Critical review of 3D digitization methods and techniques applied to the field of architectural heritage: methodological and cognitive issues.

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Abstract
This article concentrates on the epistemological aspects of architectural survey. It offers a critical observation of the technologies used in the field of 3D digitization. More specifically, the study evaluates the way in which the tools and methods used for the acquisition and representation of the data do or do not contribute to the enhancement of architectural knowledge. To understand the relationships between technology and knowledge transfer, we will carry out an observation based on a series of case studies. This is intended to highlight a dual issue of a cognitive nature: the first, perceptual, refers to the comprehension of the object and the second, descriptive, refers to the intelligibility of the 3D information model. This reflexive approach is justified by the fact that the main technological advances rarely compensate the methodological deficiencies encountered. Finally, this article offers perspectives for the in-depth study of all the cognitive mechanisms involved in the architectural survey.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Digitizing and scanning I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Curve, surface, solid, and object representations I.3.6 [Computer Graphics]: Methodology and Techniques—Graphics data structures and data types

1. Introduction

The emergence of digital technologies has been accompanied, in some research circles, by a questioning about the contribution and the integration of these technologies into fields connected with the architectural heritage. New prospects have been opened up for the communication of physical data in the form of digital information. The emergence of drawing and visualization tools (3D interface, augmented reality, etc.) has enabled systems of representation to be obtained which offer a reading of architectural spaces by immersion. At the same time, the development of survey techniques (lasergrammetry, photogrammetry, etc.) gave the possibility of obtaining digital data which can provide simultaneously three-dimensional metric data, geometric information about the morphology of the object, and information about the textures and materials of which it is made. The combination of all of these resources is of benefit to those working in the disciplines concerned by manage-

ment, analysis and conservation of the architectural heritage [Del10;LD09;GRZ04].

Nevertheless, beyond the excitement that can be provided by the arrival of tools offering highest levels of definition, the substantive issues remain. We are thinking in particular of the meaning that we ascribe to the concept, which is crucial here, of 'architectural representation', a concept which cannot be reduced to the simple question of the resources employed.

Without extending the discourse to concepts relating to the sociology of art, we can consider that the act of representing must not take anything away from the way that we look at an architectural object. In a sociological study relating to observations of researchers at the *Inventaire General de France*, Heinich [Hei09] evaluates the involvement of this *'way of looking'* in their work. She points out that the work of the inventory, and we take the liberty of comparing it here with the representation of the architectural heritage, *is what makes us look at things, even before producing, like any re-*

search work, knowledge about what there is to see [Hei09]. This observation tells us that the recording of an object, and therefore its reduction to a descriptive record (or in our case a 3D representation) first consists of constructing a way of looking at it. A way of looking that prefigures the transmission of knowledge. The analytical dimension that accompanies the reduction of an object to its graphical representation is the starting point of the study presented in this article.

Our approach has its roots in the history of architectural representation. In his treatise, *Ten Books on Architecture* (Volume I Chapter II), Vitruvius [Vit06] advocates an arrangement of spaces using figures. Thus he suggests transmitting and representing *ideas of the layout* of premises in the style of the Ancient Greeks. *i.e.: through Ichnography, Orthography and Scenography*. The description of these three modes of representation highlights the importance accorded to transmitting an idea by the codification and the *abstract nature of the figure* [BD06](1). The approach advocated by Vitruvius would find support among the humanists of the Renaissance.

Observation of some of the engravings of the Cinquecento (figure 1), or even the Quattrocento, highlight the application with which architects and architectural theorists (like Vignola or Palladio) endeavoured to offer us their 'readings' of ancient architecture. This reading, based on the survey and transmission by *the figure of an inferred knowledge* [BD06](1) compels us to engage in a reflexive questioning of our own practice of the survey [LBV03;Dom08].

1.1. Methodological and cognitive issues surrounding 3D digitization

Does the use of ever more powerful technologies in the 3D digitization work enhance and convey a better knowledge about the object studied? Although an affirmative answer may seem natural, we shall qualify this response in a number of subtle respects.

The joint development of lasergrammetry and photogrammetry, as tools for the digitization of dimensional and colorimetric aspects of the built environment do allow the reconstruction of the visual appearance of complex architectural morphologies. These advances might cause us to believe that the 1:1 scale representation of the territory referred to by Borges is no longer so far off [Bor82].

Today, the tools and technologies used in architectural survey seem to be considered as the prime source of enhancement of architectural representation. Nevertheless, these instruments appear to be a response to imperatives of precision and exhaustiveness, which are far removed from the essential issues of architectural representation, as well as the cognitive implications that it involves.

In a historical continuity of the representation methods, we shall attempt to provide a few avenues for reflection on
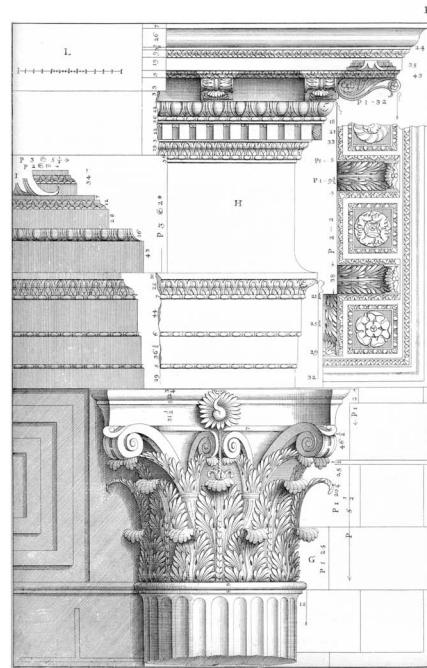

Figure 1: *Drawing of the ornaments of the portico of the temple of Mars, the Avenger. Fourth Book from Andrea Palladio. Chap. VII, Plate IX. [Pal65]*

a methodological problem, which the 'discipline' seems to be facing. This process of becoming acquainted again with a research paradigm on which the development of architectural survey has relied ever since the Renaissance. We refer to a conception that associates the cognitive dimension and the graphical dimension within the same space (Figure 1).

To respond to that, we shall evaluate initially the array of knowledge conveyed by representations produced with various techniques and methods. In a second stage, we shall try to understand whether these digitizations actually meet the scientific requirements that they are intended to meet.

To deal with the set of issues raised, this article sets out:

- An overall approach which presents the criteria used to evaluate the information content of a representation;
- Observation, following the information criteria, of representations produced with different digitization techniques and methods.
- The critical evaluation of the methodological and cognitive aspects of architectural drawing, and the highlighting of a perception and a description issue.
- Research outlook

2. Overall approach

To guide our critique of the methodological aspects of representation, we shall observe a series of digitization tasks. The objective is to enable us to assess the set of informations that describe the architectural object. In this way, we hope to evaluate the information gain offered by the document. Here, we put forward the postulate that the information conveyed can contribute to enhancing our knowledge. With work aiming to qualify the information content, from the viewpoint of reception (representation), we hope to be able better to discern the cognitive contribution for each digitizations observed. While the evaluation of this contribution is located at the level of reception, we are convinced that it (the contribution) is intimately connected with the cognitive enhancement in terms of transmission.

It should be borne in mind that the examples chosen in our study have no pretentions to be representative of an entire practice. Through the extensive range that they cover, in terms of techniques and methods, the cases studied are intended to situate a set of issues that we believe we have identified.

2.1. Criteria for evaluating the information content of a representation

Our work starts with the formulation of information evaluation criteria based on an article by Blaise & Dudek [BD06](2). This offers some methodological avenues for increasing the intelligibility of the information content of the 3D modeling. Via a modus operandi of fourteen rules plus one, the article suggests a practice based on concerns that are common to those encountered throughout the history of representation (see above). The concept of *Informative Modeling* is structured around a set of rules distributed according to four different axes: information, models, representation, abstraction [BD06](2).

Beyond the methodological resources offered by this guide of 'good practices', the rules laid down for *Informative Modelling* constitute, through a logic of symmetry, a legitimate theoretical basis for the formulation of criteria suitable for our study. The indicators extracted come from the first axis of rules, that of 'information'. This axis refers to the intelligibility of the information contained in a model. It should be borne in mind that our observation not only relates to 3D modeling work, but also to digitizations resulting from automatic, semi-automatic or manual processes.

Among the rules set out in the article [BD06](2), we identify certain criteria liable to situate the *informative* properties of a representation:

- **Informative scale** refers to the distribution of the information (within the digitization) according to various levels of reading or perception of the architectural object.
- **Informative certainty** expresses the way in which the representation shows the degree of certainty available about an architectural element (see hypothetical modelling).
- **Informative traceability** refers to the capability that the representation of referring to documentary sources (or numerical data) that could justify the presence of a digitised object.
- **Informative coherence**. On the one hand, this criterion expresses the coherence between the decomposition of the digitization and the semantic or morphological structure of the object processed. On the other hand, it expressed the coherence between the level of precision of a digitised entity in relation to the level of definition proposed for the whole project.
- **Informative intelligibility** refers to a world of knowledge that is capable of informing us about the architectural semantics of the object.

3. Observation of the methods and techniques of 3D digitization

This point presents the observation of a series of 3D representations. To ensure the clarity of our approach, we point out that each case is treated by a factual observation of the resources deployed and an observation according to the *informative* evaluation criteria (see above). The illustrations are presented according to the degree of manipulation that they involve. So we shall move from automated reconstruction towards more manual restitutions.

3.1. Automatic reconstruction

The representation (figure 2) illustrates one of the columns of the Abbey of Saint-Guilhem-le-désert (France). This column, as well as other digitized architectural elements were the subject of a campaign of lasergrammetric surveying, the main purpose of which was to offer a virtual anastylosis of the cloister [DDL08]. However, beyond the ambitions of the project itself, an interesting question arises here. How does the reading of the point cloud enhance our understanding of the object?

As the illustration shows us, capture via a laser scanner constitutes, in this case, a support for automatic reconstruction using polygon meshing. We also note that the model of the column is enhanced by the presence of a texture projected from a photographic survey. The combined result of the laser scan, the polygonal meshing and the texture show a great visual and metric coherence with the subject analysed.

Beyond the initial conclusions expressed on the object and the method of reconstruction used, other elements have to be interrogated. From the viewpoint of the informative scale, we can observe that the digitization offers three different tiers of information: on the one hand, the set of coordinates, visible in the form of points, then a polygonal triangulation

of these points, and finally, the application of RGB information to each of the polygons. Regarding the information certainty, we can consider that there are probably inaccuracies and measurement errors due to the use of 3D laser scanner (these errors are, for example, uncertainty measures defined by a margin of maximum error and the algorithm used for the noise compression). However, this digitization is based on an existing object and does not use a set of hypotheses modeled manually. About the informative traceability, the relationship between the digitization and the source, i.e. the laser capture, is made explicit by the visual presence of the coordinates measured. Finally, concerning the coherence and intelligibility of the information, the digitization proposes the reading of a single semantic entity (the column) with a homogenous definition level.

While, having regard to our criteria, we cannot make any comment about the informative quality of the representation, one can nevertheless refer to its inability to provide is with knowledge going beyond the metric and visual aspects. Although the overall morphology of the column is comprehensible, the model formed of a single group of points (or polygon) does not clarify the semantic decomposition of the element. From the cognitive viewpoint, the first two representations convey as a priority an understanding of the metric and visual aspects of the object. A shade can be applied to the last level of visualisation. The ambient occlusion associated with the textured polygonal model allows emphasis of the morphological variations in the column. The simulation of the lighting highlights the richness of the geometric variations and informs about the importance of the relief on certain areas of the column. In other words, it increases the intelligibility of the representation.

To conclude, we notice that the point cloud, although enhanced by textured polygon meshing, offers first of all an objective reading of the visual appearance of the object. Finally, we should note that the observation carried out here could lead to similar remarks in the case of 3D digitization produced by automated photogrammetric processing.

3.2. Semi-automatic restitution via semantic enhancement

To counter-balance the previous example, we wanted to interrogate other forms of representation relying on the visualisation of a point cloud. Without using a textured polygonal reconstruction of the building, the document presented (figure 3) illustrates lasergrammetric capture of the Arc de Triomphe (France) enhanced by an annotation on the structure. In this case, the point cloud is intended primarily to serve the spatial referencing of the semantic description graph [Del08].

Without returning to the evaluation of the informative content of a point cloud, one can nevertheless observe the cognitive gain allowed by the comprehension of the hierarchical and terminological links between the various parts of

Figure 2: *Column of the Abbey of Saint-Guilhem-le-désert. Visual levels (geometry, textures, occlusion + textures) [DDL08].*

the Arch. We move from an objective reading of the object (point cloud) to a reading enhanced by the cognitive input from an operator (architectural semantisation work). This additional knowledge is determined partly by the analyst's view of the architectural object. The apparent subjectivity which results from it does not lessen the scientific quality of the representation. The receiver is able at any time to separate visually the lasergrammetric representation from the semantic description.

3.3. Semi-automatic restitution by the Generative Modelling Language

The article Generative Parametric Design of Gothic Tracery [HF04] presents the result of a study relating to the parametric reconstruction of Gothic architectural elements in GML (Generative Modelling Language)[Hav05]. The digitizations presented (figure 4) emanate from an in-depth analysis of recurrent formal characters in the composition of tracery windows.

As described by their analysis, [HF04], the complexity of the motifs of the interlaces and rose windows is the result of a composition based on relatively simple geometric operations. The typical architectural elements that emanate from them refer to the technical resources and composition rules employed in their design. So, the formal variations obtained are the product of specific tools (ruler and compass) and sets of proportions. The originality of their study consists of formalising these rules in an unambiguous way, by the creation of high-level shapes starting out from low-level operations [HF04]. The geometric parameters encoded in GML thus allow both the shape of the object and its description to be visualised.

From the viewpoint of the informative scale, one can consider that the 3D representation of Gothic traceries and their parametric description propose two levels of reading. Be-
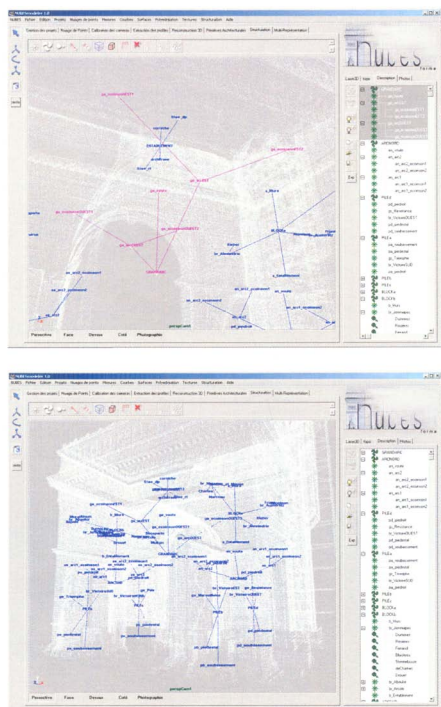
Figure 3: *Architectural semantisation of the point cloud of the Arc de Triomphe [Del08]. See also Nubes project [Nub].*

yond this initial observation, the criterion relating to the informative certainty appears more problematic. The degree of certainty that we have about the rules of composition for Gothic windows does not appear explicitly. Therefore, it is difficult to identify the theoretical elements justifying the parametric description of the geometries and proportions observed. On the other hand, the traceability of the information underlying the 3D model is enabled by the relationship between the two levels of reading. The history of operations carried out on the model allows the 3D visualisation to be linked to the description in GML. Henceforth, it is possible to understand the successive geometric operations that allowed the tracery motifs to be re-created. Concerning the informative coherence criterion, the digital construction, at low level, presupposes a description ranging from the overall geometric attributes to the specific features of the object. The creation of the model, through a textual description of the geometric operations, puts the operator in a continuous analytical process. Finally, the intelligibility of the digitization is guaranteed in this case by the filiation between the 3D model and the world of knowledge to which it relates. The model aims to comply with architectural semantics defined by the graphical codes and composition rules specific to tracery windows.

In this procedural model, the dissociation of analytical

content of the formal visualisation of the edifice enables us to focus our attention primarily on the description of the knowledge at our disposal. Through this process, the 3D representation becomes the accurate illustration of an analytical process. Beyond our reservations about the model's ability to refer back to the theory on which the analysis is based, this type of approach is of major interest for the recognition of the digital model as an investigative and analytical tool in architecture. Far from being the only ones to research this avenue of reflection, other work is being carried out into the parametric modeling of typical architectural elements. By way of example, one can note the research into the atomic units of classical architecture for the modeling of mouldings. [Del08].
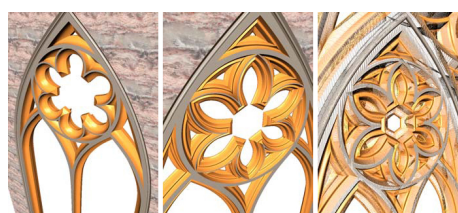

Figure 4: *Shape variation of a Gothic Window Tracery created in GML [HF04].*

3.4. Semi-automatic restitution with image-based modeling

This representation (figure 5) illustrates an image-based modeling of the current state of the refectory of Villers-la-Ville Abbey (Belgium). In this case, the digitization is intended to serve as a geometric and spatial foundation for the formulation of subsequent hypotheses. In addition, it is also intended to serve as a faithful imprint of the object at a time 't' in its history. From the technical viewpoint, the geometric reconstruction was carried out based on a photogrammetric acquisition of the facades and the space inside the refectory. Although a significant proportion of the treatment process consists of identifying corresponding image points on the photographic survey and modeling the geometry manually, we treat this digitization as a semi-automatic reconstruction process. This choice is explained by use of a camera calibration algorithm [Fau93]. To refresh your memory, it enables the cameras to be referenced spatially and each oriented in relation to the others.

At first sight, the representation produced proposes a visual and metric coherence with the subject surveyed. From the informative viewpoint, two levels of reading may be distinguished. The first corresponds to the wireframe representation. It reveals the polygonal decomposition of the model, and enables the extremes of all the planes that make up the building to be identified. The second level tells us the colorimetric appearance of the building. It is the result of a projection of photographs onto the model. From the viewpoint of

informative certainty, the model represents an existing state. As the elements modelled are known, no graphical identification of the uncertainty is present. Concerning the traceability of the information conveyed, it remains more ambiguous. If the mock-up is correctly related to the digital sources (photographs) from which it was made, the geometric (or semantic) structuring of the model can only be guessed via a polygonal decomposition for which we do not know the justification. There is no indication enabling a reading of the *generic knowledge used* [BD06](1), or a comprehension of any thesaurus employed for the reconstruction. To conclude the observation on the criterion of informative coherence, the model appears homogenous from the graphical viewpoint but remains vague about the target level of definition. Indeed, one notices that certain geometric elements have been modelled to "adhere" very closely to the object (with an accuracy of less than a centimetre), although other elements, like the deterioration present on the facade, have not been taken into account.

Beyond an overall visual coherence, this semi-manual digitisation does not enable us to assess correctly the accuracy of the proposition. It is difficult to understand whether the geometric decomposition comes from a visual interpretation of the morphological characters of the whole, or if, on the other hand, it is an amalgam between *specific knowledge of the object and generic knowledge*. To conclude, from a cognitive viewpoint, this model enables the visual appearance to be appreciated, as well as certain formal aspects of the building, but it proves less effective as a rigorous scientific vehicle of architectural knowledge.
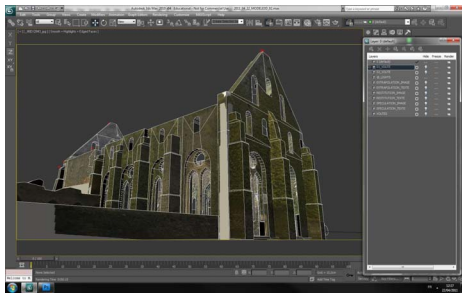

Figure 5: *Image-based modeling of the current state of the refectory of Villers-la-Ville Abbey (Belgium). Digitization done by Laboratoire AlICe, Faculty of Architecture (La Cambre Horta) of the Universite Libre de Bruxelles.*

3.5. Manual restitutions

This final example (figure 6) is a digital restitution of the forum of Augustus. This is part of a vast project modeling the city of Rome in the 4th century AD. [Uni]. Unlike previous digitisations, this example presents the result of hypothetical modeling. Here, our choice to deviate from the strict framework of the architectural digitisation is justified by the need

to propose a critical examination covering a process ranging from the data acquisition on site to the 3D modeling of hypotheses.

The hypothetical renditions found in this project meet requirements of at least two orders: pedagogical and scientific. The 3D models reflect a process incorporating the precise dimensions of the building (to the extent that these are available) and the use of architectural canons [Uni]. This results, at first sight, in a tool enabling an interactive and 'sensitive' visualisation of architectural scenes.

With regard to its informative scale, the rendition offers two levels of reading. The former corresponds to the visual appearance of the building, whereas the latter presents the set of documentary sources associated with it. On the other hand, the observation of the model from the viewpoint of information certainty becomes more delicate. Indeed, it is difficult to separate out, in this series of hypotheses, the information derived from sources (documentary or digital acquisition) of information drawn from a free interpretation of the geometry. A lack of intelligibility is therefore observed for the model as a whole; By way of example, no graphical indication allows the viewer to understand whether the presence of the decorative variations of the entablature reflect generic knowledge or a specific feature of the object. In the same way, neither the colour of the motifs on the floor nor their dimensions show graphically the status of this information, its degree of certainty or the use of any extrapolations. The capital of the columns, apparently of the Corinthian order, seem to come from an incorrect interpretation of the typical architectonic knowledge (figure 1). This element could be a reflection of a formal misunderstanding of the morphology of the element represented or absence of information that would allow it to be described. The graphic non-uniformity of the representation would probably have allowed clarification or codification of the degree of knowledge available for each of these elements. Henceforth, one wonders about the model's capability of crystallising the relative state of knowledge in an intelligible manner.

If the mock-up is presented as the tool for spatial referencing of a corpus of documents, the model could also serve as an exact reflection of the knowledge used. As we have seen, some aspects of the representation reveal a form of subjectivity concealed by the homogenous appearance of the rendition. This point probably constitutes one of the main curbs on the cognitive ambitions of the model.

Beyond the last comments, other projects recently developed provide some answers for the visualization of hypothetical reconstruction. Procedural reconstruction of Pompeii from the interface CityEngine [Mul11] allows a 3D interactive consultation of archaeological data. The model is, in this case, the result of the encoded parameters. As noted above, the major advantage of a parametric approach is to separate the geometric shapes of their factual descriptions.

Figure 6: *Digital restitution of the forum of Augustus. Restitution project: 'Le Plan de Rome' [Uni].*

4. Evaluations

The observation of the methods and techniques of 3D digitization according to the degree of automation that they require, reveals a greater cognitive involvement of the operator the closer he gets to a process of manual reconstruction. The relatively obvious causal effect also points to the existence of a dual epistemological issue.

In view of the examples analysed previously and the historic and cognitive issues involved in an architectural representation, one can draw the following conclusions:

- Keeping the operator at a distance in an automated reconstruction process (photogrammetric or lasergrammetric reconstruction by polygon meshing) leads to an increase in objectivity in the representation produced. On the other hand, these processes, and therefore the use of technologies allowing ever-greater levels of precision, do not appear to guarantee a substantial cognitive benefit.
- In parallel, the analytical mechanisms of reading and interpreting (that a 'manual' process of restitution require) naturally induce a form of subjectivity. It may also prove of major interest for the cognitive enhancement of the model. However, as certain examples show, digitization that does not show the relative level of the knowledge that it contains is difficult to justify as a tool for scientific evaluation.

Taking place at the reception level, these evaluations also question the work of the operator upstream in the process. While observation of the representations enabled us to understand their ability to convey knowledge, it also strikes us as essential to situate the cognitive mechanisms which lie behind them. With this in mind, our study enables us to pick out two major issues, a perception issue and a description issue.

Faced with the impossibility of recording, whether or not in digital form, an architectural ensemble in an exhaustive manner, the choice of elements to be input, their scale of representation and the level of semantic description of the object appear as criteria that determine the quality of the informative coherence of the survey. When producing a measured drawing, a selection of information describing the object is made in a more or less conscious way. Therefore, two questions arise: like is the nature of the choice and operations decided (depending on the nature of the commission, the typology or the object, the needs, the tools available, the comprehension of the object and the architectural knowledge of the operator) and the second question as a corollary, what are the various processes involved in act of the survey.

The second problem is one of description. The digitization of an object or its geometric study presupposes the recording and transcription of the knowledge acquired on a medium. Obviously, between the 'real' object and its representation, there is a discrepancy whose amplitude is difficult to measure. The problem that we sense here is that the digitization does not take proper account of the process of description. The final graphic result of a representation is often presented as the result of a view whose singularity may be understood but whose narration is absent. From the intellectual development to the materialised, visible reflection on the medium, a gap remains. This problem of description is symptomatic of a methodological deficit rarely taken into account. Nevertheless, some research work, such as those conducted by Claudio Silva and Juliana Freire in the project VisTrails [SF10], provide an answer to the problem of the traceability of the reconstruction process. Each geometric operation is referenced in a history tree of the model. In this way, it's possible to understand all the decisions taken by the operator. If this project permit to approach a part of the reconstruction process by answering the question of "how" it is also necessary to answer the question of "why". In other words, what are the mechanisms of abstraction mobilized by the operator during the reduction of a real form of its representation.

5. Conclusions

This article has enabled us to carry out a partial review of the methodological inadequacies surrounding the techniques and methods of digitization of the architectural heritage. By pointing out in particular the cognitive aspects of representation, our observations have led us to formulate more precisely the relationships of interdependence that exist between the level of automation and the cognitive implications of the representations produced.

But above and beyond a critical process, our approach highlighted certain limits and perspectives. The initial results of the observation and the methodological deficits which emerge from it confirm the necessity of carrying out a study that aims to identify all the perceptive, cognitive and technical processes used in architectural survey. Beyond these initial ambitions, one of the major issues is to identify priority avenues for reflection for the development of future digitization techniques and methods. At the risk of being sim-

plistic, should one not consider the implementation of tools for the visualisation of knowledge but also, and above all, for the visualisation of the underlying analytical processes? A tool which simultaneously integrates the methodological and cognitive requirements of architectural representation.

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