other researchers and with an objective of valorisation, we quickly asked ourselves the question of multiple or at least different uncertainty depending on the architectural objects questioned. Indeed, according to the available evidence we can be certain of the existence of an object without knowing its location, its shape and its dimensions. For example, it may be a fragment of a staircase, the location, shape or dimensions of which are unknown. In other cases, we are certain of the existence of an object for example a buttress whose foundations we were able to observe by excavation attesting its location but its shape and dimensions are not fully known. Thus, it appeared relevant to question 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).

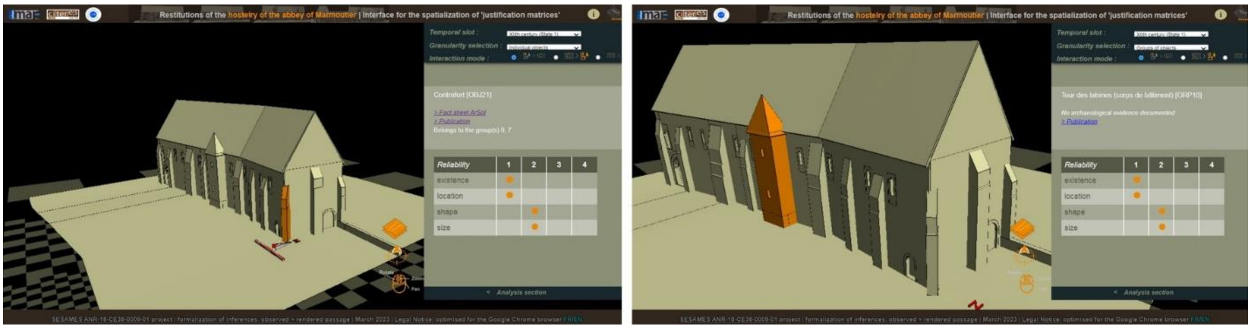

Figure 1 – Left - plausibility of an individual architectural element (angle buttress), right - plausibility of a group constituted of walls, bays and a covering.

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 primarily serve visual communication objectives. At the end of the day, 3D virtual reconstructions often do not really provide services (in terms of scientific added value) commensurate with the effort made.

In the proof-of-concept prototype we present once a plausibility evaluation is done - here formalised as *justification matrices*, comes the time when this evaluation has to be encoded visually, some would say *mapped* visually. Representing uncertainties using visual means is nothing like a new issue or practice: for instance Joseph Priestley's *A chart of Biography* is a classic timeline from 1765 that positions in time, using tiny lines running from left to right, the lifeline of more than two thousand famous men (Rosenberg & Crafton 2010). When the dates of birth or death of these famous men are ill-know the otherwise continuous line turns dashdotted, thereby intuitively transferring to the reader a sense of *uncertainty*.

A wide number of solutions have been tried out before and since the digital age, often in relation with time oriented data with for instance the planning lines visualisation, the chronographs formalism and many others readers can find in (Aigner et al., 2011). Cartographers, geographers or historians have also faced the issue of how to distribute in the space of an objectivised representation - a 2D map - items the exact position of which is not clearly assessed. Depending on the nature of the type of uncertainty to handle solutions can range from the use of glyphs conveying the uncertainty information - through colours or shapes (see for instance Reimer, 2010) to clouds of 2D points, polygons or other shapes that localise a *likelyliness area* - area within which the item is supposed to be localised, but that does not match exactly the geometry and position of the item (Davies, 1996).

Visual mapping is a task that has been both in cartography and in information visualisation somewhat rationalised with Jacques Bertin's (op.cit) graphic semiology and as part of it his identification of a finite vocabulary of graphic variables. Although written before the digital age, in the context of 2D paper based graphic outputs, his 'methodological frame' can still act as a reference model helping to explain visual encoding strategies.

The prototype we have implemented exploits five graphic variables: position, orientation, size, shape and colour. The first four variables are endowed with conveying information about the architectural elements: 3D components distributed somewhere in the 3D space. The plausibility information is conveyed by the fifth variable: colour. Depending on the interaction mode chosen by the user one or several colours are used to represent the plausibility evaluation visually in the 3D space. As will be shown in section Results a more abstract, InfoVis-inspired solution has also been developed that uses the same set of graphic variables. This solution consists of a sort of visual metaphor (Kienreich, 2006), used independently of the 3D space. Obviously our choice of using colour (and *only* colour) to convey the plausibility analysis visually could be debated. Other solutions that go beyond Bertin's original framework and base on specificities of digital platforms (such as interactive texture mapping or translucency) have been tried out but they have not been considered convincing. Translucency, typically, is not easy to handle since shapes tend to get harder to apprehend visually and what is gained in terms of visual differences between the known and the ill known can be lost in terms of global understanding of the 3D layout/structure.

Our strategy has been to privilege simplicity - as defined by J. Maeda (Maeda, 2006, Schuller, 2009) - as a mean to minimise the learning curve and augment the acceptability of the prototype. The graphic encoding is a simple bichromatic scale, allowing a natural ordering of values, with the grey used to convey information ~~lacks~~. We do acknowledge though that a thorough and robust evaluation of alternative visual encodings remains to be done: a potential perspective for this work.

3D models reuse

How can we re-use 3D content for other purposes, in our case 3D virtual reconstructions created primarily for scientific mediation and in a technological context that is obsolete today? This sub-issue can be seen primarily as a purely practical matter concerning technology. But it can also be seen as part of a broad societal movement towards more sustainability and economy of means, a movement that does affect the field of scientific research.

This is not a new issue, however, and the emergence of many XML-based formats where the information is detached from the application contexts is proof of this. But developing today such good practices does not necessarily provide practical solutions concerning the reuse of existing 3D content. The interface that we present has been developed to work online thanks to the open source Three.js library, and exploits a systematic repurposing of the original 3D models.

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

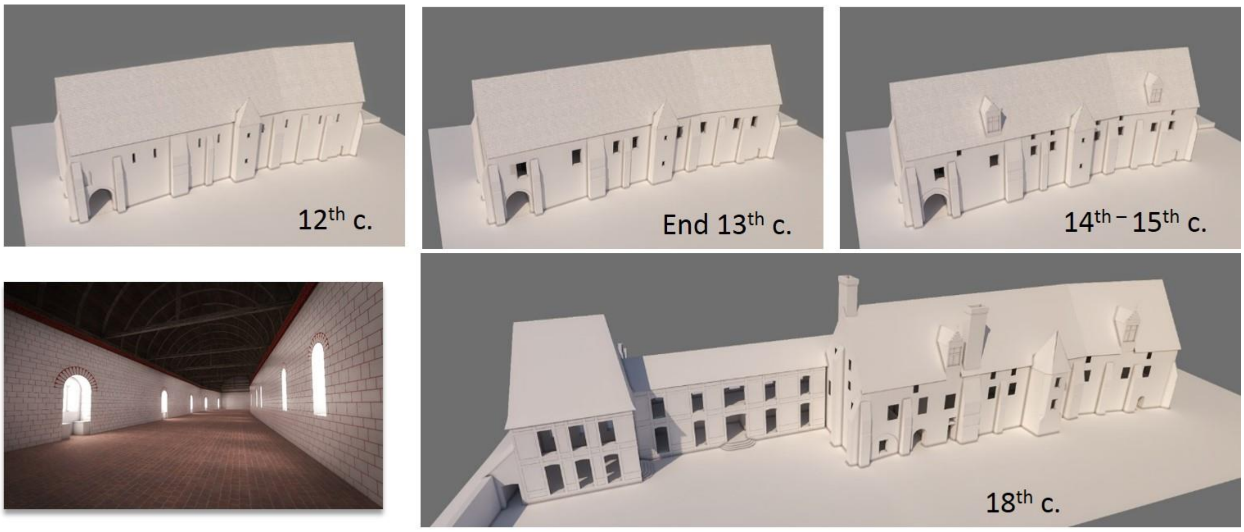

Figure 3 – The original data: four polygonal mesh models and (bottom left) an illustration of the primary purpose of these models by the LAT team : communication for the general public (including with texture mappings) (UMR CNRS/Tours univ 7324 CITERES-LAT).

Each of these four models was first divided into significant architectural elements (a wall, a door, a buttress, an alignment of windows, etc.), to which justification matrices were associated (one matrix per element, single object or group of objects). This work was carried out using the Blender software, in editing mode, and consisted of separating and, if necessary, closing each element of the model. Choices had to be made during this step such as the suppression of the internal parts of the models (vaults) insofar as the experiment concerned only the external envelope of the building.

Each element was thus given its own geometry, exported in Collada (.dae) format, and corresponding to a justification matrix described in a relational database. The link between the 3D data and the matrices is made dynamically by exploiting correspondence tables (the identifier of an element in the database is used to name the corresponding Collada 3D file). In order to optimise the use of these models in a browser, each state (each synchronous 3D model) is loaded dynamically: only one 3D model is loaded at a time, while the others are removed from memory as they are loaded, a possibility offered by the Collada loader of the Three.js library.

The interface allows the selection of elements directly in 3D by the raycasting method - a native function of three.js - which has been adapted to our needs, in particular for the first interaction mode (see *Results* section) which required this direct selection of elements by clicking in the interface.

Finally, the interface allows the display or hiding of the ground and of a dimensional grid that the user can move along the horizontal or vertical axis using the keyboard. In addition, symbols with dimensions and orientation (in accordance with archaeological standards) allow the dimensioning and orientation of the model.

The method developed had the merit of demonstrating both the feasibility of the 3D models reuse scenario that we had imagined, thus reversing the usual process of research to valorisation, and the rather generic character of this type of web3D interface, reusable with few modifications for other architectural sites.

It should obviously not be forgotten that the time needed to segment and partly redraw the 3D models is a constraint, even a limitation, but a limitation to be relativised by comparing it with the time needed to build the original models... a few days versus several weeks per model.

The case study: Marmoutier's abbey hostelry

The prototype re-uses the 3D virtual reconstructions of four phases in the evolution of the Marmoutier Abbey hostelry, a site that has been thoroughly studied for years by a team of archaeologist, the UMR 7324 CITERES-LAT. The name of Marmoutier is inextricably linked to that of Martin, bishop of Tours from 371 to 397. In fact, during his episcopate he chose this place for his retreat and attracted to him disciples who gave rise to the first or second monastic community of the West.

After several centuries of development, this great Benedictine monastery became one of the most important in France. This establishment lasted until the French Revolution, which destroyed most of the buildings in the early 19th century. Archaeological research has been conducted since 2004 under the direction of Elisabeth Lorans of the Archeology and Territories Laboratory (University of Tours - National Center for Scientific Research). These investigations relate both to the spatial organization of the monastery and the architecture of the various buildings that made it up and to the uses of the land that preceded and followed the fifteen centuries of monastic life. It is therefore a question of a global approach to the site and its environment based on the crossing, at different scales of time and space, of all possible sources: archaeological data, written sources, which have existed since the end of the 4th century, and iconographic sources, available since the 17th century.

One of the buildings partially spared by the revolutionaries is the monastic hostelry which had the function of welcoming guests of mark of passage in the monastery (Figure 4).

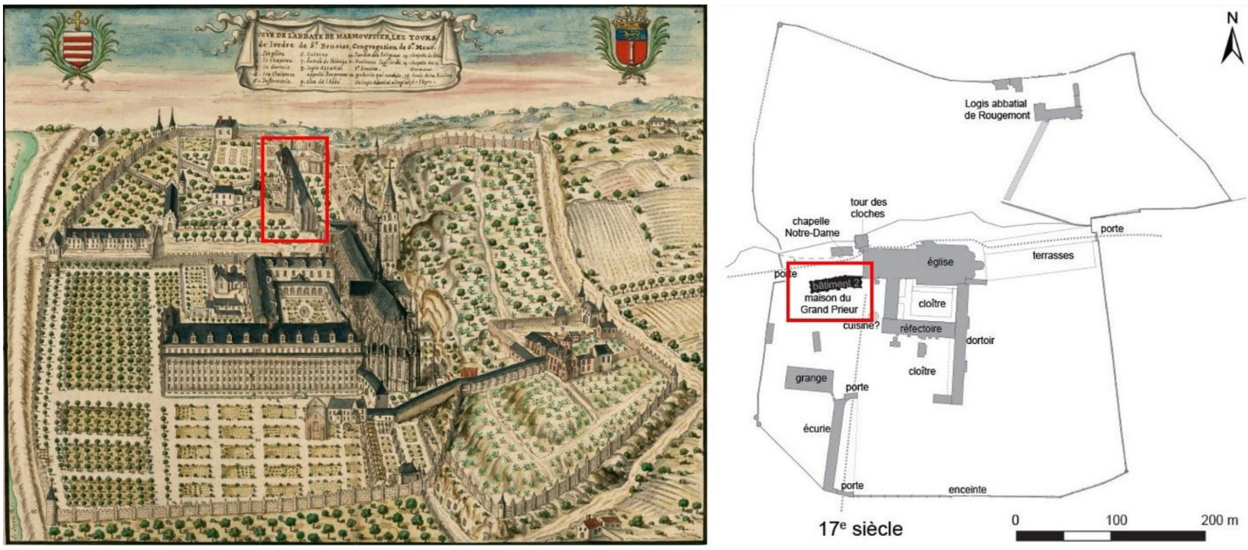

Figure 4 – Overall views of the monastery, showing (outlined in red) the position of the hostelry within the site. Left, the monastery before the destruction of the 19th century - Elevated view from Marmoutier Abbey from the east, 1699, Gaignières Collection (BNF VA 407 (1) FT 4-H-183734). Right, Reconstructed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

Installed near the main entrance, in order not to interfere with monastic life, a text from the Middle Ages indicates that it was built during the abbey of Hervé de Villepreux (1179-1189).

Today ~~preserved on 20m of length~~, it originally measured 55m, a length known before the excavation by plans of the eighteenth century (Figure 5). A study of the archaeology of the building was conducted on the elevation while the destroyed part was completely excavated from 2006 to 2017.

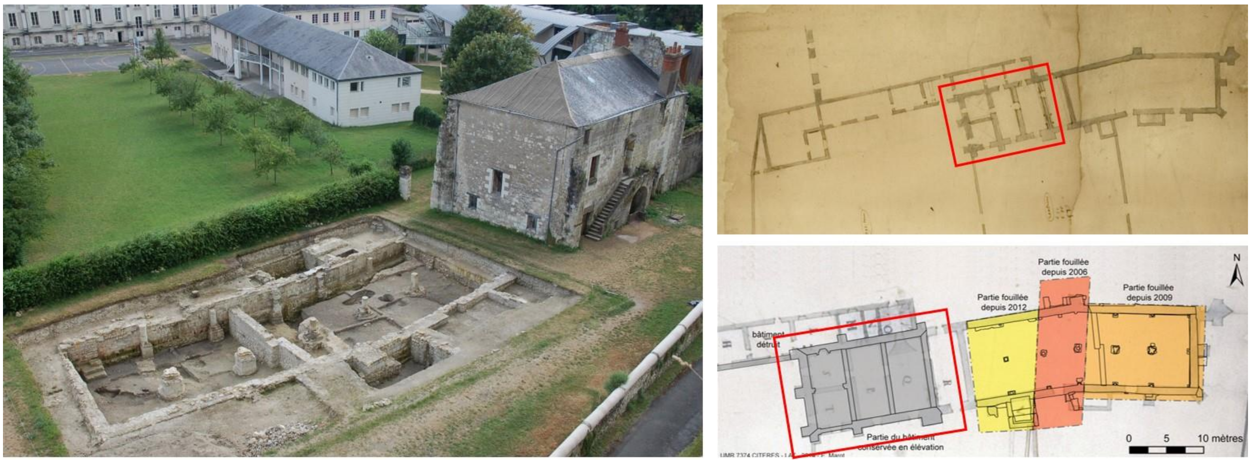

Figure 5 – Left, a view of the hostelry today showing the part preserved in elevation and elements excavated (the picture shows the north façade). Right, plans of the hostelry, with parts preserved outlined in red (UMR CNRS/Tours univ 7324 CITERES-LAT).

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.

Mode 2 : visualising elements corresponding to one matrix

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

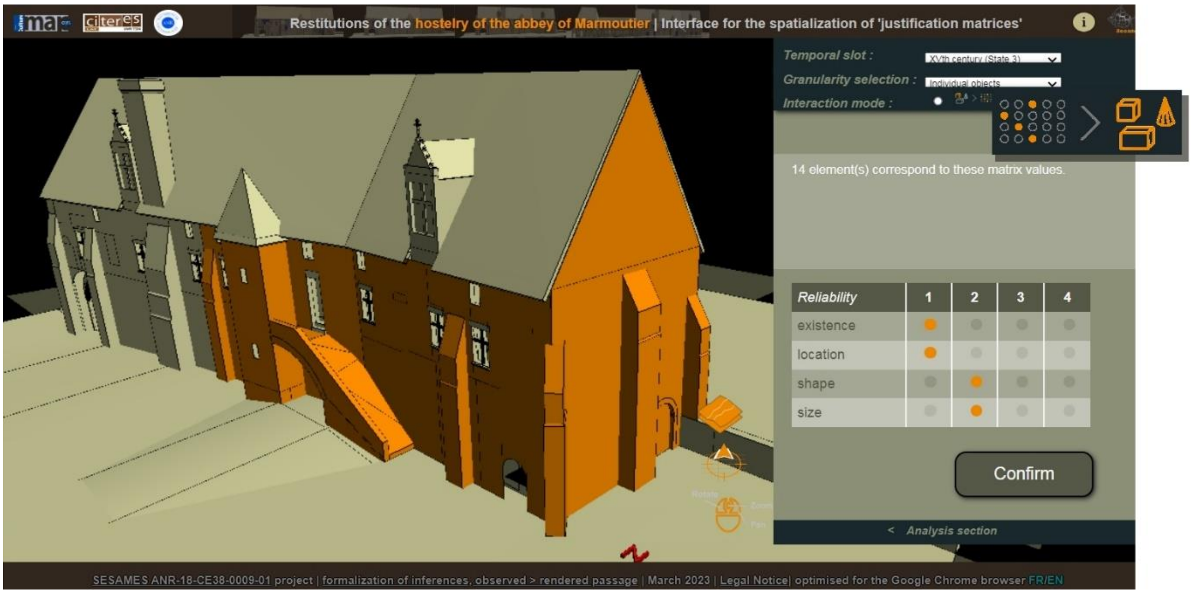

Figure 7 – *Interaction mode 2*, illustrated on the third synchronic state (15th century). All components in the 3D virtual reconstructions with a justification matrix that corresponds to the user's selection (the right part of the interface) are highlighted in orange. Note, the spatial consistency of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

Mode 3 : visualising all plausibility values for one criterion across all architectural elements

The third mode corresponds to a filtering of the plausibility evaluation. A user selects a row of the matrix ("existence" or "shape" criterion for example) and all the architectural components in the 3D model are recoloured according to their plausibility evaluation for this specific criterion (Figure 8).

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

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

The *information visualisation* layer

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

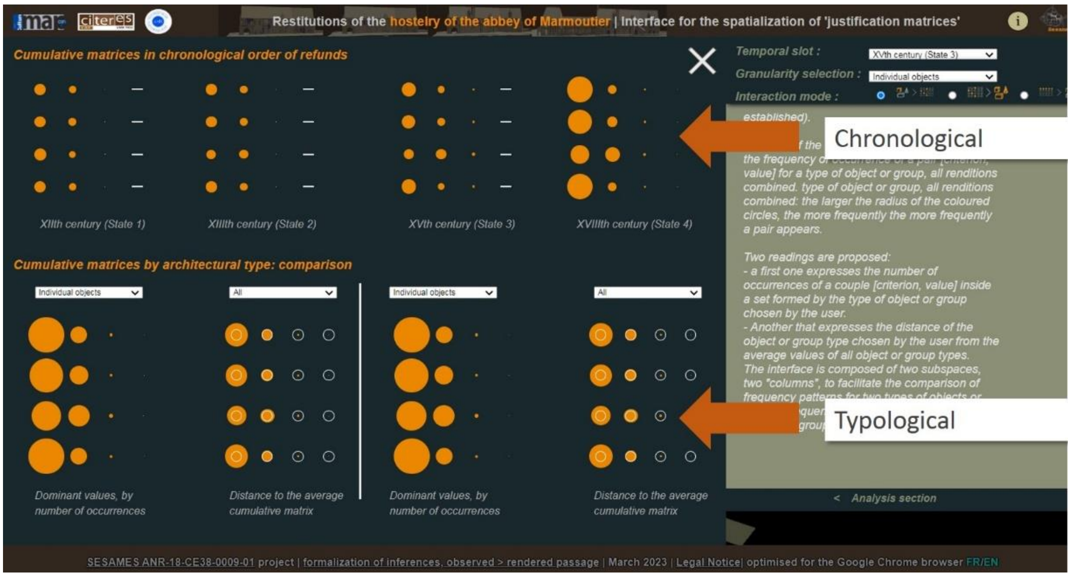

Figure 9 – Visual display of the cumulative matrices, a mean to analyse the collection of objects basing on chronological factors, or typological factors.

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

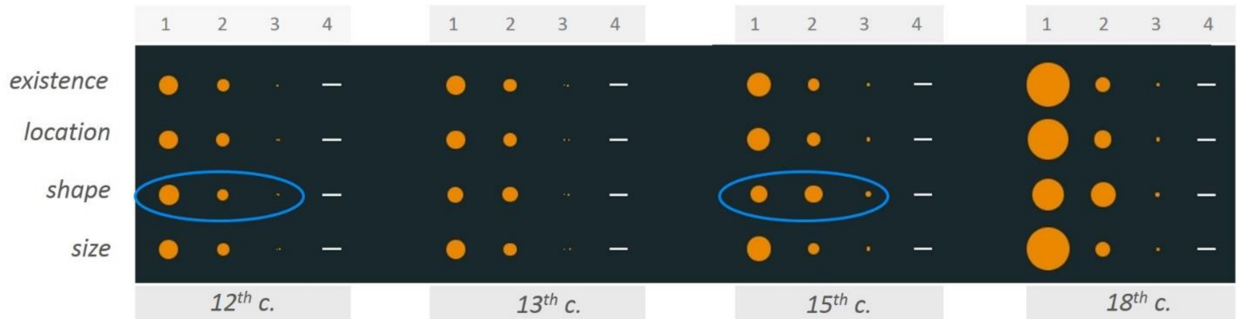

Figure 10 – Cumulative matrices for the four synchronic states – the graphics shows for instance (circled in blue) that for the third synchronic state the plausibility of shapes is lower than for the first synchronic state, a somewhat counter-intuitive finding. The circles for the last synchronic state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

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

The bottom part of Figure 9 is used for one to one comparisons of plausibility patterns corresponding to various architectural types (vaults, arches, doors, buttresses, etc.).

The graphics is composed of four visual matrices, two per architectural type. For each architectural type the two matrices correspond to two alternative readings of the plausibility information:

- the first (left matrix) expresses the number of occurrences of a [criterion, value] pair inside a set formed by the type chosen by the user. It helps spotting the plausibility pattern for the type chosen by the user.

- the second (right matrix) expresses the distance of the architectural type chosen by the user to the mean average value for all types. It helps unveiling specificities in terms of informational pattern for this or that type the user has chosen.

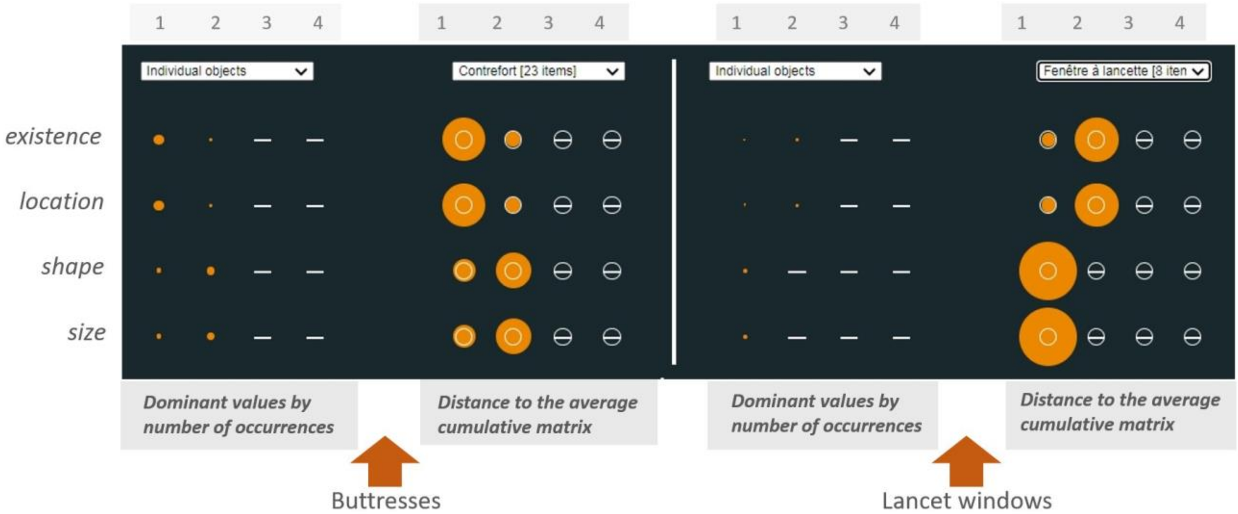

Figure 11 – Cumulative matrices for buttresses (left) and for lancet windows (right). The graphics clearly shows divergent information patterns. The white circles correspond to the mean value of each [criterion, value] pair across the collection of architectural elements. White dashes correspond to [criterion,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

Implementation

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

Discussion, limitations and conclusion

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

Limitations

Our contribution focuses on how to convey visually, in a 3D environment, the ***result*** of an expertise through which 3D architectural elements present in a virtual reconstruction are associated with a formal model expressing their plausibility (justification matrices). It does not address the issue of how to document and model the expert's cognitive process, his/her choices, reasoning paths, decisions concerning a shape and the corresponding matrix. There are ways to do so – starting from Gardin's logicism to today's MEMORIA IS - but commenting on these approaches is beyond the scope of this paper (a key issue though). If sticking to this contribution's core components various significant limitations have to be clearly stated:

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

Lessons learned and conclusions

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

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

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

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

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

Conflict of interest disclosure

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

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Appendix 1

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

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

- *a lack of readability - due to the fact that the inferences for the reconstruction are hidden in the final result;*
- *an appalling level of usefulness for the researchers, who invest time to produce a virtual reconstruction, that in the end remains a side-effect of the research process - giving no access to deeper information level and limited possibilities of updating.*

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

[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.***