University of Leiden, Faculty of Archaeology.

Uncertainty in archaeological 3D reconstructions

A case study of monument 434 at the Via Appia near Rome.

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1. Introduction

1.1 Overview

There are manifold archaeological structures and the ruins of buildings which provide a wide range of possible research opportunities. Reality-based modeling methods can capture the current situation with high detail and certainty. These snapshots can be used later for processing and interpreting the data at remote locations (Kantner 2000, 47; Reilly 1992, 162). Moreover, this method is not limited to data acquisition; it can also be used for hypothesis testing and the simulation of complex systems (Brusaporci 2017, 124). Hypothesis testing is performed as soon as the reality-based model is enriched with additional information. That information can, for example, come from the discussion about the case study. In this case, the term "*evidence-based model*" or "*hypothetical reconstruction*" can be used (Reilly 1992, 147; 3D Icons 2014, 25). Both, the reality-based and evidence-based methods have been known for quite some time and are not tied to a specific technology, such as computers (Reilly 1992, 147). Thus, in her overview of reconstructions during the last 500 years, Piccoli clearly describes the development of reconstructive approaches in history (Piccoli 2017, 225ff). In particular, the Via Appia on the outskirts of Rome has been subjected to many different reconstructions in the course of its history. Its Roman funerary monuments have attracted the attention of many scholars and artists, such as Piranesi, Ancelet, and Canina. This may be due the cultural legacy of the Romans, but also due to the fact that the material and cultural remains are often still *in situ*.

Nowadays, one is no longer dependent on manual data acquisition or hand-drawn reconstructions. Due the high availability of technology, computer-supported systems have become established in most areas of research (Brusaporci 2017, 124). They offer the possibility to simulate and test hypotheses in large quantities with a small investment of time and money (Vatanen 2003, 69). However, a scientific result also requires certain conditions (Apollonio and Giovannini 2015, 1) that are subject to change over time. The change is not only expressed in the individual technological achievements, it is also subject to constant changes within one technological period. This means that, even if a computer-supported system is established, the development of methods is continuing (Reilly 1992, 149). Therefore, the first discussions about the methodology of reconstructing archaeological structures with a computer started shortly after the introduction of computer-based 3D modeling (Miller and Richards 1995, 19). The main issues were the lack of transparency and the difficulty in visualizing uncertainties with the model (Hermon et al. 2006, 123). Much research has been conducted on this topic and international guidelines such as the London Charter (http://www.londoncharter.org/) and Principles of Seville (http://smartheritage.com/) have been developed.

Many of these approaches have similarities, whereby they suggest and introduce databases driven by metadata and prior documentation, or sometimes even calculations to determine the levels of uncertainty (Hermon and Nikodem 2008, 1). Nevertheless, in practice these methods can be inappropriate. However, this observation should not be generalized, considering the positive examples, as well as the considerable number of purposes that such a reconstruction can fulfill (Havemann et al. 2014, 67). The diversity of concerns related to this issue and also its importance can best be demonstrated by reflecting briefly on the research history and the emergence of the research problem. All in all, virtual archaeology provides much potential for new methods since it is an ongoing process.

1.2 Background and research problem

The beginning of the digital process can be traced back to the 1980s, when information technologies started to be used in archaeology (Kuroczynski et al. 2014, 1). Rapid technological growth soon led to an interest by scholars (Brusaporci 2017, 66), and a new discipline, namely "*archaeological virtual realities or virtual archaeology*" became established (Vatanen 2003, 69). One of the pioneers was Paul Reilly, who published several fundamental articles in the late-1980s (Apollonio and Giovannini 2015, 1). In these articles he defined the concepts of virtual archaeology and solid modeling (Reilly 1992, 147ff). The latter was important, because much subsequent research was built on them. At first glance, the issue of scientific transparency that was discussed in those early publications might seem self-evident, but the historical development indicates that this was not always so.

However, the issues of transparency and uncertainty predate the digital age by hundreds of years. The first intentional reconstructions of Roman objects and structures can be traced to the 14th and 15th centuries. Most of them are rather vague. Moreover, they rarely used more than one source, which was not even reviewed critically (Piccoli 2017, 226). This could be explained by a shifting target group. A representation is not always intended to be scientific (Piccoli 2017, 246). Accordingly, Piranesi is a good reference for this shift. On the one hand, his designs are scientifically imprinted and, on the other, they are more artistic (fig. 1). The drawings themselves are published in the 18th century (Piccoli 2017, 238f).

Figure 1: Artistically-inspired reconstruction of the Via Appia by Piranesi (Piranesi 1756, at http://www.nccsc.net).

The variable target group provides further insight. Depending on the result one needs, some styles might be more reliable than others. One could say that they have different levels of certainty. These problems regarding scientific transparency and uncertainty were recognized at an early stage, originally with physical objects. Therefore "*The Venice Charter 1964: The International Charter for the conservation and restoration of monuments and sites*" and "*The Charter of Krakow 2000: Principles for conservation and restoration of built heritage*" indicate how to best handle restorations and reconstructions.

Although reconstructions are used a great deal, they do not usually represent a primary component of research. Generally speaking, they emerge as a byproduct. Stanley-Price even goes so far as to say that they are valid only for the satisfaction of scientists (Stanley-Price 2009, 32). However, this is not the complete truth. For example, reconstructions can preserve knowledge (Charter of Krakow 2000, 2; Charter of Venice 1964, 1). Likewise, they are often used for educational and publicity purposes (Kantner 2000, 48f). Another use is spatial analysis; similarly to two-dimensional data, three-dimensional objects can be used to determine the visibility of certain areas (Piccoli 2015, 41) or test other hypotheses. Basically, a reconstruction corresponds to the visual representation of the entire interpretation.

However, this research is not about hand-drawn or physical reconstructions. The main focus is on modern computer-aided models. One of the reasons for the great success of such models was that they made it possible to verify theories without spending a great deal of time and money trying to rebuild the scenario in the real world; instead, the scholar could use special computer software (Vatanen 2003, 69). However, the rise of new technology brought not only advantages but also many new issues and conflicts that had to be tackled, some of which were even older than expected. Many of the emerging discussions related to transparency in computer-generated data and models, with many agents positing divergent opinions on this issue. The main reason for the problem of transparency, especially in 3D reconstructions and models, was the imprecision of the available data (Gershon 1998, 43). It was soon recognized that this was embodied in different levels, beginning with older evidence-based interpretations. For example, new points of inaccuracy were revealed when the information was converted from a 2D plan to a 3D world (Eiteljorg 2000). Consequently, well-researched 3D reconstructions can be costly and involve complex working pipelines (Manferdini et al. 2008, 221).

Referring to its high effectiveness but many difficulties, Eiteljorg describes a virtual 3D reconstruction as a "*double-edged sword*" (Eiteljorg 2000). As previously mentioned, this is due to the imperfect data. Parts of it might be missing, uncertain or not well preserved (Gershon 1998, 43). The major influence of computer-generated images can be made visible by presenting the same object of interest once as a 2D line drawing and once as 3D photorealistic rendering. Regardless of the audience, 3D photorealistic rendering is taken as the more authentic visualization. A photorealistic rendering might be more pleasant to look at it but it does not prove anything. This is a perfect illustration of the major danger (Eiteljorg 2000). In short, the realism makes the information available to a wider audience at the expense of credibility. Therefore, it is important to provide additional information to help the viewer to interpret the reconstruction correctly (Reilly 1992, 159).

By focusing only on 3D virtual reconstructions of archaeological structures, each part and component is an interpretation of a piece of evidence. Often the context becomes lost in the process. Accordingly, uncertainties, interpretations and reality are not addressed in an appropriate manner (Reilly 1992, 159). Transparency in 3D reconstructions is important due to the lasting convictions about the outcomes (Kensek et al. 2004, 175f). Following this argumentation, not only is documentation necessary, but it also has to be undertaken in a suitable way to provide an acceptable framework for the interpretation (Apollonio and Giovannini 2015, 1). Creating a model without underlying data can be seen as worthless to an academic audience (Vatanen 2003, 70). The data that we have and the interpretations that we accomplish are always a reduction of the reality. During the reduction, data is lost and uncertainty emerges (Zuk et al. 2005, 99).

1.3 Aims and objectives

As noted above, the main emphasis of this research is the issue of scientific transparency when reconstructing ancient architectural structures. The extent of the thesis is further limited by the choice of case study and the framework elucidated in the previous chapters and paragraphs. To guide the research successfully to this outcome, three objectives are formulated, each of which will be accomplished individually.

1. Present an approach that indicates how to deal with uncertainties while keeping the outcome transparent.
2. Create an overview of existing methodologies and summarize them into categories and classes.
3. Provide one final and several pre-final reconstructions of one monument on the Via Appia, based on different methods.

The primary objective is without doubt the first one. The following sub-goals are important to provide the necessary knowledge and material to fulfill the primary objective and answer the research question of the thesis. This will lead to high reproducibility and clear applicability for the conclusion of this thesis and its field of research. The major target audience is students and researchers in the academic field of archaeology.

The resulting research question is defined as follows: *“Which method ensures the highest level of scientific transparency in a virtual 3D reconstruction of a Roman funerary monument, considering the imperfection of the available data and the resultant uncertainty about using visualization, documentation and presentation?”*

The answer might imply a critical review of the existing guidelines and methods. Applying them to the case study, the result can subsequently be evaluated and discussed, providing several solution approaches to the research problem. It should be acknowledged that the results might be applicable only to similar cases, due the special character of the primary and secondary sources. The following methods describe how it was done in this research.

1.4 Research method

In order to achieve the above goals and answer the research question, the principle research method for this investigation was a case study (see Chapter *3. Case study: The reconstruction of a Roman funerary monument*). The subject was one monument on the Via Appia. The elaboration of this case study was carried out in collaboration with the "*Mapping the Via Appia*" project of the Radboud University Nijmegen, Royal Netherlands Institute in Rome, Vrije Universiteit Amsterdam and additional partners. Data and scientific support were provided for the archaeological part, as well as additional supervision. The literature review (see Chapter 2*. Literature review and theoretical framework*) was equally important, because it would later be discussed in relation to the case study (see Chapter 6. *Evaluation of the theories and results*).

Beginning with the literature review, the content of several publications was investigated. The main emphasis was placed on terms such as "*transparency*", "*uncertainty*", "*reconstructions*", "*visualization*" and "*3D modeling*". Approaches matching one of these terms were collected and categorized in classes. Among other things, this also included the analysis of available 3D models and more technical aspects of the related workflow. The London Charter and Principles of Seville were expected to hold strong relevance for this purpose, considering their wide prominence and usage among scholars. Much of the literature contained broad content that extended beyond visualization.

In the case study, the architectural composition of one of the funerary monuments on the Via Appia was investigated. The monument is referred to as 434[1] and has a rectangular base with a round structure on top of it. It is known to have been re-used in the medieval period and restored in modern times. Knowledge of the monument was obtained by studying the relevant literature and analyzing the monument directly in the field. The digital data comprised aerial and terrestrial photography, which was used for photogrammetrical purposes and the construction of a basic mesh. Likewise, measurements and sketches could be derived from it. Another source was a small collection of historical prints and illustrations. As a final point, the existing evidence was interpreted and possible reconstructions of the tomb were explained.

The methods described in chapter 2 were applied to the possible reconstructions in chapter 3. In a subsequent discussion, the results are evaluated and compared to the previously-defined research question. Furthermore, their limits are pointed out and tried

[1] The number refers to the "*Mapping the Via Appia*" project since the monument itself has no uniform denotation in the literature or elsewhere.

to resolve. This will create a method that is applicable to similar kinds of structures in archaeology. Overall, the transparency methodology is based on a threefold approach (documentation, visualization and presentation). This division will last throughout the complete research and can be seen above all in its structure.

1.5 Thesis overview

This thesis comprises seven chapters, each of which are further subdivided into several sections. The following segmentation will provide a clear setup with firmly-defined content. The individual parts mainly build upon each other.

Chapter 1: Introduction. This chapter comprises a brief introduction to the research topic, following which the research problem, aims, question and methodology are presented. Finally, this overview of the thesis is presented.

Chapter 2: Literature review and theoretical framework. In this chapter the findings from both older and up-to-date literature are outlined. The main methods and theories about uncertainty and transparency in 3D archaeological reconstructions are summarized and categorized. Along with articles, the literature also includes charters and guidelines and articles that might originate from topics unrelated to archaeology.

Chapter 3: Case study: The reconstruction of a Roman funerary monument provides the necessary data for the following chapter. A Roman funerary monument on the Via Appia is investigated and described. Apart from some historical aspects, this mainly includes architectural elements and their context in a wider field, such as analogies to similar structures. Subsequently, several possible reconstructions of the original condition are worked out.

Chapter 4: Applying diverse concepts to the data comprises the application of the methods and theories collected in chapter 2*, literature review and theoretical framework* in relation to the monument described in chapter 3, *case study: The reconstruction of a Roman funerary monument*.

Chapter 5: The reconstruction and its database. The focus here is on presenting the data relating to the previous chapter. No explanation is given and no appraisal is made in this section. The data itself is described mainly in written language or in forms of representative illustration. The main content are the produced blueprints, models and databases.

Chapter 6: Evaluation of the theories and results. In this chapter the *literature review and theoretical framework* are critically reflected on. The work of several researchers is evaluated and discussed in light of the results from the previous chapter. Furthermore, the limits of the methods are pointed out and ways to overcome them are posited. Some of these paths can also be seen as possible future perspectives.

Chapter 7: Conclusion is a summary of all the previous chapters. Moreover, a final approach to dealing with uncertainties in three-dimensional reconstructions is presented.

2. Literature review and theoretical framework

2.1 Origin of uncertainty in archaeology

Archaeological interpretations are always limited by the quantity and quality of the available data and sources (Murgatroyd 2008). But where does the limitation come from and what are the consequences of it? In the following sections, this question will be clarified.

One of these consequences is uncertainty. In archaeology it is not possible to exclude biases. Consequently, there is always a certain degree of uncertainty and in some cases several individual hypotheses are possible (Eiteljorg 2000; Kantner 2000, 47). The uncertainty is due to the differing kinds of data and the numerous ways to interpret them (Reilly 1992, 158). Many of the assumptions are based on the scientists' opinion. However, since adequate documentation is provided in many cases and the interpretation can be tracked back, uncertainty is not insurmountable (Apollonio 2016, 174 and 178). Moreover, the interpretation can be divided into further subgroups, which might be identifiable by various visualization methods (Bruschke and Wacker 2016, 263).

Conflicting data can be due to the poor preservation of artifacts. Furthermore, a lack of data can especially increase the degree of uncertainty drastically, even if it might be substituted by analogies (McCurdy 2012; Reilly 1992, 159; Sifniotis et al. 2006, 1). However, there can be many forms of uncertainty and measurement inaccuracy in the research (Brusaporci 2017, 129). Therefore, Brusaporci defines several categories, namely the "*kind of sources, source completeness, source reliability, [and] level of interpretation of sources*", as major factors for the origin of uncertainty. Moreover, he identifies the main issues regarding visualization as "*geometry, location/ position, date/ age, colour, texture, material, constructive system, contextual, [and] landscape*" (Brusaporci 2017, 142). Both, contextual uncertainty and spatial uncertainty are widespread. Moreover, direct measurements usually have high accuracy and low uncertainty (Miller and Richards 1995, 21).

By comparison, cultural interpretations are dependent upon many factors (Brusaporci 2017, 67). The main reason is the restraining documentation. Not everything can be perfectly documented and interpreted due the above mentioned corrupt data (Kantner 2000, 51). This always results in a certain degree of uncertainty in interpretation (Miller and Richards 1995, 20). Accordingly to Apollonio, the three areas most influenced by uncertainty are "*shape (geometry, size, spatial position) […] material (physical form,* *stratification of building/ manufacturing systems) […and] appearance (surface features)*" (Apollonio 2016, 177).

In general, uncertainty mostly represents a lack of data and knowledge. After questioning several scholars about their opinion, Sifniotis created a table of reliable to non-reliable sources (Sifniotis et al. 2007, 2). Most certain assumptions are based upon direct structural evidence, while written sources are generally seen as having the lowest certainty (Sifniotis et al. 2007). However, it is not only Sifniotis who has thought about it. Indeed, many other scholars have worked on possible methods to facilitate scientific transparency. Some of them even went as far as to provide charters and guidelines for researchers to follow. These documents will be examined in detail in the following sections.

2.2 Publications addressing uncertainty

2.2.1 Charters and principles

Various guidelines have been prepared to counteract the issue of uncertainty. Firstly, the London Charter which was intended by scholars to "*establish principles for the use of computer-based visualization methods and outcomes in the research and communication of cultural heritage*" (London Charter 2009, 4). Those principles are presented in a list of instructions and approaches that can be applied to a project. In general, the emphasis is mainly on the use of computer-based visualizations in the field of Digital Heritage.

Addressing the issue of uncertainty directly within the charters and principles is rare. Most of the instructions related to the issue of vagueness are provided in Principle 4 - Documentation. The only section containing the word "*uncertainty*" in this context is paragraph 4.4.

> "*4.4 It should be made clear to users what a computer-based visualization seeks to represent, for example the existing state, an evidence-based restoration or an hypothetical reconstruction of a cultural heritage object or site, and the extent and nature of any **factual uncertainty***." (London Charter 2009, 8)

Paragraph 4.4 deals with documentation. Moreover, the different kinds of hypotheses regarding the form of reconstructed models that should be made clear. Each of them is to be assigned a value of uncertainty. However, although this paragraph might describe a part of a procedure, it does not name the exact setup.

Following this line of thought, the London Charter describes uncertainty in relation to the documentation. Thus, the headings "*Documentation of research sources […] process (paradata) […] methods […] dependency relationships […] formats and standards*" of the individual sub-principles provides a good overview of the scope of this problem and in which parts of the research vagueness can be addressed (London Charter 2009, 8f).

Secondly, the Principles of Seville are known for their relevance to the field of virtual archaeology. The document is based on the London Charter. However, it specifies its objectives slightly differently and is more aimed at virtual visualizations. The added value and focus compared to the London Charter is clear. The Principles of Seville are generally seen as an extension of those above (Principles of Seville 2011, 2). However, the exact term "*uncertainty*" cannot be found within the text; the general heading is often "*transparency*" or "*authenticity*".

"*Principle 4: Authenticity*" is similar to principle 4 of the London Charter. In general, it highlights the importance of a separation of the data (real and hypothetical). Furthermore, it mentions the issue of imperfect data, which can result in diverse interpretations (Principle of Seville 2011, 6; London Charter 2009, 8f). Hence, it should always be clear on what evidence the reconstruction is built.

More details are given under "*Principle 7: Scientific transparency*", which deals with the issue of ambiguous information. This chapter is focused mainly on transparency, as the title implies. However, uncertainty can be seen as inclusive of transparency. This is shown predominantly in principle 7.1.

> "*7.1 It is clear that all computer-based visualization involves a large amount of scientific research. Consequently, to achieve scientific and academic rigour in virtual archaeology projects it is essential to prepare documentary bases in which to gather and present transparently the entire work process: objectives, methodology, techniques, reasoning, origin and characteristics of the sources of research, results and conclusion*." (Principles of Seville 2011, 8)

Hereby, the "*entire work process*" and "*reasoning, origin and characteristics of the sources*" can comprise a degree of uncertainty (Principles of Seville 2011, 8). In both the London Charter and the Principles of Seville, the data and information about uncertainty has to be saved in databases. The data about the procedure itself is titled as "*paradata*" and has to demonstrate a transparent workflow and result. Within this part the uncertainty is included in the form of imperfect information.

Charters that do not deal with digital archaeology also deal with the issue of uncertainty and vagueness in terms of reconstruction. Firstly, "*The ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage sites*" states, in "*Principle 2: Information Sources*", the importance of documenting all sources (ICOMOS Charter 2008, 4). This is further specified in principle 2.4, when it is used in combination with visual reconstructions. It is important to note the decisions of the visualization and create alternative versions that might emerge with the available evidence (ICOMOS Charter 2008, 5). Secondly, "*The Charter of Krakow: Principles for conservation and restoration of built heritage*" focuses on a similar topic. However, the aspect relevant to my research is that the style of the reconstruction should always be different from the original style. The use of digital technologies to do so is desirable (Charter of Krakow 2000, 2). Thirdly, the "*International Charter for the conservation and restoration of monuments and sites: The Venice Charter 1964*" can be seen as a template for the previous charter. In the chapter "*Restoration*" under "*Article 12*", it is stated that similar conditions to those of the other charters are required. The replaced parts must fit nicely, but must also be distinct from the original (Venice Charter 1964, 3). Additionally, documentation that describes the product is needed. It is important for the report that it is openly available for other researchers (Venice Charter 1964, 4).

In summary, all the charters point in the same direction, regardless of whether they are aimed at physical or virtual approaches, namely that it is important to retain all the documentation and discussion connected to the object. Thus, reality-based and evidence-based parts have to be clearly distinguishable from each other. Likewise, each segment should be assigned its own uncertainty. However, it is not always the case that studies follow these principles. Indeed, in some cases they try to establish their own ones.

2.2.2 Articles

In contrast to the charters and principles, general publications offer a wider range of knowledge. Instead of focusing only on the optimal result, they also work out possible problems and their solutions. In some cases this can lead to differing views. However, this makes the discussion that follows all the more comprehensive. Reilly's article is often seen as the foundation of the three-dimensional visualization of archaeological structures (Wittur 2013, 9). In general, he defines terms such as "*data visualization*" and "*solid modelling*" (Reilly 1992, 147f). One important chapter is "*Recent trends and implications*" (Reilly 1992, 156), in which the issue of validity in digital visualizations is addressed. An important aspect is to "*inform the viewer on the degree of confidence*" (Reilly 1992, 159).

The expression "degree of *confidence*" might be taken as a synonym for "*uncertainty*". As a solution, he suggests that the documentation of all the processes related to the creation of the model should be published together. Possible approaches would be color codes or fading opacity, as well as links to multimedia files containing additional information about the visualization (Reilly 1992, 159).

Miller and Richards build on Reilly's article by adding a warning about the actual development. Basically, they further describe possible implications and also new possibilities of this technology. However, the main problem is the lack of software to create a visualization of fuzzy data (Miller and Richards 1995, 20). As a solution, they recommend introducing specialized experts for this field of archaeology (Miller and Richards 1995, 21).

Five years later, Strothotte, Masuch and Isenberg published an article in which they sturdily criticized the high impact of those renderings on an observer in contrast to schematic drawings (Strothotte et al. 1999, 36). They suggested a reduction of details and a more detailed focus on the object of interest regarding its interpretation. Like Miller and Richards, Strothotte et al. are of the opinion that scholars should be trained in this topic. However, he also mentions a shift away from photorealistic renderings towards non-photorealistic ones, as well as an increasing interest in the issue of uncertainty (Strothotte et al. 1999, 37). To overcome the latter, additional data has to be encoded within the model, and uncertainty and design decisions have to be made available. However, uncertainty is a product of archaeology that cannot be neglected. Despite the fact that uncertainty can easily be phrased in words, a computer needs quantitative data. To encode the uncertainty value, Strothotte at al. use differing line styles (Strothotte et al. 1999, 38). As a conclusion, he and his colleagues suggest a classification of the data, rendered on a conditional base with encoded information indicating the uncertainty (Strothotte et al. 1999, 42).

Kensek, Dodd and Cipolla use a slightly different approach in their publication. Their main emphasis is on the transparency of virtual models. Nevertheless, they still agree with most of the previous research statements regarding uncertainty and transparency (Kensek et al. 2004, 175). However, the main topic is not uncertainty anymore but continues to appear in the form of design decisions (Kensek et al. 2004, 176). The data itself can be encoded using assorted colors and opacity (Kensek et al. 2004, 177), the render type or a mixed approach (Kensek et al. 2004, 178). Furthermore, he suggests adding additional information in the form of written text or other media files (Kensek et al. 2004, 179), which can be linked by the internet to the data (Kensek et al. 2004, 180). The user interface developed by him and his colleagues reacts interactively with input. Furthermore, it indicates the degree of uncertainty with color-coded bars, each of which is assigned a custom category (Kensek et al. 2004, 182). In conclusion, he suggests extending this system so that it can also be used for other projects (Kensek et al. 2004, 184f).

With his research, Brusaporci (2017) produces a comprehensive work about documenting uncertainty. It is one of the most recent publications covering this subject. The introduction describes in detail the need for transparency (Brusaporci 2017, 124). The metadata and paradata are seen as the essential aspect of the research process (Brusaporci 2017, 125). They are comparable with "*action*" and "*classification*". Furthermore, paradata allows the linkage of the object to its broader context (Brusaporci 2017, 126). Consequently, it also includes the discussion, which might include a scale of uncertainty. Subsequently, the London Charter and the Principles of Seville are discussed as guidelines (Brusaporci 2017, 127). However, one does not only have to understand the method; a sustainable amount of knowledge about the research topic is also needed (Brusaporci 2017, 129). When the knowledge is modeled it becomes a reconstructive hypothesis. To gain more certainty, previous research can be included (Brusaporci 2017, 130). The next section is filled with comparisons of approaches to deal with uncertainty that have been posited in recent years. According to Brusaporci, two kinds of uncertainty (spatial and temporal) are possible (Brusaporci 2017, 131). Each part of the structure has to be described. However, meaning and appearance might change over time (Brusaporci 2017, 133). The key element of this approach is the paradata, which describes sources and design decisions, and therefore comprises the necessary documentation for uncertainty. Paradata itself has to be organized in databases that provide a similar structure to the model (Brusaporci 2017, 141). Nevertheless, the reliability of geometry, location, date, color, texture, material, constructive system, context and landscape have to be investigated critically (Brusaporci 2017, 142). The visualization itself happens either spatially with graphical hints such as "*shades, transparency, colors, simplified textures and geometries, labels, tags*" or multiple windows (Brusaporci 2017, 143f). As a future perspective, BIM systems are indicated. However, they still lack the ability to process the current data (Brusaporci 2017, 145ff).

In short, even if many studies share similarities in terms of the research problem, they often suggest differing solutions. While the earlier articles focus more on visualization and trained personnel, later articles focus on extensive documentation. Accordingly, the main focus changes over time.

2.2.3 Guidelines

The guidelines differ from the articles and charters in the sense that they are almost manuals. They describe the exact execution of the individual processes and the technical background rather than the theory behind them. Nevertheless, they might contain valuable information. “*3D-ICONS*” (2014) and “*IT-Empfehlungen für den nachhaltigen Umgang mit digitalen Daten in den Altertumswissenschaften*” (2017) are broad manuals on how to deal with digital data. Both of them provide detailed sections on documenting, modeling and presenting three-dimensional models of archaeological structures. Furthermore, they give detailed instructions on the methodical procedures that have to be undertaken during the working pipeline. However, they do not offer solutions, apart from documentation, for the uncertainty issue that is dealt with in this research. The solutions can be found better in articles of different case studies. However, these articles are so numerous that they should be grouped into different categories.

2.3 Modeling and visualization techniques

2.3.1 Overview

In order to deepen our understanding of the manifold possibilities broached in the previous chapter, several concepts relating to ensuring scientific transparency are described in more detail here, with references to their original publication. Likewise, the necessary technical knowledge is also introduced in combination with archaeological examples. In some cases, this may lead to abrupt changes in the references. However, this is desirable in order to highlight different approaches and to weigh practical methods against impractical ones.

One primary application is to use integrated models. The easiest way to create them is by adding geometry or manipulating the rendering results. According to Gershon, one has to distinguish between intrinsic and extrinsic visualizations (tab. 1), which are both branches of imperfection. The symbology used can represent differing values and degrees, with the aim of conveying an intuitive understanding of the scene (Gershon 1998, 44). This circumstance makes it important to investigate their consequences in a detailed way. Not only should the model be appealing, but it also needs scientific value. However, this approach is only one of many (Eiteljorg 2000). Actual technologies such as laser scanning and photogrammetry offer high accuracy to refine those methods (Manferdini et al. 2008, 221 and 226f), as well as a high certainty, which might affect the perception of the later observer (Miller and Richards 1995, 20). Nevertheless, freely modeled structures can also indicate the perfection and realism of a scan without any scientific data supporting it (Strothotte 1999, 36). If one simple approach is not sufficient to bypass this issue, several approaches can be combined (Gerhson 1998, 44).

Table 1: Various approaches to visualize and indicate imperfect and missing data (after Gershon 1998, 44)

Intrinsic	**Extrinsic**	**Metaphors and cues**	**Redundancy**
position	dials	intuitive additions	mixing
size	thermometers		
brightness	arrows		
texture	bars		
color	different shapes		
orientation	charts		
shape	graphs		
boundary			
blur			
transparency			
animation			
extra dimensionality			

However, in archaeology the approaches can be slightly different. In this context, it is important to be able to distinguish between them. The most convenient ones will be explained in more detail and with archaeological examples in the following subsections.

2.3.2 Modeling techniques

The first approach can be summarized as modeling techniques. Those are numerous in the industry. Most of them can be used for the reconstruction of cultural heritage. The most common one is polygonal box modeling (fig. 2), which means that the objects consist of vertices, edges and faces[2]. Those individual components can be freely manipulated by the user. In general, they are grouped together and form polygons. Several polygons linked to each other are known as a mesh. A polygon usually has three (triangles) to four (quadrilaterals) vertices and edges, which form one face. The most ordinary topology is quads (quadrilaterals), since they are the most accessible form to edit and transform. It can be assumed that this method has been used in most archaeological cases, since it is defined as a template for Computer Generated Imagery (cgi) in films, games and industry (https://knowledge.autodesk.com/, a).

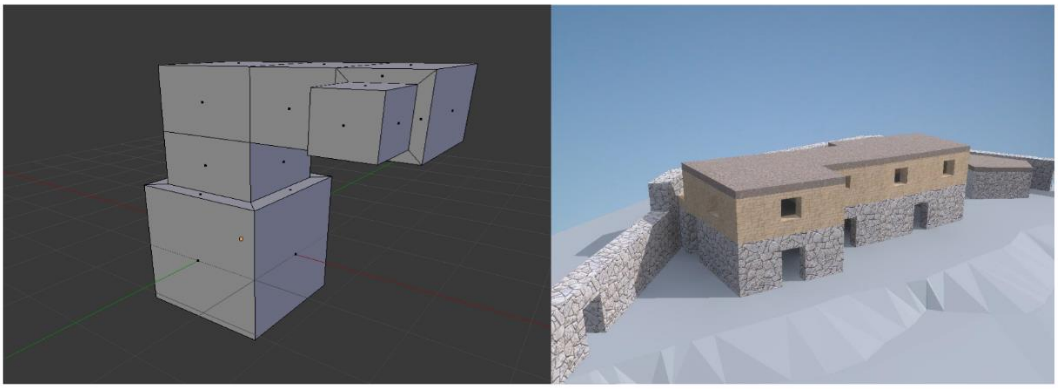

Figure 2: Comparison of a polygonal model in theory – left (Brunke 2017) and an example from archaeology – right (Alusik and Sovarova 2015, 444). Both models were created using box modeling.

To investigate a modeling technique, several hints can be followed. All of them are either hidden in the documentation, the software that was used or the model that was created. For example, Alusik and Sovarova 2015 used ArchiCAD for their reconstruction. However, the final rendering (fig. 2) does not contain sufficient clues for a final statement. Indeed, it shows surfaces similar to the faces of polygonal modeling (Alusik and Sovarova 2015, 441 and 444), but this does not constitute direct proof. In the online documentation of the software used, terms such as "*Polygon Counting tool*" and "*polycount*" are employed (https://helpcenter.graphisoft.com/) and the surfaces visible in the rendering indicate the use of polygonal modeling.

[2] Vertices are single points in a three-dimensional space. They represent the most basic form of information. Each vertex owns an x, y and z location. Two vertices connected form an edge. A face is created with at least three edges that are connected to one plane. Faces can consist of *n* edges and vertices.

Another case that can be investigated is Rua's and Alvitos's publication. The article that corresponds to the model mentions Autodesk 3ds Max as the modeling software (Rua and Alvito 2011, 3300). Furthermore, they us uv-maps[3] and similar techniques to create various textures, and these are useable with polygonal modeling. Moreover, the finished model was imported into a game engine[4] (Rua and Alvito 2011, 3304), which also works with polygonal models. Also, 3ds Max's documentation supports this modeling technique (https://knowledge.autodesk.com/, b). Lastly, Hermon and Nikodem use Blender as their modeling software (Hermon and Nikodem 2008, 5). Blender defines polygonal modeling as one of its capabilities in its online documentation under the headline "*Object Types*" (https://docs.blender.org, a). Furthermore, polygonal modeling is in this case used as a basis for encoded uncertainty within the model. This happens due to applying different colors and hints that represent various uncertainty indices of the segments (Hermon and Nikodem 2008, 4f). A fundamental version of polygonal modeling is point clouds. They represent only vertices – the basic raw data, without any relations. They are used to display measured values with high accuracy and therefore high certainty (Miller and Richards 1995, 21).

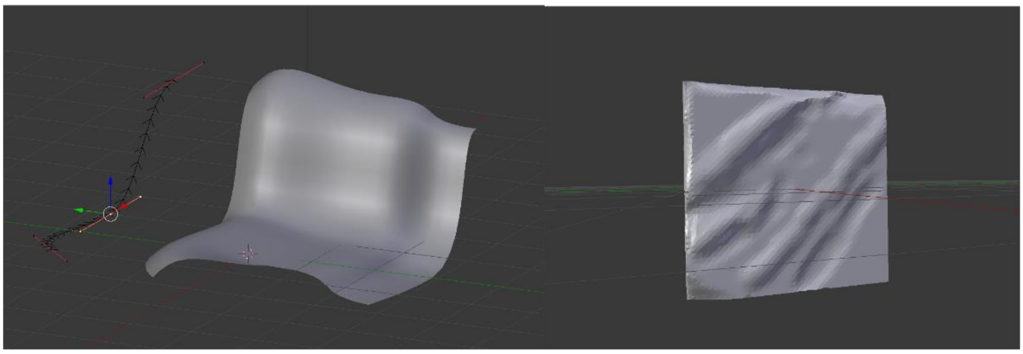

Figure 3: Example of curve modeling (left) and sculpting (right) (Brunke 2017).

Curve modeling (fig. 3), known as NURBS (non-uniform rational B-spline) and sculpting are additional options (fig. 3). However, neither can be found in any archaeological case studies as standalones at this stage. On their own, they are unsuitable for modeling architectural structures. Nevertheless, both of them can be used for individual parts or details. However, it is not always easy to confirm this method, especially due to the fact

[3] Uv-maps or uv-coordinates describe mathematically how to wrap a texture over a mesh. The coordinates are obtained by unwrapping the corresponding object, which is a common workflow step. This would be comparable to the projection and transformation of geographical maps to the curvature of the earth.

[4] Game engines were developed specially for computer games. They provide a variety of methods and functions that can also be used in virtual archaeology.

that in some cases NURBS and sculpting are seen as part of individual modeling instead of an independent method. Sculpting is mostly used in the context of organic modeling (http://pixologic.com/), whereas curve modeling finds its use in curved objects with a starting, end and control point. This means the curve might follow the orientation of the points but not always intersect with them. In addition to sculpting, another option is voxels, a technology of dividing the room into pre-defined cubes and manipulating them.

In conclusion, box modeling is the most common, while sculpting, curve modeling and voxels have to date not been used much in archaeological reconstructions. However, they are not the only possibility to indicate uncertainty. Another possibility are visual representations.

2.3.3 Visual representation

Instead of manipulating the geometry by means of box modeling, it is also possible to easily adjust the visualization to encode the levels of uncertainty. Colors can represent different values, attributes and data. A model itself can, furthermore, be rendered in wireframe, a solid or shaded/ textured object[5] (Kensek et al. 2004, 178). For Zuk et al., the use of the wireframe rendering technique offers the possibility of expressing uncertainty and indicating design decisions (Zuk et al. 2005, 102 and 104). Furthermore, it can help one to understand the general structure of an object (Reilly 1992, 156). For example, Bakker uses it to show the interior of building structures (Bakker et al. 2003, 2). Hermon and Nikodem apply the wireframe mode to their structures as soon as the uncertainty index falls below a pre-defined threshold[6] (Hermon and Nikodem 2008, 4). Therefore, only the absolutely uncertain parts are rendered, while other parts are allocated different colors in the solid mode (Hermon and Nikodem 2008, 4f). Kensek et al. uses a similar approach; he seems to mix all the methods, but wireframe indicates the lowest certainty (Kensek et al. 2004, 293). In short, the wireframe mode is usually used to represent the lowest edge of certainty. It is usually combined with other techniques to emphasize its meaning even more. From the technical point of view, it is defined in the following way: "*Objects appear as a mesh of lines representing the edges of faces and surfaces*" (https://docs.blender.org/, b).

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[5] Special forms of displaying an object in a 3D modeling software. The exact representation will be explained in more detail later on with an example (see "*4.3 Encoding the uncertainty in the model's visualization"*).

[6] The indicated threshold indicates the author's opinion about the degree of uncertainty to the linked object. This statement only applies to the case of Hermon and Nikodem 2008.

In contrast to the wireframe mode (fig. 4) is the solid mode (fig. 4) which can be further subdivided into "*Textured*" and "*Material*". In this case a single diffuse texture or multiple pbr-textures are overlaid over the mesh. The final rendering process will create high quality images out of this information (https://docs.blender.org/, b). Solid, respectively textured and material modes and shaders are usually the foundation for further classification and manipulation of the objects' appearance. One scheme that is often used in printed media is the use of transparence because of the intuitive understanding it usually conveys. However, opacity (fig. 4) can be also mixed with other shading methods (Kensek et al. 2004, 178). Regarding its intuitive use, a high transparence of objects usually implies less evidence and a lack of data (Kensek et al. 2004, 177) and therefore stands directly for a high degree of uncertainty (Zuk et al. 2005, 5). Instead of a Boolean operation, varying amounts of uncertainty can also be represented by differing degrees of opacity (Kensek et al. 2004, 183). Apart from Kensek and Zuk, Murgatroyd also uses transparent shaders to directly indicate structures with high uncertainty. His case compromises mainly the building structures of Pompeii, where the lowest certainty is on the upper ends of the walls and the complete roof. Kensek describes the use of transparency as tool to display a lack of knowledge. Non-knowledge can thus be made evident (Kensek et al. 2004, 177). However, the same form of uncertainty is not always meant. Zuk uses this method to indicate temporal uncertainty, while most of the other scholars use it for spatial uncertainty (Zuk et al. 2005).

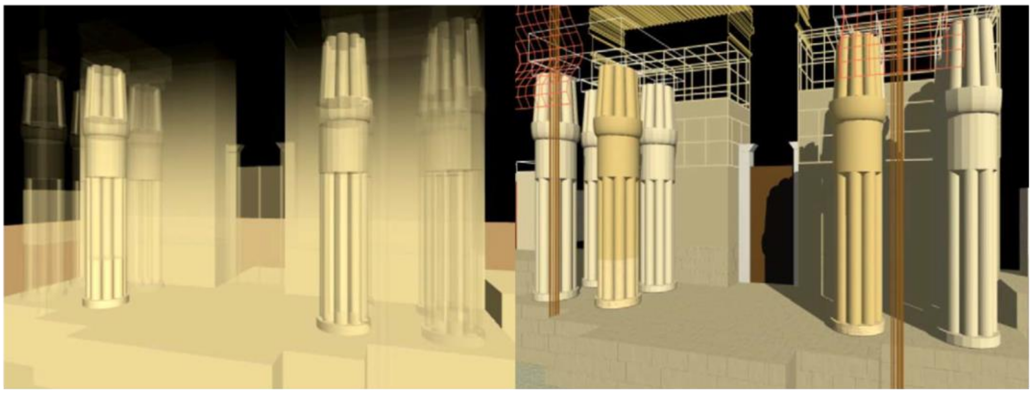


Figure 4: Indicating uncertainty with a transparency shader (left), and a wireframe modifier (right). The renderings are visualizations of the columns of the temple of Solomon in Jerusalem (Kensek et al. 2004, 178 and 179).

In short, the visual representation offers wireframe, solid, texture and material mode, that are four different approaches to visualizing three-dimensional data. Each of those formats can encode information in different ways. However, for optimal results this should be linked to rules that will be explained in the next subsection.

2.3.4 Style direction

The style is closely connected to the visual representation. It specifies how the visualization is to be applied to the object. In general, the style direction can be seen as a group of visualization rules. The only difference is that the rules and values are usually already linked to a form of data interpretation. One extreme is photorealism. The use of a photorealistic style (fig. 5) can denote high certainty since the actual geometry and appearance are based on actual measured data. Those renderings usually have a high level of detail and are expected to be seen by the public. Consequently, a lot of discussion has emerged about its use and ability to deliver uncertainty (Wittur 2013, 48). The most common belief is that this method is unsuitable for the academic environment (Olivito and Taccola 2004, 181). The first years of virtual archaeology were characterized by a trend of photorealistic renderings (Strothotte 1999, 37; Sifniotis et al. 2006, 1). However, following increasingly intense discussion, the use of this style peaked off again (Olivito and Taccola 2014, 182). According to Reimersdahl, photorealistic renderings should always be the aim, as long as they are not based upon assumptions (Reimersdahl et al. 2008, 147). Hence, a photorealistic style can be used in a mixed context with other style directions (Bakker et al. 2003, 161; Olivito and Taccola 2014, 182). However, a purely photorealistic rendering does not distinguish between real and interpreted structures (Kantner 2000, 47), as is required in many charters. Therefore, this style usually implies high certainty of the displayed object and is not suitable to display uncertainty (Kensek et al. 2004, 183; Strothotte 1999, 36). Bakker et al. summarize it as follows: "*Truth and credibility as double ambition: reconstruction of the built past experience and dilemmas.*" However, its use of visualization is more artistic than scientific (Bakker et al. 2003, 5ff). To sum up, photorealism is avoided for interpreted data in most recent scientific reconstructions.

Figure 5: Example of a photorealistic rendering of an ancient building structure. The illustration refers to the investigations of the Agora of Segesta, for which several virtualization methods were tested (Olivito and Tavvola 2014, 176 and 181).

Simple (fig. 6) or abstract styles are more used for uncertain structures (Reimersdahl et al. 2008, 147). The objects are usually default to simple geometrical forms and textures. Furthermore, the amount of details shown is decreased. Since uncertain parts are not modeled anymore, the certainty of the whole object increases. On the other hand, the accuracy will decrease (Alusik and Sovarova 2015, 438). Similar approaches are known to be followed by architects in which only the rough outline is shown first (Strothotte 1999, 36). Moreover, fewer details also mean fewer polygons, which enables a better use in real time rendering applications[7] and the connection of data and model (Fanini and Ferdani 2012, 112). As a result, schematic renderings can emphasize uncertain areas (Murgatroyd 2008). Thus, they indicate the speculative nature of the objects (Zuk et al. 2005, 3). Furthermore, they are easy to apply and are therefore often used. Frischer and Stinson use lighter and less saturated colors to indicate uncertainty in their reconstruction of a villa. Delicate details are neglected completely to emphasize the uncertainty (Frischer and Stinson 2007, 66). Strothotte completely avoids details in uncertain areas, which facilitates easy access to other methods to enrich the result (Strothotte et al. 1999, 36f).

Figure 6: Example of a schematic rendering of an ancient building structure. Hereby, the render format emphasizes the point of interest due to higher details. The picture itself is of a reconstruction of the Palace of Margaret (Brusaporci 2017, 130).

Mixing both of the previous approaches (fig. 7) is defined as overlay (Schwerin et al. 2016, 212). The value of this style lies in the ability to distinguish real and interpreted data quickly and easily (Schwerin et al. 2016, 212; Olivito and Taccola 2014, 182). For example, Schwerin uses laser scan data that is incorporated into the schematic reconstruction of the temples. Furthermore, both datasets can be easily enriched by further information, such as different degrees of uncertainty (Schwerin et al. 2016, 211f). However, in parts

[7] Real time rendering applications are usually the end product of game engines. They enable one to view and manipulate a rendered 3D model in real time. This means that this type of application is also strongly tied to computer performance. More well-known uses in archaeology are, for example, integrated models with connected databases or a 3D GIS.

with high certainty she also increases the level of detail and segmentation to provide a better scale and organization (Schwerin et al. 2016, 211). Likewise, Olivitio and Taccola mix their styles for their reconstruction of the agora of Segesta (Olivito and Taccola 2014, 179 and 181). It works by placing simple geometrical forms over the reality-based model to indicate possible structures that no longer exist. However, it is not possible to encode floating uncertainty with this method (Olivito and Taccola 2014, 182). It more or less resembles the Boolean uncertainty or crisp sets.

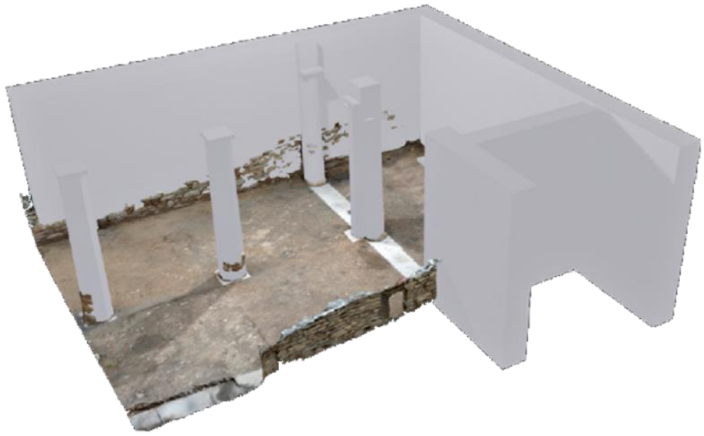


Figure 7: Example of an overlay rendering, which shows a reality-based reconstruction as a photorealistic model, combined with a schematic overlay for the hypothetical parts. The model itself refers to the agora of Segesta (Olivito and Tavvola 2014, 182).

As well as the photorealistic, abstract or mixed approaches, changes in the data itself can also give hints of uncertainty. One way is the organization of the data. This can happen with layers or segments. The exact realization is described below.

2.3.5 Organization

Even the organization of the data provides the possibility of encoding additional information. In contrast to the modeling and visualization, it does not always have a direct and visible impact on the model itself. One possibility is to consider various levels of detail. These are especially helpful when it comes to reduced hardware requirements. Basically, a level of detail represents the amount of displayed details or polygons used for a model. However, a high level of detail might give the impression of photorealism and mask the uncertainty of the scene (Frischer and Stinson 2007, 66). Guidi et al. use several levels of detail to verify the scientific background in an iterative process. Firstly, only basic and certain information is used for the model. When it is verified, the next level of detail is processed. The process is repeated until the intended level is reached (Guidi et al. 2013, 103f). However, the uncertainty also rises with a rise of detail. Therefore, the final level of detail should be chosen according to the actual data available and the audience. Apart from the geometry, the style and texture are also influenced by this process. Since the normative 3D model does not have a point of interest, this technique can be also used to guide the observer's gaze (Wittur 2013, 47).

A similar approach is the use of layers. However, layers do not necessarily represent exactly the same object with simplified geometry; they can also show the same object with an entirely different geometry. Different layers make it possible to work on different branches without changing the original file (Rua and Alvito 2011, 3000). This is especially useful since often more than one interpretation is achievable. The layers are usually organized hierarchically (Hermon 2008, 38; Kensek et al. 2004, 183). Following that, further layers can indicate changes in structure, and therefore differences in uncertainty. According to Wittur, the best result is achieved when the extreme situations and the general ones are created and the differences are pointed out (Wittur 2013, 46f).

Finally, the organization of uncertainty can be achieved through segmentation. Manferdini et al. has developed a system in which he classifies and assigns data to the individual parts of a 3D object. Consequently, the structure is split into its individual components according to basic geometric rules. Each of those parts can be used to link attributes and values (Manferdini et al. 2008, 1). Furthermore, segmentation enables the easy description of uncertainty or other attributes to the addressed parts (Manferdini et al. 2008, 2). The link between the database and model is an important aspect of transparency (Manferdini et al. 2008, 5). Kensek et al. proposes using segmentation for assigning uncertainty to individual parts of the structure and the resultant visualization (Kensek et al. 2004, 182ff). Apollonio and Giovannini use a mixture of segmentation and a level of detail whereby an uncertainty value is assigned to each of the levels and segments, which is later used as a basis for a color code (Apollonio and Giovannini 2015, 9ff). Schwerin et al. considers segmentation as a medium of authenticity or reliability. In total, she uses four levels of segmentation and detail. These were described and defined previously and each one has an own level of certainty (Schwerin et al. 2016, 211).

All in all, the organization can happen according to the level of detail, layers or the segmentation of the object. Basically, all of these approaches divide the object into smaller parts. Since those parts consist of only one unit, they are easier to work with. Several methods related to this approach can be found in the literature. However, while researchers might use the same framework, they rarely use the same parameters. The most common ones will be described in the following section.

2.3.6 Established methods

The principles outlined above have already led to established methods. These often combine several of the above-mentioned aspects in order to handle complex systems. Some of them are based on a single framework (modeling technique, visual representation or style direction), while others comprise a mixed approach.

Shaders: Transparency-based shaders and color-coded shaders (diffuse shaders[8]) are based on the solid render mode. A color code (fig. 8) is detectable in many publications and books since it is a powerful means of encoding several options and has also been previously used for many items, such as maps and drawings. Apollonio and Giovannini use a color gradient from greenish to reddish colors for their reconstructions. Each step represents an evidence-based classification (Apollonio and Giovannini 2015, 8). Bakker confirms the opinion of Apollonio and Giovannini (Bakker et al. 2003, 163). The individual colors work as a transmitter of information, in this case represented as uncertainty (Dell'Unto et al. 2013, 624; Hermon and Nikodem 2008, 144). Another term for color code is "*false color*". However, solid mode also enables the rendering in a mixed, schematic or photorealistic style, which might represent the transition from real data to interpreted information (Kensek et al. 2004, 178). However, not everyone sees the same foundation, because it is set behind the color code. While Apollonio and Giovannini use a gradient between two colors[9] (Apollonio and Giovannini 2015, 8), Sifniotis uses contrasting colors[10] (Sifniotis et al. 2006, 1). In contrast, Kensek et al. suggest either a high contrast of the colors or a similar tone to the original colors (Kensek et al. 2004, 177), while Hermon sees "*ghosts*" as the best form of false colors. Ghost colors are the original color in a much subtler form (Hermon 2008, 39). Frischer and Stinson, who use less saturated color for uncertain parts, are of the same view (Frischer and Stinson 2007, 66), and tend to use only grey tones (Frischer and Stinson 2007, 67). Schwerin applies a different approach, namely using a monochromatic color scheme of blue to express various levels of uncertainty for her reconstructed Mayan temples (Schwerin et al. 2016, 213). Another article in which a color code is used is one by Apollonio, and the code is based on evidence (Apollonio 2016, 187). Nevertheless, disregarding the chosen color and/or harmony, all the authors seem to agree that the relation and description are essential to the outcome. The relation between color and the uncertainty value in detailed para- and metadata documentation is extremely important (Frischer and Stinson 2007, 66; Kensek et al. 2004, 183). A detailed

[8] Technical term for color representation in Blender.
[9] = analogous colors (see "*2.7.2 Colors*").
[10] = complementary colors or triadic harmony (see "*2.7.2 Colors*").

investigation of different color concepts and their perception is briefly summarized in *2.7.2 Colors,* since the rules of harmony and contrast are not taken into consideration in some archaeological case studies.

Figure 8: Project for twin columns from Palladio in which a color code is used to encode the uncertainty within the columns (Apollonio 2016, 191).

Textures: One step towards further complexity are textures. Textures can hold images of real objects and are consequently also displaying the color and material with high certainty. Textures are a basic element for photorealistic approaches (fig. 9) (Agapiou et al. 2011, 20). Textures can be derived from the objects directly in the field, which might be still *in situ* or relocated (Fanini and Ferdani 2012, 112). Therefore, this approach can imply a high degree of certainty and a photorealistic appearance (Kensek et al. 2004, 183; Reilly 1992, 158). Alusik and Sovarova use schematic versions of textures for their materials. However, they are not photorealistic yet, to avoid too much confidence (Alusik and Sovarova 2015, 441f). Physically based maps[11], such as bump maps[12], can be used to improve the visualization even more (Manferdini et al. 2008, 227). A more detailed explanation of this kind of rendering can be found in 2.7.3 *Physically based rendering*. These methods can enrich the information about the real material (Rua and Alvito 2011, 3303). The above-mentioned physically-based textures in particular seem to be a

[11] Special type of texture that encodes the physically-correct behavior of the surface in several individual textures.
[12] Shows shadows and bumps on a three-dimensional surface where non are.

promising new technology to code further information into models without changing the geometry.

Figure 9: Photorealistic reconstruction of the Stevensweert Castle. The authors are using a reddish texture for uncertain parts and a greyish texture for certain parts (Bakker et al. 2003, 4).

Symbols and cues: Lastly, uncertainty can be represented with symbols and cues. One possibility would be simple lines (fig. 10) that separate two degrees of uncertainty (Hermon 2008, 39). Furthermore, the kind of line can add an additional dimension and represent the actual value of the attribute (Strothotte 1999, 39f). In general, line drawings denote a lower certainty than photorealism (Eiteljorg 2000). According to Zuk et al., "*side views, pseudo color, contour lines, blinking material properties, texture mapping, bump mapping, oscillation, displacement, and blur*" (Zuk et al 2005, 102) are also described as cues. They can give a first impression of the visualization's certainty. However, it is difficult to represent reality with only hints of visualization (Murgatroyd 2008).

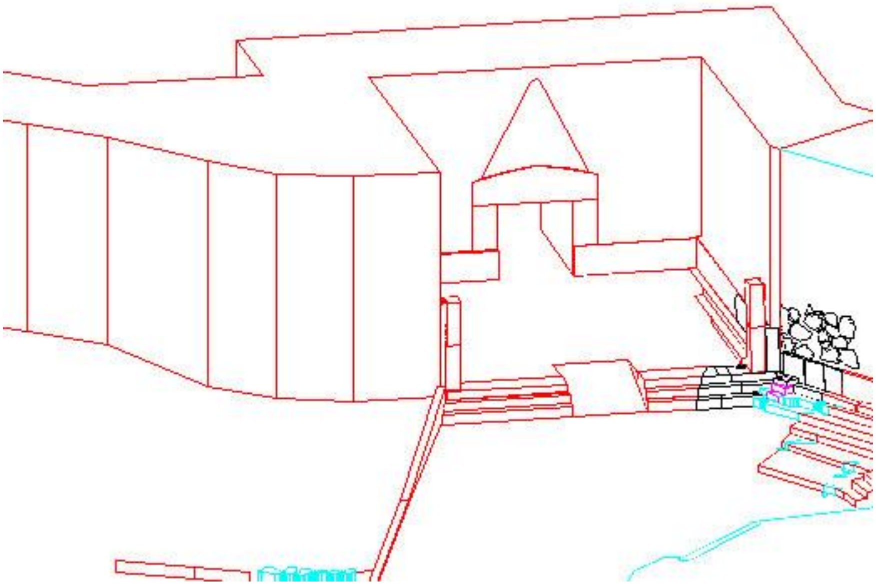


Figure 10: Eiteljorg is using different kind of lines and color to encode uncertainty in his reconstruction of the entrance of the Athenian Acropolis (Eiteljorg 2000).

In summary, there are many ways to encode information directly into the model. Roughly, they can be summarized as modeling technique, visual representation and style direction. Each of them has its own tweaks and techniques to refine the information load of the object. In practice, they are already in use, either as a single or mixed method. Combining these frameworks in a well-elaborated concept might offer a powerful tool to indicate an object's uncertainty. These techniques are applied to the individual segments of an object. However, as the false colors already suggest, there is no uniform regulation. Scholars just choose the method that fits their data best. In doing so, they do not consider that they lose immense potential in terms of gaining the optimal results. More potential can also be achieved through the data. To this end, the next subchapter deals with the handling of information and databases in more detail.

2.4 Documenting the research

2.4.1 Overview

Next to the visualization of the model, the documentation of the design decision plays a major role. The London Charter and Principles of Seville even provide complete chapters for this process, since documenting research is important in order to provide a sustainable level of transparency (Brusaporci 2017, 124f). Hereby, all the data has to be described for later analysis (Reilly 1992, 160). In an optimal case, the researcher creates his or her own documentation (Alusik and Sovarova 2015, 438). When doing this, the long-term use of the data (Stanly-Price 2009, 41) and the research question has to be considered (Kantner 2000, 48). In general, the content is based on metadata and paradata (Brusaporci 2017, 125). While metadata is a description of the more technical aspects, paradata comprises the decisions and interpretations. Both are required to gain a certain degree of reliability (Brusaporci 2017, 125 and 142f).

It is also recommended that critical data is documented. This might enable a wide variety of different interpretations (Reimersdahl et al. 2008, 147). Likewise, the subjective decisions and ideas of the leading scientist should also be noted, apart from quantitative data and illustrations. These might be helpful in the later stages of analysis (Bruschke and Wacker 2016, 257). One new form of documentation is reality-based models. They store the quantitative data of the spatial and color information of the object with high accuracy (Agapiou et al. 2011, 22). Furthermore, a standardized ontology is suggested by Apollonio and Giovannini when describing an object. This can provide a cross-compatibility over several projects (Apollonio and Giovannini 2015, 9). Each segment of the model should be annotated individually with the corresponding data (Manferdini et al. 2008, 221).

In conclusion, the documentation is necessary to explain the results and make them transparent. This also emphasizes the uncertainty of the object. However, no standards are established yet, especially for archaeological purposes (McCurdy 2012). Eiteljorg summarizes it best with the sentence: "*[We] must [be] explicit about [the] methods used to create the images. How do we get the textures and surfaces? How do we position [the] lights? How do we decide [on] reflectivity and ambient light? In short, how much reality is included in the images and how much [is] artistry?*" (Eiteljorg 2000). Skipping this process will damage the scientific background and value of the research immensely, especially with a 3D model (Hermon et al. 2006, 123). Likewise, the visualization is usually the result of the research, so a linkage of data and interpretation is obligatory (Bruschke and Wacker 2016, 257). Accordingly, the following possibilities for documentation are presented. Furthermore, three concepts of uncertainty are introduced.

2.4.2 Various forms of documentation

The last main form of documentation is the written text. Additional information can be added by, for example, illustrations or tables (Reilly 1992, 160; Alusik and Sovarova 2015, 439; Kensek et al. 2004, 179). However, publications in print form previously limited the extent of possible media formats (Reilly 1992, 148; Ryan 2001, 257). With the progress of time, databases (tab. 2) and semantics were added to the traditional form of documentation (Kensek et al. 2004, 108). With the establishment of databases, the explicit documentation of paradata and metadata became more popular and important (Hermon 2008, 39). From now on "*spatial, temporal and functional aspects or even* *multiple levels of uncertainty*" can be recorded and analyzed (Bruschke and Wacker 2016, 262).

Since the exponential increase of information records, databases have proven in many cases to be standard containers for data storage. Moreover, they also are able to link external objects and models (Guidi et al. 2013, 102; Hermon and Nikodem 2008, 143). Furthermore, real time interactions are possible for analysis purposes (Fanini and Ferdani 2012, 108). Therefore, a model can be linked with its corresponding discussion (Manferdinie et al. 2008, 221ff). However, an intuitive understanding is hard to accomplish. The databases are usually highly complex. Flow charts and diagrams help one to understand and use them, and are therefore highly recommended (Hermon 2008, 38). Additionally, 3D models that are described in a database need to be broken down into smaller segments of logical geometry or architectural parts.

Table 2: Overview of several documentation formats. The table is limited to the best-known examples from archaeology. The most common form of databases in archaeology are marked in blue (Brunke 2017)

Language	Text	XML	SQL	Cypher
Software	Microsoft Word, Open Office Writer, …	Notepad ++, Atom, …	Microsoft Access, PhpMyAdmin, …	Notepad ++, Atom, …
Structure	Written text	Hierarchical	Relational	Graph

XML is one possible data format (tab. 2). Its advantages are clearly its dynamic structure and the easy way to extend already existing databases. Furthermore, it is readable by humans. The database itself was created with a hierarchic structure. Moreover, the resource description framework is often associated with it. To provide cross-compatibility, an open ontology is advised (Kurocynski et al. 2014, 4; Vatanen 2003, 71). In some cases, it is even possible to incorporate an XML database directly into the file of the 3D model. It is required that the file is also based on an XML structure, such as X3D. However, this should be done only for less complex situations (Martini and Ono 2010, 435; Ryan 2001, 257). A popular ontology that is used with XML based databases is the CIDOC CRM (Bruschke and Wacker 2016, 267).

Another database format is that of the above-mentioned relational databases (tab. 2), which uses SQL as query language. They are the most prominent examples and have already been in use for 40 years in archaeology. However, creating relations between datasets from different tables has its weaknesses. For example, another table must be created that contains only the information for the relation, a so-called join table[13]. The organization and design are often more complex than that from XML-based databases (Bruschke and Wacker 2016, 267).

A database that is not based on SQL can be a graph database (tab. 2). It can use XML as background language but also has its own languages. These forms of databases are highly suitable for linked datasets with many relationships between the nodes. Each node and relationship can furthermore own properties. If necessary, they also accept ontologies such as the CIDOC CRM (Bruschke and Wacker 2016, 267). The name was coined because the datasets of such databases can be visualized and analyzed as graphs. If this is not desired, the results can also be returned in the form of tables or text (Bruschke and Wacker 2016, 268).

Triple paths can be put under the label of XML databases. They use the same language but a different structure to common xml databases. The structure itself is quite similar to the structure of graph databases. Several publications already recommend the use of this database for archaeological purposes. According to Ryan, they might offer a good opportunity to describe research in virtual archaeology (Ryan 2001, 245). Their value lies in the possibility of connecting uncertainty directly with several alternatives by multiple relationships (Ryan 2001, 246). As ontology, the Dublin core is advised (Ryan 2001, 248; Kuroczynski et al. 2016, 151). Triple paths are related to the resource description framework (rdf), which is understandable by computers and consist of a "*Subject (a resource) – Predicate (a property name) – Object (a literal property value*)" and a form of ontology. Transferred to a 3D model, the subject is the name of the segment, the predicate the property, such as the size and the object, and the value of the size. As many entries as possible are saved in the form of URIs (Ryan 2001, 254f; Kuroczynski et al. 2016, 152). As previously mentioned, some file formats are capable of incorporating small xml databases in the form of triple paths (Ryan 2001, 257). Those are SMIL (Ryan 2001, 259ff), SVG (Ryan 2001, 261ff) and X3D (Ryan 2001, 263ff).

In conclusion, triple paths provide the opportunity to connect sources, data and interpretation with visualization – another form of interpretation (Kuroczynksi et al. 2016, 150). However, it is not the only possibility to store data. The choice of format depends

[13] Join tables are a special kind of table in relational databases. They have to be used when a m:n (multiple to multiple) relation occurs. Basically, they contain at least two indices in one row. These represent the index of distinct databases, but are hereby connected over a relationship.

on the available data and the desired final results. While graph databases are strong in terms of relationships, relational databases can more easily hold and order much larger amounts of data. However, there are also overlaps. For example, a written text can be enriched with XML annotations, or a graph database can display data in tables. However, it is also from importance how the design decisions are processed and stored in such databases. It is not always easy to express them in an understandable way for computers and humans equally.

2.4.3 Express and detect design decisions

In order to find the right form of database, it is important to understand the existing data. That includes knowing its type and origin. Likewise, it is also important to determine what kind of analysis might be done with it. In this case, the main concern is uncertainty. However, all interpretations and assumptions are based upon data. In an ideal case, each of the processes involved is somehow documented. However, how are uncertainty and especially the design decisions stored to provide a transparent result? Firstly, all sources and available data are classified (= class-based uncertainty)[14]. Each classification can represent an own level of certainty (Wittur 2013, 38). Usually a gradient from certain to uncertain is used. In a later processing step, each value of the gradient can be assigned to a specific visualization representation, such as a color code. Apollonio and Giovannini use this method. However, the background data is more important. The sources are ordered in terms of reliability, where the most reliable are actual measurements and least reliable are missing data. The space between is filled with a smooth transition. In this case a certainty scale is applied in relation to the geometry of a building structure, with classifications of possible sources (Apollonio and Giovannini 2015, 8).

By contrast, Strothotte does not use an uncertainty scale at all. He describes it as "*design decisions […] Type of reason*". Those are classified in "*excavation […] physical constraints […] period features […] analogies […] deductions*". However, in the end they still represent a gradient from certain to uncertain (Strothotte et al. 1999, 3f). Dell'Unto's approach is to encode the uncertainty of the reconstruction in terms of "*objectivity […] testimony […] deduction […] comparisons […] analogies […] deductions*", which likewise means the same as the two approaches mentioned above (Dell'Unto et al. 2013, 624f). In contrast to the former methods, he gives the analogies a much higher degree of reliability than the other authors. Furthermore, he directly represents the uncertainty rather than a degree of

[14] For the sake of clarity, this method will hereafter be referred to as "*class-based uncertainty*". The reason for this is that the individual sources are grouped in classes that represent one unit.

uncertainty. Each class is assigned to its own color, which is directly applied on top of the mesh surface (fig. 11) (Dell'Unto et al. 2013, 626). In Apollonio's publication, he follows a similar approach. Classes are described by the sources and each class is allocated a color. The term "*uncertainty*" is disregarded completely, since everyone can decide for him- or herself (Apollonio 2016, 187). In general, it should always be made clear that, at one point, all discussions, arguments and assumptions are described in a structured way (Wittur 2013, 38).

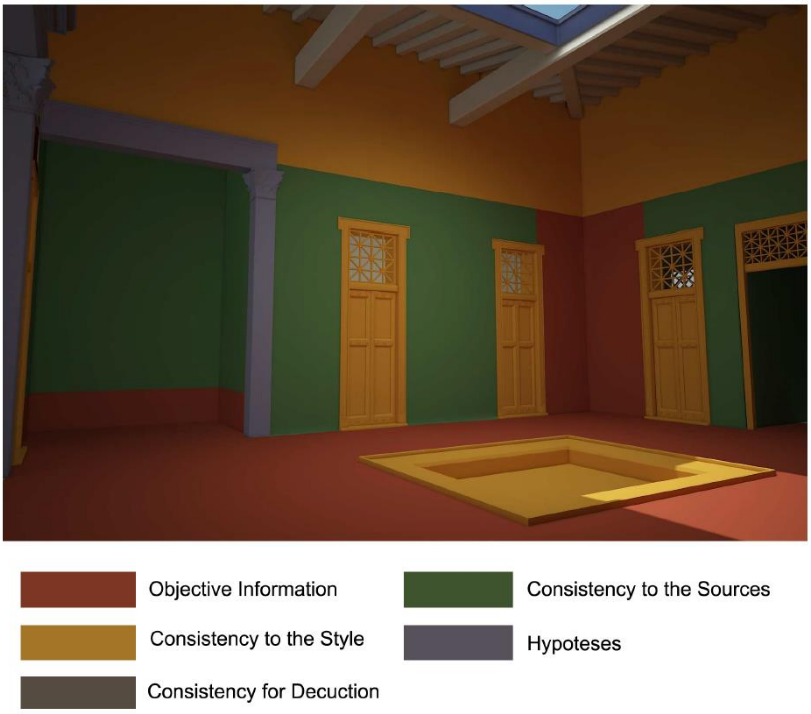


Figure 11: Example of class-based uncertainty. The reconstruction represents the atrium of a building in Pompeii. A color code is used as coding for the classes (Dell'Unto et al. 2013, 626).

Thirdly, instead of using words as synonyms for the uncertainty, direct numerical values can be used (= fuzzy-based uncertainty)[15], as in Hermon and Nikodem's approach (fig. 12). With the help of fuzzy logic they calculate explicit values out of a reliability and importance index. This value is treated as an uncertainty index and assigned to building components (Hermon and Nikodem 2008, 4f). However, their approach lacks some points of explanation or transparency in the discussion, since the original values represent only the authors' opinions about their confidence. Kensek et al. seem to use a similar approach, since their visualizations allow for conclusions about absolute values in their automatic reports (Kensek et al. 2004, 178ff).

[15] For the sake of clarity, this method will hereafter be referred to as "*fuzzy-based uncertainty*". The reason for this is that the numerical values are based upon fuzzy logic. Sources are also involved here. However, these are enriched with numeric values.

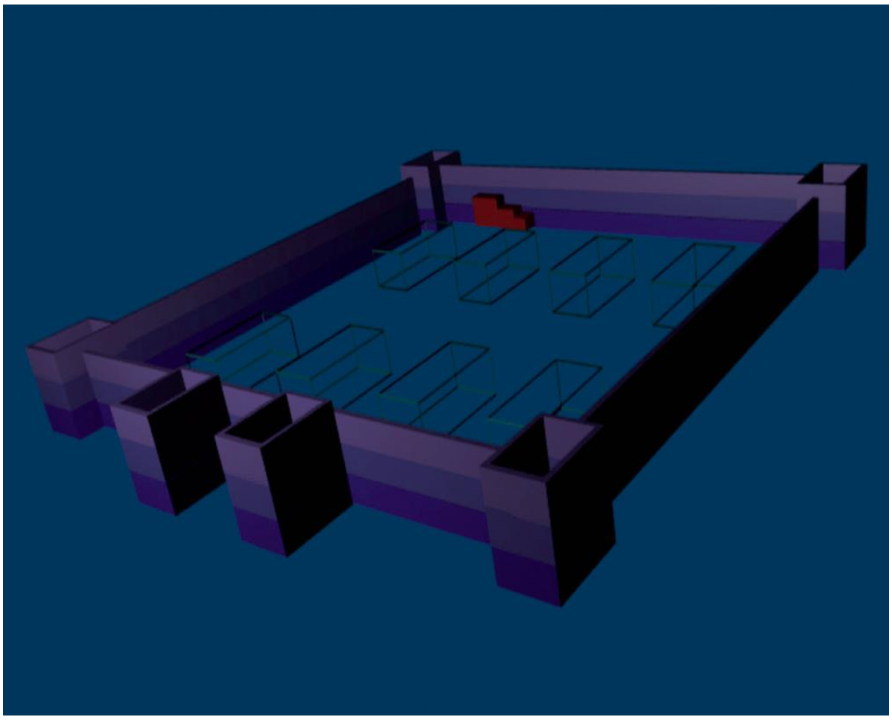


Figure 12: Example of fuzzy-based uncertainty. The reconstruction represents a Roman house in Pompeii. A color code is used to encode the numerical values (after Hermon and Nikodem 2008, 5).

Finally, instead of several classes, Boolean operators or crisp sets can be used. Bakker et al. differentiate only between the actual remains of the building and his interpretations (Bakker et al. 2003, 4). Thus, he has only two states, namely certain (photorealistic) or not certain (schematic) (Bakker et al. 2003, 4). Reimersdahl et al. use a kind of mixture. Their datasets contain more states than certain and uncertain. However, the visualization shows only two classes, whereby certain areas are encoded by photographs (Reimersdahl et al. 2007, 4). However, this case is an exception. Likewise, Patay-Horváth also follows the principle of crisp sets when visualizing the statues of the Zeus temple (Patay-Horváth 2014, 18ff). A Boolean visualization can be found in many papers (fig. 13).

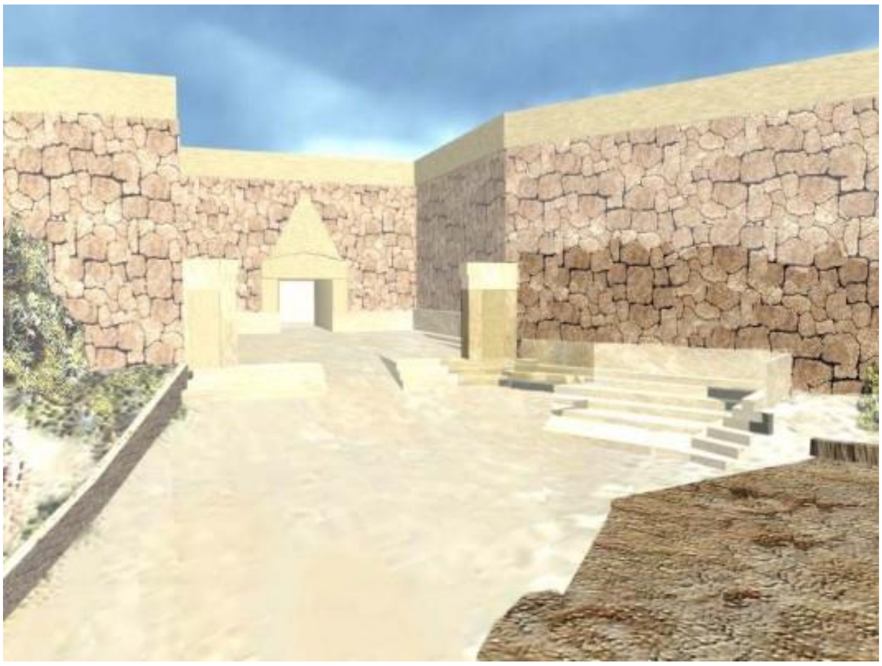


Figure 13: Example of a Boolean representation. The rendering shows the walls and gates of the Athenian Acropolis. The less saturated textures are uncertain, while the more saturated ones are certain (Eiteljorg 2000).

However, uncertainty can also be completely neglected in visualizations and documentation. Case studies related to this are not further discussed in this chapter, since they do not improve the result. Nevertheless, Sifniotis et al. investigated the extent to which sources can influence the uncertainty of a model. He asks other scholars to order "*Features […] Artefacts […] Biofacts […] Textual evidence […] Absolute comparison […] Contextual comparison […] Topography […] Peer review*" according to their reliability as sources for reconstructions. His results are indicative of the fact that most scientists agree with the lowest and highest term. However, the mid-levels might vary (Sifniotis et al. 2007, 7). Therefore, most reliable and powerful seems to be the actual feature or artefacts.

In general, however, three concepts of uncertainty can be distinguished. Firstly, there is source classification. Different sources are grouped together and classified according to their relative uncertainty. In the course of this work, this approach is described as "*class-based uncertainty*". Secondly, there is the numerical allocation of uncertainty values to an object. Hereby, the scholar assigns his confidence in the form of a number to a specific object. This is correspondingly best described as fuzzy-based uncertainty. Finally, there is the use of Boolean operators, which allow for only two states, namely certain or non-certain, or reality-based and evidence-based. As can easily be seen in the illustrations, certain data types fit best with certain databases and also a certain type of visualization. The difference can be seen in the choice of colors. The classifications are represented by several contrasting colors, while the numerical values use a gradient of one color. The Boolean value must show only a high contrast. Like in above's paragraph indicated many visualizations consist of static images. Not always this form of medium is optimal for archaeology. Other formats might be animation or interactive models and are described following.

2.5 Modern publication methods

3D reconstructions can usually be found as 2D renderings and print in nowadays publications. They have become popular and diverse in their use. The main emphasis is on architectural reconstruction, as, for example, in Alusik and Sovarova (2015, 444); Bakker et al. (2003, 2) and Huggett and Guo-Yuan (2000). This form of publication is not optimal since most of the spatial information gets lost or reduced to planar faces. Some authors, such as Apollonio (2016, 190), enrich their renderings by using textures that might encode certain data. Additional legends might be added.

Animation provide moving scenes. Even more information can be stored within animations. Time is added as an additional dimension (fig. 14), and sequences or building phases, for example, can be encoded. This is especially popular in museums or for film productions. The next level is caves. Furthermore, they can interact with the observer and show integrated animation (Frischer and Stinson 2007, 59).

Integrated animation or interactive models offer some huge advantages. The models are fully navigable and can be used in a variety of ways (Rua and Alvito 2011, 3305ff). Three-dimensional data can be measured, analyzed or enriched (De Kleijn et al 2016, 26ff; Schwerin et al. 2016, 219). Therefore, they are highly suitable for adding all kinds of information, including uncertainty, discussions, or alternative versions. This data is usually stored in databases and can be directly connected to the model. Using this method, Kensek et al. developed a system in which several alternative versions of columns can be chosen interactively and the information and uncertainty is refreshed automatically (fig. 14) (Kensek et al. 2004, 181ff). However, they still used rendered 2D images mixed with an interactive approach. Nowadays, game engines, for example unity, web players such as Sketchfab or all of the common 3D modeling software are tools that offer similar solutions.

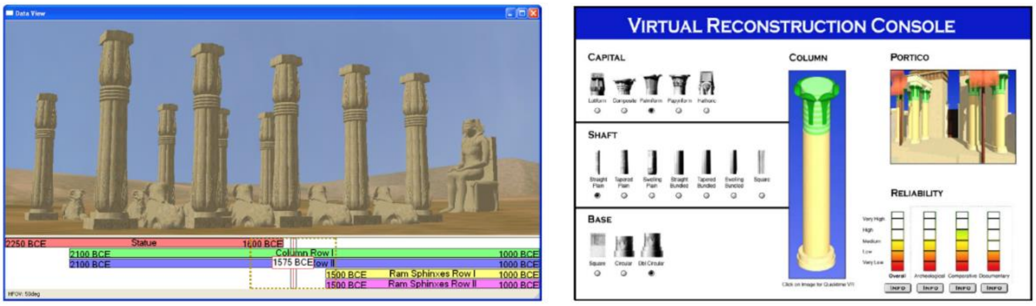


Figure 14: Zuk et al. use animation and transparent shaders to display temporal uncertainty over time (left) (Zuk et al. 2005, 105), while Kensek et al. are working on an interactive approach to offer several alternatives and additional information (right) over and above uncertainty (Kensek et al. 2004, 183).

Therefore, three publication methods are available. While static images are in wide use, interactive models might represent future approaches. They enable the connection of visualization with data. Likewise, similar concepts are already in use for architecture and engineering. The applications are known as building information modeling and they are described in the next section.

2.6 Building information modeling

Building information modeling (fig. 15) is often seen as extension or even development from CAD systems. To manipulate BIM data, ArchiCAD, Revit Architecture, Allplan Architecture, or similar tools are needed (Logothetis and Stylianidis 2016, 28f). The main component, apart from simulation and modeling, is the possibility to connect the created geometry with actual data, which converts the file into a 3D database (Apollonio et al. 2012, 42, 58; Logothetis and Stylianidis 2016, 28). The method of parameterizing virtual objects is mainly used in engineering and architecture. However, archaeology might profit from this development as well, since any data can be saved in relation to the model (Logothetis and Stylianidis 2016, 28). It would fulfill its purpose in the archiving and documenting of virtual reconstructions and facilitate the evaluation of architectural credibility. Garagnani names this principle ArcheoBIM (Garagnani et al. 2016, 77).

Figure 15: The process of a BIM object. In contrast to a regular model, it clearly contains several steps. Furthermore, documentation and analysis are required from the beginning and non-optional (Syncronia 2011 in Logothetis and Stylianidis 2016, 29).

The base unit of each BIM is comprised of the geometrical and architectural fundamental forms. The linking to the data works over the semantic regulation (Apollonio et al. 2012, 42). Parametric modeling (Logothetis and Stylianidis 2016, 29) can bridge gaps and draw data from analogies (Apollonio et al. 2012, 47) and are object based. This means the object or category has to be defined before it is modeled. After that, parameters and geometry can be assigned to the object (Appollonio et al. 2012, 48). The objects are gathered in catalogues and linked semantically (Apollonio et al. 2012, 52). However, most of the existing libraries are focused on current objects and have a lack of historical ones. Consequently, work on a HBIM (= historical building information modeling) is done (Logothetis and Stylianidis 2016, 29).

As a small example, the research of Garagnani et al. 2016 is to be considered. They investigated the use of a BIM system for an Etruscan temple. Before the parametrization and creation of objects, the data was collected during fieldwork and literature work. The focus of the literature research was especially on the books of Vitruvian. According to the project leader "*the primary aim was to establish [the] credibility of architectural and engineering criteria expressed by a virtual building process*" (Garagnani et al. 2016, 78 and 80). Consequently, the decisions and arguments of the reconstruction process were described in a detailed report (Garagnani et al. 2016, 78-81). This ensured that the BIM relied on a fundamental basis of knowledge and offered a wide variety of data and connections between the data (Garagnani et al. 2016, 82). The BIM system proved to be a valuable addition to the storage and organization of data, coupled with the model, and can be seen as a "*knowledge management system*" for 3D archaeological heritage data (Garagnani et al. 2016, 84). Apart from the data storage, three different theories and concepts from mathematics, color and design sciences can be used for a higher information density in the final model. However, these approaches need a detailed introduction in order to deliver the expected results.

2.7 Theories and concepts

2.7.1 Fuzzy logic

The principle of vagueness is common in spoken language. While describing a certain object, the exact attributes and parameters become substituted by vague expressions (fig. 16), which indicate only the real-world data. However, they still have to describe the degree of membership, especially when using them in mathematical analyses (Kruse et al. 1994, 2). Since there are fewer rules, the system is seen as quite intuitive (Cox 1994, 7). Due to imperfect data it becomes even less complex (Kruse et al. 1994, 1). The core element is the fuzzy sets, which describe the degree of membership. The degree is represented by an interval of [0, 1] (Cox 1994, 2; Dubois and Prade 1988, 14). Therefore, it becomes highly suitable for representing uncertainty (Klir and Yuan 1995, 4). Crisp sets (fig. 16) describe the opposite and are either 0 or 1. Instead of numbers, the Boolean operators "*true*" and "*false*" can also be used. This sharp distinction of data might work only in theoretical models. The real world usually does not build up on this system (Klir and Yuan 1995, 4 and 220).

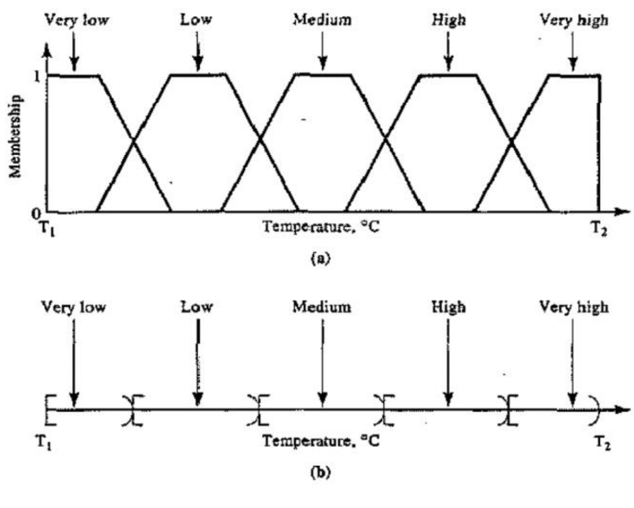


Figure 16: Comparison between a fuzzy dataset (a) and a crisp dataset (b). The graphs clearly indicate that fuzzy sets have no sharp boundaries and can flow smoothly into another one. The single value, here temperature, can be perceived over a longer range. In contrast, crisp sets allow only the assignment of a temperature to predefined intervals (Klir and Yuan 1995, 15).

The membership function of the fuzzy logic describes the degree of membership of an individual object to a subject. Hereby, each object is assigned an own value (Klir and Yuan 1995, 4). A similar approach is provided by the probability theory (Klir and Yuan 1995, 187). By contrast, the probability theory deals mainly with random distribution, while fuzzy logic uses actual data (Cox 1994, 19; Nicolucci and Hermon 2010, 30). Consequently, fuzzy systems can describe real-world behaviors in most cases best (Klir and Yuan 1995, 15). Transferring the idea of fuzzy systems to an archaeological context, the membership function indicates to what extent a piece of evidence might prove or disprove a certain theory, which results in a degree of uncertainty. A crisp set would represent perfect data, which would make each investigation unnecessary (Klir and Yuan 1995, 177), while fuzzy data might represent the best data from archaeological research and should be used as a leading method (Sifniotis et al 2006, 1; Nicolucci and Hermon 2010, 28). While fuzzy logic is completely based on mathematical principles, colors seem to be more subjective. However, the theory indicates soon that also the colors are based on static rules.

2.7.2 Colors

Colors are a major factor in design and serve in many cases as information transmitters (Wäger 2017, 15). However, the reception and interpretation of colors are heavily dependent on the society. Changes over time and from one geographical region to another are not uncommon (Wäger 2017, 64). The primary colors cannot be created by mixing (Wäger 2017, 81). Therefore, secondary colors emerge when two primary colors are mixed in a ratio of 1:1 (Wäger 2017, 82f). Primary and secondary colors are rare in the natural environment. Most natural colors are from tertiary nature (Wäger 2017, 84). The actual colors depend on the blending mode and can be separated in additive (light) and subtractive (particles) nodes (Wäger 2017, 81). Black, white and grey are defined as achromatic colors since their emergence is slightly different from the other ones (Wäger 2017, 86). Technically, colors are usually described with the RGB or HEX code for digital end products. Other codes would be CYMK, lab and the grayscale used in photography or printing. Each of them indicates the amount of primary color that has to be added to obtain a certain color (Wäger 2017, 94). Nevertheless, it should be noted that up to 8% of the male population has an eye malfunction, which might result in color blindness or shift (Wäger 2017, 142).

Various rule sets have been established over time to give the color combinations a meaningful interpretation. Most of them are known as contrast (tab. 3) and harmony theories (tab. 4). Firstly, there is the dark and bright contrast. This contrast is mainly used to differentiate between a foreground and background. The highest contrast that can be achieved in achromatic colors is black (0%) and white (100%), while blue (20%) and yellow (80%) represent the highest dark and bright contrast in chromatic colors (Wäger 2017, 254). Secondly, there is the color contrast. The color contrast contains assorted colors. The saturation and brightness might vary between pallets. The contrast itself is determined by the distance of the colors on the color wheel. However, all kinds of contrasts can be combined and mixed. Moreover, manipulated or mixed primary colors are usually more suitable for scientific representation since they are more pleasant to observe (Wäger 2017, 256). Thirdly, there are complementary contrasts, in which two opposite colors on the color wheel are used to express a high contrast between two datasets (Wäger 2017, 258). Fourthly, one has to consider warm and cold contrast, whereby the color wheel is rotated slightly so that blue is on the top and red at the bottom. This enables an easy categorization in warm and cold colors (Wäger 2017, 260). Fifthly, there is the saturation contrast, which is small rather than high (Wäger 2017, 262). Sixthly, the chromatic and achromatic color contrast is similar to the previous one, but with a higher contrast in total since it also includes all the black and white tones. Therefore, achromatic color can further emphasize chromatic colors when chosen correctly (Wäger 2017, 264). Finally, there is the area contrast, which is highly subjective and consequently less in use (Wäger 2017, 268).

Table 3: Colored examples of the various contrast theories. The examples are just a combination of countless possibilities (after Wäger 2017, 252-266 and http://paletton.com)

Contrast			
Dark and bright			
Color			
Complementary			
Warm/cold			
Saturation			
Chromatic and achromatic			

The color harmonies (tab. 4) can have similarities to the contrast. They relate to the combination of several colors with a pleasing color palette as outcome matches (Wäger 2017, 268). The harmonic triad uses three colors with the same contrast at the color wheel. When using primary colors, it is advisable to slightly manipulate the brightness, tint or hint to take away some of their prominence (Wäger 2017, 270). Similar to that is the tetrad harmony, which has four colors instead of three (Wäger 2017, 272). The complementary color harmony shows the complementary contrast by using two opposing colors from the color wheel. It can represent opposite opinions (Wäger 2017, 274). The analogous harmony bears a resemblance to a gradient. It combines neighboring colors on the color wheel and represents the opposite of the complementary harmony. The former harmonies can be interpreted mainly intuitively (Wäger 2017, 280). Lastly, we have the monochromatic color harmony. Hereby, the same color is used with different saturations and brightness (Wäger 2017, 284), which makes it suitable to display related data.

Table 4: Colored examples of various harmony theories. The examples are just a few of countless combinations (after Wäger 2017, 268-287 and http://paletton.com)

Harmony				
triad				
tetrad				
complementary				
analogous				
monochromatic				

Pbr-shaders are related to the color theory, but are not based upon the same principles. In contrast to the previously described theory, they encode another kind of information. Rather than showing harmonies, they encode information about light behaviors during the rendering process. The exact functionality and possible use for archaeology is explained in the next section.

2.7.3 Physically-based rendering

Physically Based Rendering (PBR) is an upcoming technology in the virtual reality world rather than a standard. In the process of pbr rendering, render information about light behavior is encoded in different kinds of texture maps (fig. 17). The main aim is to improve the behavior and the approach to reality (McDermott, 2f). This can be created by oneself or purchased on specialized websites, such as http://poliigon.com/ or http://textures.com. One set of maps usually includes a diffuse, albedo, ambient occlusion, normal, displacement, reflection and gloss texture map of the same object. Each texture map encodes a different kind of information for the lighting behavior (http://poliigon.helpscoutdocs.com/).

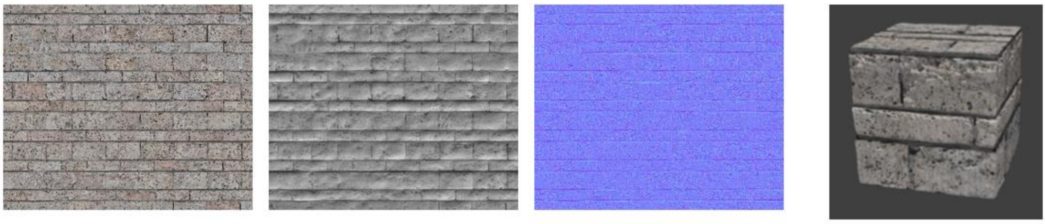


Figure 17: Texture maps of a material. The figure represents only a selection of the most common ones. From left to right: Diffuse map (+ ambient occlusion), displacement map, normal map and the rendered model (textures from/ after http://poliigon.com/).

Accordingly to Allegorithmic, the company that provides software to create and edit this data, one major advantage is that it "*provide[s] a workflow for creating consistent artwork, even between different artists*". Consequently, each map describes a different attribute of the same object (McDermott, 3). And a standard between several users is established.

In this case it might describe the behavior of light and manipulate geometry, but would it not be possible to transfer this concept to our problem and use distinct texture maps to encode various kinds of uncertainty directly upon the object? It might be even possible to use this form of data enrichment as base for conditional rendering.

2.8 Summary of the literature and theory

All in all, chapter two is responsible for providing important basic knowledge about various theories and methodologies. What is important to remember is the emergence of uncertainty. Uncertainty occurs with any form of interpretation of data, since it can be assumed that data is never perfect. Uncertainty can be expressed by blurred boundaries but also by various alternatives. However, consideration must be given to how this process occurs and that the leading factors are encoded in the working pipeline of three-dimensional reconstruction. This approach has resulted in as many different methods.

The first one is the visualization of uncertain data. The research has shown that this area is extremely diverse. Nevertheless, it can be summarized in a few key points (tab. 5). These key points represent the framework for further research. Each of them contains various sub-elements in how to visualize uncertainty explicitly. This can be, for example, the representation of a certain code or behavior.

Table 5: List of the various visualization and modeling techniques in archaeology. The last row indicates on how uncertainty is best encoded in this category. All the rows and columns are subordinate to the segment and layer of the object (Brunke 2017)

Segment & layer			
Modeling technique	**Visual representation**		**Style direction**
Box modeling	Wireframe		Photorealistic
Sculpting	Solid	Colors	Simple
Curve modeling	Texture		Abstract
Voxel	Material		Overlay
= Level of detail	**= Render mode**	**= Color Code**	**= Mixed**

The second is the documentation of the data. Although the variety is lower than with visualization, one still has the possibility to choose between different approaches (text and databases). However, the expression of uncertainty is more demanding and needs an exact definition. Currently, there are three possibilities: crisp sets, fuzzy-based uncertainty and class-based uncertainty. The literature already indicates a relation between special definitions of uncertainties and commonly used methods of visualization linked to this definition (tab. 6).

Table 6: Usual visualization of different uncertainty concepts. The table combines the data of the documentation with the method from the visualization. The background colors are related to the colors from table 5 (Brunke 2017)

Relational database in combination with a written text				
Crisp set	**Fuzzy-based uncertainty**		**Class-based uncertainty**	
Box modeling	Box modeling		Box modeling	
Mixed	Simple/ abstract		Simple/ abstract	
Wireframe	Wireframe			
Solid	Solid	Color	Solid	Color
Texture and Material	➔ Analogous or monochromatic colors		➔ Complementary colors	

Thirdly, we have the presentation method. The presentation itself cannot change much with respect to uncertainty. However, the data can be connected directly with the model and this linkage is essential for the final interpretation. Future approaches, such as building information modeling systems hold much potential since they also include tools for analysis.

Finally, the theories behind fuzzy logic, colors and physically-based rendering were presented. All these belong to outer-archaeological sciences but could contribute to the thesis with new ideas and approaches. In general, the framework that has been laid is multifaceted and has to be tested in an isolated environment. For this purpose, the following case study, which deals with the Roman architecture of a funerary monument, will be especially useful.

3. Case study: The reconstruction of a Roman funerary monument

One secondary objective of this research was the establishment of a representative reconstruction of the monument 434 (fig. 18) at the time of its construction. Likewise, providing an isolated case study to test the previous and afterwards elaborated methods. This necessitated using several reconstructive approaches due to incomplete data. Each of them will be represented with a prior discussion and evaluation of the reassembled parts. Emphasis is placed on a transparent outcome with the main emphasis on the uncertainty factor. To narrow the research down further, only the Roman period of this structure is investigated. Nevertheless, some later changes might also be important for the interpretation of the object.

Figure 18: The scan of a 1950s' postcard of the monument, seen in the left half of the photo between two pine trees (in Brunke 2017, scan from original).

The information in this chapter was collected during three weeks of fieldwork in Rome in 2017. The fieldwork was founded by a scholarship from the Koninklijk Nederlands Instituut Rome. Despite the ordinary procedure, only the Roman parts were investigated in detail. The monument (fig. 18), which is identified in the "*Mapping the Via Appia*" project with the ID 434, is described in various publications. These date back to Canina's

19th century report "*Della Via Appia: Dalla Porta Capena a Boville I & II*". Notably, most of the later descriptions cite his or Eisner's publication from 1986. However, these descriptions are mostly limited to the architectural context and contain little information about the history of the monument. Furthermore, one gets the impression that in many places the monument is treated rather superficially. Consequently, in the following sections an attempt is made to describe and interpret the architecture of the monument in detail. As a result, at least one hypothetical reconstruction is prepared. However, firstly general roman architecture and structures need to be discussed.

3.1 Roman architecture and tombs in general

Interpretations of Roman architecture contain a certain degree of subjectivity. To diminish this component, it is advisable to define the scope and content beforehand (Wilson 2000, 71). The absolute arithmetic scale and geometry in which Roman structures are often presented are mostly a vestige of the post-renaissance era (Wilson 2000, 87). Nevertheless, deviations often occur because of changed environmental conditions (Wilson 2000, 72 and 91). However, most of the structures have similarities in terms of proportions or geometry (Wilson 2000, 74). These similarities are often due to repeating proportions and patterns on simple geometric objects (Wilson 2008, 87).

The materials used for the construction are manifold and range from stone to wood and metal (MacDonald 1982, 145). The use of metal and wood is often underestimated, since it is not directly linked to the building remains (Mac Donald 1982, 146). The main function of wood was scaffolding (MacDonald 1982, 145f) and casings for concrete (Malcarino 2010, 152), while metal, usually lead, was used as clamps to further stabilize the structure (Lamprecht 2001, 33). The most obvious part is the stones, which can be walled up in diverse types (Malacrino 2010, 12). After Vitruvius, tuff, peperino, pumice, lime, travertine, sandstone, basalt and granite were the most common ones in Roman times (Vitruvius in Lamprecht 2001, 14f). Various suitable stone quarry deposits can be found in the region of Rome (Malacrino 2010, 10). The masonry itself was held together by mortar (Malcarino 2010, 67).

The foundations of a Roman building can be several meters deep under the ground (MacDonald 1982, 155). The base as well as the core of the upper parts is made up of opus caementicium (fig 19) (MacDonald 1982, 156). This was a widely distributed Roman building material, comprised of concrete mixed with stones that was poured into a form. Beneath the surface the casings were usually constructed out of wood (MacDonald 1982, 155). However, the parts above the ground level required better protection against environmental influences (MacDonald 1982, 163). These shells could be bricked and combined in diverse ways. Dating the bricking technique is not always possible due the intersections between them (Lamprecht 2001, 40). The first of them was opus quadratum (fig. 19), whereby a case was made of regular blocks, while irregular and unworked blocks were used in the opus incertum technique (Lamprecht 2001, 40). Opus reticulatum (fig. 19), a more advanced technique, comprised small, ordinary pyramids that were arranged in net patterns. If the natural stones were replaced by rectangular bricks, the technique was called “*opus testaceum*” (fig. 19) (Lamprecht 2001, 42). Nevertheless, the techniques could also be mixed, in which case they were labeled “*opus mixtum*” (fig. 19) (Lamprecht 2001, 43).

Figure 19: Illustrative examples of the different construction techniques based on examples from Ostia Antica. From left to right: opus caementicium, opus reticulatum, opus vittatum and opus quadratum (Brunke 2017).

Regardless of the construction technique, Roman funerary monuments were mostly located along ancient streets (Hesberg 1992, 13). Cremation, inhumation or embalming were the common mortuary practices. However, the architecture of the monument was not affected by the selection of the preferred practice (Hesberg 1992, 15). Often the tombs comprised a high diversity of architecture, which might bedevil their classification into a typology (MacDonald 1986, 164). Additionally, they can be separated by the direction of their facing (Hesberg 1992, 16f).

Apart from the practical aspect, the burial practice might also have been part of the power play between wealthy families (Hesberg 1992, 26). The form of a pyramid and tumulus might have been established as common among the monuments (Hesberg 1992, 27). To increase their reputation, even more terraces and other decorative structures could be placed next to them (Hesberg 1992, 32). Due to this an overlapping symmetry can be assumed (MacDonald 1986, 147). Nevertheless, a tendency to erect modest shapes is confirmed (Hesberg 1992, 58). In summary, the ordinary typology of Roman funerary monuments in encircled districts is characterized by their demarcation from the environment (Hesberg 1992, 57). As time progressed, the surrounding walls become more massive. The walls itself could contain openings in the form of narrow slots (Hesberg 1992, 58 and 60). Another category comprises the venerable tombs. They are based on even older traditions and constructed quite modestly. Their symbol is the mound of earth called a "*tumulus*" (Hesberg 1992, 93). Adding a podium might have boosted the prestige, which made this a common choice for the aristocracy (Hesberg 1992, 94). The appearance of tumuli is known to have changed a great deal over time (Hesberg 1992, 94). Reducing this category to the key points, a tumulus is often seen as a rectangular podium with a cylindrical tambour and an earth mound on top of it (Hesberg 1992, 95). Furthermore, this case study will investigate in such a tumulus in the next sub-sections.

3.2 Introduction to the monument and its location

The monument, most likely a tumulus, is located between the fourth and fifth mile of the Appian way near Rome (fig. 20) and consists of a rectangular podium of about 10.7 m x 12 m x 3 m and a cylindrical tambour with a height of about 3 m and an outer diameter of 8 m (Schwarz 2002, 185; Eisner 1986, 53). The inner diameter of the cylinder encompasses about 5.5 m with four small stairs in front of the oval shaped walls. The stairs are each about 65 cm high. Additionally, in every corner a slot is located, originally 1.7 m in height and width, which decreases by about 50 cm on the inner site to about 30 cm from the outside, according to Eisner. The slots were enlarged in later times and then completely closed again (Eisner 1986, 53). No burial chamber has been identified to date (Schwarz 2002, 128-132; Eisner 1986, 145), which does not mean that none was present (Eisner 1986, 146). The only indication of a burial place is the center hole of the cylinder, which might have provided access to the chamber (Leoni and Staderini 1907, 163) and an old print from the late 19th century (fig. 35).

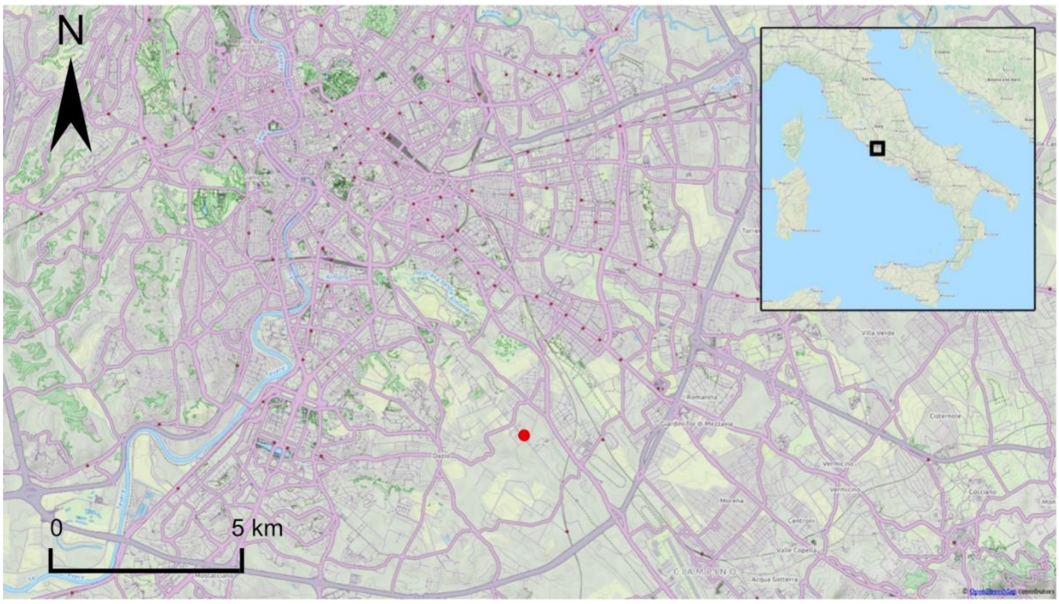


Figure 20: Location of the monument in relation to Rome. The red dot in the main map indicates the monument (Brunke 2017, base map is derived from OpenStreetMap contributors 2017).

Next to the building, the back parts of the podium are covered by debris. In other parts the monument is heavily weathered (Eisner 1986, 53; Leoni and Staderini 1907, 163). The building technique was opus caementicium, with diverse height levels. Each of these levels is separated by white joints (Eisner 1986, 52). On the inside, parts of the original opus reticulatum are still preserved (Schwarz 2002, 185; Eisner 1986, 53). The outer wall covering might have been opus quadratum (Schwarz 2002, 55; Spera and Mineo 2004, 139). With the current knowledge, no accurate dating is possible. The monument most likely belongs to the Augustan or post-Augustan period (Schwarz 2002, 120). In medieval times, additional walls were added to the top of the cylinder (Eisner 1986, 53).

This monument was chosen for several reasons. Firstly, Roman architecture is often repetitive. Patterns from one structure can be transferred into another structure. Furthermore, those patterns are often a geometric form. Secondly, Roman structures have been well researched. What this means is that there is already a large pool of knowledge that can be accessed. The knowledge is extremely diverse. Thus, sources of all kinds are available, as well as preserved structures of the monument. This is important in order to achieve a great diversity and improve the results by comparing several alternative reconstructions and approaches. Additionally, this allows for a greater variety of uncertainties to be achieved, which is particularly important to this research. Therefore, a segmentation of the monument would be a great help. The segments give the opportunity to process the data piece by piece and provide an effective structure.

3.3 Classification of the architecture

In general, the tomb has the typical regularities of ancient Roman architecture. To facilitate the description and interpretation in a suitable way, the building is divided into individual subjects (fig. 21). Each of these chunks will be interpreted individually and used as basic components for the final reconstruction. Furthermore, this scheme will simplify the actual modeling and documentation process by providing a modular and hierarchical structure with objects and attributes. It is most likely that those components might relate to each other. It is important to clearly point out those relationships.

Figure 21: Segmentation of the monument in terms of its logical components. Each color represents one object category with its corresponding subjects. The different shades on the right encode the transition from one building phase to the next (Brunke 2017).

Moreover, each of these components (=subjects for the later database) can own several parts (=objects for the later database). These objects can further be used to evaluate and describe the nature of the monument. However, the objects are predefined and therefore classified as building technique, material and form. Following that, a combination of the subject and object can be used to describe one specific part of the monument. This combination can also be expressed by a key[16], which is composed of the individual components of a segment. The attribute can represent either today's values, which can usually be measured or described with high certainty, or an interpreted value of its original state, which has to be deduced logically.

The nature of this case study makes it necessary to interpret the evidence directly after describing the object. Sources and references are named as conscientiously as possible. To further limit the scope of this chapter, already described and explained singularities are not described again, but rather refer to each other. When speaking of the zero point or origin, this refers to the front left bottom corner, where the structure is touching the underground. Likewise, this point can also be defined as point with the least distance to the current Appian Way. According to this definition, the tomb is always described from the perspective of the street (front). Therefore fig. 21 is aligned towards the front face of the tomb 434.

[16] The exact creation and operation of a key is explained in detail in the later chapters. At this point it is only of importance that it can be used as the identification of a segment.

The next chapter serves the purpose of a simple catalogue of the monument. It contains descriptions as well as interpretations and illustrations of the individual parts. The individual segments are identified by keys.

3.4 Archaeological and architectural composition of monument 434

3.4.1 The podium

Key: ***pdm_cr_bp1_bt; pdm_cr_bp2_bt; pdm_cr_bp3_bt; pdm_cr_bp4_bt*** (building technique)

Description: The core of the podium is constructed out of at least four layers of opus caementicium (fig. 21). These layers are visible by a change of material (fig. 22) or white and horizontally-extending joints (fig. 22). These joints have a distance to the zero point of 85, 155, 185 and 225 cm vertically. However, the values are only an approximation since the transition is not always clearly visible.

Interpretation: The type of building technique seems clear. In addition to the unambiguous instructions in the field, historical illustrations (Plate 1; Plate 2.4), analogies along the Via Appia and the Roman influence area, as well as the available literature (Eisner 1986, 53) also confirm it as opus caementicium. However, it is not equally developed everywhere. Slight changes in the masonry technique and mortar might appear. The podium has undergone particularly strong erosive processes from above.

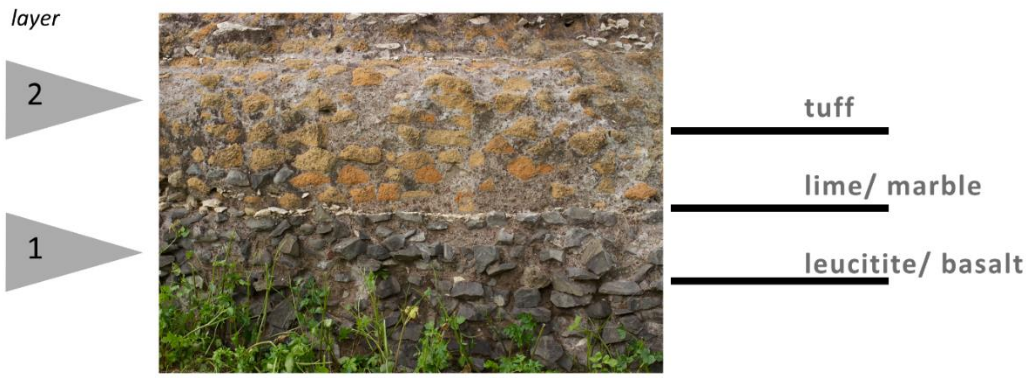


Figure 22: The change of building layers one to two of the podiums (Brunke 2017).

Key: ***pdm_cr_bp1_mtl; pdm_cr_bp1-2_mtl; pdm_cr_bp2_mtl; pdm_cr_bp2-3_mtl; pdm_cr_bp3_mtl; pdm_cr_bp3-4_mtl; pdm_cr_bp4_mtl*** (material)

Description: Figure 22 also indicates the main materials used for the podium. Layer one is made up of dark and dense material. Little octagonal crystals in its structure indicate leucitite (fig. 23). Similarly to the reddish tuff in layer two to four, the individual stones are about 6 x 10 cm to 10 x 20 cm big in length and width (fig. 23). The mortar used to bind the stones is unknown. However, the joints are most likely out of lime or marble.

Interpretation: The use of basalt was not uncommon in Roman architecture, especially along the Via Appia. Often the lower parts of buildings were created out of it because of its firmness. In higher parts it is substituted by the much lighter and porous tuff. The main function of this construction is the compensation of pressure (MacDonald 1982, 149). Field research indicates that the mortar has been renewed in many places to protect the walls against further erosion.

Figure 23: One leucitite crystal in the dark material on the left is highlighted by a red-dashed circle. One exemplary tuff block is located on the right (Brunke 2017).

Key: ***pdm_cr_bp1_frm; pdm_cr_bp2_frm, pdm_cr_bp3_frm; pdm_cr_b4_frm; pdm_cr_bpA_frm*** (form)

Description: The overall form and dimensions of the podium are hard to grasp in detail. This is mainly due to severe weathering. In addition, the ascending terrain to the rear (fig. 24) makes further analysis more difficult. This has negative implications for reliability.

Figure 24: View from the right side. The dashed black line indicates the rising terrain towards the back of the monument (Brunke 2017).

Description: There are differing values in the literature for the total size of the podium. With 10.7 x 12 x 3 m, Eisner and Schwarz provide the smallest dimensions (Eisner 1986, 53; Schwarz 2002, 185). Canina posits 12 x 12 x 2 m (Plate 6.1). However, this also includes the casing. Although Ancelet and Pinza also provide plans (fig. 25), they differentiate only between a quadratic and rectangular ground plan without scale. Also notable is the fact that Pinza directly indicates another monument to the left side. The left side still seems to be in very good condition due to its sharp boundaries (fig. 21), in contrast to the right side. Furthermore, it seems as if the tambour is placed off center, on top of the podium (fig. 21).

Interpretation: Considering Eisner's and Schwarz's values, it seems possible that these have been copied from each other. Most likely they represent today's extensions of the visible part and not a reconstruction of the original stage. Caninas' suggestions might be more reliable since he actually worked with this monument (Canina 1853). The current off-center position does not imply a conflict, since a similar behavior can be observed at a tumulus near Pompeii (Kockel 1938, 85ff). However, in general, symmetrical alignments can be expected in Roman architecture (Wilson 2000, 74 and 84). Moreover, the actual evidence leads us to assume that the left side of the podium still represents the original dimensions of the podium, while the right side most probably eroded over the time.

The one can deduce that the left side can be mirrored. Therefore, about 1.2 m has to be added to the right side. This results in an overall width of about 11.5 m. By applying the same method for the length, the result is approximately 12 m. The mathematical results indicate a slightly rectangular ground plan for the podium. However, it has to be considered that the measurement inaccuracy or the restoration might result in a biased conclusion; the podium might have actually been quadratic.

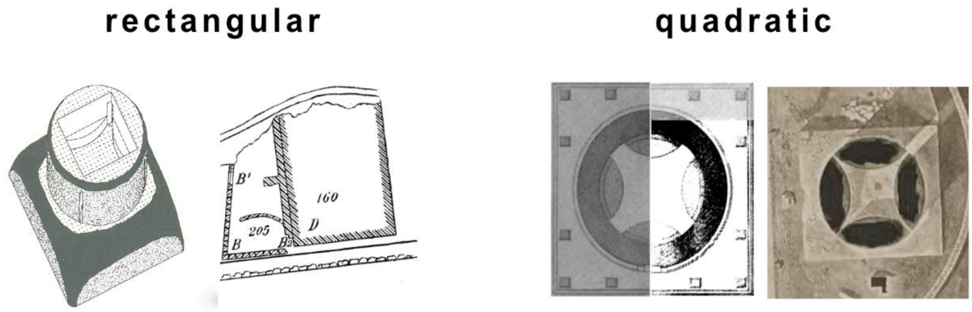


Figure 25: Ground plan of the monument from rectangular (left) to quadratic (right) (Eisner 1986, 52; Pinza 1907 in Spera and Mineo 2004, 140f, 191; Canina 1853, TAV XXVIII and Ancelet in Cassanelli 2002, 191).

Description: The current height is more problematic, even though it is already stated by different authors. The difficulty lies in the fact that the podium merges smoothly into the tambour. Above 1.55 m, the extensions of the podium decrease with increasing height and a deceiving cone. At a height of 2.25 m it has totally approached the current tambour. Likewise, restorations might falsify the result too. A slightly better observation can be made by examining some historical photographs (Plate 1).

Interpretation: The straight walls (fig. 22) suggest that at least building layer one and two of the podium keep the extensions at 11.5 x 12 m and the erosion is not as advanced as in other layers. Possible later building layers can be seen in figure 26. As a reference for this illustration, the profile from the front side was chosen, looking from the left. Interpretations 1 to 4 are based on simple geometrical forms and comparisons with other monuments. Almost all the tumuli along the Via Appia have a rectangular ending of the podium. However, the Mausoleum of Augustus seems to have a cone. It may be far-reaching to use this analogy and there may be great differences in material and dimension. Nevertheless, it is also defined as a tumulus. A stepped podium is known from the tomb of Gaius Utianus Rufus in Lucanien (Schwarz 2002, 170f and Tafel 41). Nevertheless, the exact changes cannot be determined anymore for monument 434.

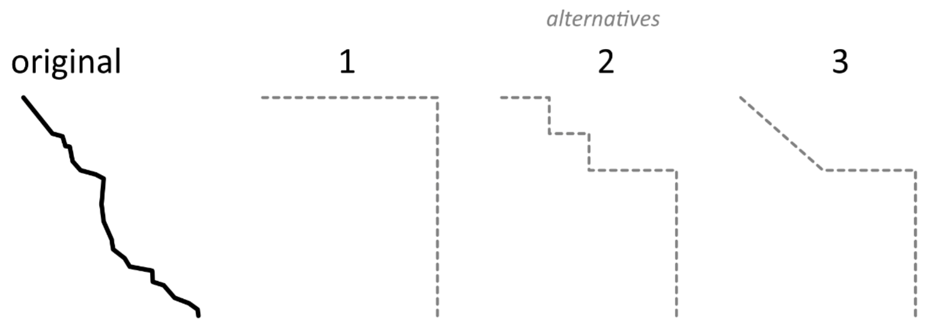


Figure 26: The alternatives for the podium core. Firstly, the regular rectangle, secondly the steps and thirdly a cone for the upper two building layers (Brunke 2017).

Key***: pdm_cs_bp1_bt; pdm_cs_bp2_bt; pdm_cs_bp3_bt; pdm_cs_bp4_bt*** (building technique)

Description: The podium casing is completely absent today.

Interpretation: There are several references that indicate that opus quadratum might have been the building technique used in this case. Firstly, the actual height of one building phase can indicate the height of the blocks that were used (Eisner 1986, 154). Secondly, opus quadratum is used with many other tumuli (fig. 27), especially along the Via Appia (Eisner 1986, 147-162; Schwarz 2002, 133). Nevertheless, there are also exceptions, such as the "*Rundgrab Süd 18*" in Pompeii (Kockel 1983, 85ff). Thirdly, some historical paintings (Plate 2.3; Plate 2.4) indicate big blocks around the monument. However, John Linton Chapman suggests opus reticulatum as the covering for the podium (Plate 2.5). The construction technique of opus reticulatum is particularly easy to recognize in the left view in this painting. Yet the field remains give no hint of former opus reticulatum at this location. Not even negative imprints are visible. Furthermore, paintings can also often contain the interpretations of the artist. Finally, some of the historical photos (Plate 1.3; Plate 1.4; Plate 1.6) show big bright blocks near to the monument. Those do not prove the building technique, but they support the idea of opus quadratum.

Key***: pdm_cs_bp1_mtl; pdm_cs_bp2_mtl; pdm_cs_bp3_mtl; pdm_cs_bp4_mtl*** (material)

Description: The podium casing is completely absent today.

Interpretation: Similarly to the aspect mentioned above, one can only speculate about the material. Paintings (Plate 2.4; Plate 3.1; Plate 3.2; Plate 3.3; Plate 3.4) and photographs (Plate 1.3; Plate 1.6) indicate stones with a bright texture. Travertine, marble or peperino (fig. 27) could be possible materials. Small pieces of all of them are found in the restored parts of the tambour (Plate 4; Plate 5) and similar monuments. Historically seen marble is unlikely for the Augustan period because of its high costs. In some cases, as for Caecilia Metella, it was used only for the decorative parts. However, at least one big marble block is now placed in front of the monument. The exact context with respect to the tomb is not clear anymore. Comparing it with the other tumuli, a bright travertine or peperino seems to be most likely if the covering was built as opus quadratum.

Figure 27: Similar tumuli with partly intact casing of opus quadratum along the Via Appia (left and central) and in Rome (right). The casing is of peperino and travertine and the individual blocks are about 50-60 cm high (Brunke 2017).

Key***: pdm_cs_bp1_frm; pdm_cs_bp2_frm; pdm_cs_bp3_frm; pdm_cs_bp4_frm*** (form)

Description: The podium casing is completely absent today.

Interpretation: The speculation also extends to the dimensions of the formwork. Considering the high diversity in Roman funerary buildings, analogies are difficult to justify. Therefore, blocks from Caecilia Metella cannot be used as a reference. One possibility would be to use the height of the individual building layers and equate them with the height of the stone blocks. This approach is not unusual with respect to Roman architecture, since it is strongly related to the construction technique of opus caementicium (Eisner 1986, 154). Regarding the building layers, the stone bricks could have had heights of 85, 70, 30 and 40 cm. However, comparing the monuments of similar sizes and types along the Via Appia, most of the remaining masonry stones have a height and width of about 50 to 60 cm (fig. 27). The length varies between 50 cm and approximately 150 cm. The block in front of the monument can be used as a reference only with caution. Its material, curvature and the absence of imprints used for metal clamps obscures its true function. Nonetheless, it does not prove the opposite.

Key: ***pdm_dc_bp1; pdm_dc_bp4*** (general)

Description: Decorative parts are completely vanished in the field.

Interpretation: Canina gives some impression of his interpretations with a drawing (Plate 6.1). Clearly simple ledges and profiles are visible at the bottom and top of the podium. Indeed, that kind of decoration seems to be common for Roman podia (Eisner 1986, 159 and Schwarz 2002, 56f). However, it is not clear on what evidence Canina's reconstruction is based. Nonetheless, some of the historical photographs (Plate 1.3; Plate 1.6) and paintings (Plate 2.4) indicate one of those items on the front left corner (fig. 28). The decoration can be recognized, although only roughly. Considering the past conditions, it is clear that this object is not *in situ*. Moreover, it seems to have been intentionally placed on this corner since the surfaces of the podium core are already heavily weathered. The material of the decoration can be determined to be travertine or the more expensive marble, based on a comparison with the other monuments like Caecilia Metella.

Figure 28: Decorative element at the front left corner (www.ebay.it, c).

3.4.2 The tambour

Key: ***tmb_cr_bp1_bt; tmb_cr_bp2_bt; tmb_cr_bp3_bt; tmb_cr_bp4_bt; tmb_cr_bp5_bt; tmb_cr_bp6_bt*** (building technique)

Description: The core elements of the tambour are built out of several layers of opus caementicium. As with the podium, the separation is recognizable due to the white joints. Since many faces and parts of the tambour have been restored, the joints are only partially visible and missing parts have to be interpolated. In total, six successive layers can be determined in the field.

Interpretation: Due to the construction technique, the original brickwork can be delimited from the restorations. Firstly, there are the medieval remains. They are clearly built as thin-walled walls in parallel layers (Plate 4; Plate 5; fig. 29). Secondly, the opus caementicium on the left side (fig. 29) differs from the opus caementicium on the other sides. On the one hand, the brickwork is considerably cleaner and weathering is hardly present. Furthermore, there are no white dividing joints, isolated bricks, or nails, but there are quadratic holes in a row at the lower end of the tambour. Likewise, many historical illustrations (Plate 1) represent a much more damaged wall from this view.

The holes and nails could indicate a restoration and therefore represent the remains of a wooden formwork or scaffolding. Finally, the back of the building (fig. 29) has two features that need to be discussed. The first one is the rectangular canal. More insight into it is given in the section about the decoration. Secondly, there are the two window-like openings. The back around those openings has similarities to the left side. Furthermore, new materials were used. However, it appears that the back wall of the openings shows the original masonry and opus caementicium. It may well be possible that these openings were intentionally placed there to illustrate the extent of the restorations.

The upper end of the core has a further peculiarity, namely a ring of darker material and a building technique similar to opus caementicium. In general, the ring sticks out a little bit above the structures below. Furthermore, the block size of the individual components is subjectively smaller. The exact function and age is not known. It might be a foundation for the medieval parts. However, it could also be the end of the core. In general, however, it seems to be proven that the core of the tambour was also built as opus caementicium.

Figure 29: Left: Back view of the monument with the canal and the two window-like openings. Middle: the left side of the monument with the restored facade and clean masonry, also partly the medieval parts on top of it. Right: The right side, with heavily weathered parts and clearly visible joints (Brunke 2017).

Key: ***tmb_cr_bp1_mtl; tmb_cr_bp1-2_mtl; tmb_cr_bp2_mtl; tmb_cr_bp2-3_mtl; tmb_cr_bp3_mtl; tmb_cr_bp3-4_mtl; tmb_cr_bp4_mtl; tmb_cr_bp4-5_mtl; tmb_cr_bp5_mtl; tmb_cr_bp5-6_mtl; tmb_cr_bp6_mtl*** (material)

Description: The main material for the core is a reddish tuff. Its shape does not differ from the material of the podium's building phases 2-4. However, other materials might also be present, but in less frequency. For example: bricks, travertine, marble, peperino, leucitite and iron nails (fig. 30; Plate 4; Plate 5). The distribution might give insight into the construction time. In between, an unknown type of mortar binds all those stones together. One layer of an unknown dark material is placed on top of the tambour. It could be leucitite or another type of basalt. Exact determination is not possible due its height.

Interpretation: As previously discussed, material can also be used to identify the restored parts of the building. Most material used for the core in the Roman times was without a doubt the red tuff and the mortar to keep it together. It is also clear that a lime or marble mixture was used for the white joints. These materials were quite common in Roman architecture and can be found in many other monuments along the street and in Rome in general. One has to particularly consider the material (Plate 4; Plate 5) that is at the back of the monument or in the fillings of the corner slots. Both of these materials, mainly peperino and probably leucitite, cannot be found anywhere else in the monument. On the other hand, other materials also appear in surfaces that might not fit into the rest of the funerary, such as iron nails, bricks and marble.

Figure 30: Overview of new materials in the tambour. From left to right: marble, peperino, travertine and bricks. Plates 4 and 5 provide information about the distribution (Brunke 2017).

Key: ***tmb_cr_bp1_frm; tmb_cr_bp2_frm; tmb_cr_bp3_frm; tmb_cr_bp4_frm; tmb_cr_bp5_frm; tmb_cr_bp6_frm*** (form)

Description: The form and dimension of the core are quite complex. Several alternatives seem to be possible. Furthermore, serious interventions in the building substance were made over the last two thousand years. Firstly, let us consider the general extensions to the cylinder. According to Eisner, the tambour has an outer diameter of about 8 m and an inner diameter of about 5.5m. The height today is about 3 m (Eisner 1986, 53). In contrast, Canina suggests a height of 5 to 6 m in his drawing, while the width and length is about the same (Plate 6.1). The exact measurements are nowadays difficult to determine due the pronounced weathering and restoration. Nevertheless, the outer diameter is about 8.5 m. It is important to consider that many of the outer surfaces are not Roman anymore. Indeed, on some edges additional substance on the tambour would be conceivable. The inner diameter is more difficult to determine. Obviously, the inner form is not evenly stretched. In addition to that, the walls' thickness tapers towards the upper end. Consequently, several measurements were taken. Firstly, the ground plane of the tambour was measured, which resulted in about 3.8 and 3.9 m and, secondly, the height of the ring was measured, which resulted in 5.6 and 5.1 m (fig. 31). The first value represents the distance from the front to the back, and the second one from the left to the right.

Interpretation: Some of the differences in the measurements might originate from differing weathering rates and measuring inaccuracy. Thus, for example, the inner diameter is 3.8 and 3.9 m. Most likely the values were originally the same. In contrast to that, the height is quite constantly between 2.8 and 3 m. Considering the structural changes during the medieval and modern period, it is not necessarily Roman. Only a few pieces of evidence might indicate a trend.

Therefore, Schwarz provides a list that contains several proportions of tumuli in Italy. However, since this tumulus cannot be accurately classified, the comparison is difficult (Schwarz 2002, 120f). In general, however, a ratio of between 1:1 and 1:2 are quite common. Nevertheless, ratios of 1:5 and 1:7 are also mentioned, both of which were used in more monumental tombs, for example the Adriano mausoleum and Caecilia Metella. In conclusion, a minimum height of about 3 m is granted, with possible extensions of up to 6 m in total.

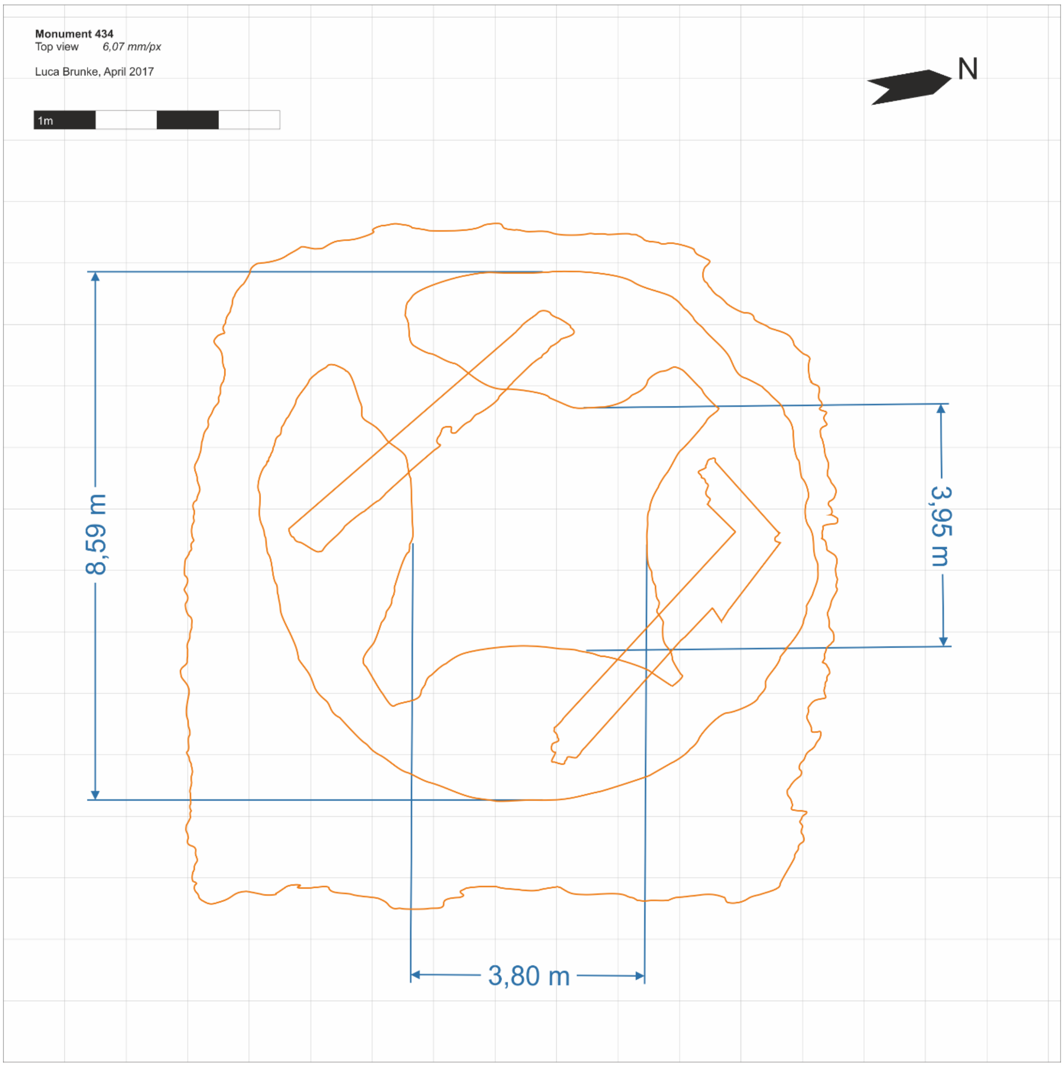


Figure 31: Measurements on the tambour of the monument. The irregular edges show the difficulty of finding suitable start and end points. The drawing is derived from the reality-based model (Brunke 2017).

Description: The second intervention was the four oval-shaped wall segments. Each of them is opposite another one. It is not completely clear whether they were closed or whether the small slots were left open in Roman times. While Canina suggests closed walls, Eisner argues for small openings. Each of the slots are high rather than wide.

Interpretation: Both intentions can be evaluated by completing the outer contours. It seems that two segments nearly touch each other (fig. 32). The opening on the front right might yield more insight. This is the opening with the retroactive interventions in the building fabric. Indeed, on top a narrow plank made of tuff can be assumed (fig. 32). However, using this evidence as proof might be weak. In this case, it is assumed that the monument comprised four similarly shaped ovals, each parallel to one of the podium edges.

It also clear that they were widened at a later time. This is recognizable due to the irregular boundaries. The historical illustrations (Plate 2.2; Plate 2.3; Plate 2.5) and the unusual materials (Plate 4; Plate 5) indicate that they were closed fairly recently. The height of 1.7 m, which Eisner suggests (Eisner 1986, 53), probably comes from the front and right shaft, which still has a small grade of reddish tuff as its upper boundary (fig. 32).

The exact dimensions of the opening are difficult to determine since a lot of substance was removed over time. Completing the walls, as in the previous section, might give an idea of one possibility. Furthermore, Canina suggests that they might have been closed with a covering panel of opus quadratum (Canina 1853, TAV XXVIII). Open slots could have a different meaning. Hesberg mentions them in combination with encircled districts and high walls. In this case their function was to enable the visitor to see the inside of the monument (Hesberg 1992, 57). Likewise, they could have been used as water drainage, if the cavity inside was filled with earth (Eisner 1986, 168) or as a material saving.

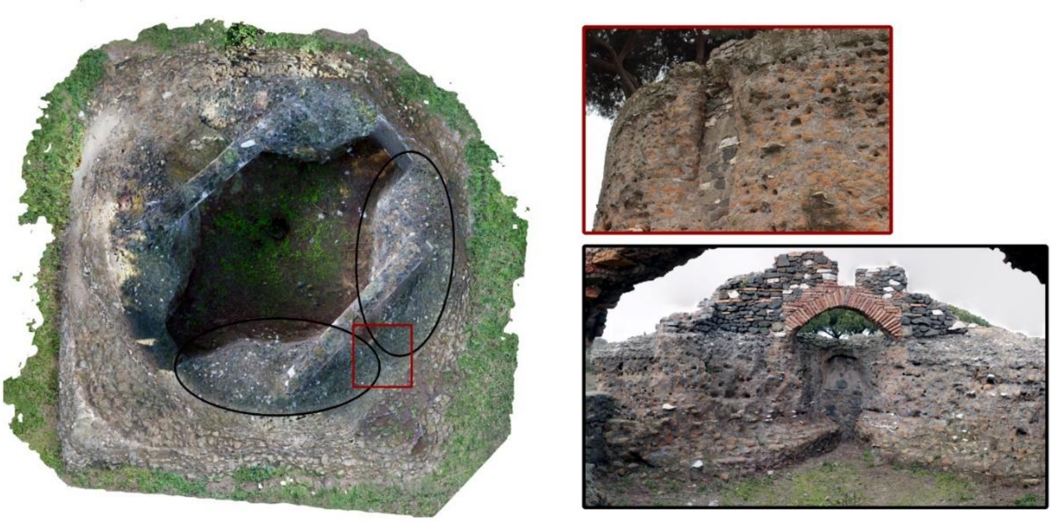


Figure 32: Shape and form of the tambour core wall segments (Brunke 2017).

Description: There are four steps of similar structure on the inside. These give the four wall segments an oval shape. However, they have only a low height.

Interpretation: In the previous paragraphs the remains were interpreted as four equally and regularly shaped ovals. However, they could also have had a more rectangular shape on the inside, while the inside ovals represent small advanced stages (Eisner 1986, 52f). One argument against the inner parallel walls is the trend of the oval, which is particularly visible on the ground, and the intact opus reticulatum at a higher position, following this trend.

Furthermore, an interesting perspective is offered by the historical map from Ancelet (1856) (Plate 7.1). Information about the wall structure is supplied in two black tones, from a bird's eyes perspective. Unlike minor differences, it is quite similar to Canina's ground plan of the monument (Plate 6.1). It might even be possible that the colors encode actual remains and a possible reconstruction. In such a perfect reconstruction, each of the four wall segments has the same features. In total, this would result in an outer diameter of about 9 m, which would mean that about 0.25 m of material had to have been added to the outside of the walls. Each oval would have been about 2.5 x 5 m in size. However, since the actual remains seem to be not perfectly symmetrical, mirroring the objects with features is difficult to execute. Furthermore, uniform meter numbers nowadays mean no increased certainty, since other units were in use in the Roman era. The exact data can be best determined by construction drawings and a reconstruction of the three-dimensional room. Assuming that the tambour is not actually a cylinder but four separate oval-shaped wall segments gives the monument a new appearance. It is not clear and cannot be proven which interpretation is actually true and which one of the scholars is absolutely right with his reconstruction of the monument. Nevertheless, this kind of architecture represents strong masonry, which is able to bear high pressure.

Key: ***tmb_dc_bp1; tmb_dc_bp6*** (decoration)

Description: The decorative elements of the tambour are now almost completely absent. The only evidence of this feature is a worked stone in the canal at the back (fig. 33).

Interpretation: Comparisons with other Roman funerary monuments confirm that it was probably not always like this. Possible elements might be a profile, frieze or coronal castellation (Schwarz 2002, 50, 57 and 59f). Observing the monument in detail, a block inside the small channel (fig. 33) at the back of the building can be found that has striking similarities with one of Canina's drawings (fig. 33). This part is later used by him to form a fictitious door at the front of the monument. The stone block is currently placed next to similar stones that are used as a ceiling for the small channel and cannot be accessed easily. It is unclear whether it was actually a part of a door. It is also unknown how this stone came to be in this position and how the rear wall can now be interpreted. Might the other stones hide more decorative parts that became lost over time? Nevertheless, statements about the decoration are speculative rather than reasoned in this case. Therefore, the kind of decoration can be determined but not the exact appearance.

Figure 33: Worked stone and possible interpretation and drawing by Canina (Brunke 2017; Canina 1853, TAV XXVIII).

Key: ***tmb_cs_bp1; tmb_cs_bp2; tmb_cs_bp3; tmb_cs_bp4; tmb_cs_bp5; tmb_cs_bp6*** (case)

Description: The tambour casing is completely absent nowadays.

Interpretation: The case of the tambour will most likely largely coincide with the case of the podium. The difference might be the block size and the rounding, since it is based on a cylinder and not a cube. Each building phase can have a height of about 50 cm or 40, 45, 65, 60, 40 and 60 cm. The primary evidence (fig. 34) indicates that the inside of the tambour was originally covered by opus reticulatum. Indeed, this is the only evidence that probably still shows the Roman facing. The heavily weathered surface of this object furthermore indicates its great age. Opus reticulatum was a rather popular masonry technique in Roman times.

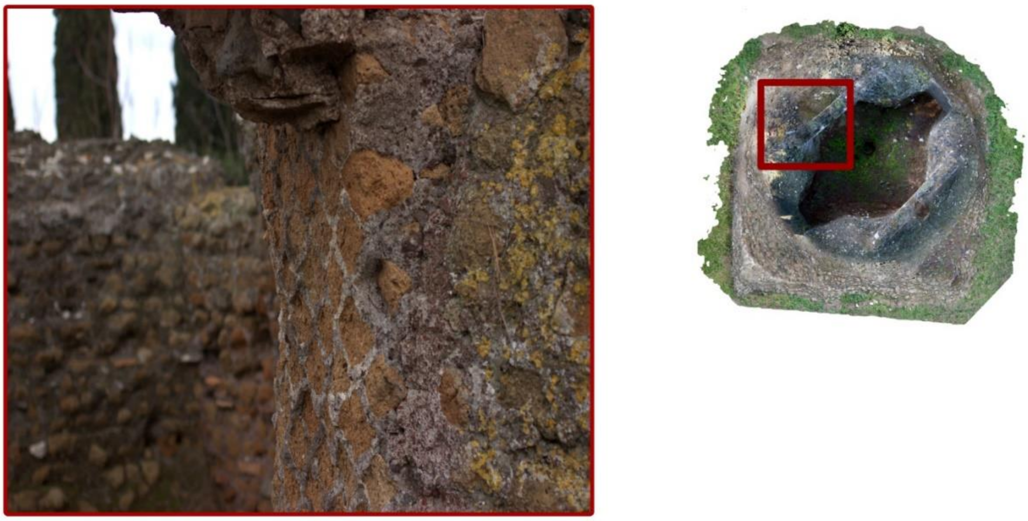


Figure 34: Part of the opus reticulatum on the inside of the monument (Brunke 2017).

3.4.3 The filling and roof

Key: ***far_cr_bpA*** (filling)

Description: The tambour is no longer filled.

Interpretation: The monument's tambour has massive and inwardly curved walls, which could indicate a filling of ground. This would be comparable to other monuments along the Via Appia (fig. 27). However, an earth filling makes it questionable that an internal formwork of opus reticulatum was used. Indeed, it is not necessarily a contradiction, since examples of such constructions do exist (Eisner 1986, 154ff), but it nevertheless seems needless. Another possibility would be an open monument without any filling, similar to what is preserved today. This example would be more like an encircled district than a tumulus, which is described in detail by Hesberg (Hesberg 1992, 57) and similar to what Eisner had suggested (Plate 6.2). In conclusion, the evidence for a filling is rather weak. Moreover, reuse in the medieval period led to changes being made to some of the structures.

Key: ***far_cs_bpA*** (roof)

Description: The tambour does not have a roof and is open at the top.

Interpretation: Artistic paintings (Plate 3.1; Plate 3.2; Plate 3.3; Plate 3.4) of similar monuments often suggest a flat or cone-shaped roof. Also, Canina provides a suggestion (Plate 6.1). Another possibility would be an open monument without any roof, similar to what is preserved today. This indicates Hesberg's encircled district (Hesberg 1992, 57) and Eisner's interpretation of the monument (Plate 6.2). In the case that the inside was filled with earth, a probable earth mound seems to be the most probable. It can be still seen for most tumuli along the Via Appia (fig. 27). However, the evidence is weak. Likewise, the medieval extensions on top of the monument have destroyed the original structures.

3.4.4 The burial chamber

Key: ***bc_cr_bpA_frm*** (form)

Description: The existence of a burial chamber remains an uncertainty. It might be possible that the podium had some cavity or that the remains were stored within the tambour (Schwarz 2002, 25).

Interpretation: In general, the room that was used for this function does not exceed the needed size (Schwarz 2002, 26). Therefore, it could well have been hidden in an unknown part of the podium, or was placed in the tambour but later removed. Various references could provide information about the chamber. On the one hand, there is a hole in the center of the podium. This hole is described in only one publication, by Leoni and Staderini, who considered it an access to the grave chamber (Leoni and Staderini 1907, 163). However, the pit is not large enough to serve as an entrance, but a light or ventilation shaft might be still a reasonable argument. Nevertheless, some conflicts occur, assuming that the tambour was once filled with earth. The earth would have been washed completely into the chamber, which would indicate another function. The hole could have served as a water drainage outlet. A water drainage system would make a chamber in the center of the podium unlikely. Furthermore, it is possible that the hole in the center of the podium was constructed at a later time, perhaps to hold wooden beams.

With a print (fig. 35) of the monument, Ferdinand Keller (1874) indicates another opportunity. This illustration clearly shows a vaulted entrance-like opening at the right side of the podium. Nowadays, this part is almost covered by rising terrain. However, it seems peculiar that this opening, drawn by Keller, and the opening on the top of the podium never drew the attention of other scholars. In contrast to other archaeological features, the issue of a burial chamber will only have a small impact on the outer appearance (Hesberg 1992, 15) and can therefore be downgraded in priority.

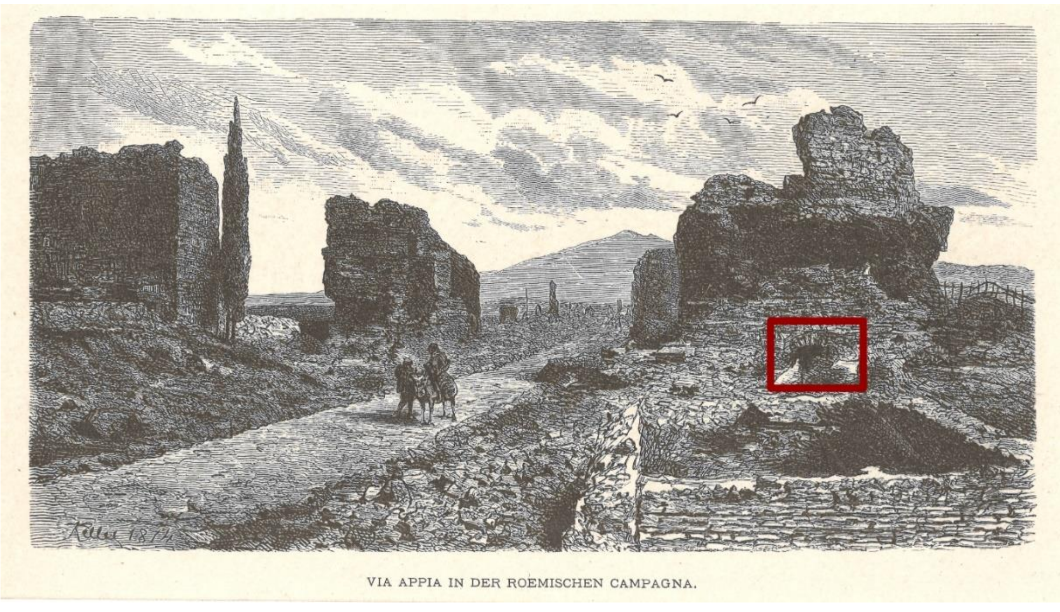


Figure 35: Historical print of the Via Appia and monument 434 by Ferdinand Keller from the end of the 19th century (Keller 1874, scan from original). A vaulted basement entrance in the podium seems to be possible.

3.5 Conclusion of the case study

In conclusion, the architecture of Roman funerary buildings is diverse. Furthermore, comparisons with similar structures might help one to recover the original appearance of individual aspects. Moreover, they are able to determine the rough shape of the research. Historical illustrations can also be a powerful tool. However, they need to be in a good condition and should be considered with caution. Literature is, in most cases, the author's own description and interpretation of the local evidence and can be one of the most powerful pieces of evidence since interpretation are already done.

In total, many aspects of the monument could be recovered. The best way to do this is to divide it into a basic geometrical shape and assign each of the parts individual properties with corresponding attributes, such as building technique, material, form and dimension. As headline objects, the podium, tambour, burial chamber, filling and roof were chosen. Further segmentation is possible regarding the building phase and alternative. The alternative is always present if the actual evidence allows at least two values for the same property.

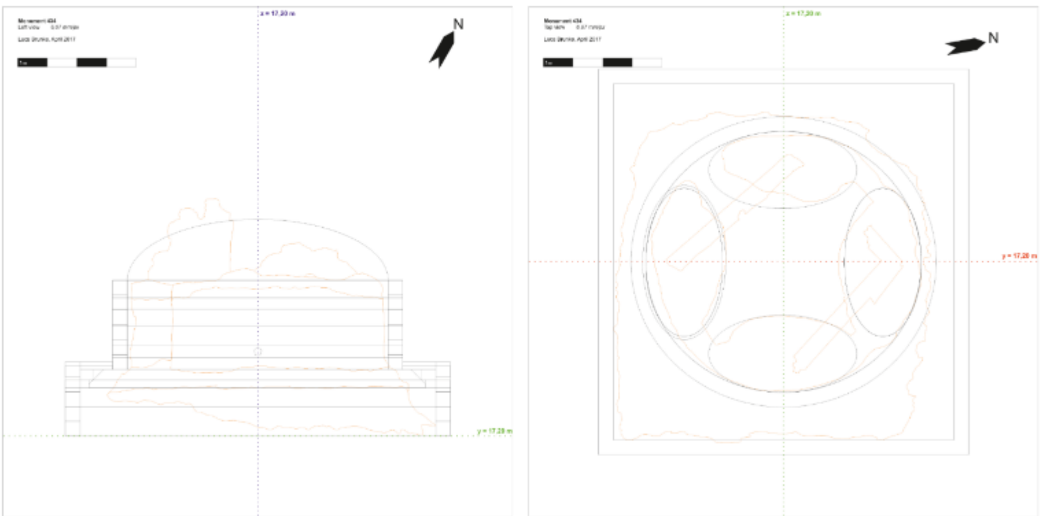


Figure 36: Drawing of monument 434 from the left and top perspectives. Orange indicates the actual remains, while black and grey are possible reconstructions. More detailed plans can be seen in Plates 8, 9 and 10 (Brunke 2017).

A comparison of one's own reconstruction (fig. 36) with those of another researcher reveals similarities, but also differences. The previous sections of this case study provide as much information and insight as possible to facilitate an interpretation. Therefore, we have a podium of about 12 x 12 x 2.25 m with a round cylinder on top of it. The cylinder has an outer diameter of about 9 m and a height of 3 m. As main materials, namely reddish tuff and some kind of mortar, were used for opus caementicium. The lower layers also include leucitite. The outer casing was most probably travertine or peperino blocks[17] while on the inside of the tambour there were tuff blocks in opus reticulatum style. There were definitely decorations but they cannot be restored in detail due to missing evidence. The same is true of the roof and filling. All in all, it is possible to reconstruct some of the structures of the original Roman tomb. Nevertheless, some parts may be quite speculative due to incomplete data. Higher resolution images and other illustrations can be found in the electronic repository. Following, the next chapter will describe the application of the methods elaborated in chapter 2 on top of the data chapter 3.

[17] **Supplement**: Recent measurements have shown that many opus quadratum blocks along the Via Appia have a height of 1 or 2 feet. It is very likely that the other dimensions are also based on the unit of feet and might have to be adapted slightly.

4. Applying diverse concepts to the data

4.1 Segmenting and organizing the data

As described in chapter "*2. Literature review and theoretical framework*", a well elaborated concept is important and it must possess all the appropriate methodical aspects. Furthermore, the segmentation and data interpretation provide a degree of reliability and guides the viewer into the highly complex and connected process of reconstructing archaeological remains. The following chapters are intended to describe the exact process of applying the methods to the case study.

Thus in this chapter, first the file system (fig. 37) that stores all the data is explained. This forms the foundation for further research, as well as the possibility to collect or add own data. It is important that, even if the path of the whole structure is changed, all the results are still available. Therefore, everything is stored within the folder "*Brunke_filesThesis*". A detailed description of all data types and their use can be found in the "*Technical Note. How to use the data most effectively*" in the appendix. The Pascal and Camel naming scheme are there used to provide names that are easy to understand and self-explanatory. Further structures are derived from sustained experience and computer-related work. The upper folder also represents the various categories from which the work was composed.

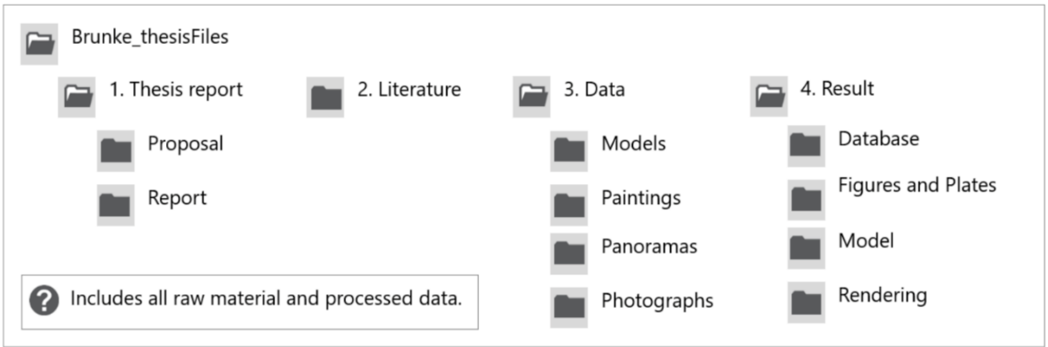


Figure 37: Schematic structure of the file system that was used (Brunke 2017).

It is not only the project that has to be organized, but also the data. The Roman monument needs a great deal of attention, because it is to be addressed by means of various applications, such as the database and the three-dimensional model.

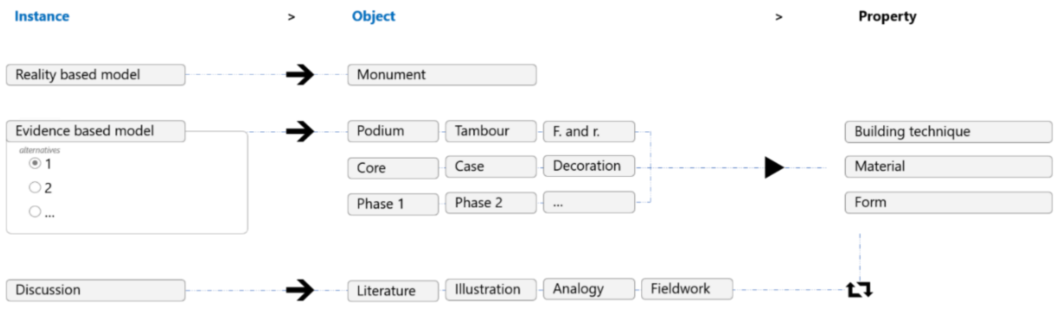


Figure 38: Segmentation and organization of the monument and all monument-related data (Brunke 2017).

The segmentation (fig. 38) might need further explanation. Most of it was explained in "*2.3.5 Organization*". Since the dimensions are limited, we are working with only one main level of detail. Therefore, the segmentation is also limited to one level of detail. However, layers are important to store alternative versions of the same object. Nevertheless, those two aspects are more important for the actual modeling and are therefore discussed and described in the relevant chapter. Segmentation implies the simplification of the original structure in smaller pieces, covering an own aspect. From now on they can be described and addressed directly. No direct standards are applied yet (Schwerin et al. 2016, 211). However, the segmentation of architectural objects and geometrical forms are common. The discussion of the case study already provides us with a rough framework.

In this case, we have the reality-based 3D model available as one related mesh. Secondly, the research consists of the sources and discussions, and finally the reconstructed monument. The rough segmentation of the reconstruction is possible in terms of the podium, tambour, roof and filling. This applies to geometrical aspects as well as architectural ones. They are all independent parts with a particular form and therefore represent the first level of reconstruction. However, each of them might have several building phases. In this case, for example, only the Roman ones are observed. If the building phases differ with variations in their properties, they might become an extra level of segmentation. Alternative reconstructions always require a completely new instance, since one can never be sure to what extent the changes apply. The exact relations and accumulative structure is indicated in figure 38. The next step of organizing the model is to design a database with a convenient naming scheme considering uncertainty as focus point.

4.2 Storing the metadata and paradata

The applied segmentation is also used when storing assigned and project-relevant data in the database. In order to focus on the uncertainty, the design is kept simple. Following that, the entity relationship diagram in figure 39 should support the creation and understanding of it. The diagram is based upon the Chen notation and provides objects and relationships. For the sake of clarity, the attributes of each object and relationship were excluded from this illustration.

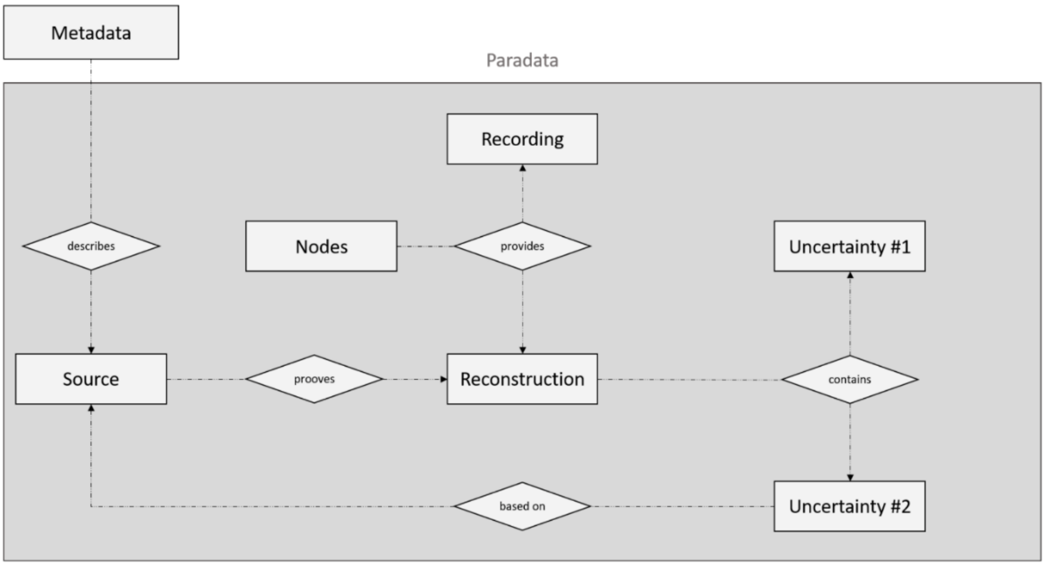


Figure 39: Entity relationship diagram for the database design following the Chen notation (Brunke 2017).

Each object might represent an own table or node in the latter database, while the metadata relates to the technical background, such as the hardware and software used. "*The London Charter*", "*Principle of Seville*", "*3D Icons*" and "*IT Empfehlungen*", as well as many independent smaller publications, offer a wide variety of elements that should be included here. However, as mentioned above, the elements are reduced to the basics to focus more on the uncertainty nodes. When the rest of the nodes are categorized, this is done with the help of paradata. The documentation of the discussion on the paradata and the technical aspects in the metadata ensures that most of the principles relating to the issue of documentation and scientific transparency are addressed.

The breakdown of the paradata shows a complex structure. The first node that has to be focused on is the sources. They represent mainly articles and books but also fieldwork and laboratory work. Each source used for the reconstruction is encoded in this part in its most basic form. The reconstruction and recording node are equal in structure. However, they differentiate in the content. While the present recording represents appearance and analysis of the moment, the reconstruction represents the status at its time of construction. Both of them use the same nodes, also known as "*levels*" in the segmentation section. Each entry of these nodes describes small components of the monument and is able to address them directly due to standardized vocabulary. They were stored as outboards to make easy changes and facilitate administration of the data in the database. This becomes important when changes are made to the structure, ontology and a normalized database[18]. The last two nodes of uncertainty are as equal as they are different. They represent two differing concepts of uncertainty for the monument. One seems to be quite independent, while the other is strongly related to the sources. Those two nodes (= class-based and fuzzy-based uncertainty) should render the uncertainty evident, as well as the discussion that was dealt with during investigation of the monument.

All of the above-mentioned nodes are connected by relationships with at least one other node. Those relationships are directed, which is indicated by an arrow in figure 39. For example, the reconstruction cannot prove the sources, but each source can prove a part of the reconstruction. Furthermore, these relationships can be supplemented by attributes, for example representing values, which might specify the page or chapter of the source.

Since the uncertainty is the primary aspect of this research, it will be analyzed more closely. In addition, a link to previous works will be made. Therefore, two example publications were chosen "*A paradata documentation methodology for the Uncertainty Visualization in digital reconstruction of CH artifacts*" (2015) and "*3D Modelling as a Scientific Research Tool in Archaeology*" (2008). Although, similar approaches can be found in many other publications, Hermon and Nikodem, and Apollonio and Giovannini represent the two opposite extremes of the scale with their approaches (fig. 40).

Firstly, Hermon's and Nikodem's concept shall be described. It will be used for the fuzzy-based uncertainty ("*uncertainty #1*" in fig. 39). One of their main objectives, apart from the visualization, is the transfer of data between applications, in this case Blender and a relational database. The database scheme is printed on page four of their publication. It also focuses on the relation between source, component and data quality (Hermon and Nikodem 2008, 4f). The core table includes components that describe general parts of the building such as "*surrounding wall*", "*corner tower*", "*gate*", etc. Each of them is assigned further details and sub-parts. For the "*gate tower*", for example, "*existing*", "*estimation*",

[18] A database is normalized when as much data as possible is split up into its smallest components and is distributed over several related tables.

"*internal steps*", "*top*" and "*antechambers*" are used. A similar system is approached with the node or level. Each object owns the attribute reliability and importance, which is determined by the scientist. The value 0 represents complete uncertainty, while 1 represents absolute certainty. The numbers are based on the foundation of fuzzy logic and can assume an infinite number of values in the interval [0,1]. However, in the scholar's opinion the values are "*expressing our doubt of certainty about the choice*" (Hermon and Nikodem 2008, 2-4). The authors define the reliability index as follows: "*The reliability index reflects the confidence the researcher has in his or her interpretation of primary data and is subjective to the researcher's decision*", while "*the important index measures the 'contribution' of a part of the model in relation to the model overall, it is a subjective evaluation and reflects the researchers opinion about the potential contribution of the part to the whole*" (Hermon and Nikodem 2008, 4). A formula that is accessible on page four of the publication is used to calculate the final uncertainty index of the object, whereby reliability has more impact than importance on the resulting outcome. The index itself can be used in a combination of different thresholds for conditional rendering (Hermon and Nikodem 2008, 4).

Secondly, Apollonio and Giovannini provide another concept to fulfill the necessary requirements for scientific transparency (Apollonio and Giovannini 2015, 7), which is expressed by means of class-based uncertainty. In the beginning they follow a similar approach to Hermon and Nikodem. However, each of their components is stored in an extra table with an increased level of detail. In contrast to the previous documentation, the vocabulary seems to be taken from a standardized ontology. An overview is provided on page 10. Page 12 is containing their database scheme, which seems much more complex. The scheme indicates that each object is related to some kind of source or measurement (Apollonio and Giovannini 2015, 11f). In this case, the uncertainty is not drawn from a value assigned by the authors but from the number and quality of the connection to the sources. Therefore, special sets of sources are classified in categories of uncertainty, in which "*based on laser scanning survey of archaeological fragments*" represents the most reliable ones and "*failing references*" the least reliable ones (Apollonio and Giovannini 2015, 8). The classification can be compared to some approaches that were explained in the theory section. However, more details regarding the uncertainty classification are given in Apollonio's publication "*Classification Schemes for Visualization of Uncertainty in Digital Hypothetical Reconstruction*". Firstly, there are different properties of the same component that can have different levels of certainty. He points out aspects such as shape, material and appearance (Apollonio 2016, 177).

Accordingly, their uncertainty is based on the available data and its interpretation (Apollonio 2016, 178). He analyses the types of sources (Apollonio 2016, 185). He lists "*architectural/ structural elements, archaeological evidence; size/ geometry; stylistic/ formal; temporal correspondence; building materials*" as properties that can have uncertainty (Apollonio 2016, 186). Based on the type of available sources, he categorizes the scale of uncertainty and applies the individual categories to the uncertainty slider (Appollonio 2016, 188f).

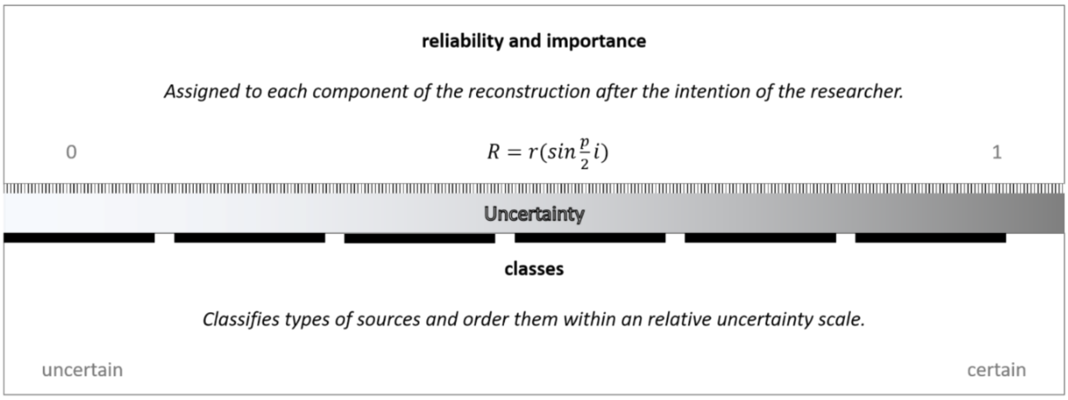


Figure 40: Schematic comparison between the fuzzy-based uncertainty above the gradient and the class-based uncertainty below the gradient (Brunke 2017).

In short, two sets of uncertainty coding in the databases are available (fig. 40). In the first one absolute numbers and clearly identifiable indices are used, whereas for the second one a relative classification of sources is used, ordered by their reliability compared to each other. Both of these systems were used and will be discussed for this research. However, the database design will be kept simple and the approach was the first one of Hermon and Nikodem, whereas the identification of the objects and segments was done as in Apollonio's and Giovanni's approach. Those techniques seem to ensure the best results regarding the visualization of uncertainty. Both of the above-mentioned authors, as well as most of the others, use relational databases. They have proven to be robust and useful. Data can be easily changed, added or read. For the creation of the relational database Microsoft Access 2016 was used because of its stability and widespread use. However, a quite new approach in archaeology is the use of graph databases. During the course of this research no 3D application with the documentation of a graph database could be found. Despite their differing structures, their datasets are highly linkable and offer a complete new set of queries and relationships, in contrast to relational databases. Therefore, a graph database was chosen as an additional and experimental form of documenting 3D models in addition to relational databases and written text. The software Neo4j with the query language Cypher was used. All databases can be derived from the schemata previously mentioned before in this section. Several visualization schemes are available to finally express the values of uncertainty. How they work and how the data is assigned is the topic of the next section.

4.3 Encoding uncertainty in the model's visualization

Several forms of visualization were used to encode the values of the database. To provide a basis, the actual remains of the monument were recorded with a Canon Eos 600D and a dji drone. The images from the dji drone were provided by the University of Nijmegen and the "*Mapping the Via Appia*" project. As a consequence, the photographs were processed in Photoshop and corrected in color, brightness and contrast. After that, Photoscan calculated a 3D model from the available data. The reality-based model, which was derived from photogrammetry, had to be decimated in order to further investigate in its geometry. Currently, the polycount blasts most computers' hardware. The context and later the audience facilitated the use of the automatic decimation method instead of manual repairing, retopologizing and remapping the uv-coordinates[19]. As a next step, the reconstruction of the ancient structures was modeled by means of polygonal modeling in Blender, with the assistance of the reality-based model and the databases. Therefore, scaled blueprints from different perspectives were prepared in Corel Draw to enable endless zoom factors. They were saved in vector files and aligned to the virtual spatial axis of Blender. The visualization itself happened with Cycles, a build in render engine[20] from Blender.

However, the main purpose of this chapter is to explain how the uncertainty was encoded into the visual elements of the final rendering. If possible, parts of the discussion of the case study also had to be considered an important aspect of visualization. Considering malfunctions such as color blindness, not all available methods seemed to be suitable for this exploitation. In some cases, slight adaptations were necessary. The approaches themselves were presented and applied in three categories: color code, render mode and level of detail (tab. 5 in Chapter 2). During each attempt, an effort was made to retain the same geometry in order to reconcile the subsequent evaluation of the results. Additional, binary systems, which often appear in publications, were neglected. They are only capable of deciding between actual remains and the interpretation, which did not correspond with our own conditions.

[19] Common steps to enhance 3D scans for a real-time render engine or extensive post-processing. Roughly, they optimize the model and correct errors in the geometry.
[20] Correct calculation of light, shadows and the representation of the object with its material.

The first method relates to color coding and mostly refers to section "*2.3.3 Visual representation*" and "*2.7.2 Color*", but it also includes approaches from "*2.7.1 Fuzzy logic*". Color coding means that certain color values are assigned to the individual objects, depending on their uncertainty. The color palettes (fig. 41) themselves were generated with the help of www.colorbrewer2.org and www.paletton.com. For the fuzzy-based uncertainty concept, a color gradient from two complementary colors (fig. 41) was used because of the diverging data. Instead of complementary colors, analogue colors can also be used, since they stand for sequential data, which also applies to fuzzy-based uncertainty. Nevertheless, complementary colors are more suitable for emphasizing extreme points of scale. Furthermore, the gradient is robust against most forms of color blindness and approaches the often used red/green contrast. In order to justify the level of detail of the interval [0,1], the transition between the colors was kept smooth. A similar approach was used by Zuk et al., who used a transparency gradient to display temporal uncertainty (Zuk et al. 2005). By contrast, another system appears to be more suitable for the class-based uncertainty concept. The data was more divergent, so four complementary colors (fig. 41) were used in order to represent the four source categories. In this case it was not possible to choose complementary colors that were also robust against color blindness. However, three of them still represent primary colors and can thus be easily distinguished from each other in the natural environment. The concept on which they are based is the extended triadic and is called a tetrad. Dell'Unto et al. in particular use the concept of contrasting colors to represent varying categories of uncertainty (Dell'Unto et al. 2013). Both color palettes were used to encode the uncertainty of one possible reconstruction, regarding its form and dimensions.

Figure 41: The top part represents a color gradient from a brownish (#*543005*) to a greenish (#*003c30*) tone, passing over a neutral white (#*f5f5f5*). The certainty increases from left to right. The bottom part represents the four complementary colors of the tetrad and its related source categories. Red (#*aa3939*): literature; Yellow (#*aa9739*): analogy; Green (#*2d882d*): fieldwork and blue (#*403075*): illustration (Brunke 2017).

The second method corresponds to the render modes and mostly refers to "*2.3.4 Style direction*" and "*2.7.3 Physically based rendering*". Render modes basically paraphrase a form of shading provided by most cad software. In this case wireframe, solid, texture and material (fig. 42) were used. Hereby, the certainty increases with each step; the details also increase proportionally. Therefore, wireframe (abstract/schematic) mode represents the lowest certainty, whereas the material and texture mode (photorealistic) represents the item with the highest certainty. The lineup here may imply similarity to crisp sets which it does not necessarily mean. The uncertainty acts anti-proportionally. Even if the appearance changes a lot, the geometry remains the same. Since the changes are stepped and follow each other in a relative order, the same template can be used for the fuzzy-based and class-based uncertainty. The results might be similar but the threshold can be slightly shifted. This method has a special strength against color blindness because it is not dependent on color rendering and color truthfulness. This approach is not used much in the literature. However, there are portioned approaches to this in various publications, so Hermon and Nikodem use the wireframe mode for uncertainty levels above a certain threshold of uncertainty. All other objects are displayed in the solid mode, combined with a color code (Hermon and Nikodem 2008). In contrast to that, Alusik and Sovarova used simple material textures to indicate the probable material of the reconstructed structures (Alusik and Sovarova 2015).

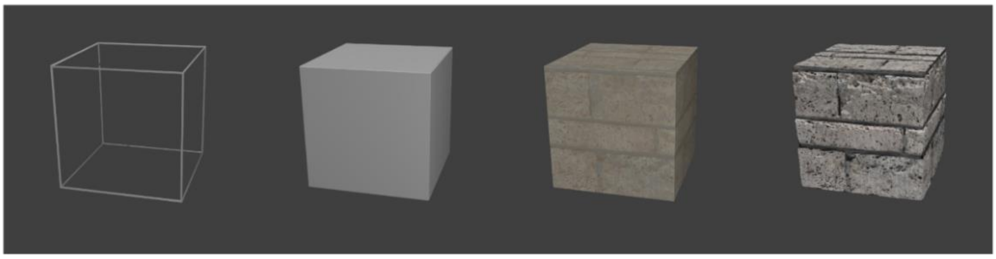


Figure 42: Different render modes of the same cube with an increasing certainty from left to right: Wireframe, solid, texture and material. The material is achieved by using physically-based rendering texture maps (Brunke 2017).

The third and last method corresponds to the level of detail. In contrast to the previous ones, it will not have much impact on visualization since this monument does not allow much variance in its detail and has a quite homogenous degree of uncertainty in its outer form. However, this means that the higher the certainty of specific parts the higher the details of the model. The lowest uncertainty will be presented as a reality-based model of the actual appearance, whereas the highest uncertainty is only a schematic box model, bounding the parts that might have been there. Method three has intersections with method two, since both involve a manipulation of details. The difference is that method two does not touch the geometry, whereas method three only manipulates the geometry.

In total, three versions of the evidence-based reconstruction were produced. One was done using the solid mode mixed with a color code, for another one the render mode was used, while for the last one the level of detail was mixed with a photorealistic style. All three variations required manipulating different properties of the model in order to display the object's uncertainty. Finally, these approaches were evaluated and used to develop a final method. However, before doing so one had to decide about an appropriate presentation of the model. The selected method is described in the next chapter.

4.4 Final rendering of the object

As final step, the visualization has to be rendered and published. Some methods of doing this were described in the theoretical chapter above. A 2D image rendering was chosen for this research. This might not have been the best solution, but it represents most of the past and present publications. It will be delivered as a high-quality rendering with a corresponding description and legend. An interactive model or animation might be better at displaying uncertainty, the processes and exact values, but it also requires specific equipment and digital publication methods. Furthermore, this thesis is going to be evaluated as a printed version, which does not support those two forms of presentation. Brief samples of an animation and interactive model are added as digital attachments to the other thesis-related files.

4.5 Summary of the applied concepts

In total, two databases were created (relational and graph). However, the graph database was more of an experimental approach and has therefore no real fuzzy-based uncertainty values included yet. Nevertheless, all design decisions and sources were saved in both databases. The databases show the same segmentation as the model and case study. The same key was used in all three parts for the identification.

The reality-based model was created out of photographs, while the hypothetical model was created by hand with the help of the blueprints and discussion about the databases. Uncertainty was applied to the hypothetical model using three different approaches: firstly, a solid render mode with an assigned color code; secondly, only render modes; and, thirdly, varying levels of detail. The previously mentioned color code can be further split into gradient or complementary colors, depending on the uncertainty concept used.

Finally, the model was rendered as an image. Furthermore, the digital data was prepared in order to provide a preliminarily interactive model and animation. The results are presented in detail in the next chapter.

5. The reconstruction and its database

In total, two databases were created with the available data. Both of them share the same interpretation and structure. However, in contrast to the written form, they contain additional data in the form of illustrations or references to analogies. The sources are grouped into four categories: fieldwork, literature, illustration and analogy. "*Fieldwork*" means that the data was either directly measured in the field or derives from the data collected during fieldwork at the monument. To separate those sub-categories and still combine the data of the actual monument in one table, the Boolean operator "*isReal?*" was introduced. It basically describes whether the value represents a real measurement or whether it is derived from one. However, "*isReal? = true*" does not necessarily mean that the part is Roman; it can also describe a medieval or modern change. "*Literature*" includes publications of the monument in particular or Roman architecture in general, whereas "*illustrations*" mainly contain historical photographs, paintings and drawings. The "*analogy*" category is a list of tumuli all around Italy, which might be useful as references.

The first database (fig. 43) was created with Microsoft Access 2016 and contains eight tables, in which all the important information are stored. Furthermore, they are all connected with each other, except "*cat_ontology*". Cat_ontology represents a catalogue of common terms that are used repeatedly in this database. The nature of the data makes it unnecessary to connect it with other tables over database relationships. Moreover, references for the content were set. All the other tables contain actual data or information about the relations between them. The relationships between the tables are either n:1 or n:m. Hereby, the relationship sheet (fig. 43) already indicates the contrast of the individual tables and their position with respect to uncertainty. Apart from the structure, the accumulative character of the database also is emphasized.

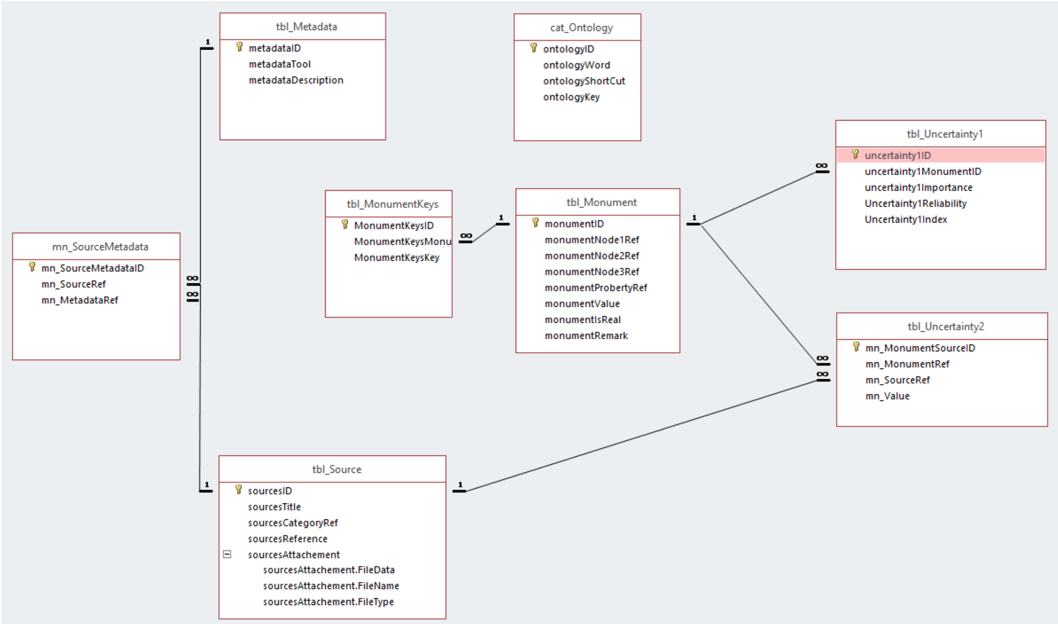


Figure 43: Database relationship sheet that contains all the tables and relationships. A higher resolution image can be obtained directly via the database application Microsoft Access 2016 (Brunke 2017).

However, since a plain database is hard to access, queries and reports were provided. They are responsible for simplifying further investigation and provide basic references, such as a bibliography or list of figures. The main important reports and queries are the "*Uncertainty #1*"[21], "*Uncertainty #2*"[22] and "*Uncertainty #2_2*". Each of the queries is represented in a table, which was later used for feeding the related report with data. The selection of the datasets is done through keys. They are stored in "*tbl_MonumentKeys*" and connected to the monument and its interpretation. The keys consist of a short form of the differing object levels and are clearly identifiable. The translation can be derived from "*cat_ontology*", which also stores their shortform and the common terms. Accordingly, "*pdm_cr_bp3_mtl*" indicates only the material of the podium's core in building phase 3. With this understanding, one or multiple monument segments can be queried. Such a key is required with each call of an uncertainty report.

[21] Uncertainty #1 corresponds to fuzzy-based uncertainty in the relational database and consists of numerical values.

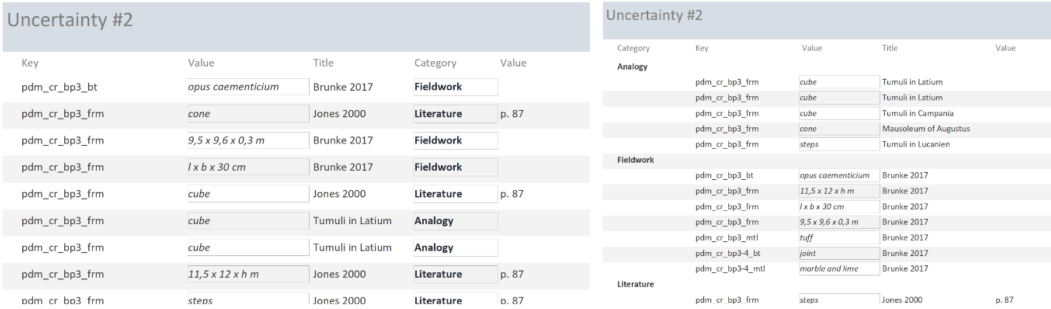
[22] Uncertainty #2 corresponds to class-based uncertainty in the relational database and consists of grouped sources.

Uncertainty #1

Key	Value	Index	Importance	Reliability
pdm_cr_bp3_bt	*opus caementicium*	1	1	**1**
pdm_cr_bp3_frm	*11,5 x 12 x h m*	0,6	1	**0,6**
pdm_cr_bp3_frm	*9,5 x 9,6 x 0,3 m*	1	1	**1**
pdm_cr_bp3_frm	*cone*	0,05	1	**0,05**
pdm_cr_bp3_frm	*cube*	0,95	1	**0,95**
pdm_cr_bp3_frm	*l x b x 30 cm*	1	1	**1**
pdm_cr_bp3_frm	*steps*	0,1	1	**0,1**
pdm_cr_bp3_mtl	*tuff*	1	1	**1**
pdm_cr_bp3-4_bt	*joint*	1	1	**1**
pdm_cr_bp3-4_mtl	*marble and lime*	1	1	**1**

Figure 44: The results of the report "*Uncertainty #1*", when using "*pdm_cr_bp3*" as the key. The key does not imply any property that will result in a return of all podium core instances of building phase 3 and its uncertainty indices (Brunke 2017).

"*Uncertainty #1*" and "*Uncertainty #2*" both return the uncertainty of a monument's segment. Still, they are not the same. As described in previous chapters, they represent two different methods. In detail, this means that "*Uncertainty #1*" provides several numerical values in the interval [0,1]. These values consist of importance, reliability and the uncertainty index. Since the case study is aimed at a general reconstruction, there is no need of importance. Consequently, reliability corresponds one to one in the uncertainty index, which represents the author's opinion of its interpretation. Each key is connected to at least one value, which corresponds to a possible interpretation. The result is a list (fig. 44) with numerical values assigned to the monument's parts. In contrast to that, "*Uncertainty #2*" uses the sum of its sources. Instead of representing a numerical value, it lists (fig. 45) all the sources that have contributed to this interpretation. In the database it is represented by the join table of source and monument. The only difference of reporting in "*Uncertainty #2*" and "*Uncertainty #2_2*" is the way of sorting and grouping the results, which are in both cases identical.



Uncertainty #2

Key	Value	Title	Category	Value
pdm_cr_bp3_bt	*opus caementicium*	Brunke 2017	**Fieldwork**	
pdm_cr_bp3_frm	*cone*	Jones 2000	**Literature**	p. 87
pdm_cr_bp3_frm	*9,5 x 9,6 x 0,3 m*	Brunke 2017	**Fieldwork**	
pdm_cr_bp3_frm	*l x b x 30 cm*	Brunke 2017	**Fieldwork**	
pdm_cr_bp3_frm	*cube*	Jones 2000	**Literature**	p. 87
pdm_cr_bp3_frm	*cube*	Tumuli in Latium	**Analogy**	
pdm_cr_bp3_frm	*cube*	Tumuli in Latium	**Analogy**	
pdm_cr_bp3_frm	*11,5 x 12 x h m*	Jones 2000	**Literature**	p. 87
pdm_cr_bp3_frm	*steps*	Jones 2000	**Literature**	p. 87

Uncertainty #2

Category	Key	Value	Title	Value
Analogy				
	pdm_cr_bp3_frm	*cube*	Tumuli in Latium	
	pdm_cr_bp3_frm	*cube*	Tumuli in Latium	
	pdm_cr_bp3_frm	*cube*	Tumuli in Campania	
	pdm_cr_bp3_frm	*cone*	Mausoleum of Augustus	
	pdm_cr_bp3_frm	*steps*	Tumuli in Lucanien	
Fieldwork				
	pdm_cr_bp3_bt	*opus caementicium*	Brunke 2017	
	pdm_cr_bp3_frm	*11,5 x 12 x h m*	Brunke 2017	
	pdm_cr_bp3_frm	*l x b x 30 cm*	Brunke 2017	
	pdm_cr_bp3_frm	*9,5 x 9,6 x 0,3 m*	Brunke 2017	
	pdm_cr_bp3_mtl	*tuff*	Brunke 2017	
	pdm_cr_bp3-4_bt	*joint*	Brunke 2017	
	pdm_cr_bp3-4_mtl	*marble and lime*	Brunke 2017	
Literature				
	pdm_cr_bp3_frm	*steps*	Jones 2000	p. 87

Figure 45: Section of the results of the report "*Uncertainty #2*" (left) and "*Uncertainty #2_2*" (right), when using "*pdm_cr_bp3*" as the key. The key does not imply any property that will result in a return of all podium core instances of building phase 3 and its uncertainty indices (Brunke 2017).

Likewise, the structure of the graph database had to be slightly adapted. Tables were no longer necessary. Instead, individual nodes were used. Overall, this makes the entire structure more complex and detailed with several hundreds of nodes and relationships. However, the main nodes can be summarized in "*Nodetree*", "*Property*" and "*Source*". Each of them was allocated several sub-labels to enable a more detailed determination of the object. Furthermore, relationships such as "*:HAS_PROPERTY*" and "*:IS_CONFIRMING*" were added. All of these can have optional, additional values and properties. One important property of *":HAS_PROPERTY*" is the "*uIndex*". It describes the uncertainty of the objects interpretation similar to a membership function of the fuzzy logic. In contrast "*:IS_CONFIRMING*" has a "*reliability*" property which is describing the reliability of a single source. When querying the complete database (fig. 46) the return is incomprehensible rather than helpful.

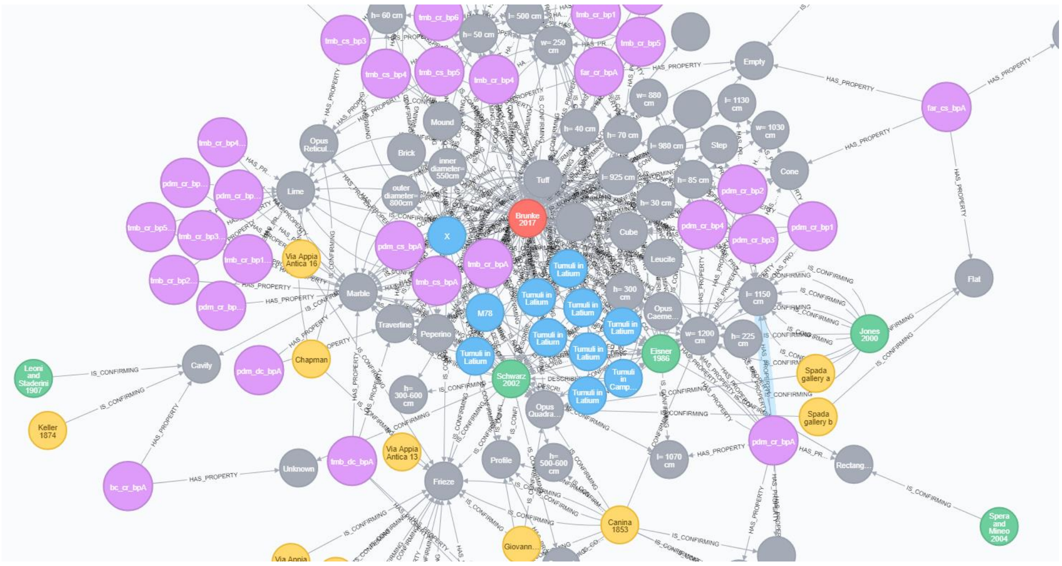


Figure 46: Section of the graph database, querying all the results. The query code used was: "*MATCH (all) RETURN (all)*", which basically returned the complete content, including relationships. The blue dots are the analogies, the red dots are the fieldwork, the grey dots are the properties, the green dot are the literature and the purple dots the segments of the 3D model. However, the color is a custom setting might change from application to application (Brunke 2017).

To avoid information overload, prepared queries are also useful here. However, it is not as easy as with Microsoft Access, since the architecture is based on text-based cypher queries. Nevertheless, standard queries similar to "*Uncertainty #1*" and "*Uncertainty #2*" of the relational database are provided, which work in the same way and additionally return a graph next to the listed results (fig. 47). To ensure the belonging of a path to the origin node of the node trees, each property was given the monument key. In this way, a path can be traced back to its origin even when it crosses others. Likewise, the keys can be used to later identify the individual segments in the 3D room later on. They go through all parts of the work. To simplify the analysis even more, sub-labels were added to each main label, representing the main properties of the object, such as the values of node1, node2 and node3. However, in this database, the property had to be separated from the monument and forms. Furthermore, no media files could be attached to the database.

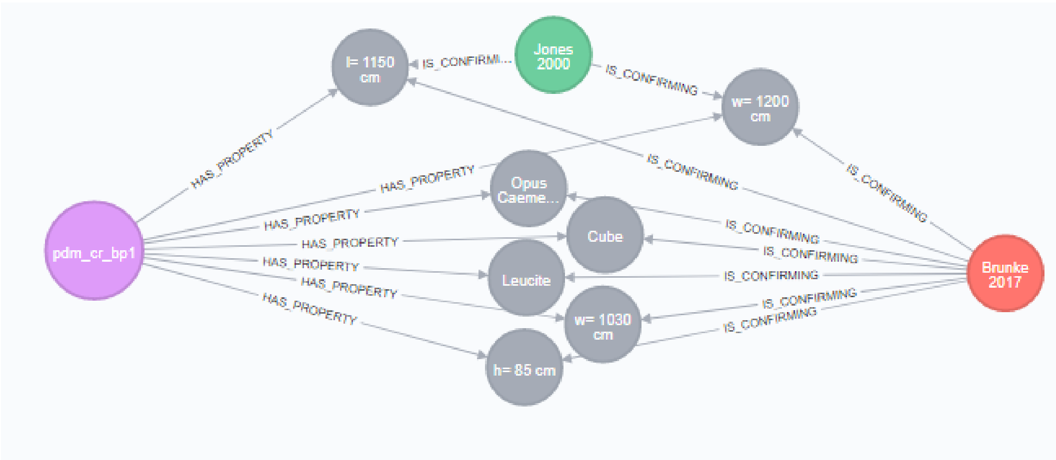


Figure 47: Example of an uncertainty query at the graph database. Hereby the key "*pdm_cr_bp1*" is used and all the properties are displayed. The fuzzy-based uncertainty is stored in the relation "*[:HAS_PROPERTY]",* while the class-based uncertainty is the sum of the dots highlighted in green and red. To get this graph, the following query is necessary: "*MATCH (object:Nodetree)-[rel:HAS_PROPERTY]->(value:Property)<-[rel2:IS_CONFIRMING]-(source:Source) WHERE object.key = rel2.key = 'pdm_cr_bp1' RETURN object, rel, value, rel2, source*". If only the fuzzy-based uncertainty is requested, the following adjustment would be necessary: "*MATCH object, rel.index, value*" (Brunke 2017).

In addition to the database, the three-dimensional visualization also plays an important role. As an intermediate step to the final 3D modeling, vector-based blueprints were created using a reality-based 3D model and the interpretations from Chapter 3. *Case study: The reconstruction of a Roman funerary monument*. The reality-based model (fig. 48) emerged from the fieldwork pictures taken by Rens de Hond (2016) and Luca Brunke (2017). A scale was added by distributing several black and white targets around the monument itself and measuring their distance to each other.

Figure 48: Reality-based model of the monument, derived from aerial and terrestrial photographs (De Hond 2016 and Brunke 2017).

The blueprints (fig. 49) are available as vector files and contain an orthographic picture, drawings of the actual remains and several interpretative approaches as individual layers. Since they are scaled, they can be used for measurement and as a template for the evidence-based 3D model. In total, blueprints from three perspectives were created: the front, left and top side.

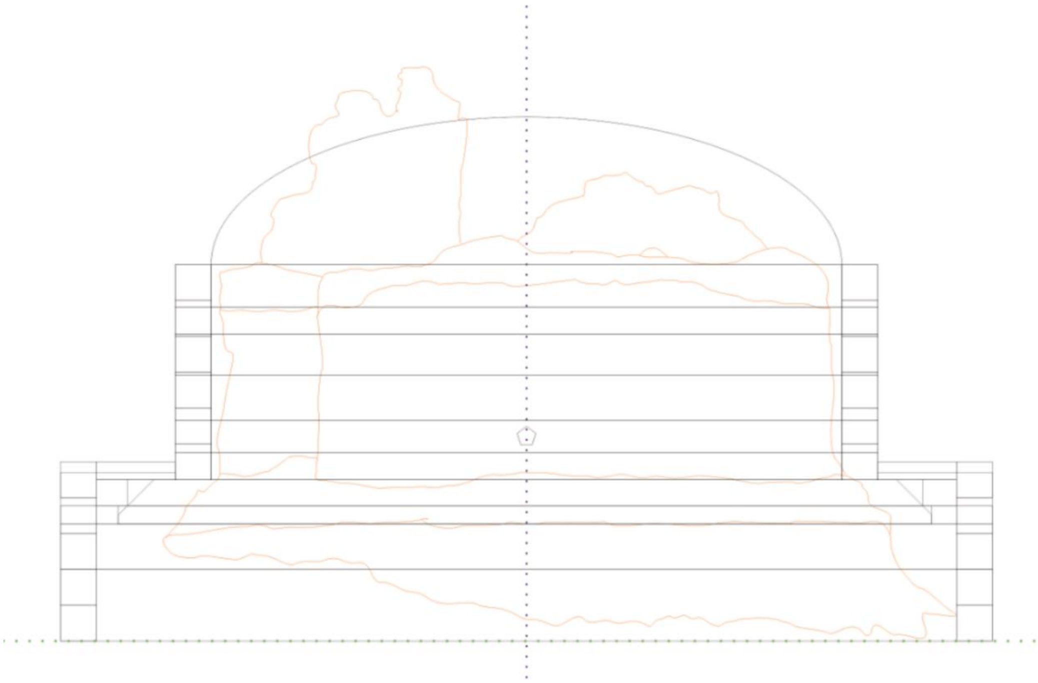


Figure 49: Blueprint of the left side. The interpretive structures are drawn in black, whereas the actual remains are highlighted in orange. Plates 8, 9 and 10 provide the remaining perspectives in more detail (Brunke 2017).

The core of this work is based on a plain 3D model (fig. 50). Individual parts are available in several alternatives, according to the interpretation (Plate 12 till Plate 18). Within the model, these parts are marked with the suffix "_*aX*", in which X represents an increasing integer and is a substitution for alternative. The 3D model itself was created in its entirety with Blender, using the previously listed databases, blueprints and reality-based model as help. Using the Blender' build in parenting and child systems allows one to organize all the parts in a hierarchical system, following the object key structure, which also represents the name of an individual object. In total, approximately 80 objects were created. In addition, a bevel was added to the panels of the case to emphasize the individual building phases and optimize light scattering during the rendering process.

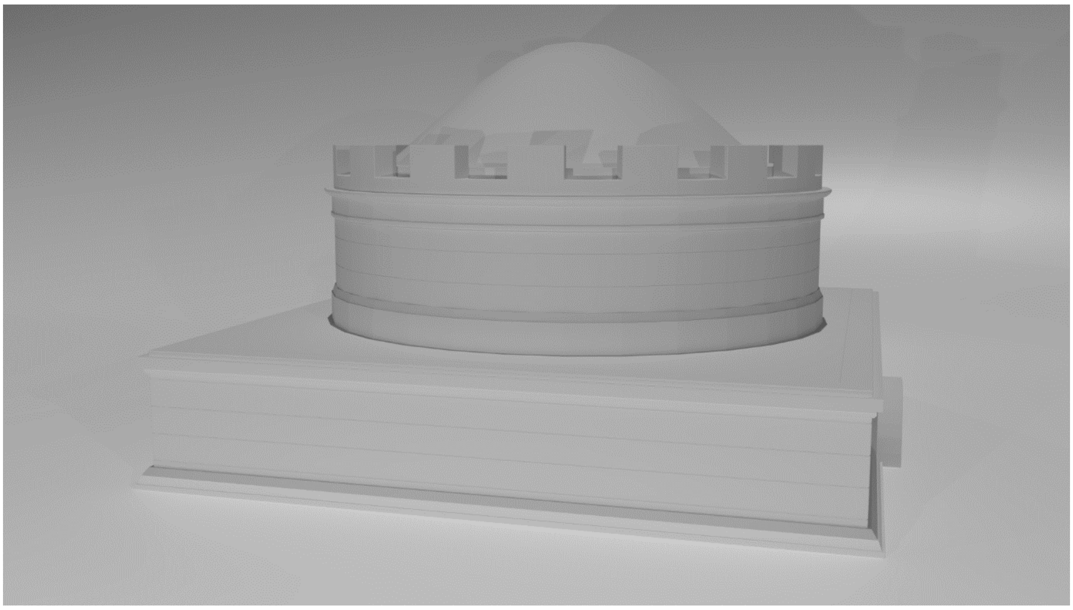


Figure 50: Plain model of one possible reconstruction. Detailed illustrations that include further alternative versions can be found from Plate 11 to Plate 18 and in the related Blender file itself (Brunke 2017).

The color code (fig. 51) was accomplished with an uncertainty library. This library contains prepared shaders for each degree of uncertainty, which only have to be assigned to the objects. The colors follow the color scheme from "*4.3 Encoding the uncertainty in the model's visualization"* for color codes. It is noticeable that, despite the differing concepts of uncertainty, the distribution of the color change is similar. Also, not much of a gradient is visible anymore, derived from the fuzzy-based uncertainty.

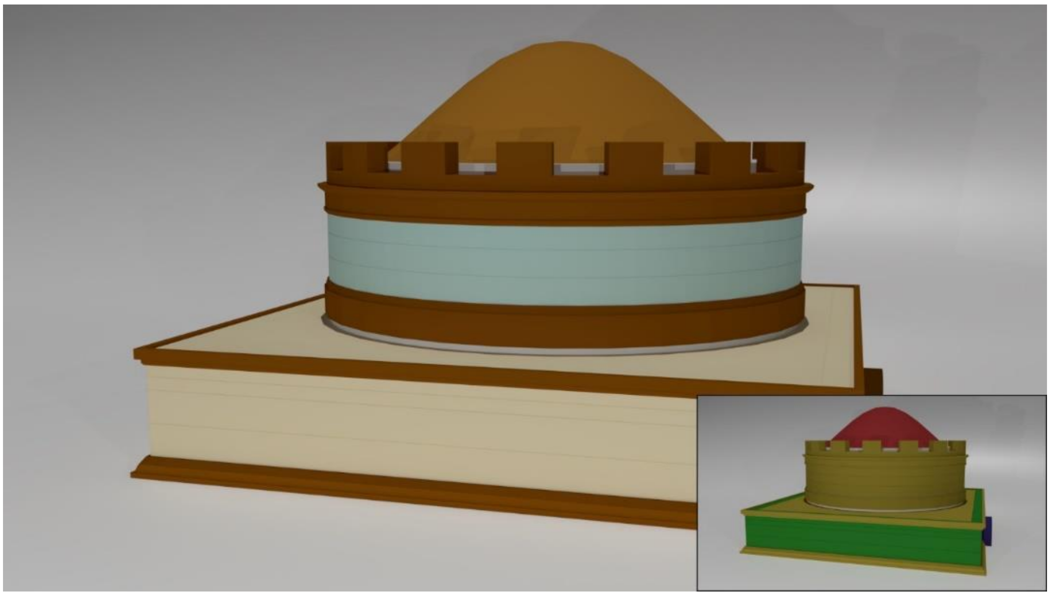


Figure 51: Visualization with the color code. The larger image corresponds to the fuzzy-based uncertainty and the color gradient from brown to green, whereas the smaller image in the right lower corner represents the source classification. For the big illustration, the browner the tone the more uncertain the representation of the form and the actual dimensions is. For the small illustration, information about the form and dimension are derived from analogies if the parts are yellow, from the fieldwork if they are green, from literature if they are red and from illustration if they are blue. More detailed images are available on Plate 19 (Brunke 2017).

The uncertainty scaling via render mode (fig. 52) was achieved by manipulating details in the visualization. The greatest uncertainty was achieved with the wireframe modifier, which reduced the faces to the edges. The solid mode is equal to the color code but without any color overlay. Instead a neutral grey was used. For the texture, a stone wall of travertine, similar to the most probable interpretation was chosen and overlaid. The height of the blocks is scaled, whereas the length remains unscaled. A wireframe modifier was added to indicate the most uncertain parts. Today there is no evidence anymore. However analogies, illustration and fieldwork indicate that something similar to that must have been there. For parts that most likely existed in the past, and whose exact form and dimension was not clear anymore, a normal solid mode was used. Texture was applied to parts that were not there anymore but for which there was clear evidence of their presence. Travertine masonry was chosen to denote texture. It is important that it is not real Roman texture. The height of the blocks on the image might fit, but not their length. Fuzzy-based and class-based uncertainty were more or less mixed in this approach.

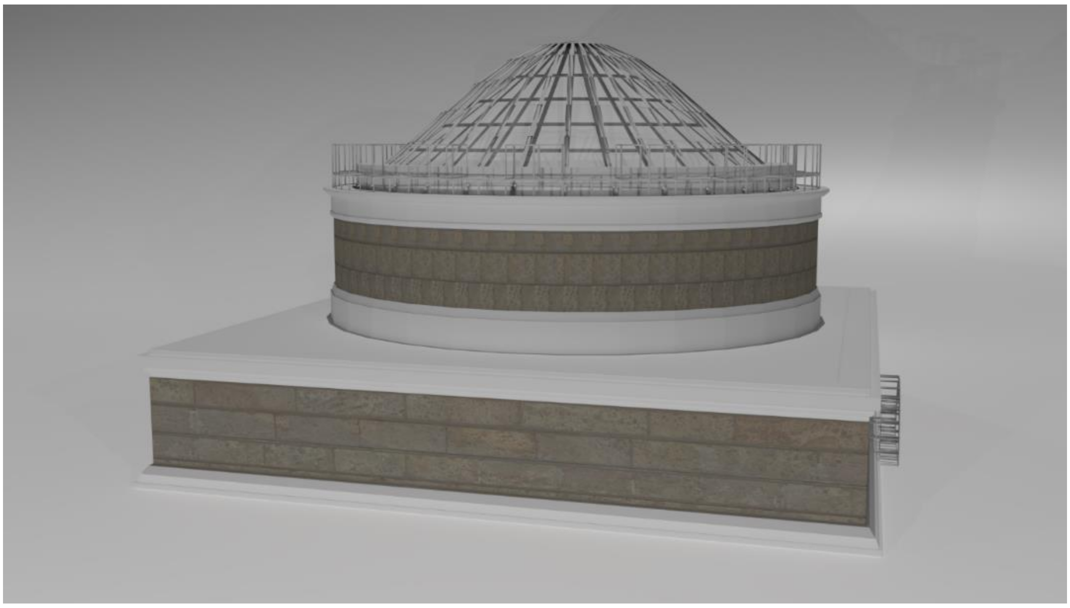


Figure 52: The wireframe parts are not present anymore and there is almost no evidence of them today. The solid parts should have been available according to analogies, literature and illustration, while textures indicate relatively certain parts. A more detailed illustration can be found on Plate 20 (Brunke 2017).

The level of detail method (fig. 53) is the only approach in which geometry was used to encode uncertainty at the object. In most cases it behaves similarly to the render mode, in which details are added with increasing certainty. However, the already simple forms of the monument do not provide many opportunities to further simplify the model. Nevertheless, the reality-based model can be used to show the absolute certain parts. The only problem is that those parts are limited mainly to the core and are not visible from the outside.

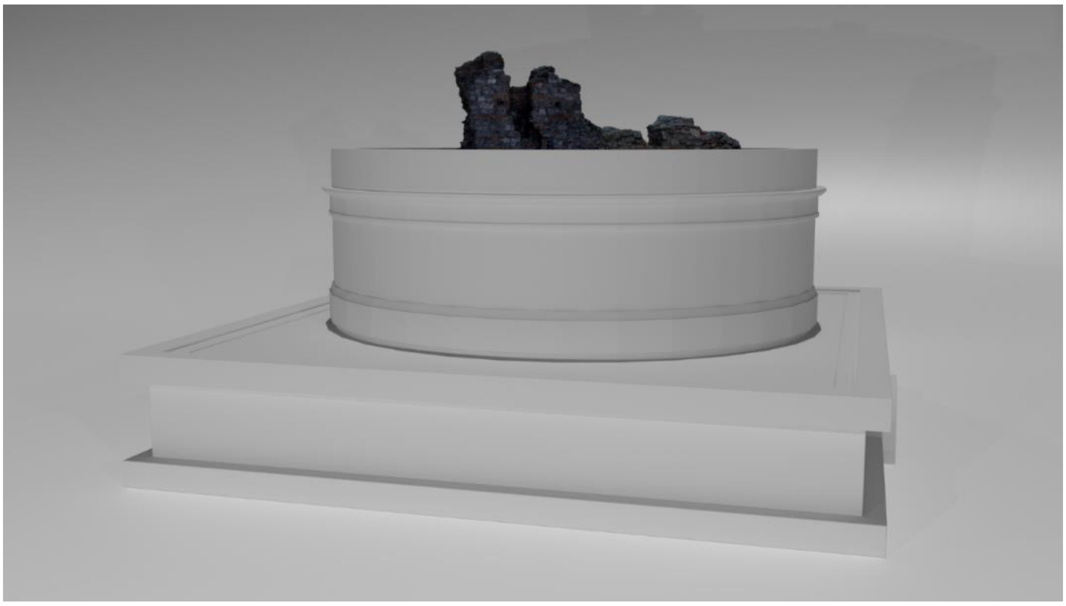


Figure 53: The level of detail also allows one to omit objects completely (such as the roof). Decorations are shown only as simple cubes and the structure from the motion model as overlay. More details can be found on Plate 21 (Brunke 2017).

The results presented here are not always optimal. They follow the examples of the literature. Even if they are summarized, there are at least two databases and three different visualizations. Likewise, not everything can be combined freely. The next chapter deals with the pros and cons of each approach. The general theories of uncertainty are also discussed and their limits are determined.

6. Evaluation of the theories and results

This chapter covers a large part of the discussion. The focus is on the role of uncertainty in the academic environment (see *6.1 Uncertainty as part of scientific transparency*) and the different ideas of uncertainty concepts in general (see *6.2 Fuzzy-based uncertainty in comparison with class-based uncertainty*).

The discussion will be extended by several subsections, in which the limitations of the current methods and concepts are highlighted. The limitations are discussed and investigated with respect to their impact. Afterwards possible solutions are suggested. These sections are as follows: *6.3 Fluctuating and cumulative uncertainty* and *6.4 The organization of 3D data.*

In the next section, *6.5 Uncertainty encoded as color code, render mode and level of detail,* the research methods, my own results, and their limitations are discussed. The advantages and disadvantages are evaluated. In this section, the content of *2.7 Theories and concepts* is particularly relevant, because it has immense bearing on the main objective of the thesis.

The discussion about the research shifts smoothly into future perspectives. This is due to the fact that two new and promising approaches are touched on during the research, firstly graph databases for reconstructions (see *6.6 Graph databases as a novel approach of documenting uncertainty*) and, secondly, Blender as an interactive platform (see *6.7 Blender as an interactive approach*). Nevertheless, section 6.6 also includes a small introduction and discussion regarding relational databases in contrast to graph databases.

6.1 Uncertainty as part of scientific transparency

The London Charter and the Principles of Seville provide an advanced guide for transparency in virtual archaeology. Likewise, they refer to the importance of documentation and the separation of actual data and interpretation. However, uncertainty is not mentioned explicitly; it is paraphrased and substituted with the term "*transparency*". This raises the question of its purpose and whether uncertainty can be equated or at least linked to scientific transparency.

Uncertainty is always a part of the discussion and emerges when the available data provides more than one possible interpretation. Accordingly, it always plays a major role in the discussions about research, even if it is not mentioned directly. Thus, not directly addressing an issue does not mean it is not important or that it does not exist. Indeed, in order to deliver transparent research, the documentation needs to be reliable. This provides other scholars with the possibility of picking up the research easily.

There might be several reasons for the absence of the term "*uncertainty*". Firstly, it is seen as a sub-area of scientific transparency and is therefore not necessarily mentioned. Secondly, it is a by-product of written reports. It is impossible to hold a discussion and not to paraphrase uncertainty in any way. Instead of being a primary component, it is hidden in the general assumptions and proves. Lastly, so far it has never been necessary to express uncertainty directly. The hidden assumptions in the text are sufficient enough. In general, the last two points seem to be similar. However, in my view they do not consider the requirements a scientific and transparent research needs to fulfill in virtual archaeology. Part of the difficulty is that uncertainty is conveyed in various ways, for example, by separating reality-based and evidence-based reconstructions or by means of extensive discussions. However, the discussions can have a low truth content. Until the use of digital analysis, it was not necessary to make quantitative statements regarding uncertainty. It was enough to describe them with vague words or slip them into the discussion. In current research, however, uncertainty seems to have developed into a sub-area of transparency.

To return to the written text, it is one of the most popular forms of publishing data in archaeology. Despite its clear structure and easy comprehensibility, it does not live up to its potential. Part of this potential consists of the direct connection between discussion and geometry. There are various options available for this process. On the one hand, it is possible to use databases and link them to the object. On the other hand, the geometry and visualization of the available data can be manipulated. Additionally, it is possible to annotate the text and thereby create a mixture of database and text. However, the method used should be well discussed in light of the targeted audience group. Hints of possible approaches to targeting a scientific audience can be found in the Charters and Principles. They offer some valuable information. However, exact instructions are rather rare and vague, since they are not intended to be used as step-by-step manuals. In contrast, the "*3D Icons*" and "*IT-Empfehlungen*" offer detailed descriptions of possible workflows.

Table 7: Overview of the development of uncertainty and scientific transparency in publications. The first row shows the authors of the publications, the second one their topic and the last one their suggested solutions (Reilly 1992; Miller and Richards 1995; Strothotte et al. 1999; Kensek et al. 2004; Brusaporci 2017)

Reilly, 1992.	Miller and Richards, 1995.	Strothotte et al., 1999.	Kensek et al., 2004	Brusaporci, 2017.
Concerned by the photorealism.		How to express uncertainty?		Documentation.
Documentation, color code or experts.		Mixed visualization.	Data enrichment.	Metadata and paradata.

However, comparing the statements in the guidelines and charters with the case studies, one notices that the guidelines are followed only in some cases. This might be because the reconstruction is not the core part of the research, or they are simply not aware of it. Furthermore, the definition of transparency seems to change over time (tab. 7). Clearly, Reilly, Miller and Richards outline their first concerns with respect to photorealistic renderings. As one possible solution, they suggest extensive documentation, a color code or an expert elaboration of those models. Strothotte et al., however, plead more for a mixed approach of visualizations and an interactive system for the presentation. Kensek, Dodd and Cipolla extend these approaches with the data enrichment of the model. Lastly, Brusaporci deals only with the documentation of 3D models in the form of paradata and metadata.

In general, the written text still plays a major role in documenting research in academic environments. It is not foreseeable that this will be completely replaced by new methods in the near future. However, a transmitting database that passes the information on to the model would undoubtedly enrich the research. However, for that to happen it is important to formulate a unique definition of uncertainty and its documentation, as well as an approach that is time appropriate. The two definitions of uncertainty used in this research will be compared in the coming sub chapter.

6.2 Fuzzy-based uncertainty in comparison with class-based uncertainty

For the purposes of this research, the most important data stored in the databases is uncertainty. The uncertainty itself is available in two different approaches, fuzzy-based and class-based. In summary, both concepts might be problematic in terms of describing design decisions. It has to be reckoned that this can lead to certain tradeoffs. With the fuzzy-based concept, uncertainty is described as an absolute value. This value is in the interval [0, 1] and derives from the mathematical principle of the fuzzy logic and membership functions. However, even if the theory pledges on blurry and corrupt data, the infinite amount of numbers that a membership function allows suggests a sharp distinction. Likewise, an impression of high certainty might be implied, similarly to a photorealistic rendering.

However, fuzzy sets are only an expression of the author's opinion regarding the object's uncertainty. A formula might obfuscate this issue but not solve it. It is just moving to another stage and seems to look right. However, a formula is useful when it comes to analysis or combining several values. Accordingly, absolute uncertainty, also known as fuzzy-based uncertainty, should be viewed with caution. Using this concept can provide clear data; however, it also contains a high degree of subjectivity. The following example (tab. 8) is intended to illustrate this:

Table 8: Example of a dataset containing fuzzy-based uncertainty. The key used is: "*pdm_cs_bp1_frm*" (Brunke 2017)

Value	Importance	Reliability	Uncertainty
l x b x 85 cm	1	0.4	0.4
l x 50 x h cm	1	0.6	0.6
l x b x 50 cm	1	0.6	0.6

Let us assume that these values were set by me after an extensive discussion. Firstly, one might notice that they form a cluster around 0.5. Secondly, exactly the same value exists for two objects in an infinite range of numbers. From a statistical perspective, this is highly unlikely. Likewise, how should it be possible to differentiate 0.60 from 0.61 or even smaller steps? Additionally, all the values are rounded to one place after the decimal point. This is by no means an intention, but rather an attempt to limit the fine division of the subliminal grouping. Considering those two aspects, objectivity cannot be guaranteed throughout the project. Nevertheless, fuzzy-based uncertainty also has some strengths. All the values are absolute and each segment gets at least one of its own. The values can be easily used for analyses or the realization of a specific visualization. Furthermore, post processing is not always required. All the data can be stored and queried directly in big lists. Data conflicts can be solved by simple mathematical equations. It is easier to calculate the average uncertainty out of a list of values than from a group of sources.

Table 9: Example of a data set containing class-based uncertainty. The used key is: "*pdm_cs_bp1_frm*" (Brunke 2017)

Value	Title	Category
L x b x 85 cm	Eisner 1986 Brunke 2017	Literature Fieldwork
L x 50 x h cm	Eisner 1986 Via Appia	Literature Analogy
L x b x 50 cm	Eisner 1986 Via Appia	Literature Analogy

Class-based uncertainty represents a contrasting attempt. It is defined as the classification of sources. Its biggest problems are the cumulative uncertainty and differing uncertainty values within one class. Taking table 9 as an example, different instances of segment *pdm_cs_bp1_frm* have different properties. Since the instances are separated from each other, this is no problem. However, changes within one instance are more problematic. For example, the membership of two different classes can be problematic. A combination with fuzzy-based uncertainty might bypass this issue in an impressive way (fig. 54). An advantage is that in most databases no extra tables or lists are needed. Class-based uncertainty is basically a byproduct of each database. It is the connection from the interpretation to the source. This circumstance ensures some kind of objectivity since it is not dependent upon a personal opinion. Likewise, analyses are easier to conduct because of the consistently equal structure. The graph database is particularly suitable for this data. Despite being grouped, the data is not absolute anymore and is represented by dozens of nodes and relationships. These nodes can provide the right balance of details and subjectivity.

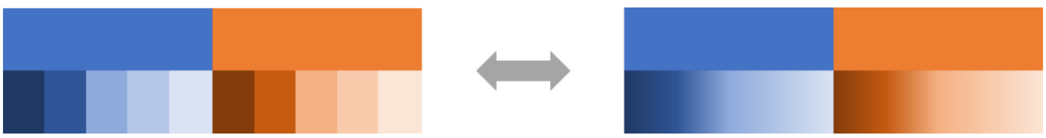


Figure 54: Concept drawing of the mixed approach from uncertainty one and two. Instead of a relative subscale, an absolute subscale can be added. This approach is similar to figure 56, but is contrasting the stepped and smooth gradient of the 2nd level uncertainty (Brunke 2017).

Thus, both fuzzy-based and class-based uncertainty have strengths and weaknesses. Choosing the right concept depends largely on the available data and the aim of the researcher. However, the special thing about it is that they can neutralize each other's weaknesses when combined (fig. 54). Hereby, class-based uncertainty is used as rough framework, while fuzzy-based uncertainty is responsible for the fine details. It still needs to be clarified whether a smoothed or stepped gradient (fig. 54) is better suited to represent the fuzzy-based uncertainty. In general, it can be said, that it behaves similarly to the absolute values discussed earlier. The concept provides enough data; however, it might be too detailed for this purpose. As an alternative, the infinite scale can be divided into five relative steps. However, the arrangement does not always work smoothly. There may be certain problems that are limiting the use of the visualization in models. These issues are related to the nature of the data and their storage. Therefore, they are discussed in detail in the next section. Furthermore, possible solutions are suggested.

6.3 Fluctuating and cumulative uncertainty

6.3.1 Fluctuating uncertainty in class-based systems

Fluctuating and cumulative uncertainty are two issues that arise when using either the class-based or fuzzy-based approach. They can emerge due the normalization process of databases and the nature of the argumentation. Both are based on similar principles but have to be solved in different ways. The descriptions and approaches were dealt with in the previous chapter, but should be discussed in detail here. In general, this can be seen as the first limitation of the actual results.

Firstly, with fluctuating uncertainty one source can contain several sub-sources. Each of them provides another individual range of uncertainty values. The class-based uncertainty is particularly affected by this. However, fuzzy-based uncertainty can also be subject to this circumstance, although much less frequently. An example of fluctuating fuzzy-based uncertainty is if the literature has inconsistent argumentation. One argument in the literature might be stronger than another one.

Figure 55: Example of fluctuating class-based uncertainty in the illustration category. The uncertainty rises from left to right (Via Appia Antica 6 in www.ebay.it, b; Keller 1874; Vincenzo Giovannini in https://nl.m.wikipedia.org).

Figure 55 is an example of class-based uncertainty. An illustration can have numerous subgroups such as photographs, drawings and paintings. In this case, most of them are from the 19th century and can be found in the research's case study. However, it should be clear that the reliability of a photograph is not the same as the reliability of a painting. This might not be an issue for fuzzy-based uncertainty, since each source is assigned an individual value. However, class-based uncertainty allows the assignment of only pre-defined classes and there is therefore no differentiation of individual sources. Currently it is not possible to distinguish between a photograph and a picture as a source for the argumentation.

In comparison with other publications, Apollonio and Giovannini 2015 divide the class of illustration along a global gradient of uncertainty. Apollonio 2016 uses only one group to represent illustrations. However, this group contains only technical drawings and therefore does not need any further subdivision.

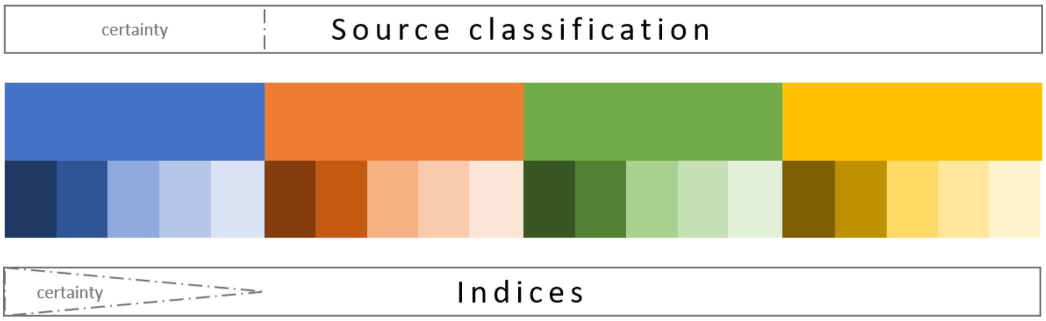


Figure 56: Concept drawing of the theoretical approach from uncertainty in 3D models by creating sub-categories for the individual source classes. The certainty for the source classification is equally distributed for one color, while the certainty for indices decreases with increasing brightness of the color (Brunke 2017).

Hence, I suggest a subscale of relative or absolute uncertainty that is added to each of the four categories (fig. 56). This subscale is powered by the fuzzy-based uncertainty approach presented in the previous section. Picking up the example of illustration, this would mean a further subdivision into photograph, drawing, painting and unrelated paintings with increasing uncertainty from left to right. The ordering provides a rough overview of how much impact each subcategory should have. Unrelated paintings are seen as paintings with structures that are similar to the tomb but not with an actual connection. The same principle should also be applicable to literature, analogy and fieldwork. In an optimal case, the classification would be intuitive. In addition, it should be considered whether the class literature should not be dissolved. In general, it refers to only one of the other classes.

6.3.2 Cumulative uncertainty in fuzzy-based systems

Secondly, cumulative uncertainty might correspond to the problem of fluctuating uncertainty for fuzzy-based approaches. It appears, when one dataset contains differing values of uncertainty. To clarify what is meant, another example is taken from the case study. Querying “*pdm_cr_bp3_frm*” in one of the available databases returns a width of 12 m (tab. 10) three times. Each of them has a differing degree (30%, 50% and 70%) or class (literature: Eisner 1986, Schwarz 2002 and Canina 1853) of uncertainty. This is due the fact that the same value is available in three different contexts but each of them has a different degree of uncertainty. Those values are artefacts of the database normalization and should have been summarized. In the actual instance this is not possible.

Table 10: Example of a dataset containing fuzzy-based and class-based uncertainty. The used key is: "*pdm_cr_bpA_frm*". The uIndex is equal to reliability and is the short cut of uncertainty index. It is clearly visible that the changes do not have any effect on the classes (Brunke 2017)

Value	uIndex	Class
12 m	0.3	literature
12 m	0.5	literature
12 m	0.7	literature

While fuzzy-based uncertainty is vulnerable to this problem, class-based uncertainty has fewer problems because it classifies the sources before the actual analysis. Taking the previous case, this would be the literature category. However, if only one segment requires sources from different classes, uncertainty two also has its problems. The main issue is how to deal with such a situation. Which of the values will prevail?

Possible solutions are mathematical equations, rule sets (highest, lowest, average) or neglecting the issue. Ignoring the problem is not an option since it can have a high impact. Likewise, it is self-evident that the certainty of one source within one classification category can vary, which is referred to as the issue of fluctuating uncertainty in the previous section. As an example of analogies instead of illustration, many of them suggest opus quadratum and travertine. However, even if they are all tumuli, some of them might be better suited than others. It could be because of the time period, architecture or location. No unification should be forced. Group classification does not allow several uncertainty values within one cluster.

Table 11: Example of a dataset containing fuzzy-based uncertainty. The used key is: "*pdm_cs_bpA_frm*" (Brunke 2017)

Method	Result
Lowest value	0.3
Highest value	0.7
Average	0.5
…	

In an optimal case, interactions between the classes are possible with actual simple mathematical equations (tab. 11). Nevertheless, *2.7 Theories and concepts* and *5. The reconstruction and its database* offer some quite promising possibilities. Another possible approach is presented in *6.6 Graph databases as a novel approach of documenting uncertainty*. However, not all limits are related to the datasets in the database, also some issues arise during the organization of the 3D model.

6.4 The organization of 3D data

When focusing on the 3D model instead of the datasets, not all theoretical results and blueprints are as accurate as previously thought. They are not faulty; they rather have minor deviations in their dimensions. The aberrations most likely emerge because of the non-uniform body of the monument. Within the core those deviations are hardly recognizable. However, the case is more sensitive. To highlight each case layer, a slight bevel has been added to the edges of the reconstruction.

More related to uncertainty is the level of detail. Considering past discussions among scholars, a moderate level is used rather than a detailed one. With decreasing details the uncertainty might decrease as well, but so will the information density. Hence, a correct balance must be found. There is no benefit in imitating the reality one by one or simplifying it until no information is left. One promising way could be to use the highest measurement inaccuracy of the object as a minimum for the detailed appearance in the monument. However, the level of detail is part of the discussion about visualizing uncertainty and will be discussed in the corresponding paragraph in detail.

Secondly, what part of the model is going to be rendered (fig. 57)? Interactive simulations and animation can render everything. For interactive simulation, the observer can even decide which layers should be visible. In contrast, images can show only one perspective. Additionally, objects can cover other objects or face away from the camera. One possibility is to filter the objects that are displayed. Only the interior or exterior parts can be shown. Enforcing a filtering is not optimal because it might filter out inaccurate segments as well. Another possibility is the use of transparent shaders to enable a look through. However, this aspect also belongs to the field of visualization and should therefore be discussed there. It could be confused with the visualization of uncertainty.

Figure 57: Multiple renderings of the same segment in different variations and separated from its total context. This example shows four variations of the roof: mound, cone, plane and none. All renderings in high resolution are available from Plates 11 to 18 (Brunke 2017).

Thirdly, one could provide several renderings from different perspectives and using different segments (fig. 57). The advantage is that alternative versions can be displayed without any difficulty. The disadvantage is that many images have to be rendered, making it difficult to recognize the overall picture. In total, an image rendering is always a reduction of possibilities and information and should be avoided whenever possible.

However, not disturbing the overall context, neglecting specific parts or using visualization methods, one can remove some of the geometry in the form of a cross-section. Rather than cutting the complete monument in half, only up to a quarter should be removed to expose a partial cross section. Since the object is often symmetrical in Roman contexts it facilitates insight without losing too much information. Nevertheless, only one variation at the time can be rendered. This leads us to the next issue. Assuming only one variation can be displayed, which one should be chosen? A change in variation also means a change in uncertainty. Usually many different alternative versions are available, but only a few suits the context. Basically, each source projects its own version into the room. Instead of modeling all of them, it is better to assess the approaches based on their uncertainty and elaborate the reconstruction with the least degree of uncertainty. Additionally, some extremes might also be good to indicate the possible range of alternative versions. Each of the variations needs its own uncertainty. Aspects such as material, building technique, form and dimension are available. The form and dimension fit best as overall uncertainty, since it is the spatial data that is displayed initially.

Furthermore, exact and three-dimensional spatial data is difficult to implement on a conventional database. One reason is the irregular nature of the heavily weathered and changed object. The number of corners and transitions makes it impossible to transfer it to a clear set of quantitative data. It also complicates the current measurements of data, which results in measurement inaccuracy and further compromises the reliability. To minimize the impact of spatial measurement uncertainty a scale and detailed documentation might be beneficial (fig. 58). In this context, it is also important to point out the currently described uncertainty and how it is encoded into the model.

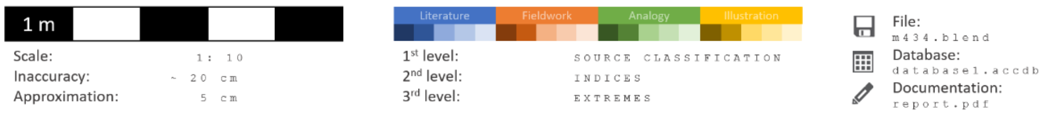


Figure 58: Concept drawing of the theoretical approach from uncertainty in 3D models, by adding a definition and scale. The inaccuracy provides the measurement accuracy of the reality-based model, while the approximation returns the rounding factor. The uncertainties are stacked according to their priority and visualization. Finally, the location of the most important data is announced. The graphic can be superimposed on the final rendering (Brunke 2017).

However, it is problematic to place a two-dimensional scale in a three-dimensional space as an overlay because of the missing perspective and spatial information. Instead of using a 2D overlay, perhaps put them directly into the model. Furthermore, issues also arrive with the colors in the legend. The light of the rendering or reflections might bias the perception. Too much or too little light may even clamp the colors.

In general, there are still many problems with 3D modeling, namely the inaccurate data, the blocking view, the level of detail, the choosing of the right segment and the description of the results. Although all of these problems have been identified so far, they must be dealt with and solved individually. An attempt will be made to do so in the following sections by discussing different forms of visualizations.

6.5 Uncertainty encoded as color code, render mode and level of detail

6.5.1 Color theory as a framework for class-based and fuzzy-based uncertainty

Encoding uncertainty via the visualization is a common approach in virtual archaeology. Basically, one takes the information from the documentation and applies it to the previously described model. In return for that, various approaches have been established, although the color code is by far the most common method.

Firstly, there is the color gradient. In this research and many others, it is used to display numerical values along a scale. This best corresponds to fuzzy-based uncertainty. With the used brown to red gradient, several aspects can be covered at once. It is:

- Intuitively comprehensible. Brown stands for uncertain areas while green covers certain areas.
- A complementary pair of colors.
- Able to connect successfully a numerical value to a color value.
- Robust against most color blindness.
- Possible to map fine details.

However, when using a smooth gradient, utilities are necessary to determine the exact value since the difference might be too subtle to be detectable by sight. A stepped gradient that groups the scale into value ranges could be a solution (fig. 54; fig. 56). However, it also increases the inaccuracy of the measurement. Considering the results of the case study (fig. 51), the assignment of a color gradient works smoothly. Nevertheless, the result is slightly different than expected.

Instead of a three-dimensional reconstruction with a color gradient, a reconstruction similar to the class-based approach is achieved. The only difference seems to be the actual colors themselves. Since the gradient is not visible anymore, it loses all of its significance. One reason might be the clustering of similar values among similar segments. However, even with regard to this peculiarity, it is difficult to recognize a gradient. A possible way to counteract this might be the reduction of the colors used. Instead of using complementary colors, only monochromatic colors (fig. 59) could be used. The monochromatic colors have their variation in brightness instead of color. Since the priority is to maintain the behavior of a gradient, this might be the best solution.

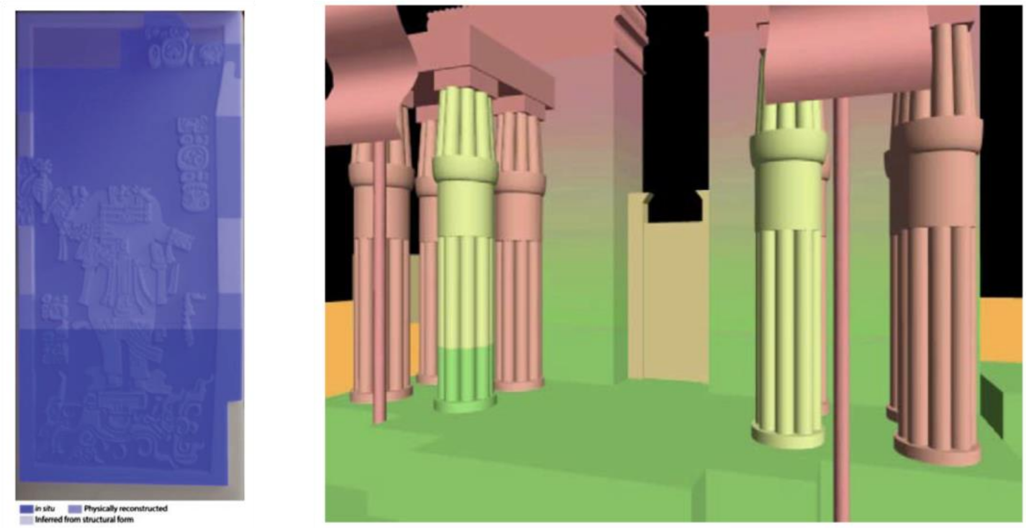


Figure 59: Comparison of a monochromatic gradient (left) indicating the uncertainty of a Mayan temple relief (Schwerin 2016, 213) and a complementary gradient (right) indicating the uncertainty of several columns (Kensek et al. 2004, 178).

In contrast to the gradient, the harmonic tetrad can be used for the class-based uncertainty. The harmony consists of four complementary colors. They are all assigned the same distance from each other at the color wheel. In theory, that is the best way to indicate contrasting opinions. However, the opinions are not always contrasting in this case study; they can also be supportive. One could solve this by bringing the colors closer together and thus weaken or strengthen the contrast. Despite the change of the color meaning, this process would be highly speculative and not eligible for scientific research. Nevertheless, Sifiniotis et al. 2007 determined the impact of several classes on scholars in a survey. This survey might serve as rough outline. Likewise, when reducing the classes to three active ones, primary colors (fig. 60) can also be used. However, they might form a harmony, but no complementary contrast. Blue and green are too close to each other.

A solution might be the substitution of either green or blue by another color. Likewise, they could be assigned to related classes. For example, the class fieldwork and analogy both describe actual structures. Therefore, both classes contain similar data and might be more closely related to each other than to illustrations. However, if the primary color green is used for the fieldwork and red for illustration, there might be the intention of a red and green contrast, which in this case would be undesirable. Still, primary colors can be helpful in solving cumulative or fluctuating uncertainty. They offer the advantage of being known and are easy to distinguish from each other. Furthermore, they are seldom found in natural environments and can be easily mixed with each other. Basically, they form the root of the color theory, in which the classes will form the root for the uncertainty theory.

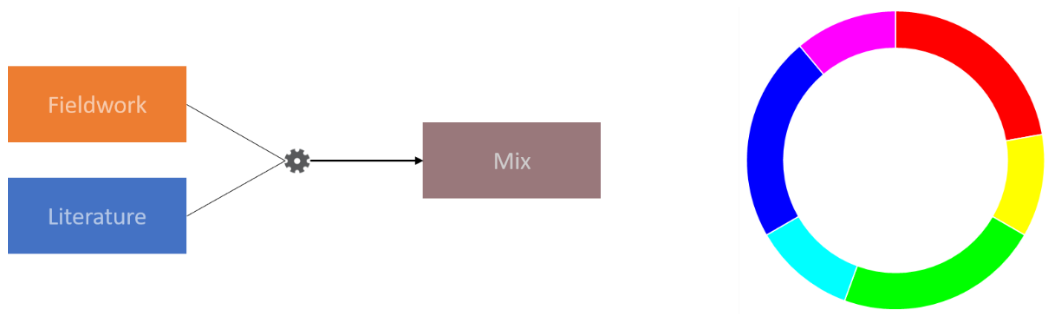


Figure 60: Concept of color mixing at the source classification. The colors of two categories can be mixed. The ratio relates to the impact of each color. Primary colors are used as a base, which will transform into secondary colors – right circle (Brunke 2017).

The only problem with primary colors is their intrusiveness, and inauthentic harmony and complementarity (fig. 60). Improvements of perception can be made by adjusting the brightness and saturation. Likewise, tiny bits of other colors can be added. Further improvements will be made if the color classes are mixed with the color gradient. A two-parted scale can deal with fluctuating uncertainties, as well as with cumulating.

To sum up, each classification will have been assigned one complementary color. Each of the color classes receives a subscale with differing brightness representing a relative or absolute subscale of uncertainty. In cases of several sources, the two representing colors can be mixed together (fig. 60) in accordance with their influence on the interpretation.

The emerging color will be the actual complementary color of the color class that is not used in this process. For example, fieldwork (red) and analogy (blue) are mixed. In an additive system they will result in a kind of purple, which is the complementary color used for illustration (green). This can further exclude or include parts of the discussion. The new color is now called a secondary color. They can be easily broken down into their individual single colors. To display different weightings in the argumentation, the mixture ratio of those two colors can be adapted. The exact value can be then easily measured with a color picker or the modeling software used to determine the ratio.

Material libraries that can be created for Blender are especially suitable for this purpose and they can be used in multiple projects simultaneously. Those are usually based upon easy shaders or textures. More complex patterns might require physically-based textures. The principle of physically-based textures can be also transferred to the uncertainty concept and used for encoding different types of uncertainty within one material. Each segment then becomes an extra piece of material assigned for each uncertainty instance. The user can switch and render the most convenient or requested one.

In short, complementary colors and the class-based uncertainty concept are better suited to revealing the nature of the source, whereas gradients and fuzzy-based uncertainty can easily display values. Considering the results of the case study (fig. 51), it might not even matter which concept is chosen since both forms of visualization feature similarities. They might look similar, but the highest information density can only be reached in a mixed approach for both of them, namely using color classes as containers for the rough framework, and color gradients for a subtle scale with fine details. To cover even the outer extreme of the scale, additional render modes can be added as described in the next section.

6.5.2 Render modes as an indication of extreme tendencies

With the render mode, a concept other than the colors is used. Instead of assigning classes and values to colors, it manipulates the degree of details on top of the monument without changing the geometry. However, it is still based on colors. Nevertheless, trying to use this approach in the traditional way to indicate fuzzy-based and class-based uncertainty is problematic. The render mode behaves irregularly and does not fit the theory of those two thoughts.

Considering, that fuzzy-based uncertainty requires regular steps and class-based uncertainty needs distinct groups, the render mode provides an entirely new concept of visualization. By means of this, the patterns emerge out of the situation and are not evenly distributed along a straight line of uncertainty. While wireframe and solid might have similarities, texture and material are quite distinct to them. Because of the variable distance, only a relative order is possible regarding its uncertainty. Furthermore, the projection of these techniques becomes more difficult with a higher complexity of the model. The reason for that is that wireframe and solid are based on faces, edges and vertices, while material and textures are based on uv-coordinates. However, uv-coordinates allow a much finer division of surfaces for materials and textures. This means that there can be variations of visualization within one segment or even one face. Additionally, they contain an extra dimension for storing data (fig. 61).

Figure 61: Cube with an applied material based on a difuse, ambient occlusion, displacement, gloss, normal and reflection map. Combined, they give the impression of a photorealistic rendering. However, they also express properties like brick size, building technique and material (https://www.poliigon.com).

Texture and material can imply spatial information such as height, length or width, as well as color, material and building techniques, while using the texture of actual real-world objects (fig. 61). This is also an important issue. Textures and materials can imply knowledge about objects where none exists and approach photorealistic behaviors. In order to emphasize, this figure 52 from the results and figure 61 give a good example of misleading information provided by a texture. The uncertainty is projected as texture, which means it has less uncertainty than the roof or decoration in the wireframe mode. However, this does not mean that the material, building technique and the block size in length, width and height is the same than indicated by it. Currently, the texture implies knowledge about all of them, while only the height of the blocks is derived from available data. What I mean by that is that the observer is unable to determine which property is evidence based and which is not.

Another point is that high quality textures and materials have to be bought from specialists. Creating your own often results in visible seams or damaged pbr-maps. Websites such as https://www.textures.com or https://www.poliigon.com offer a huge number of them but in most cases they specialize in general or modern materials. Looking for Roman masonry that can represent the building's surface is a hopeless endeavor. Nonetheless, there is no reason not to try to use self-created materials and textures. A possible way is to use photogrammetry to record actual structures and overlay the results on top of the evidence-based reconstruction. However, this is possible only if the original surfaces have been preserved.

In summary, wireframe objects are especially qualified to show high uncertainty. In this mode edges are rendered and the spaces in between are left blank. Those blank spaces cannot be interpreted incorrectly. Additionally, when using the wireframe mode, the interior or background structures also become visible. It is difficult to assign the wireframe mode to one of the two existing concepts. Instead of representing a constant value, it seems to be a shared possibility. In that way it represents the highest edge of uncertainty. Translated to fuzzy-based uncertainty, the segment might have a reliability of below 0.1 or is only vaguely identifiable in one of the sources. In general, the best use for the wireframe mode might be objects with no clear evidence at all and a high ratio of speculation. If this is transferred to the case study, dimensional uncertainty of the roof and decoration might be affected, since we no longer have any evidences of it left. However, analogies and illustrations make it clear that it had to be apparent in earlier days.

Considering another type of uncertainty, such as material, it would also affect the visualization and most likely affect the result in the solid render mode. The solid render mode behaves similarly, but has closed surfaces. Those surfaces can be colored according to the previously discussed color groups and gradients. The solid mode forms the moderate midfield (fig. 62) and can easily encode classes and degrees of uncertainty. It can serve as the foundation of a color code.

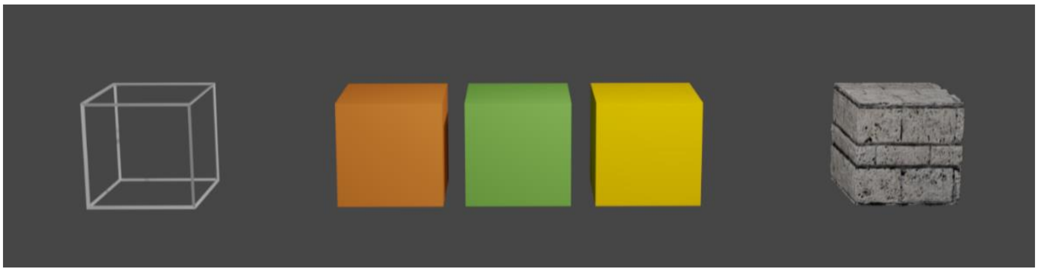


Figure 62: Concept rendering of a combined solution of render mode and color code. The wireframe cube on the left represents the highest degree of uncertainty and almost no evidence, while the photorealistic cube on the right represents actual remains, or structures with almost no uncertainty. The mid-values are represented by solid cubes with an assigned color code. Wireframe and material mode are independent from the actual fuzzy-based and class-based uncertainty concepts because they cannot be further classified (Brunke 2017).

The arrangement of materials and textures is more difficult. As already indicated, more than one value can be encoded. Furthermore, they approach a photorealistic visualization. Firstly, material and texture are grouped together. Technically a material includes color, normal, roughness and a height map. This makes it an extremely detailed version of a color map and is also known as physically-based material or rendering. When intending to show the material, building technique or outer faces, it might be a good possibility. Nevertheless, for encoding uncertainty it is a terrible choice. It encodes everything except uncertainty. A possible use for materials and textures are segments that still exist today and when actual textures can be created directly on the field.

Wireframe and material are similar, because they both represent extreme positions of uncertainty (fig. 62) and do not claim one of the uncertainty concepts. While wireframe represents a high degree of uncertainty, material has virtually no uncertainty anymore. In other words, they indicate a high and a low level of detail in the visualization. The geometry can also be split into different levels to indicate uncertainty. However, it is used rarely and it has some problems, which are described in the following section.

6.5.3 Problems with the level of detail

In contrast to the render mode, the level of detail necessitates manipulating the geometry in order to display uncertainty. Hereby, the amount of detail proportionally increases the reliability of the sources and argumentation. However, there is no fixed way of describing the factor of change. Likewise, a change in detail is not always possible. There are cases, such as the rectangular ground plan of the podium, which does not offer any further simplifications. Furthermore, how can a classification or reliability index of sources be applied to the level of detail? Is it even possible to classify different sources over the level of detail? As a rule, segments can be modeled only when knowledge about them already exists. Does this not imply a certain degree of certainty?

One should also be aware of the fact that the level of detail also plays an important role in native 3D modeling. It was originally used to save computer resources and achieve optimal results between render time and image quality. Mixing the two applications could have fatal consequences. For example, the reality-based model of monument 434 had to be reduced in its level of detail too. The reason for this is not an increasing uncertainty but rather the possibility of continuing to work with the obtained data and limited computer performance. Similarly, a kind of paradox arises when comparing the uncertainty of the reality-based model to the evidence-based model (fig. 63). This means that the reality-based model has the lowest possible degree of uncertainty and the highest amount of detail, not considering the lod (=level of detail) of the performance-based reduction.

In contrast, two alternative versions of the evidence-based model are available; one with more detail, such as individual building layers, decoration and roof, and another one with less detail, only simplified boxes symbolizing the case and podium (fig. 63). Following the idea of a proportion between the level of detail and uncertainty, the version with more details should be less uncertain. However, it is not. In this case the behavior is anti-proportional. To simplify the discussion, we will focus only on the podium's case and the two evidence-based models (lod1 and lod2).

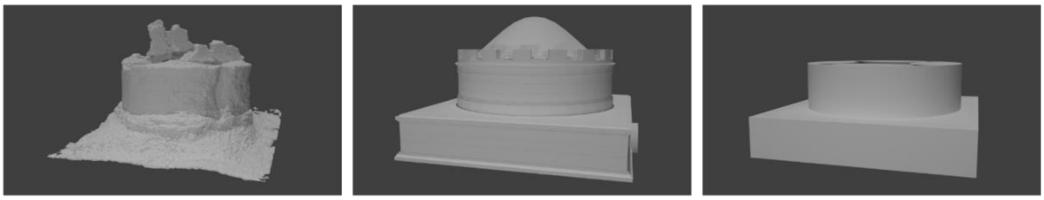


Figure 63: Concept rendering of different levels of detail of monument 434. The rendering on the left shows the reality-based model (lod0), with the highest degree of certainty and possible details. The two models to the right are evidence-based. The middle one (lod1) shows more detail than the right one (lod2), but has less overall certainty (Brunke 2017).

Lod1 clearly shows individual building layers. Technically, they are realized by creating individual objects, with a slight bevel on each edge. Lod2 does not. It has only one block with the total dimensions of the podium and does not distinguish between individual construction phases. The remaining properties are all the same between lod1 and lod2. Comparing this with the actual remains of lod0, there is no clear evidence of the actual height of one building layer of the case. There is only the probability that it might be the same as in the core, or it might be similar to some other tumuli along the Via Appia. Both assumptions have a rather high degree of uncertainty but still imply the exact opposite at lod1. Lod2 indicates only the total height, which has a much lower degree of uncertainty, since it can be fitted much better with the core of the podium. Yet the illustration with the bevel and individual building layers is regarded as the most representative. This is because the right balance has to be found. Likewise, the bevel was not chosen to illustrate uncertainty, because the case was built up from several layers. It displays a completely different kind of information. If one tries to assign the level of detail to one of the two concepts of uncertainty, it is not possible to achieve a classification after the class-based method. An ordering after the fuzzy-based method might be possible when using the uncertainty index as the factor that has to be multiplied with the level of detail. However, the level of detail does not offer such a unit yet.

Similarly to the render mode, the level of detail is best used as a tendency and not as a representation of actual values. As a definite reinforcement, it shows robustness against color blindness and it allows one to indicate parts with almost no evidences. This is one of the reasons for which it was used in the case study for the burial chamber, decoration, roof and filling. Taking the decoration as an example, almost no evidence is left. Some of the historical illustrations might show parts of the decoration. However, the literature describes specific kinds of ornamentation that occur on many monuments of this kind. In this case, there is most likely an object in the monument with no evidence of its actual appearance. Something similar is true for the roof. Nowadays, no roof is present, but several analogies and illustration suggest a cone, mound or plate as roof. Therefore, the rough form is known but not the exact exposition. In this case, it is better to use simplified geometric objects and only as much detail as necessary to recognize the object.

The significance can be enhanced by the wireframe representation of the render modes. The additional wireframe mode is important to make it clear that the simplicity of the segment originates from uncertainty and not the architecture.

Another example is the size of the facing bricks. It is known how high the building layers are and how high the average blocks along the Via Appia are. Therefore, there are two most likely possibilities for this part. Both can be modeled to indicate the range. However, since the length is highly speculative and due to the fact that there is no additional evidence, no length is added. It is basically one ring. Width can be derived from other blocks around the Via Appia. The previously named bevel is assigned only a height, but not a width or length.

The level of detail might be one of the most complex visualization methods of uncertainty. It is extremely difficult to draft firm and comprehensive rules. The main point is supposedly the recursive uncertainty, considering the paradox between reality and the evidence-based model, and their relation of uncertainty and details. The best estimation is achieved through experience and simplification of uncertain segments to reduce their general unevenness. Similarly to render mode, it can be overlaid with the realty-based model to show today's extant surfaces. It is important to note that not all of the surfaces preserved today necessarily originated from the construction phase of the monument. It is precisely in this case study that medieval use and modern restorations are proven. Furthermore, it is not advisable to compare or connect the level of details of a reality-based and an evidence-based reconstruction. In conclusion, not all issues regarding the level of detail can be solved. The level of detail and especially the documentation are eminently suitable for future research. In particular, the graph database offers a unique approach.

6.6 Graph databases as a novel approach of documenting uncertainty

Apart from the written text, a database can be used to store the design decisions. The database was tested in a twofold execution. The traditional relational database was tested first and, secondly, the novel graph database. Both of them contain the same data and there are only slight differences in their structure. However, graph databases have never been used for the encoding of uncertainty in three-dimensional models and therefore constitute an experimental and novel approach.

One major advantage of relational databases over graph databases is the ability to store digital media content. Those could be, for example, photographs of comparison structures or scans from the literature. Another one is their prominence. They are widely known and used. Consequently, many software solutions with a graphical interface are available. The data itself is stored in big tables and can be linked over indices. The relationship itself plays only a minor role. In contrast, relationships are a central component of graph databases. Accordingly, they emerge between interpretation and source. Due to the large number, the graph database clearly benefits from this structure. Likewise, it provides a set of queries that are specifically designed to investigate highly connected data. Nevertheless, even without filtering the data, first impressions can be obtained. This can be among other things, a rough overview of the discussion or the direction of individual lines of argumentation. Lines of argumentation are indicated by the direction of the relationships between the nodes. This considerably simplifies the assignment of individual uncertainty values, since they are assigned to the relationship instead of the source.

One problem with the relational database and graph database is the assignment of actual uncertainty indices. In both cases they are highly subjective and might vary from case to case. A theoretical workaround for a graph database (fig. 64) might offer a solution to this difficulty. Essentially, it includes three components. Firstly, the *impact* of the source is determined by counting the incoming relationships towards a value and taking it as a multiplicative inverse. Secondly, the *reliability* is coded into the relationship as the subjective opinion of the author. It expresses one's confidence about how reliable the argumentation is. Importantly, it can vary for one source. This is because it is not always the case that all the argumentation of one source is reliable. Finally, the *authority* determines how many values one source can prove. If importance, reliability and authority are combined, a value is received that is anti-proportional to the object's uncertainty. The higher the value, the lower the uncertainty. However, this statement represents a concept that still has to be balanced and normalized in order to use it correctly. To achieve the same workaround in a relational database, much more complex algorithms are necessary. Graph databases are naturally capable of this.

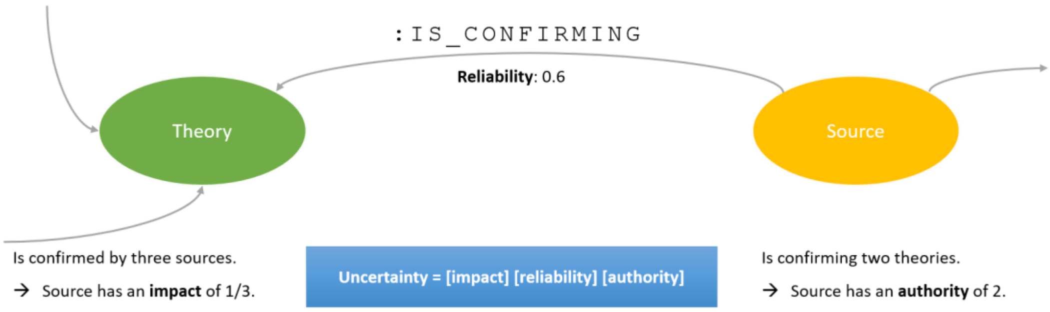


Figure 64: Concept drawing for an approach to determine fuzzy-based uncertainty in a graph database. Basically, incoming and outcoming relationships are evaluated and brought together. This idea will work effectively only within one classification and has to be updated frequently (Brunke 2017).

Further advantages of the graph database are the use of multiple labels for the same node, providing a fast and effective way to query and order large amounts of data. Likewise, only minor changes are necessary to exclude or include specific parts. However, a major weakness of graph databases is the lack of a graphical user interface and the resulting size of the cypher queries. The use of keys (fig. 65) is common for the relational and graph database. They are necessary to identify individual segments and trace back the path of argumentation. Moreover, they also serve as an interface for the cad software by using them as names for the objects. Since both databases provide a python api, it is possible to easily query datasets from third-party applications in the form of scripts. Graph databases also allow returns in form of tables and lists.

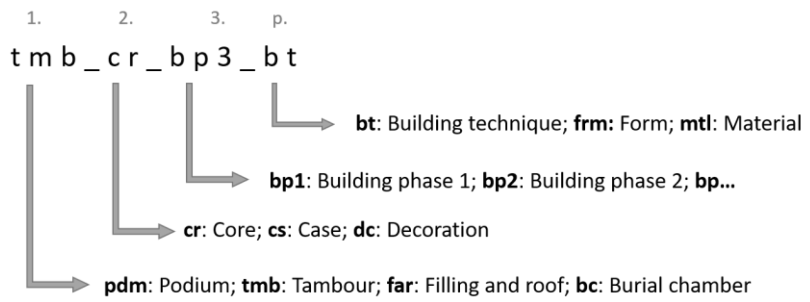


Figure 65: Structure of a key. Basically, it follows the segmentation from chapter *3.3 Classification of the architecture* and *4.1 Segmenting and organizing the data*, whereby the individual elements can be changed as desired. A dataset owning a key means that it belongs to the segment encoded into the key (Brunke 2017).

Generally speaking, the relational database seems to be best suited to fuzzy-based uncertainty since it includes only a list of numerical values, while class-based uncertainty and/or a combination of both can draw real strength from the relationship-based nature of graph databases. However, the graph database, which is rarely used, especially offers huge potential. It seems it would be promising to examine this form of database in more detail. It might be even possible to discover new ways of documenting uncertainty, but also to analyze it. Likewise, it seems appropriate to develop more user-friendly interfaces with regard to archaeology. One of them could be Blender, which connects the 3D objects directly with information in the database over a Python script. Furthermore, Blender already offers some valuable tools for organization and analysis. More will be explained about it in the following sections.

6.7 Blender as an interactive approach

Blender was used as the main tool for creating the reconstruction. Therefore, the Blender project files include the highest density of information together with the databases. However, the actual database is still separated from the Blender object. This might be fixed by additional add-ons in future work. The keys used in the databases are equal to the object names used for the three-dimensional segments and allow therefore an easy linkage.

The big advantage of Blender is that it offers an excellent infrastructure that can be easily and efficiently expanded by means of Python scripts. By default, however, it already contains many important tools. Some of them allow manipulation, measurements or analysis of the objects. In total it is an interactive platform for three-dimensional models. The self-written add-ons also facilitate an approximation to BIM systems with little effort.

With its manifold capabilities, it offers solutions to most of the issues discussed previously. The layer management and hierarchy (fig. 66) provide enough room for a reality-based and evidence-based reconstruction. Furthermore, several possible alternatives can be added and put next to each other.

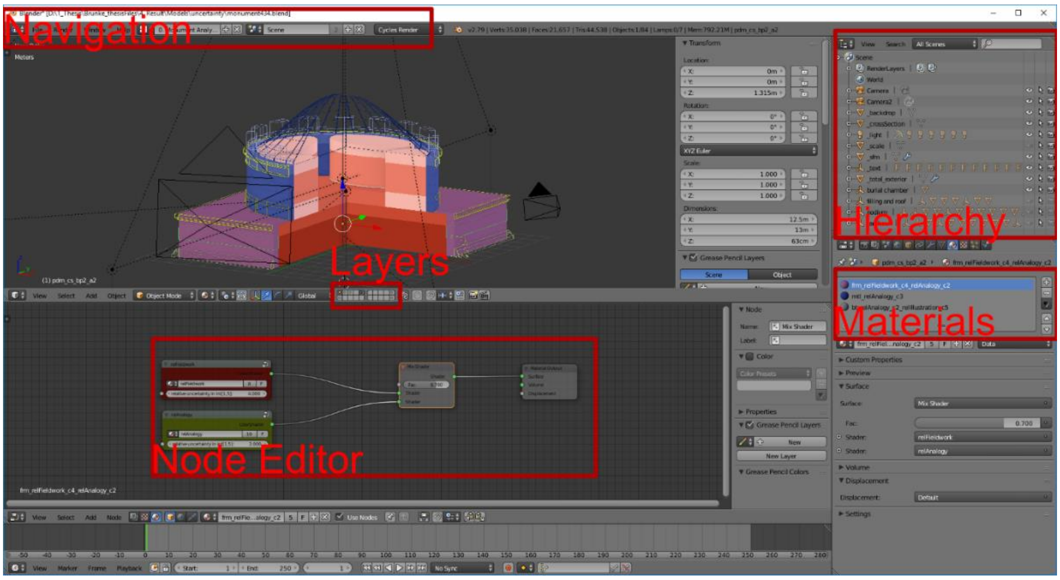


Figure 66: Screenshot of the Layout "*0. Monument Analysis*" and the user interface of Blender. Red markings indicate the position of important tools (Brunke 2017, Screenshot in Blender 2.79).

The materials (fig. 66) allow one to add several materials to one object. These can consist of different kinds of uncertainty, such as one material for the form, one for the material and one for the building technique. Blender's interface allows easy and quick switching between them.

The node editor (fig. 66) allows one to create those materials according to the rules of the color theory. The framework of source classification can easily be realized. A material library provides the most convenient classes, with further subdivision of the relative or absolute subscale.

If necessary, the model itself can be exported or rendered for use in publications or on the web. The only weakness of Blender as an interactive approach might be its difficulty to use for beginners in this field of technology. In some cases, it might be not as intuitive as other software, since, for example, the left and right mouse click is switched for basic operations by default. However, in the near future it might be possible to investigate architecture in a better way. As already indicated in the previous section, it can show its real strength in connection with a database. This should be kept in mind for future research. In the following section the discussion will be briefly summarized. Furthermore, a final method will be proposed, which was designed in light of the research question and objectives.

7. Conclusion

In this chapter the content of the research project as a whole is summarized. This includes all of the previous chapters and sections. Afterwards, the most appropriate way to create an evidence-based reconstruction regarding the main objective is proposed. The conclusion ends with the answer of the research question and a future perspective.

All in all, transparency and uncertainty comprise a wide field of research in virtual archaeology. The discussions can be traced back to the late 1980s and early 1990s of the 20th century. In those years Reilly published one of his publications, in which he warned about photorealistic 3D renderings. He was not the only one concerned about the development; Miller, Richards and many other scientists supported his argumentation as well. However, a shift of focus in this discussion can be determined. Photorealistic renderings no longer symbolize the optimal solution. Moreover, schematic or abstract renderings with encoded information have become a popular means of encoding uncertainty. New methods have also been developed. Nevertheless, in recent years the trend has been towards extensive documentation of paradata and metadata. Although many approaches share similarities, they also have many differences. The London Charter and the Principles of Seville were introduced in 2009 and 2011 respectively to provide a widely accepted standard.

However, the issues under discussion did not just emerge with digital technologies. Many examples show that people with manually drawn and physically built reconstruction had to deal with similar issues. Uncertainty itself is a traditional part of archaeology, especially of interpretations and discussions. In general, it can be encoded in different ways. For 3D models the manipulation of geometry or texture are the most usual way. This can include several levels of detail, layers, color code, opacity, render modes and so on. However, it is not only the visualization that has a high impact; the documentation of all data and design decisions is as important as the rest of the research. Databases offer a wonderful solution to this issue. However, the actual presentation of the data is of high importance too. This relates to the step in which the data is connected to the model and presented to the public. The data itself derives from a case study.

The case study of this research was used to evaluate the methods in an isolated environment. Therefore, research into Roman tombs was conducted. The investigation included mainly the archaeological and architectural composition of a building structure on to the Via Appia. Due to some fieldwork that was funded by a scholarship from the

KNIR, a lot of important information could be gathered and used for analysis. Finally, several possible reconstructions were available that could be used for deeper research into uncertainty about ancient building structures. The monument itself can most likely be regarded as a tumulus, including a rectangular podium, tambour and earth filling with a small mound. The approximate dimensions might have been 12 x 12 x 8 m at the time of its construction. Subsequently, several three-dimensional reconstructions could be accomplished by the previously described methods.

As argued in chapter *6. Evaluation of the theories and results*, several possibilities for visualizing insecure data are available. However, not all of them are equally suited for this purpose. Hence, the next paragraphs describe in which way the actual visualization methods in the literature can be improved and raised to a new level.

In an optimal situation, all sources are consolidated under the categories fieldwork, illustration or analogy. Each of these categories is assigned to one of three primary colors of the additive or subtractive color wheel. Subtle changes in brightness and saturation are possible to facilitate a better perception. The data used during this work stage belongs to the class-based uncertainty concept and serves as rough framework. For fine details a sub-scale of uncertainty (relative or absolute) can be added. The sub-scale consists of a monochromatic gradient based on the base color of the related class-based object. Hereby, the gradient can be either stepped (relative) or smooth (absolute). The values derive from the fuzzy-based uncertainty concept. In general, the color parameters should remain uniform throughout the entire project.

The issues of fluctuating and cumulative uncertainty can be best solved by using the previous mentioned sub-scale and the mixture of the primary colors. Since the result will most likely be secondary colors or approximations of secondary colors, everyone with a basic knowledge of color theory can break down the color code. It is also advisable to note the mixing ratio. As an additional aid, a legend is mandatory. It has to contain all the primary colors and their definition as well as the kind of sub-scale which is used.

For extreme positions the color code can be enriched by different render modes and the level of detail. Absolute uncertainty is best achieved by using the wireframe mode, while absolute certainty can be represented by using a photorealistic approach, such as a reality-based model from photographs. Textures and materials alone should be avoided, since they never contain unbiased information nowadays. The basics of physically-based rendering can be used to apply different kinds of uncertainty to one segment.

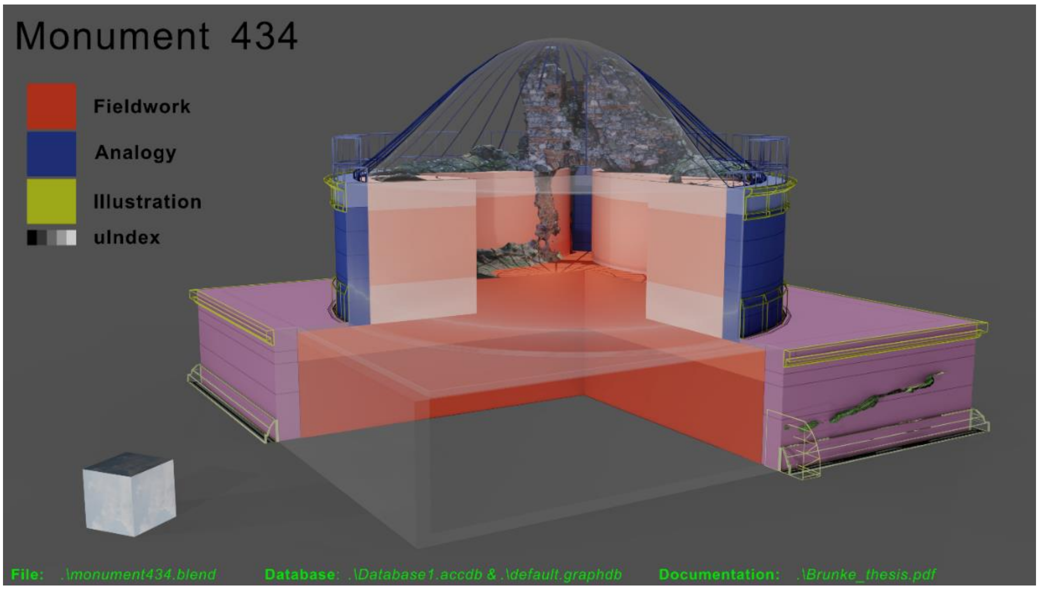


Figure 67: Final visualization of monument 434 with a partial cross-section and updated uncertainty values. The results are available as an image rendering, animation and interactive model with a separated database. The primary colors are red, yellow and blue. The colors had to be adapted slightly for a better perception. Furthermore, the darker the color, the less is the uncertainty (indicated by the uIndex – relative scale). The edge length of the small cube corresponds to 1 m. More detailed information are on Plate 22 or in the Blender project files (Brunke 2017).

This brings us to the attempt to answer the research question. The research question basically addresses scientific transparency, Roman reconstructions and imperfect data as theory and visualization, documentation and presentation as a methodology. The main objective is thus the provision of a scientific and transparent reconstruction of the monument with respect to its uncertainty.

Therefore, a transparent virtual 3D reconstruction of a Roman funerary monument (fig. 67) needs a detailed documentation. In this documentation actual structures need to be separated from interpretative ones. Moreover, the design decisions have to be made clear for each interpretative segment. When following these suggestions, a transparent model according to today's standards is produced. Further enrichment can be accomplished by using advanced techniques of visualization, documentation and presentation.

The documentation is best compiled in the form of a written text for publication or in a database for analysis and semantics. The graph database in particular offers new and innovative methods to process uncertainty and connect interpretations to their sources. The best visualization method is a mixed approach of color coding. The colors and their mixture are suggested to follow the color theory. In addition, the level of detail and render modes offer possibilities to differentiate the extreme forms of uncertainty. Apart from the actual uncertainty value, this approach also provides information about the backend data, from where the uncertainty has emerged. The best way to pass on the results is to use the native Blender project with all associated data and databases. However, printed media requires at least one possible image rendering of the structure (fig. 67).

In conclusion, the research might have revealed some new methods in encoding values into three-dimensional objects, but it has not capped the discussion. The optimal form of publication (interactive models), documentation (graph database) and the encoding of uncertainty (mixed approach) can provide suitable starting points for future research. The rise of computer technologies will therefore provide many new possibilities in the coming years.

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Appendices

The appendices begin with the following page.

Plate 1

Fig. 1: Via Appia Antica 1
(www.aeria.ohil.uni-erlangen.de, a).

Fig. 2: Via Appia Antica 2
(www.aeria.ohil.uni-erlangen.de, b).

Fig. 3: Via Appia Antica 3
(www.romasparita.eu, a).

Fig. 4: Via Appia Antica 4
(www.romasparita.eu, b).

Fig. 5: Via Appia Antica 5
(www.ebay.it, a).

Fig. 6: Via Appia Antica 6
(www.ebay.it, b).

Historical photographs of the monument from the end of the 19th century

Plate 2

Fig. 1: Magnification of "*Via Appia 1871*" (after Charles Quaedvlieg in https://commons.wikimedia.org, a).

Fig. 2: "*La Via Appia al V miglio verso Albano*" (Ettore Roesler Franz in https://it.pinterrest.com).

Fig. 3: "*Ruins*" (Gaetano Facciola in www.invaluable.com).

Fig. 4: "*Via Appia all'altezza del IV Miglio 1884*" (Vincenzo Giovannini in https://nl.m.wikipedia.org).

Fig. 5: "*The Appian Way 1869*" (John Linton Chapman in https://commons.wikimedia.org, b).

Historical paintings of the monument from different times and artists

Plate 3

Fig. 1: Painting of a tumulus similar monument. Found at the Spada Gallery in Rome (unknown in Brunke 2017).

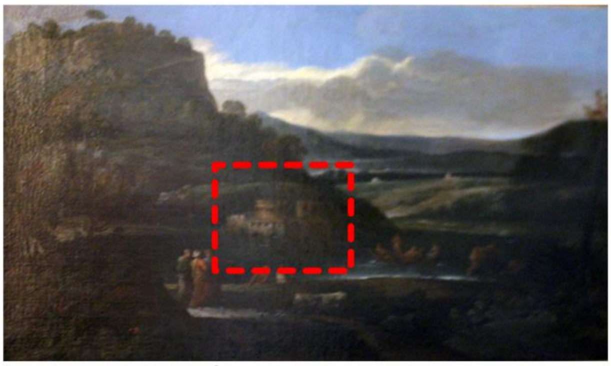

Fig. 2: Painting of a landscape with tumuli similar monuments in the background. Painting found at the Spada Gallery in Rome (unknown in Brunke 2017).

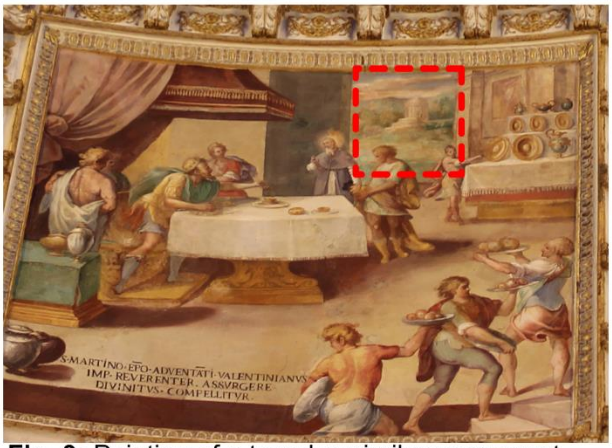

Fig. 3: Painting of a tumulus similar monument. Found at the Vatican (unknown in Brunke 2017).

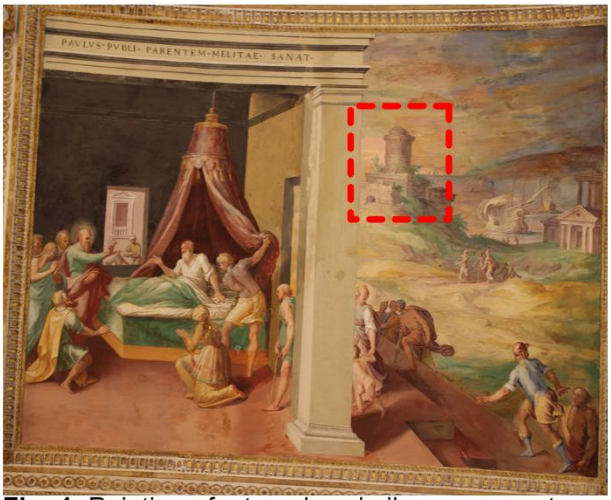

Fig. 4: Painting of a tumulus similar monument. Found at the Vatican (unknown in Brunke 2017).

Fig. 5: Painting of the Via Appia Antica. Found at the Vatican (unknown in Brunke 2017).

Fig. 6: Painting of the Via Appia Antica. Found at the Vatican (unknown in Brunke 2017).

Historical paintings which show similarities to the monument and its architecture

Plate 4

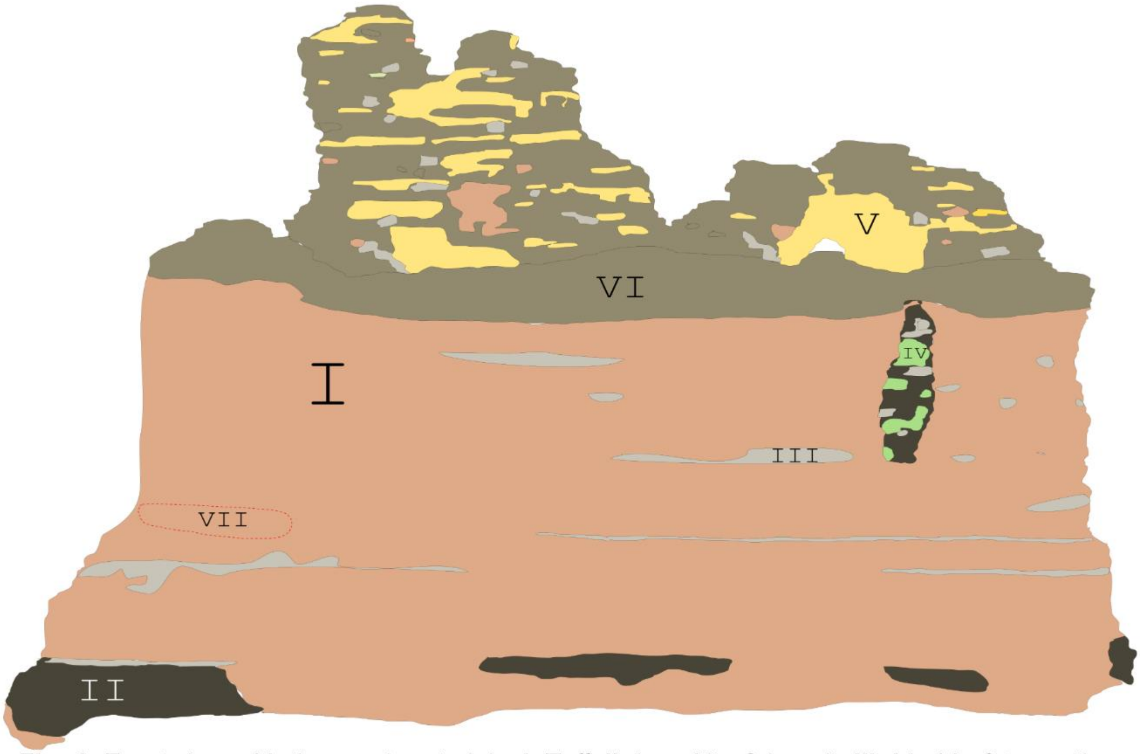

Fig. 1: Front view with the used materials. **I:** Tuff; **II:** Leucitite & basalt; **III:** Marble & travertine; **IV:** Peperino; **V:** Bricks; **VI:** Unknown; **VII:** Area with nails (Brunke 2017).

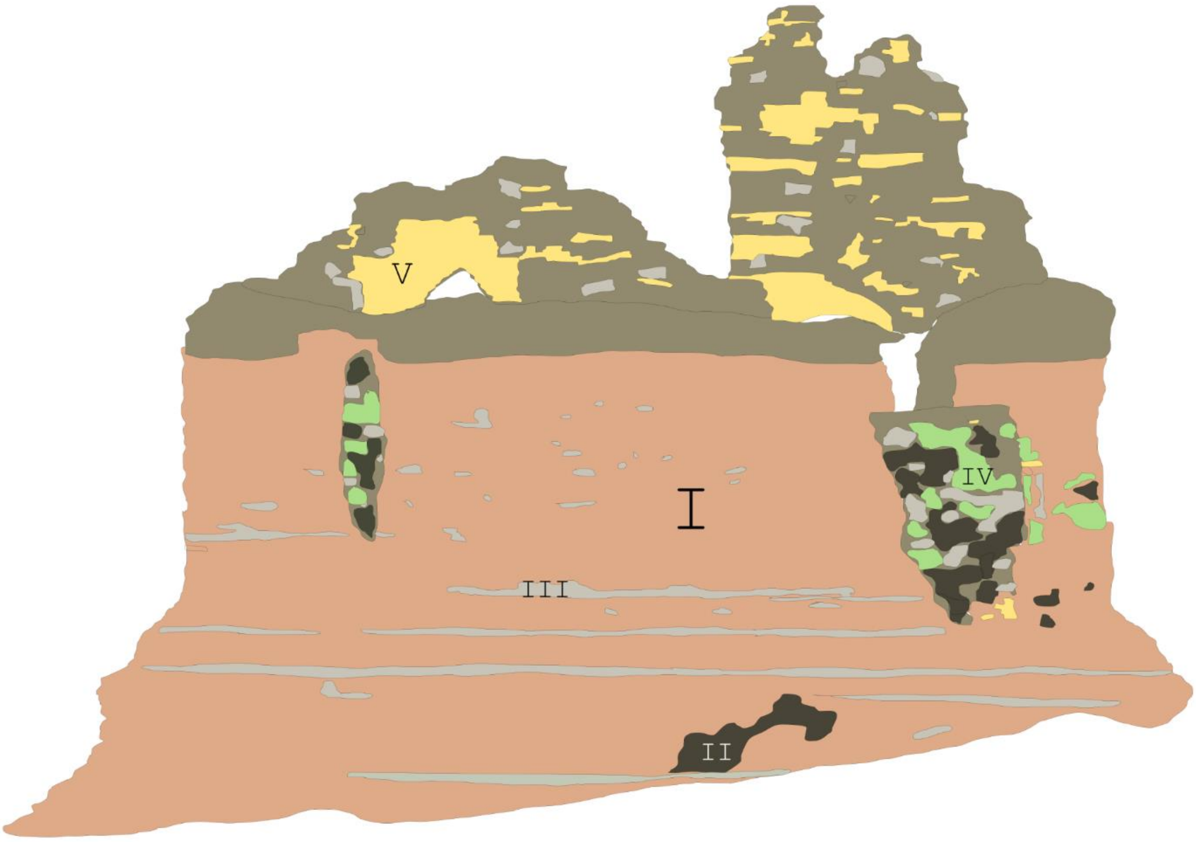

Fig. 2: Right view with the used materials. **I:** Tuff; **II:** Leucitite & basalt; **III:** Marble & travertine; **IV:** Peperino; **V:** Bricks; **VI:** Unknown; **VII:** Area with nails (Brunke 2017).

Materials of the monument

Plate 5

Fig. 1: Back view with the used materials. **I:** Tuff; **II:** Leucitite & basalt; **III:** Marble & travertine; **IV:** Peperino; **V:** Bricks; **VI:** Unknown; **VII:** Area with nails (Brunke 2017).

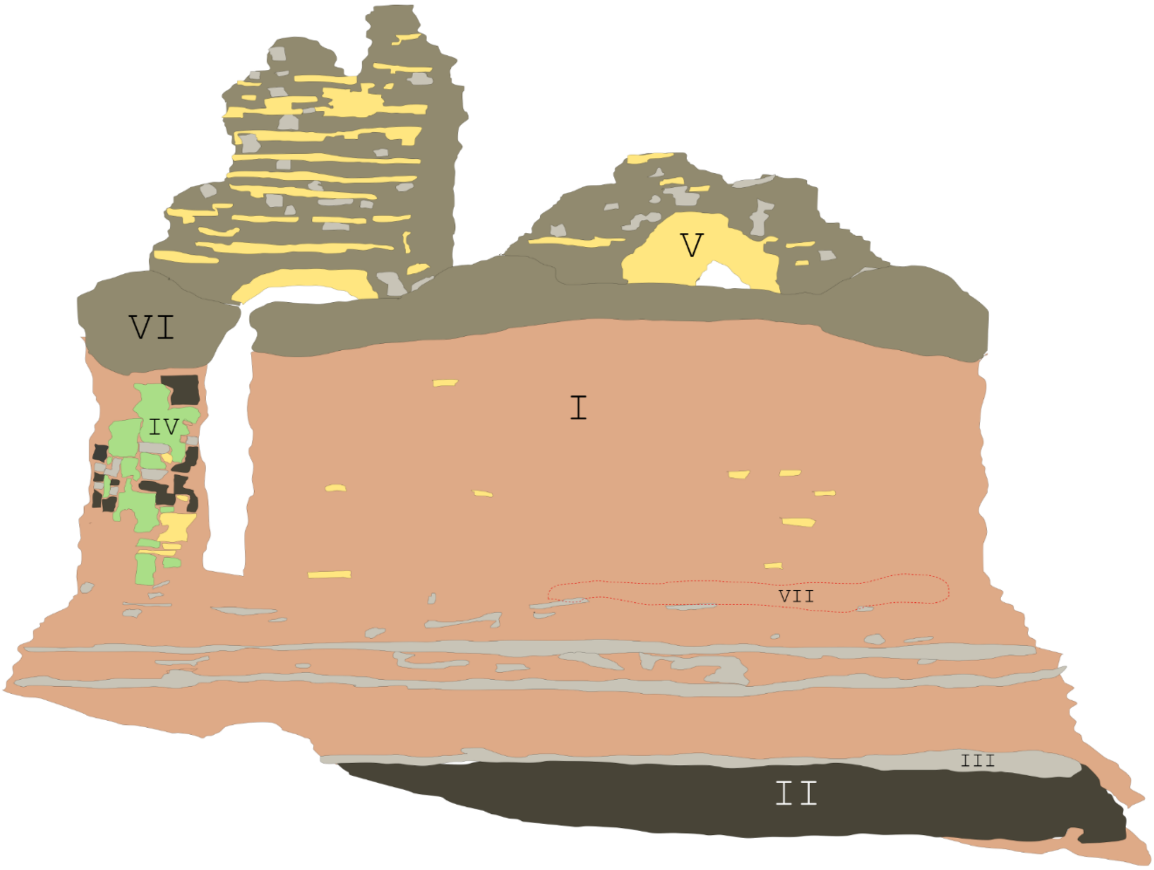

Fig. 2: Left view with the used materials. **I:** Tuff; **II:** Leucitite & basalt; **III:** Marble & travertine; **IV:** Peperino; **V:** Bricks; **VI:** Unknown; **VII:** Area with nails (Brunke 2017).

Materials of the monument.

Plate 6

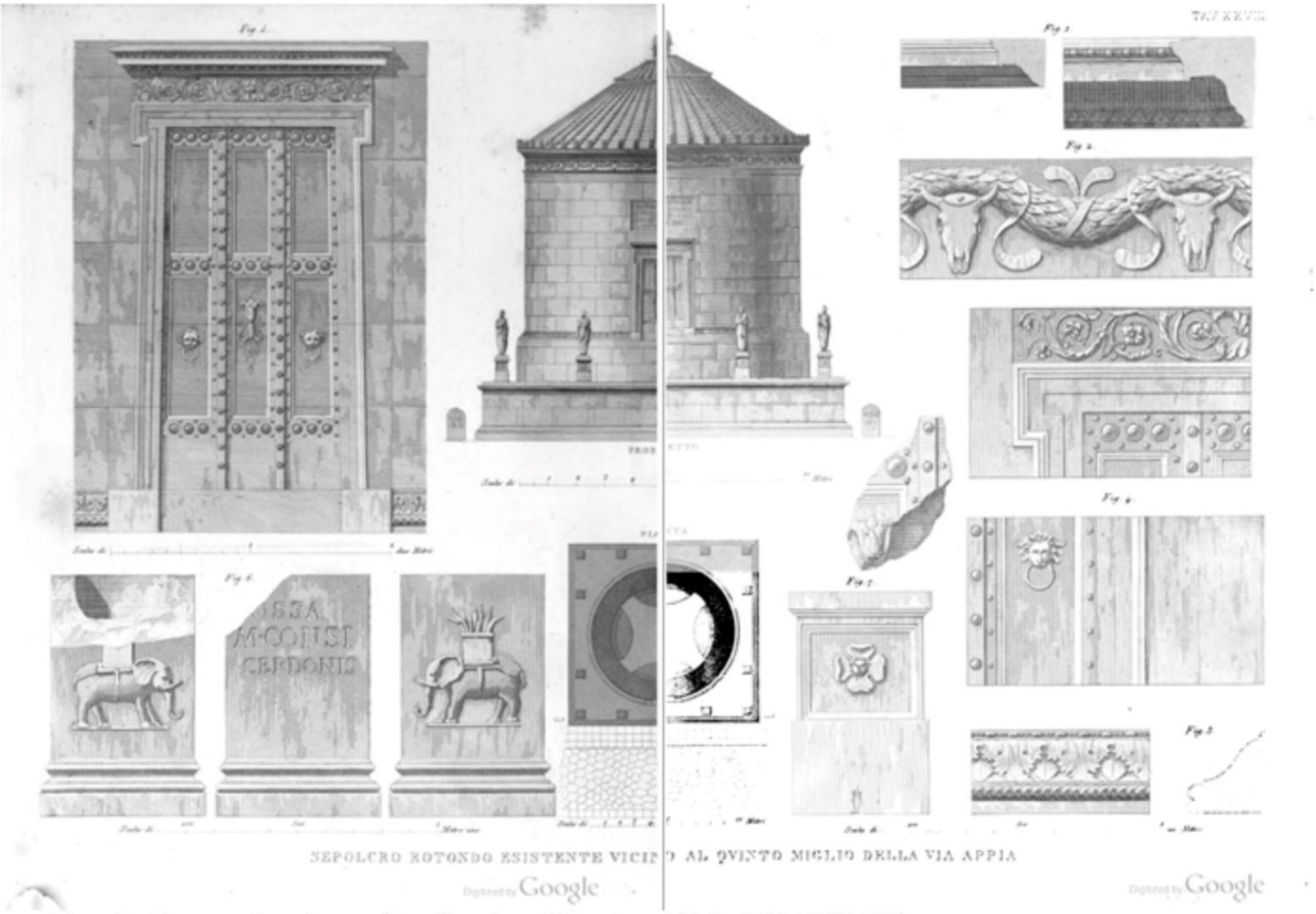

Fig. 1: Reconstruction after Canina (Canina 1853, TAV XXVIII).

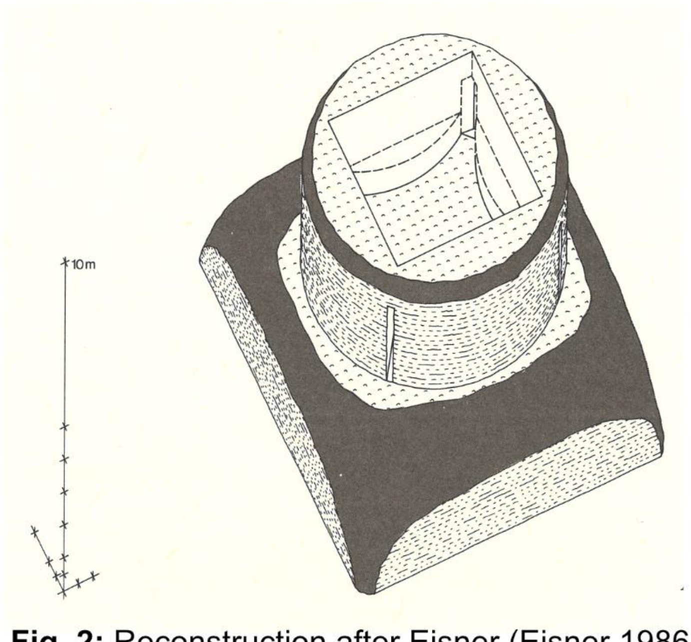

Fig. 2: Reconstruction after Eisner (Eisner 1986, 52).

Previous reconstructions of the monument

Plate 7

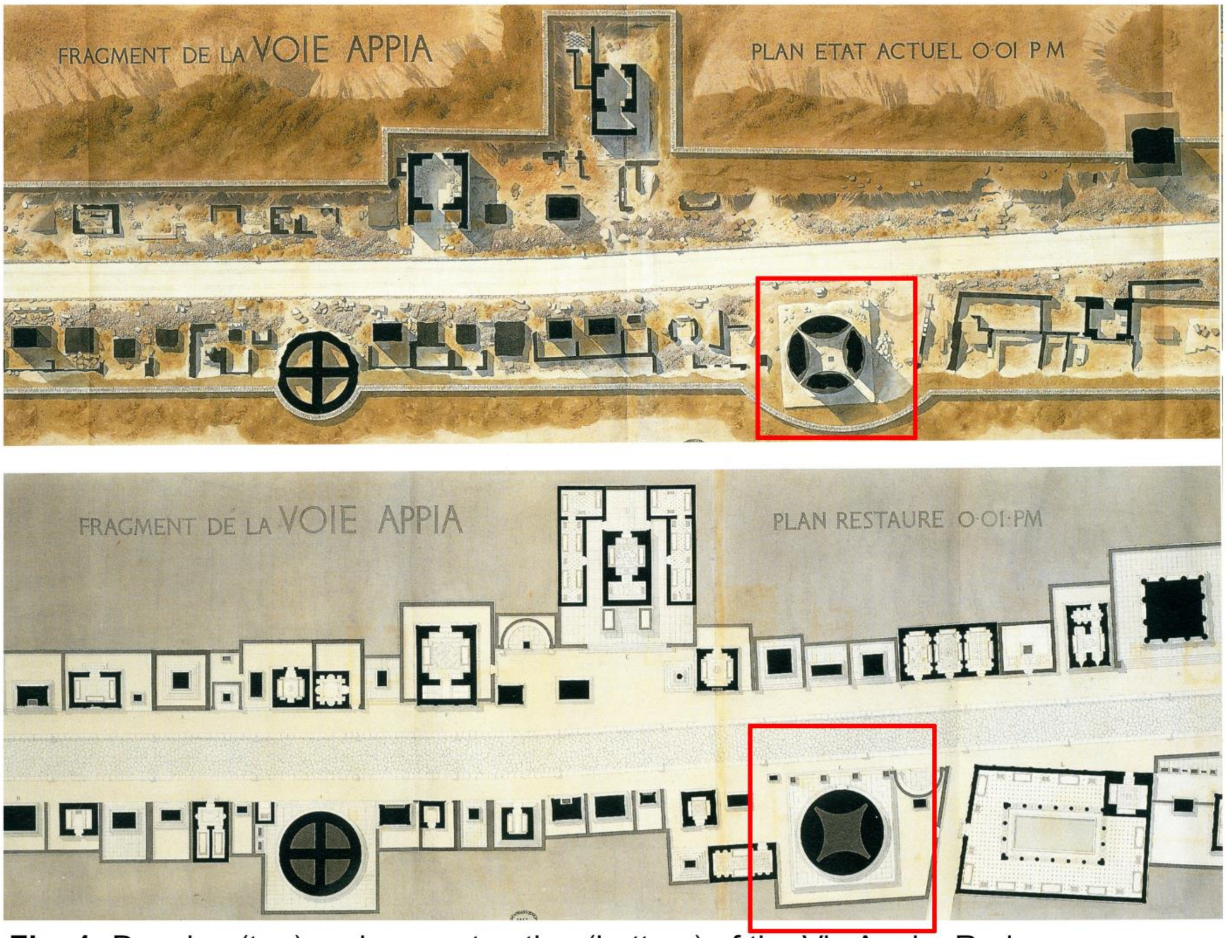

Fig. 1: Drawing (top) and reconstruction (bottom) of the Via Appia. Red squares are marking the monument (Ancelet 1856 in Cassanelli 2002, 191).

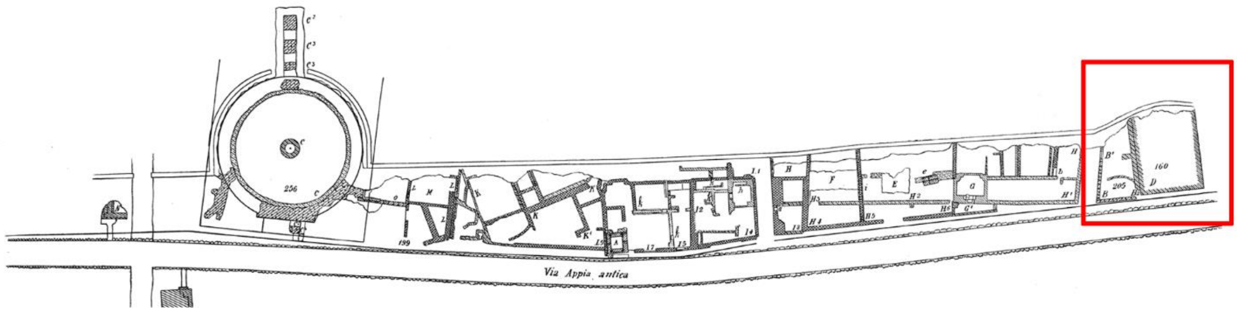

Fig. 2: Groundplan of monuments along the Via Appia. The monument 434 is marked by a red square and is labelled as 160 D (Pinza 1907 in Spera and Mineo 2004, 140f).

Plate 8

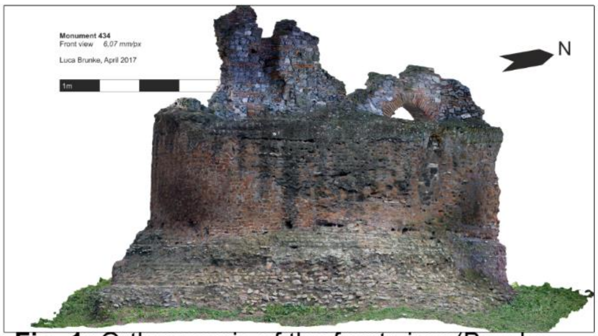

Fig. 1: Orthomosaic of the front view (Brunke 2017).

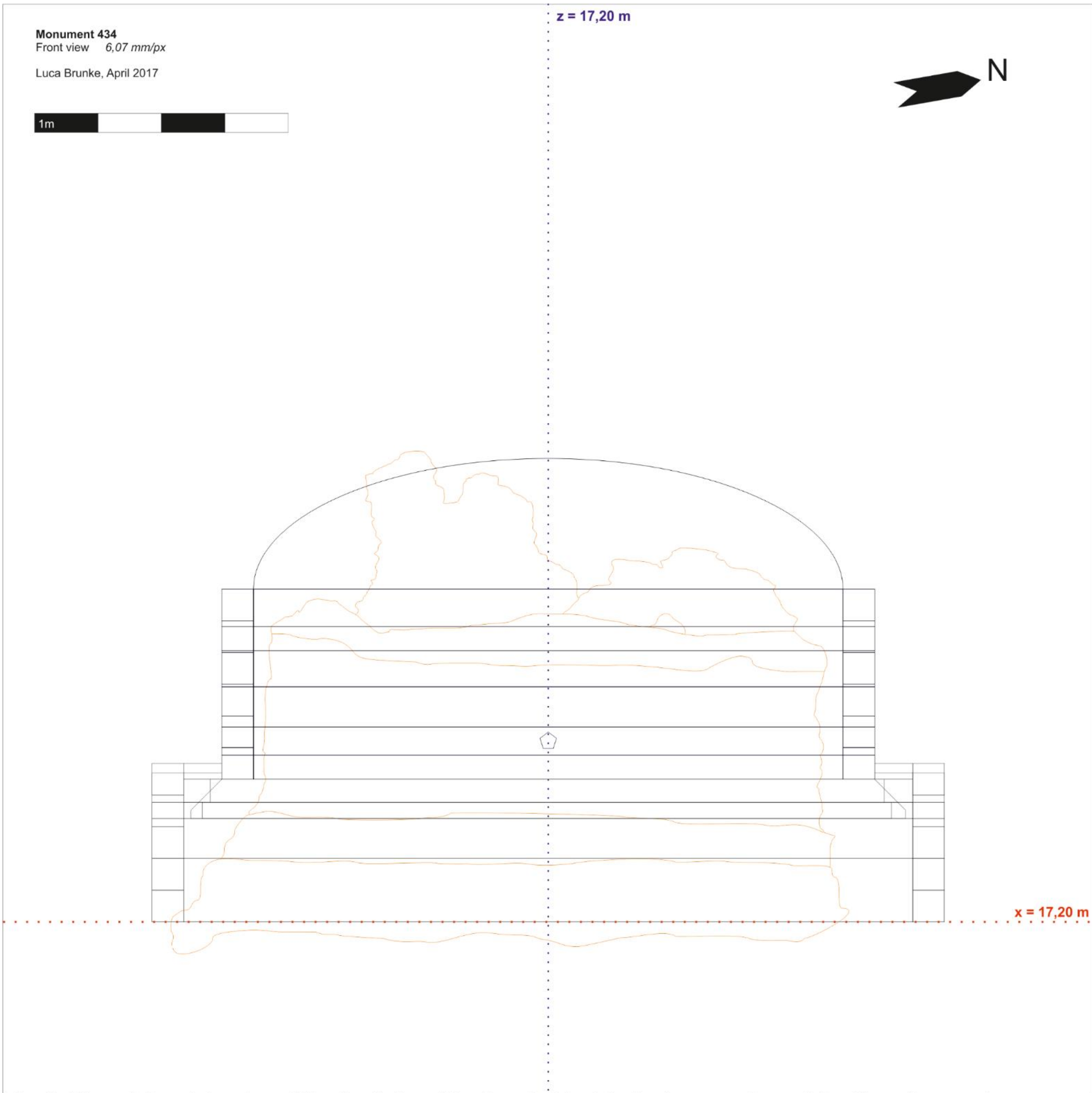

Fig. 2: Blueprint and drawing of the front view. The lines in black indicate several possible alternative versions of the monument while orange only shows the actual remains (Brunke 2017).

Blueprint of the monument 434

Plate 9

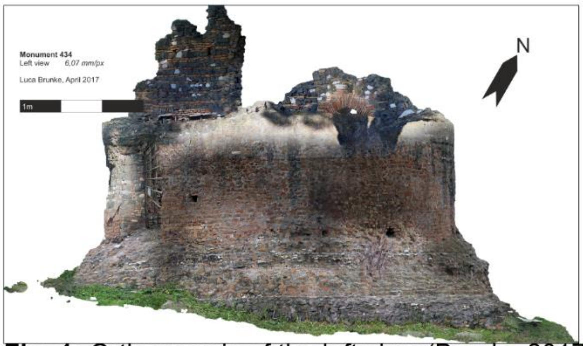

Fig. 1: Orthomosaic of the left view (Brunke 2017).

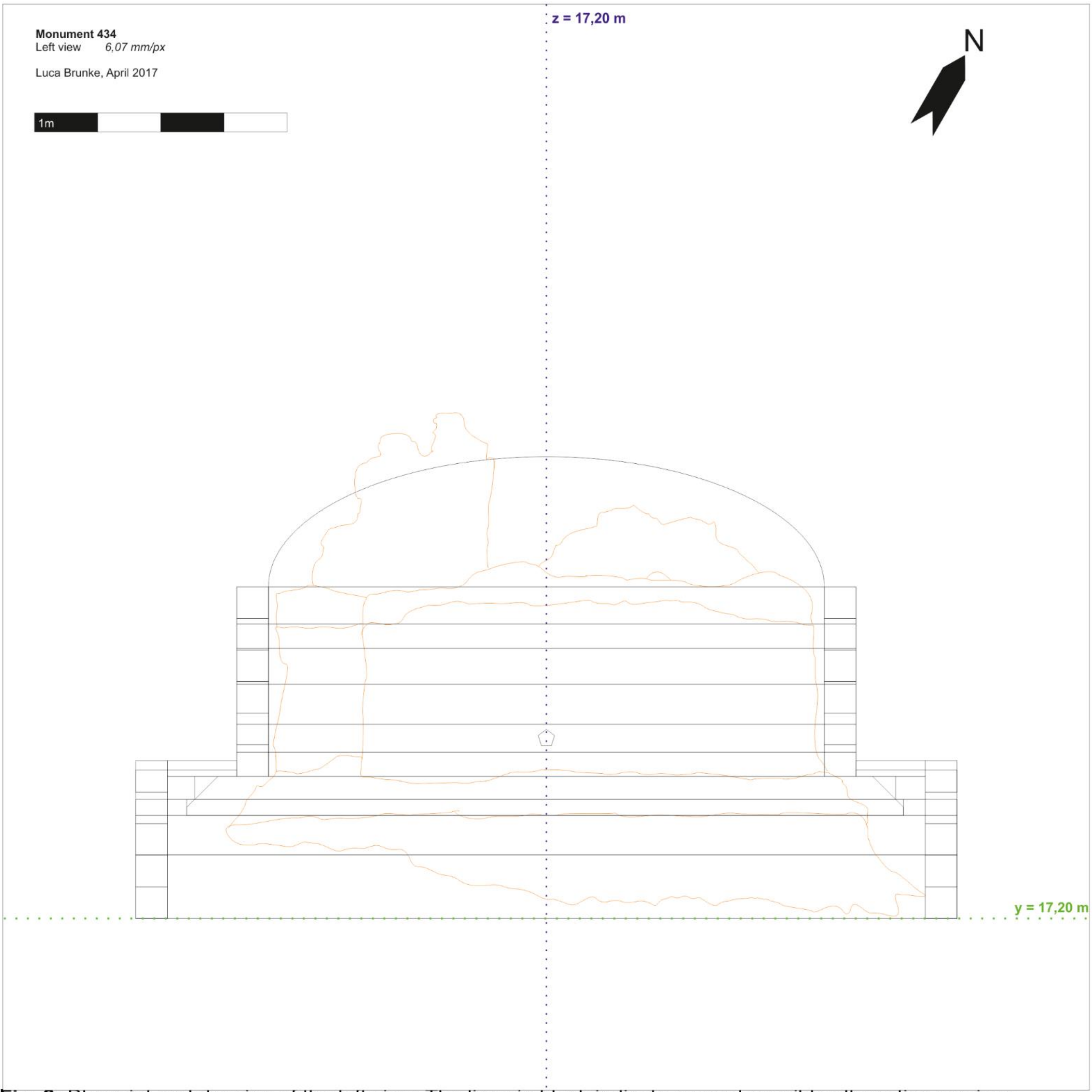

Fig. 2: Blueprint and drawing of the left view. The lines in black indicate several possible alternative versions of the monument while orange only shows the actual remains (Brunke 2017).

Blueprint of the monument 434

Plate 10

Fig. 1: Orthomosaic of the top view (Brunke 2017).

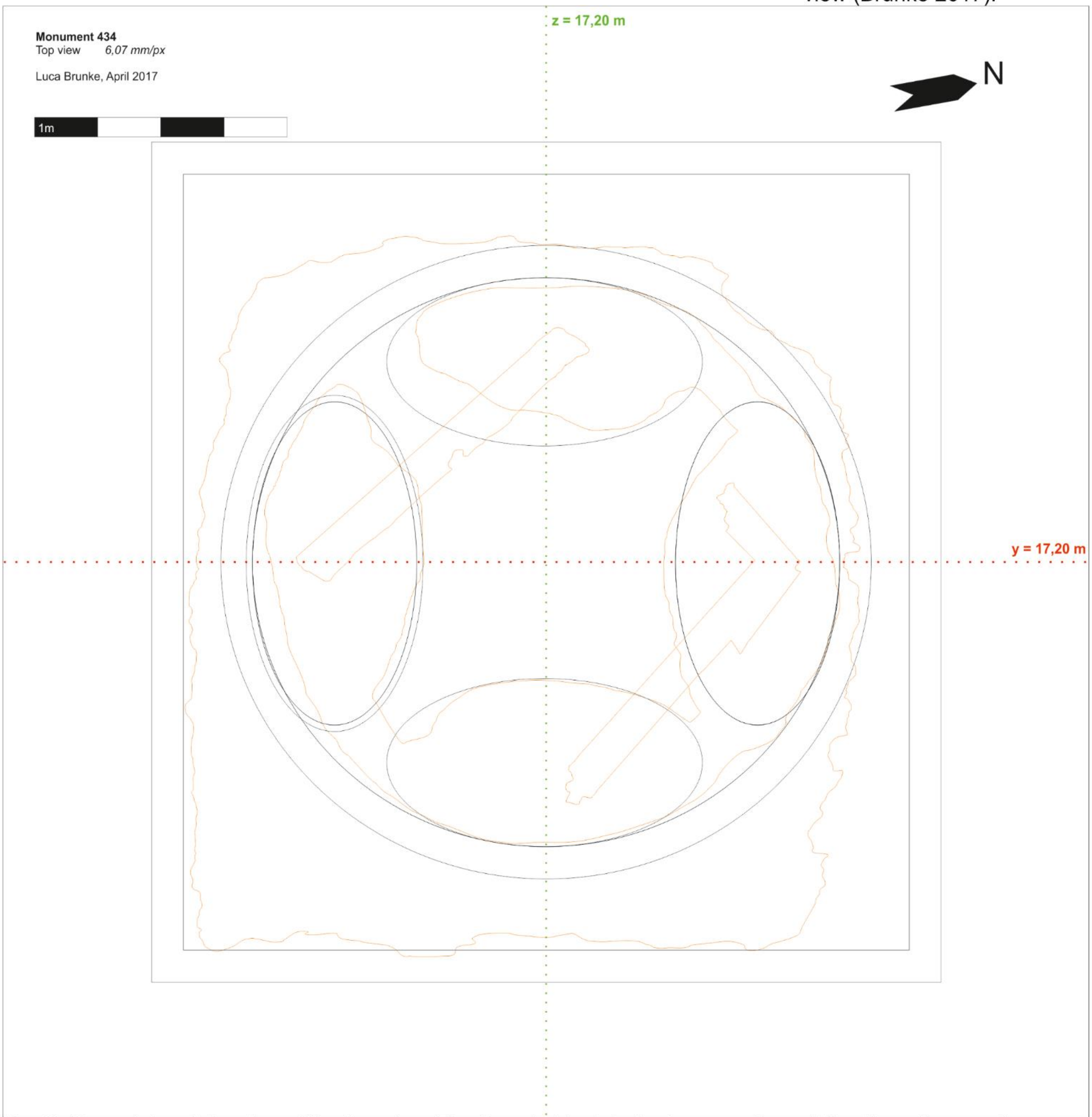

Fig. 2: Blueprint and drawing of the top view. The lines in black indicate several possible alternative versions of the monument while orange only shows the actual remains (Brunke 2017).

Blueprint of the monument 434

Plate 11

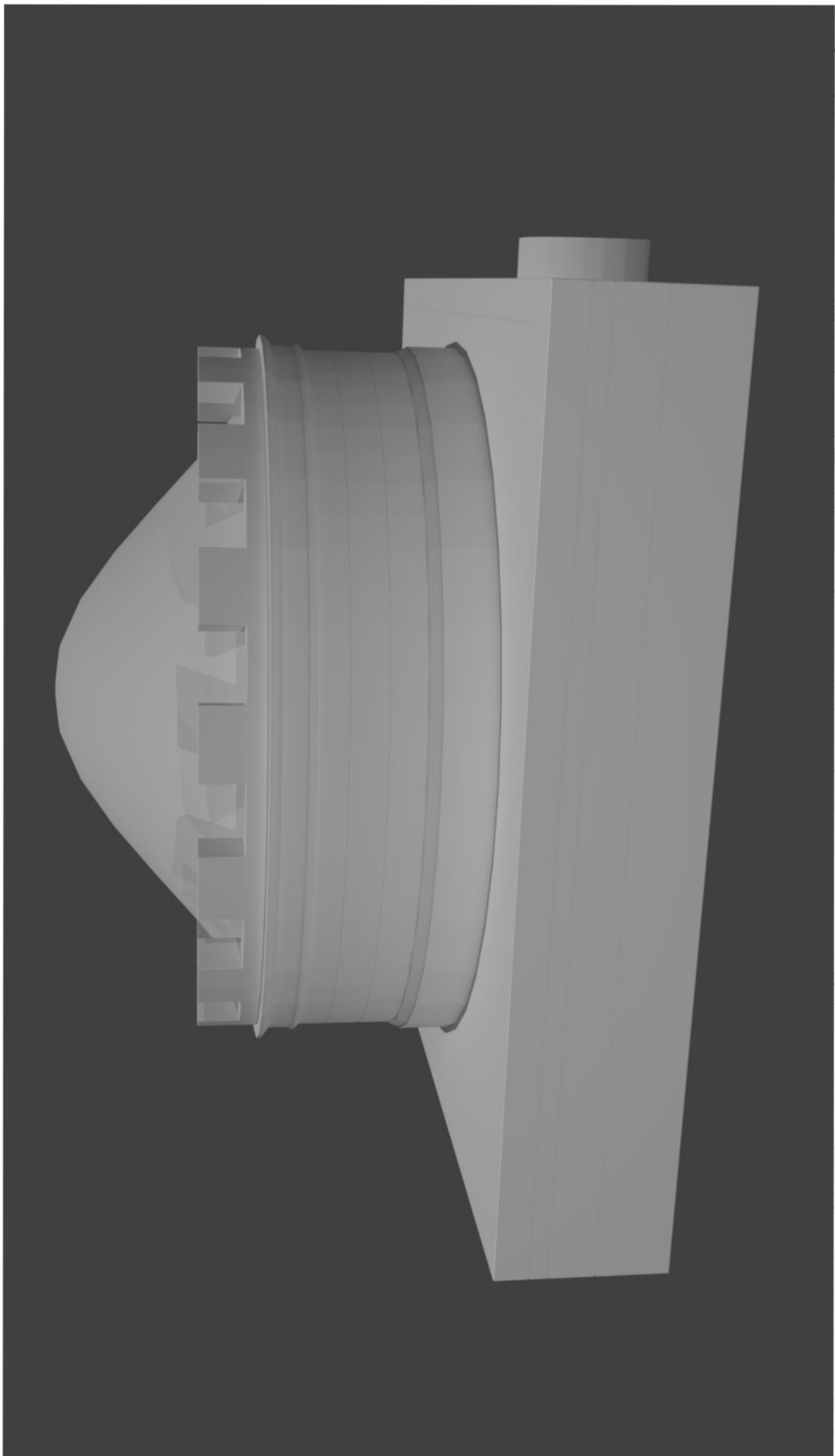

Fig. 1: Concept rendering of the plain monument. Shown are segments from all degrees of uncertainty. This version will later server as container for uncertainty visualization (Brunke 2017).

Concept rendering of the plain model

Plate 12

key: pdm_cs

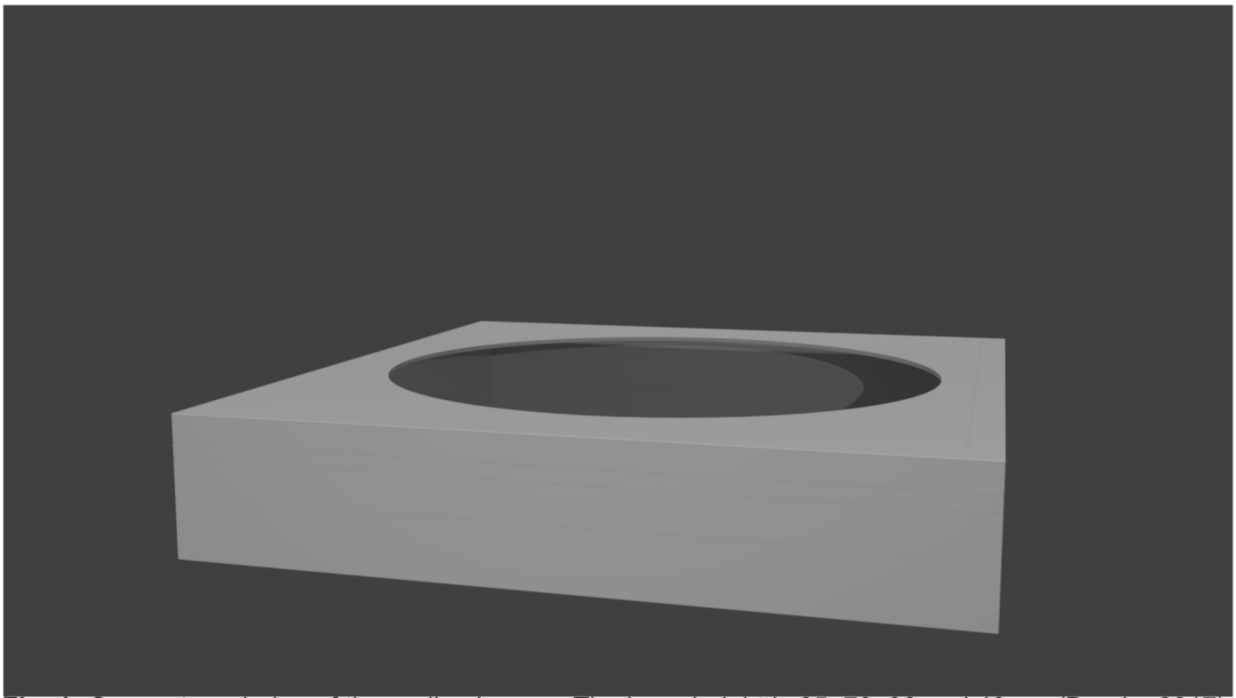

Fig. 1: Concept rendering of the podium's case. The layer height is 85, 70, 30 and 40 cm (Brunke 2017).

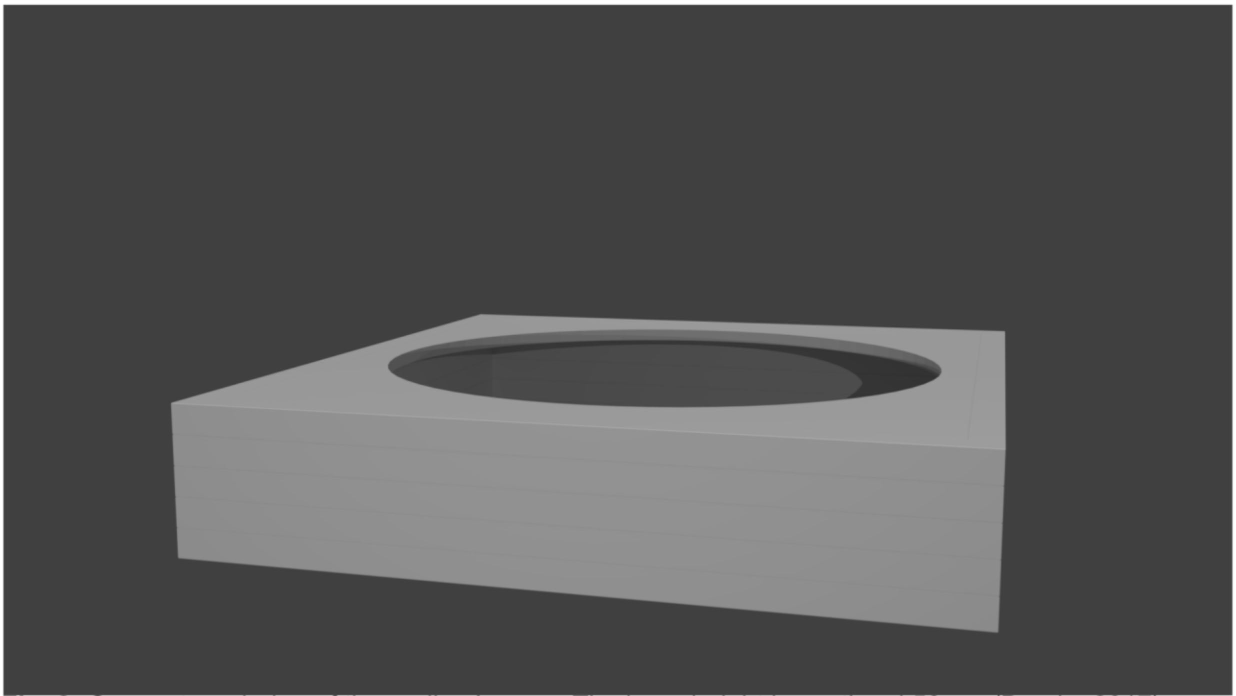

Fig. 2: Concept rendering of the podium's case. The layer height is continual 50 cm (Brunke 2017).

Concept rendering of the podium's case

Plate 13

key: tmb_cs

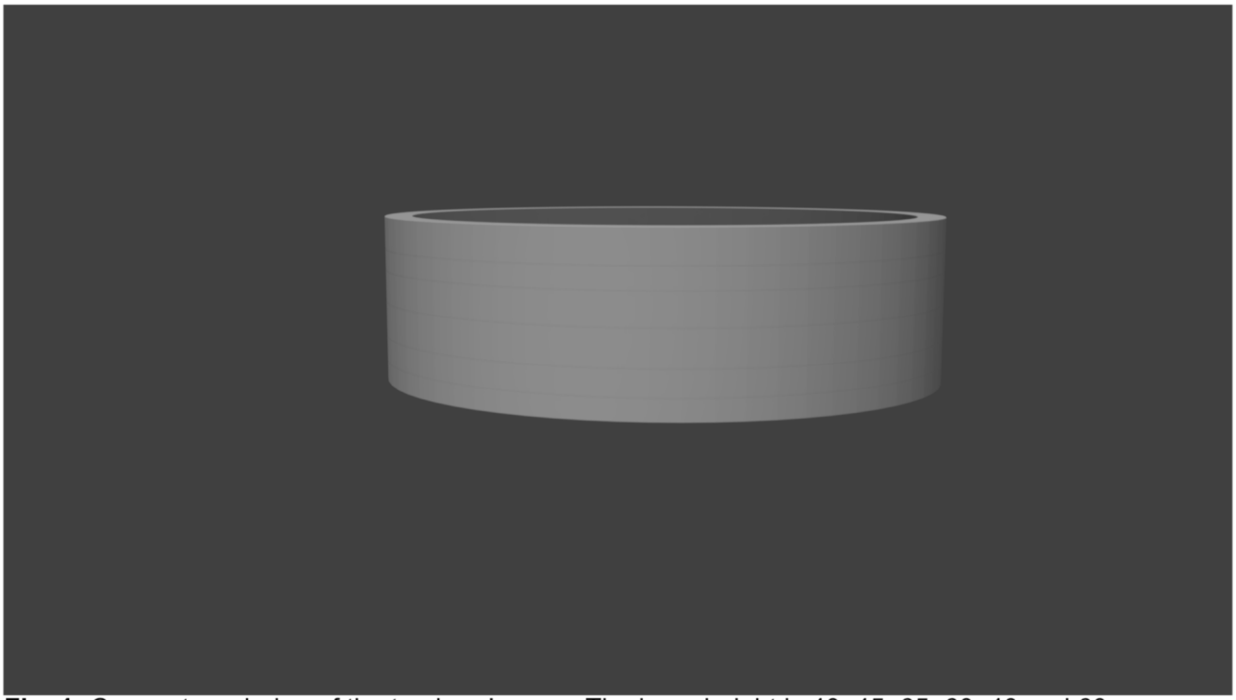

Fig. 1: Concept rendering of the tambour's case. The layer height is 40, 45, 65, 60, 40 and 60 cm (Brunke 2017).

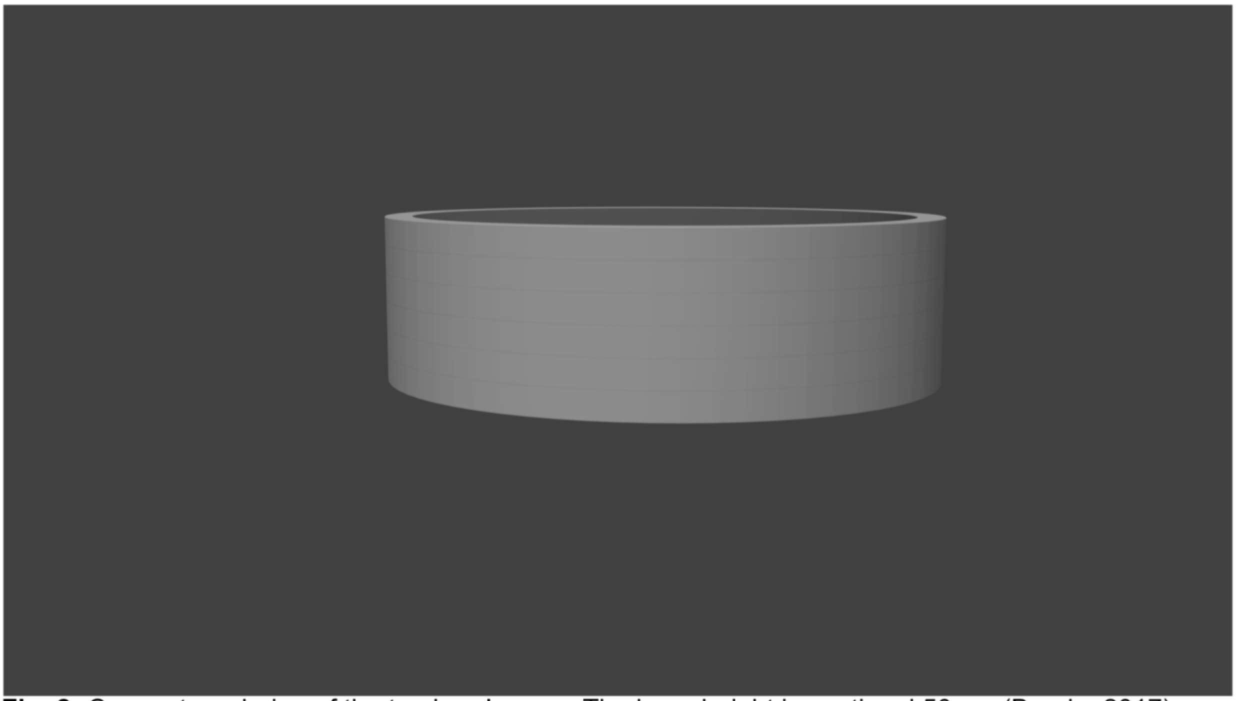

Fig. 2: Concept rendering of the tambour's case. The layer height is continual 50 cm (Brunke 2017).

Concept rendering of the tambour's case

Plate 14

key: far_cr

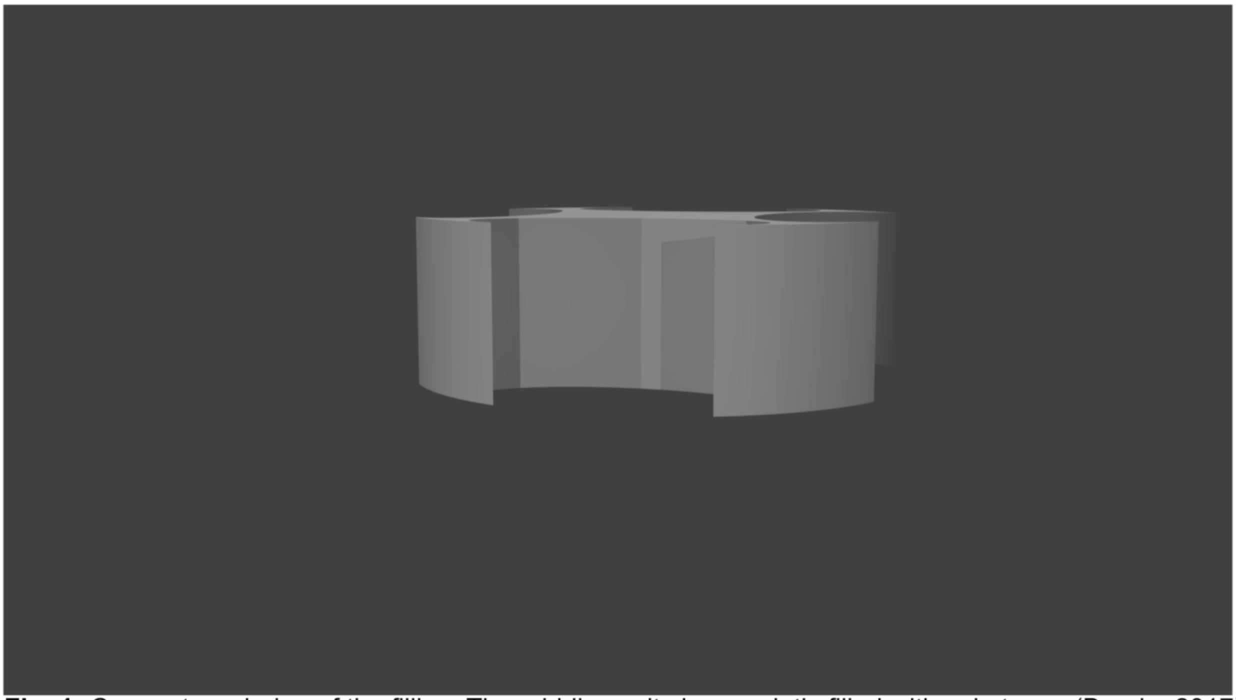

Fig. 1: Concept rendering of the filling. The middle cavity is completly filled with substance (Brunke 2017).

Fig. 2: Concept rendering of the filling. The middle cavity is hollow (Brunke 2017).

Concept renderings of the filling

Plate 15

key: far_cs

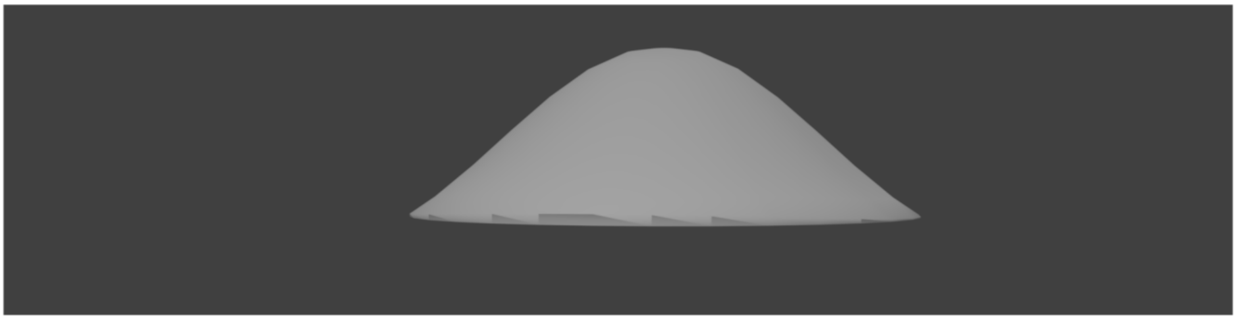

Fig. 1: Concept rendering of the roof as mound (Brunke 2017).

Fig. 2: Concept rendering of the roof as plate (Brunke 2017).

Fig. 3: Concept rendering of the roof as cone (Brunke 2017).

Fig. 4: Concept rendering of the roof as non existing (Brunke 2017).

Concept renderings of the roof

Plate 16

key: pdm_dc;
tmb_dc;
bc

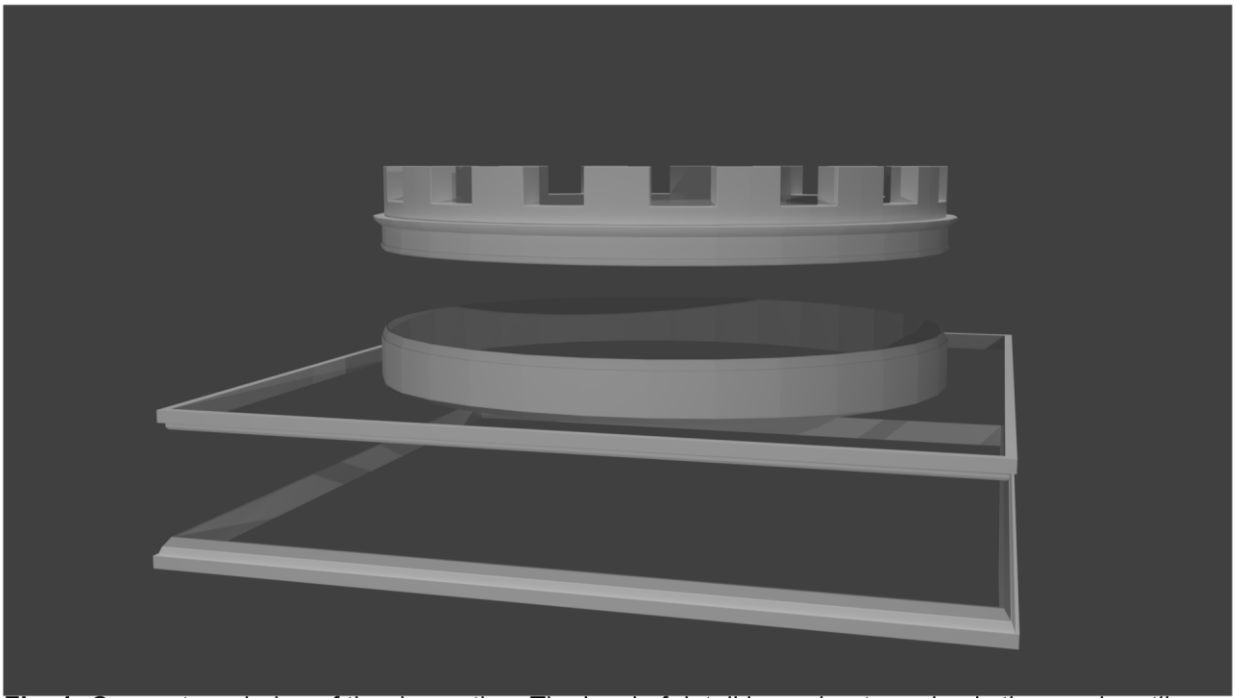

Fig. 1: Concept rendering of the decoration. The level of detail is moderate and only the rough outlines are modelled. Detailed ornamentation is avoided (Brunke 2017).

Fig. 2: Concept rendering of the burial chamber entrance. The level of detail is low (Brunke 2017).

Concept rendering of the decoration and the entrance to the burial chamber

Plate 17

key: pdm_cr

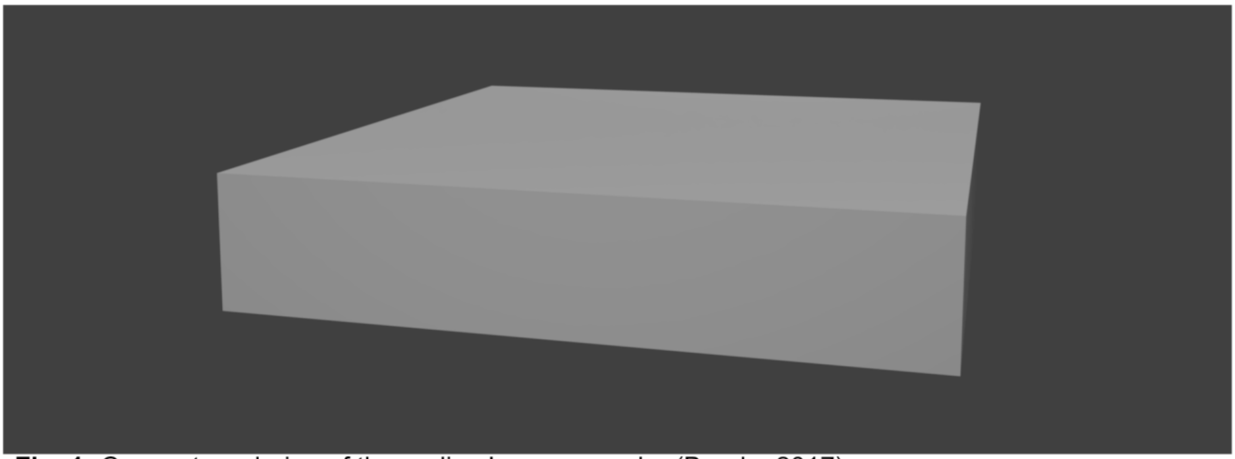

Fig. 1: Concept rendering of the podium's core as cube (Brunke 2017).

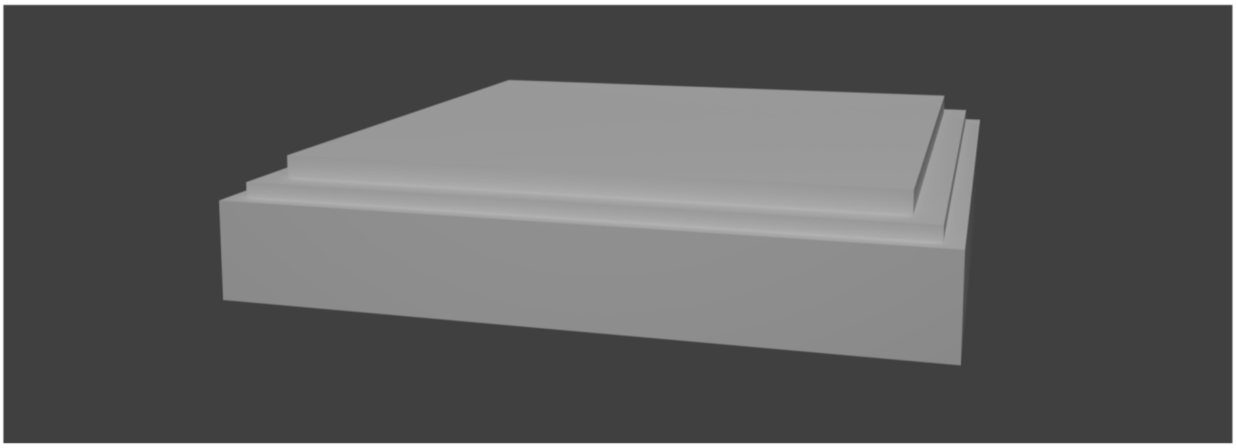

Fig. 2: Concept rendering of the podium's core as cube with steps (Brunke 2017).

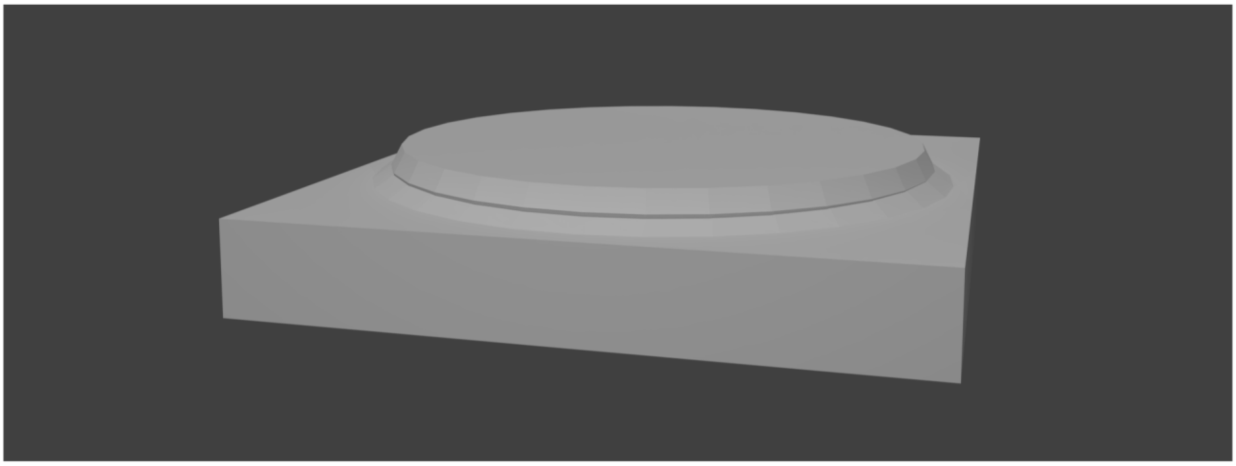

Fig. 3: Concept rendering of the podium's core as cube with cone (Brunke 2017).

Concept rendering of the podium's core

Plate 18

key: tmb_cr

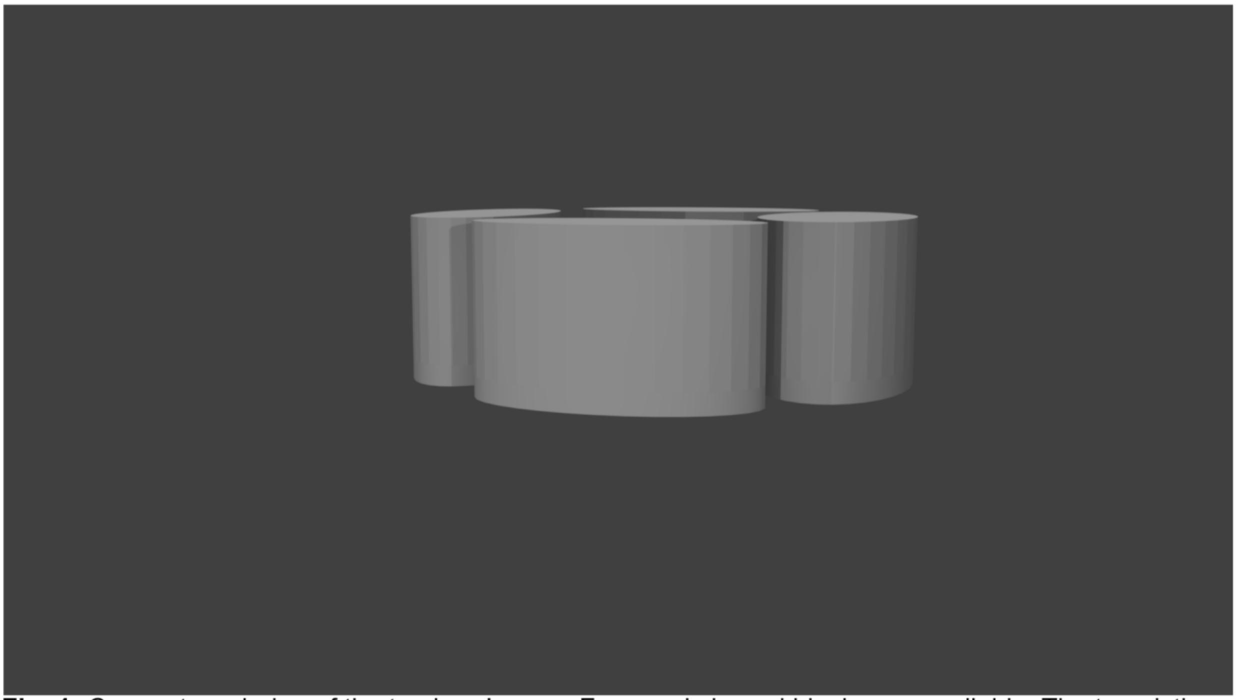

Fig. 1: Concept rendering of the tambour's core. Four oval shaped blocks are available. The transistion from one building phase to another one is not visible in this rendering(Brunke 2017).

Concept rendering of the tambour's core

Plate 19

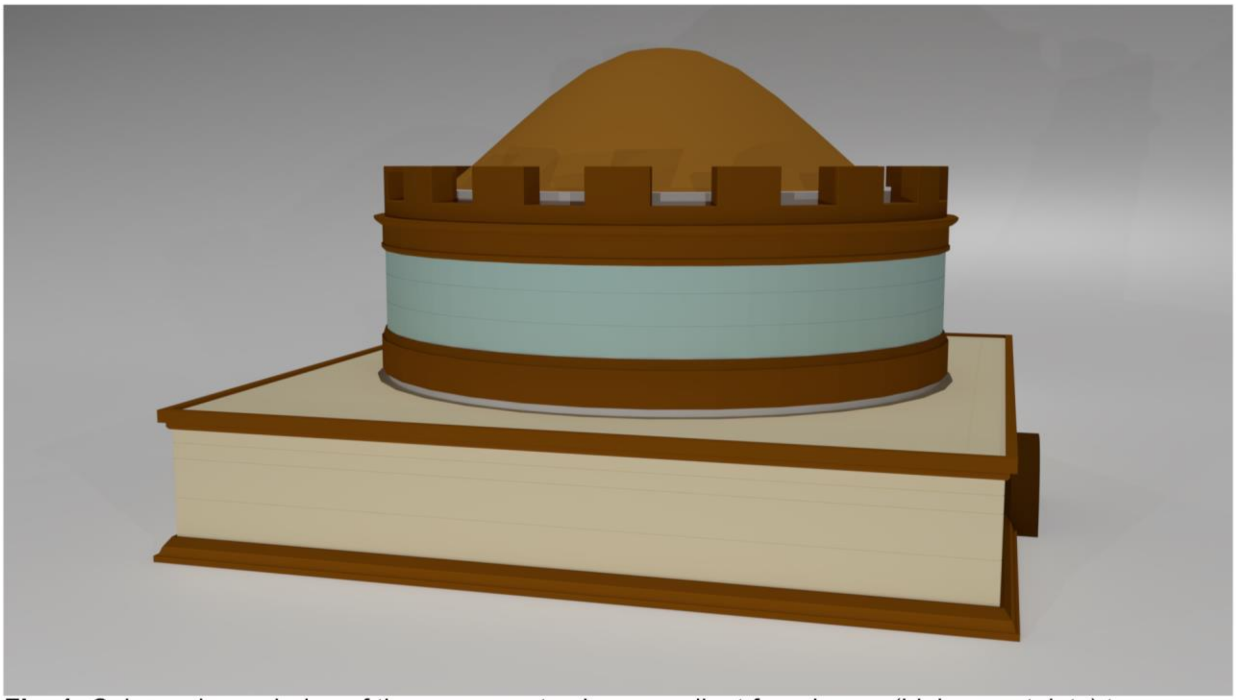

Fig. 1: Color code rendering of the monument using a gradient from brown (high uncertainty) to green (low uncertainty). This method is using the fuzzy-based uncertainty concept as framework. Indicated with the colors is the uncertainty of form and dimension (Brunke 2017).

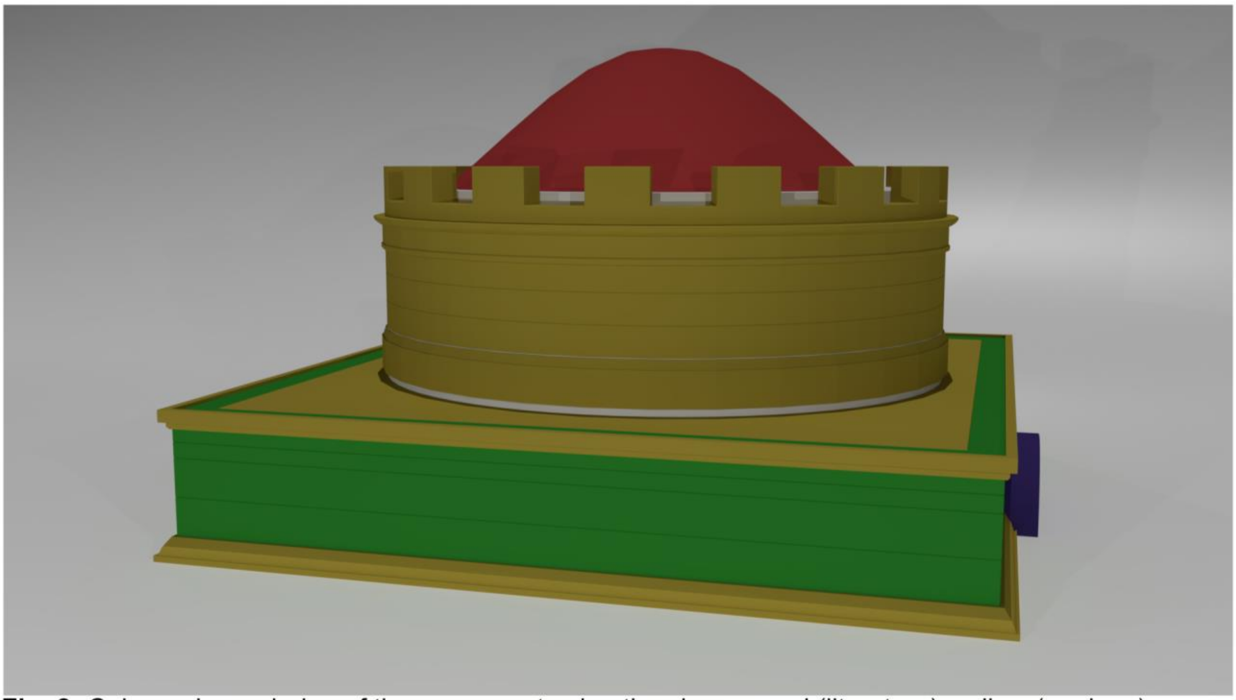

Fig. 2: Color code rendering of the monument using the classes: red (literature), yellow (analogy), blue (illustration) and green (fieldwork) from the class-based uncertainty concept. Indicated is the uncertainty of form and dimension (Brunke 2017).

Concept rendering with the color code

Plate 20

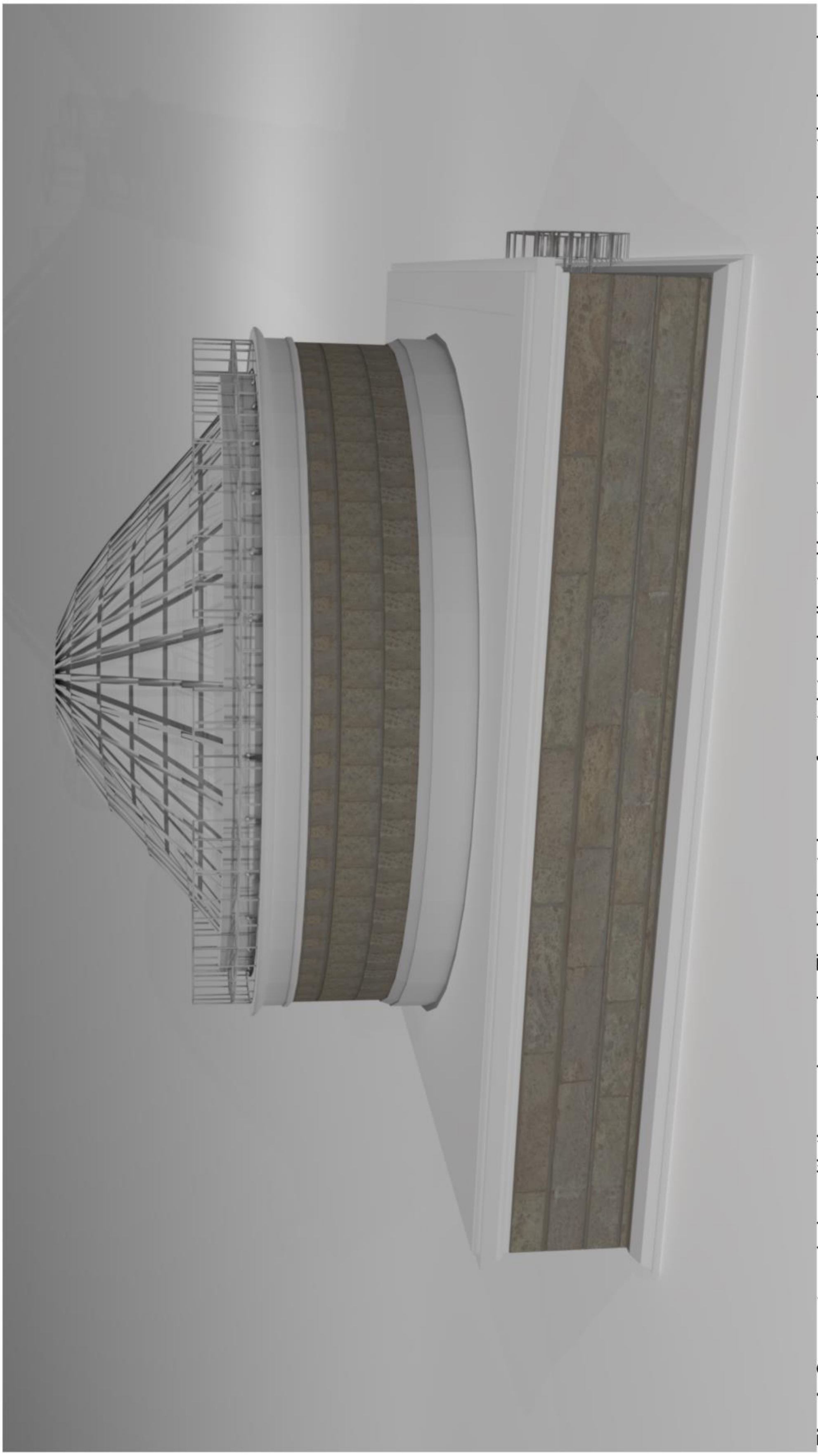

Fig. 1: Concept rendering with the render mode. The highest degree of certainty is indicated by textures and materials while the lowest is shown by the wireframe mode. The midfield is indicated by a solid grey. The uncertainty is based on the form and dimensions (Brunke 2017).

Concept rendering with the render mode

Plate 21

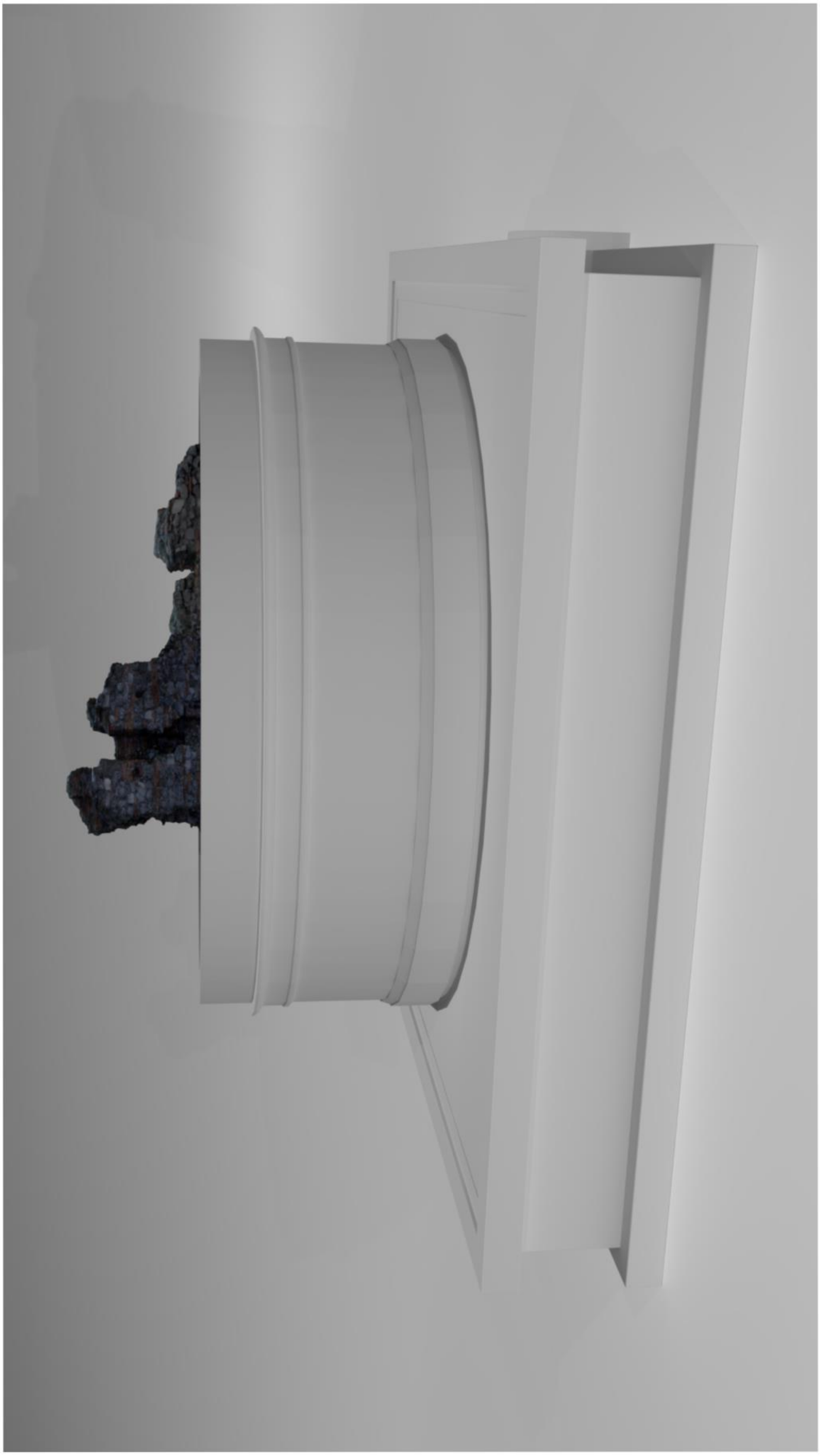

Fig. 1: Concept rendering of the level of detail visualization. Less details indicate a higher uncertainty. The reality-based reconstruction is added as overlay (Brunke 2017).

Concept rendering with the level of detail

Plate 22

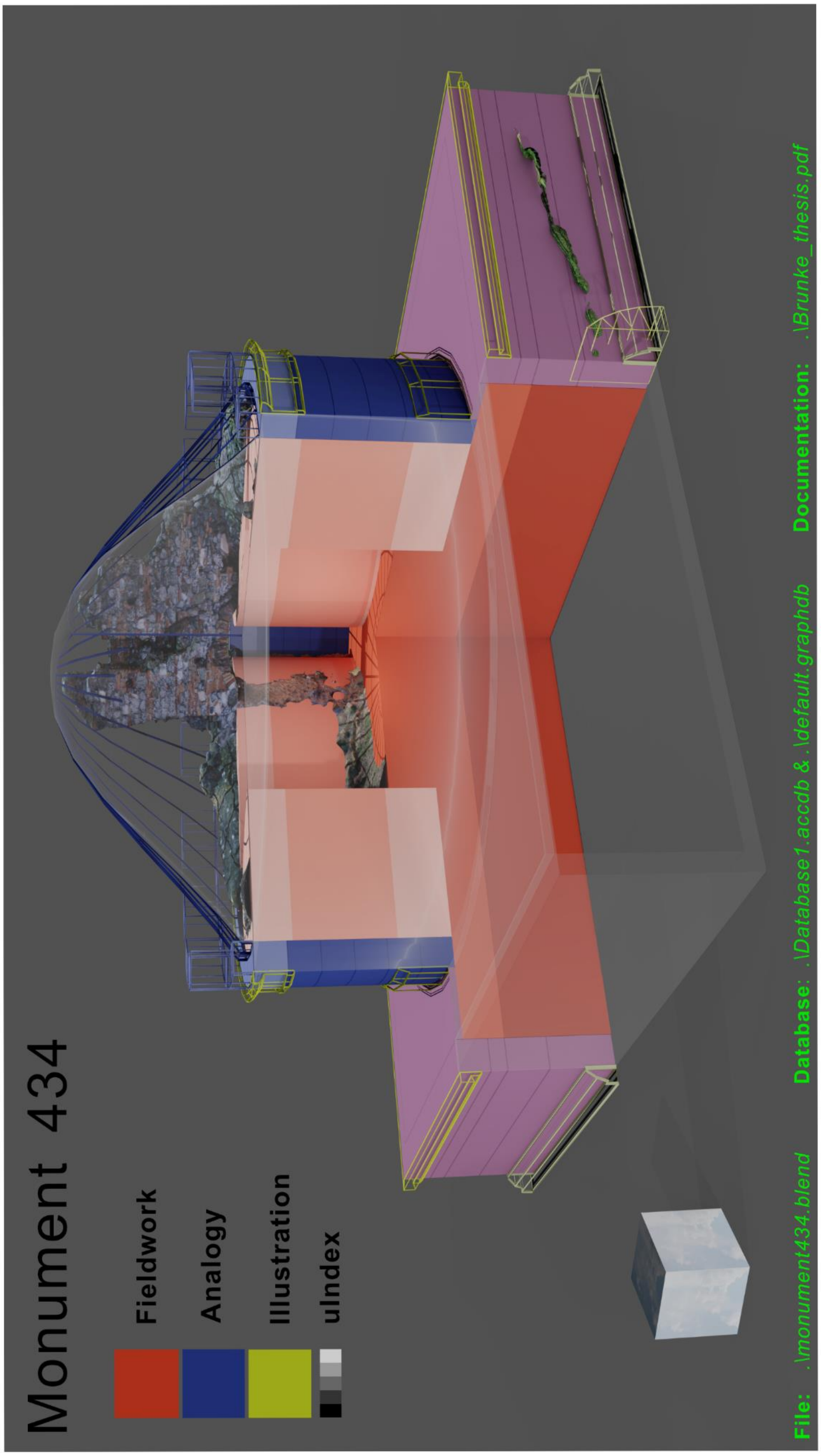

Fig. 1: Final visualization of monument 434 with a partial cross-section and updated uncertainty values. The results are available as an image rendering, animation and interactive model with two seperated databases. The primary colors are red, yellow and blue. The colors had to be adapted slightly for a better perception. Furthermore, the darker the color, the less is the uncertainty (indicated by the uIndex - relative scale). The edge length of the small cube corresponds to 1 m (Brunke 2017).

Final rendering

Technical note

How to use the available data most effectively

Table of content

List of figures

All figures are screenshots from the used software.

List of tables

1. Access the data

This technical note is a description of the digital data and how to use it. Among other things, support for its interpretation is also provided. The data itself is ordered as follows: "*1. Thesis report*"; "*2. Literature*"; "*3. Data*"; and "*4. Results*". These folders contain both raw and processed data.

Download: *https://drive.google.com/drive/folders/0B7uPvfqWrRXxYXBKWTVJSGNyTHc?usp=sharing*

Expiration date: *28 February 2018*

1.1 Thesis report

This folder contains all the reports and proposals that are connected to the master thesis. It also contains a digital version of the thesis itself. The software required for viewing it is any available PDF reader.

1.2 Literature

The literature folder contains most of the literature that was sourced. It is separated from the actual case study and the theoretical framework. The main objective is to provide a simple and quick way to review text references cited in the thesis. Each publication is named after its main author or editor and the year of publication. A PDF viewer and/or a web browser is needed to open the document.

1.3 Data

This folder contains mainly the raw data that was used for the actual research and interpretations. Post-processing was done only in order to receive more ordinary file formats. It might also be noticeable that not all of the data is mentioned in the text. This is due to the large amount of information that is available.

The subfolder "***models***" contains a reality-based model of Monument 434. It is scaled and available in several levels of detail. Agisoft Photoscan is needed to open the project files. The exported files can be opened with Meshlab or Cloud Compare.

The subfolder "***paintings***" contains numerous artistic renderings of monument 434 or similar structures. The paintings are ordered by facility and artist. In an optimal case, each painting provides a thumbnail, metadata and the actual painting in high resolution. The files are saved as JPG or PNG and are therefore viewable with either image viewer.

The subfolder “***panoramas*”** contains images of large structures that could not be captured with a single photograph. The stitched images are saved as TIFFs. They can be opened by either image viewer, but it might take a long time to load.

The subfolder “***photographs*”** contains pictures of tumuli in and around Rome. However, most important is Monument 434. The structure of the file system is similar to the structure used in the subfolder “*paintings*”. In contrast, photographs can have extra data and information, such as edited or converted pictures. However, most of them are saved as CR2, which usually requires special software, such as Adobe Photoshop, Adobe Lightroom or Affinity Photo to open and edit.

1.4 Results

This folder contains mainly the processed data and completed interpretations. The main emphasis is on the two databases and the three-dimensional reconstruction.

The subfolder “***databases*”** contains a relational and a graph database. Both databases are based on the same discussion and data. Additionally, they might contain some of the extra data in the form of illustrations or analogies. Microsoft Access and Neo4j are needed to view and manipulate the data.

The subfolder “***drawings*”** contains technical vector drawings. Each of them can be viewed from the front, left and top perspective of the monument. The drawings show the material, actual structures and possible reconstructions. As software, Corel Draw is recommended.

The subfolder “***figures*”** contains all the figures used in the thesis and related reports in digital form.

The subfolder “***models*”** contains the final reconstruction. The project has to be opened in Blender and contains the reality-based model and several hypothetical models. The main reconstruction is furthermore coded to reveal its uncertainty in light of the results and values from the database and discussion.

The subfolder “***plates*”** contains all the figures used in the thesis and the related reports in digital form.

2. How to use the data

2.1 Graph database

Open a database with Neo4j. Since only the community edition was available the queries need to be imported manually by drag & drop in the favorite windows or by copy and paste in the content window. The necessary queries are available at ".*4. Results\Databases\graph\queries*". The names should be self-explaining.

Database Information

- The database information (fig. 1) can be opened with a click on the database symbol in the navigation bar on the left side.
- All the "*Node Labels*", "*Relationship Types*" and "*Property Keys*" are summarized here. A click on one of them applies them as a filter.

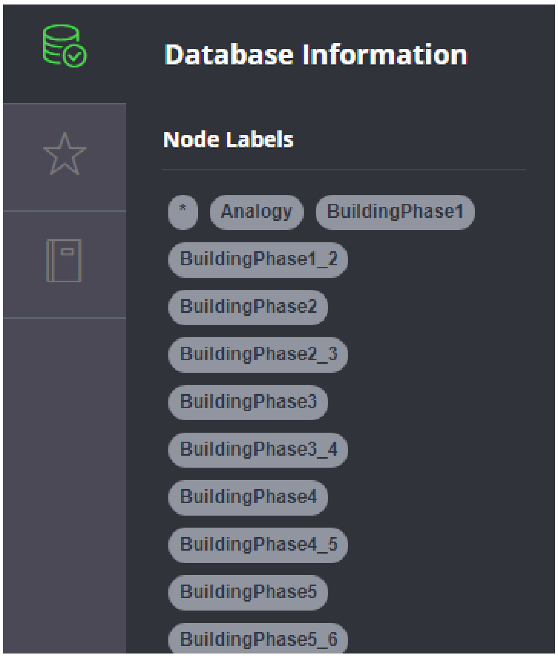

Figure 1: Database information of the graph database (Screenshot in Neo4j 3.2.2).

Favorites

- The favorites can be opened with a click on the star icon in the navigation bar on the left side.
- Under the headline "*Saved Scripts*", several queries are provided (fig. 2). The same queries can also be found in the folder of the database as text files.

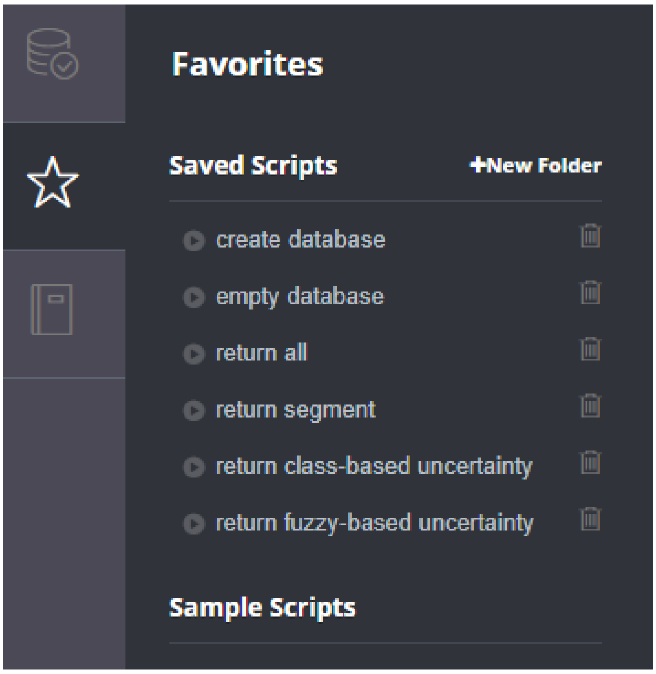

Figure 2: Favorites of the graph database, including custom scripts. Custom scripts can be important in this window by drag & drop (Screenshot in Neo4j 3.2.2).

Manipulating the visualization and data

- After data is returned by a query, it is displayed as a graph by default (fig. 3). It can be changed in the main windows menu by selecting either "*Graph*", "*Table*", "*Text*" or "*Code*".
- Individual nodes can be moved and ordered with the mouse.
- The properties of the nodes can be changed when necessary (fig. 3). These are:
  - Color
  - Size
  - Caption
- To manipulate data, cypher queries have to be entered in the text box above the content. Auto suggestions might help.

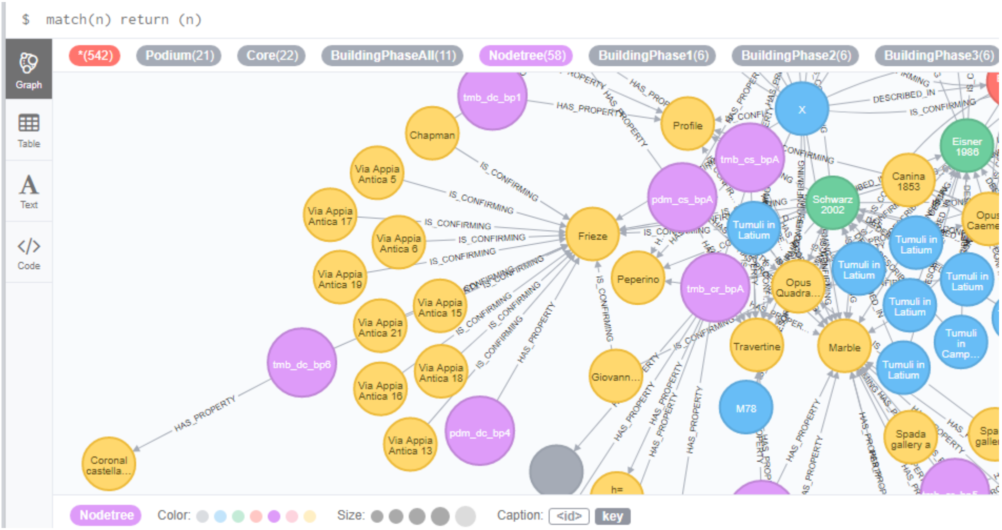

Figure 3: Section of the return of all datasets in a graph (Screenshot in Neo4j 3.2.2).

List of the queries provided

- <u>Query</u>: *"create database"*
- <u>Query</u>: *"empty database"*
- <u>Query</u>: *"return all"*
- <u>Query</u>: *"return segment"*
- <u>Query</u>: *"return fuzzy-based uncertainty"*
- <u>Query</u>: *"return class-based uncertainty"*

```
MATCH (object:Nodetree)-[rel:HAS_PROPERTY]->(value:Property)<-[rel2:IS_CONFIRMING]-(source:Source)
WHERE object.key = rel2.key = "pdm_cr_bp1"
RETURN object, rel, value, rel2, source
```

Figure 4: Example of the query "*return segment*" (Screenshot in Neo4j 3.2.2).

It is possible to create queries for everything. Therefore, only the most common ones are provided by me. Help for creating a custom query can be found in the online documentation (https://neo4j.com/docs/). When using one of the queries provided, one has to keep in mind that the key has to be adapted to the actual segment (fig. 4). The creation of a basic node is described in table 1.

Table 1: Template for creating the basic nodes with a relationship. However, this does not include any attributes and values. Another way to review the structure is to investigate the query "*create_database*"

CREATE(	Var1	:Nodetree	:Podium	:Core	:Buildingphase1
			:Tambour	:Case	:Buildingphase2
			:BurialChamber	:Decoration	…
			:FillingAndRoof		
	Var2	:Property	:Material		
			:Form		
			:BuildingTechnique		
	Var3	:Source	:Literature		
			:Fieldwork		
			:Illustration		
			:Analogy		
	(Var1)-	[:HAS_PROPERTY]	-> (Var2) <-	[:IS_CONFIRMING]	-(Var3)
)					

However, as the work around in the thesis demonstrates, the graph database might get its strength from a slightly different structure and queries. Nevertheless, fuzzy-based (fig. 5) and class-based uncertainty can be easily queried. Since another system is used, no actual values for "*reliability*" and the "*uIndex*" are embedded in the database yet.

Figure 5: Return of the query "*return segment*" with the key "*pdm_cr_bp1*" (Screenshot in Neo4j 3.2.2).

In the next section the use and interpretation of the relational database and its content will be described.

2.2 Relational Database

Open the database with Microsoft Access. When editing datasets, a combo box often appears, displaying a selection of values. If the needed value is not available, go to "*Add*" or "*edit ontology*" and have a look at how to add new suggestions.

1. Add or edit a source

- <u>Open table:</u> "*tbl_Source*"
    - Either click on an existing line to change it (fig. 6) or click on a new line to add a dataset.
    - Fill in all the relevant data.

tbl_Source

ID	Title	Category	Reference
1	Eisner 1986	Literature	Eisner, M., 1986. Zur Typologie der Grabbauten im Suburbium Roms. Mainz: von Zabern.
2	Hesberg 1992	Literature	Hesberg, H. von, 1992. Römische Grabbauten. Darmstadt: Wissenschaftliche Buchgesellschaft.
3	Kockel 1978	Literature	Kockel, V., 1978. Die Grabbauten vor dem Herkulaner Tor in Pompeij. Mainz am Rhein: von Zaber

Figure 6: Editing or adding a dataset in "*tbl_sources*" (Screenshot in Microsoft Access 2016).

2. Add or edit a segment

- <u>Open table:</u> *"tbl_Monument"*
    - Either click on an existing dataset to change (fig. 7) or click on a new line to add a dataset.
    - "*Node 1*", "*Node 2*", "*Node 3*" and "*Property*" provide predefined values regarding the segmentation of the monument. One of them has to be chosen.
    - Add a value to the segment that is defined by "*Node 1*", "*Node 2*", "*Node 3*" and "*Property*".
    - Set "*isReal?=true*" if it is an actual measurement or knowledge derived from the ruins without any discussion.
    - "*Remark*" is optional and can be used for additional information.
    - With a click on the small "*+*", a sub-data sheet is opened and sources can be added to or edited directly for one segment (fig. 2).

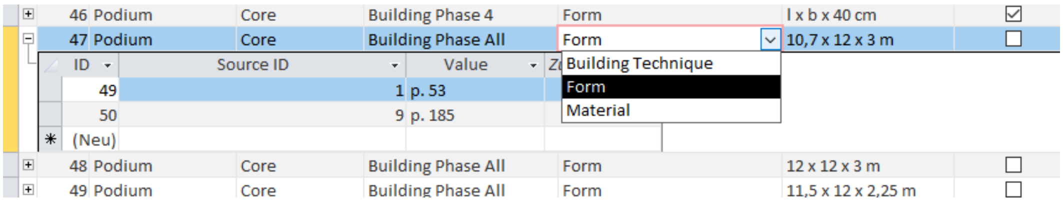

Figure 7: Adding or editing a segment. The sub-data field is opened and indicates two sources. Furthermore, one of three properties can be chosen (Screenshot in Microsoft Access 2016).

- <u>Open table:</u> *"tbl_MonumentKeys"*
  - Click on the column "*Monument ID*" (fig. 8).
  - Choose the newly added segment. The software provides suggestions. One of them has to be selected.
  - Add a key to another row. A key is basically the short form of the defining parameters of each segment. Each shortcut is stored in table "*cat_ontology*".

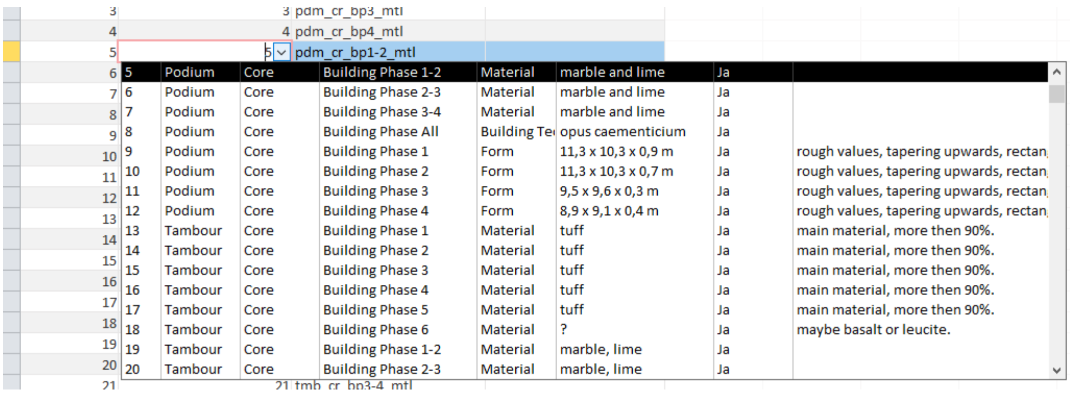

Figure 8: Adding a monument key. A click on the "*Monument ID*" column opens a list box with all the available segments (Screenshot in Microsoft Access 2016).

3. Add or edit the fuzzy-based uncertainty

- <u>Open table:</u> *"tbl_Uncertainty1"*
  - Click on the column "*Monument ID*" and choose the segment to which you want to add the uncertainty values. It looks similar to figure 8.
  - Fill in "*Importance*" and "*Reliability*". The "*Index*" is currently equal to "*Reliability*" and is later used to encode uncertainty in the monument (fig. 9).

ID	Monument ID	Importance	Reliability	Index	Zun
1	1	1	1	1	
2	2	1	1	1	
3	3	1	1	1	

Figure 9: Adding an uncertainty index to a segment (Screenshot in Microsoft Access 2016).

4. Add or edit the class-based uncertainty

- <u>Open table:</u> *"tbl_Uncertainty2"*
  - Click in the column "*Monument ID*" and choose the segment to which you want to add a source.
  - Click on the column "*Source ID*" and choose the source you used for the interpretation of the segment represented by "*Monument ID*".
  - Choose one source you used for the interpretation.
  - Optional: Add a "*Value*" in the form of a book page or similar.
  - Repeat this process with a new dataset until all the sources for one segment have been added (fig. 10).

ID	Monument ID	Source ID	Value	Zu
1	1	12		
2	2	12		
3	3	12		
4	4	12		

Figure 10: Example of the class-based uncertainty (Screenshot in Microsoft Access 2016).

Easier and better to use are the sub-datasets in "*tbl_monument*" (fig. 7). This makes it possible to see directly which source is connected to which segment.

Add or edit the ontology

- <u>Open table:</u> *"cat_Ontology"*
  - Add or edit one dataset.
    - "*Word*": The full name of the object. It is used for displaying purposes.

- "*Shortcut*": The shortcut of the word. This column can be used as reference.
- "*Key*": Is used for queries and references in the database. It is necessary to create one of those automatic suggestions; for example, when you want to add "*Time period*" to the properties as a further container for uncertainty. The same key has to be used as that for "*Building Technique*", "*Material*" and "*Form*".

Request bibliography, figures, list of analogies and list of figures

- Open report: *"Bibliography"*
- Open report: *"Figures"*
- Open report: *"List of analogies"*
- Open report: *"List of figures"*

Request fuzzy-based uncertainty

- Open report: *"Uncertainty #1"*
  - Enter the "*Key*" of the requested segment. The key can also be partial. It does not need to be the complete key. For example, "*pdm*" as a key will return all the uncertainty values related to the podium regardless of their building phase or core or case (fig. 11). The values are based on my personal opinion about the segment's reliability and importance.

Uncertainty #1

Key	Importance	Reliability	Index
pdm_cr_bp1_bt	1	1	**1**
pdm_cr_bp1_frm	1	0,8	**0,8**
pdm_cr_bp1_frm	1	1	**1**
pdm_cr_bp1_frm	1	1	**1**
pdm_cr_bp1_frm	1	1	**1**

Figure 11: Example of the report "*Uncertainty #1*" with the key "*pdm*" (Screenshot in Microsoft Access 2016).

Request class-based uncertainty

- <u>Open report:</u> "*Uncertainty #2*" or "*Uncertainty#2_2*"
    - Enter the "*Key*" of the requested segment. The key can also be partial. It does not need to be the complete key. For example, the "*pdm*" key will return all the uncertainty sources related to the podium regardless of their building phase or core or case (fig. 12; fig. 13). "*Related*" means that they were used for the segment's interpretation.
    - The only difference between those two reports is that they group the results differently.

Uncertainty #2

Key	Title	Category	Value
pdm_cr_bp1_bt	Brunke 2017	Fieldwork	
pdm_cr_bp1_frm	Brunke 2017	Fieldwork	
pdm_cr_bp1_frm	Brunke 2017	Fieldwork	
pdm_cr_bp1_frm	Brunke 2017	Fieldwork	
pdm_cr_bp1_frm	Jones 2000	Literature	p. 87
pdm_cr_bp1_frm	Brunke 2017	Fieldwork	

Figure 12: Example of the report "*Uncertainty #2*" with the key "*pdm*" (Screenshot in Microsoft Access 2016).

Uncertainty #2

sourcesCategoryI	Key	Title	Value
Analogy			
	pdm_cr_bp2_frm	Tumuli in Latium	
	pdm_cr_bp2_frm	Tumuli in Campania	
	pdm_cr_bp2_frm	Tumuli in Latium	
	pdm_cr_bp3_frm	Mausoleum of Augustus	
	pdm_cr_bp3_frm	Tumuli in Campania	
	pdm_cr_bp3_frm	Tumuli in Latium	

Figure 13: Example of the report "*Uncertainty #2_2*" with the key "*pdm*" (Screenshot in Microsoft Access 2016).

In general, it is always possible to manipulate or change the database to suit one's requirements. This database provides only the most basic statements that I used to create the reconstruction. Likewise, its main emphasis is on uncertainty and not the user-friendly archive of all possible data. In the following section, the 3D modeling software is presented. This includes the interpretation of the available data.

2.3 Evidence-based reconstruction

Open the project file with Blender. The navigation might be confusing at the beginning. However, the online documentation (https://docs.blender.org/manual/en/dev/) provides a good introduction. For the purpose of this thesis, a custom layout, "*0. Monument Analysis*", is provided. It should be used as standard and can be changed in the navigation. When using the "*0. Monument Analysis*" layout, the individual components are already placed most optimally (fig. 14). However, changes and adaptations to own behaviors are always possible.

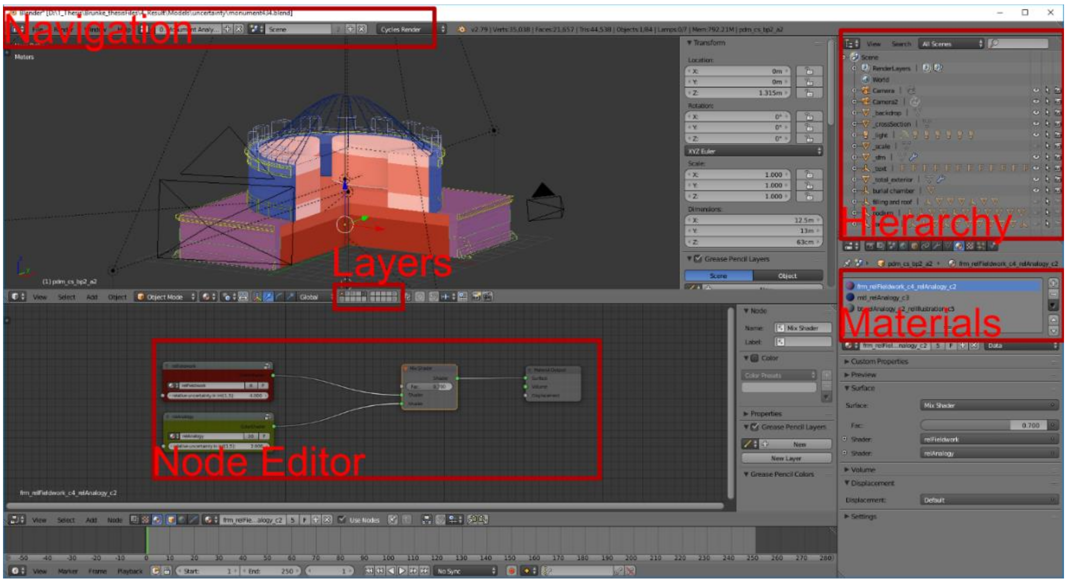

Figure 14: Layout of the "*0. Monument Analysis*" and the distribution of the important tools (Screenshot in Blender 2.79).

Layer

The data is stored in several layers (tab. 2; tab. 3). A layer can be displayed either individually or combined. This control (fig. 15) is placed beneath the 3D View. Clicking on one of the squares opens the layer. Likewise, click + shift opens several layers. The listing goes clockwise.

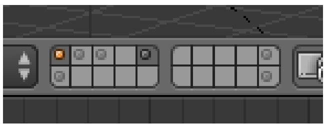

Figure 15: Layer control of Blender (Screenshot in Blender 2.79).

Table 2: Occupancy of the first 10 layers

Layer	Content
1	Reconstruction of monument 434 with color code.
2	Transparent cutout object.
3	Reality-based model of the monument.
4	
5	Light and cameras.
6	Parent objects for the project structure.
7	
8	
9	
10	

Table 3: Occupancy of the last 10 layers

Layer	Content
11	
12	
13	
14	
15	Cutout form for the cross-section.
16	
17	
18	
19	
20	Backdrop.

Hierarchy

The empty objects from layer 6 are used as parents for all the other objects. This enables a structure similar to the database and discussion. In the hierarchy (fig. 16) the nodes are stacked on top of each other to address specific address rooms or namespaces. The hierarchy also offers alternative reconstructions, which are indicated with a suffix of "_*aX*" whereby "*X*" is substituted by the enumeration of the interpretation.

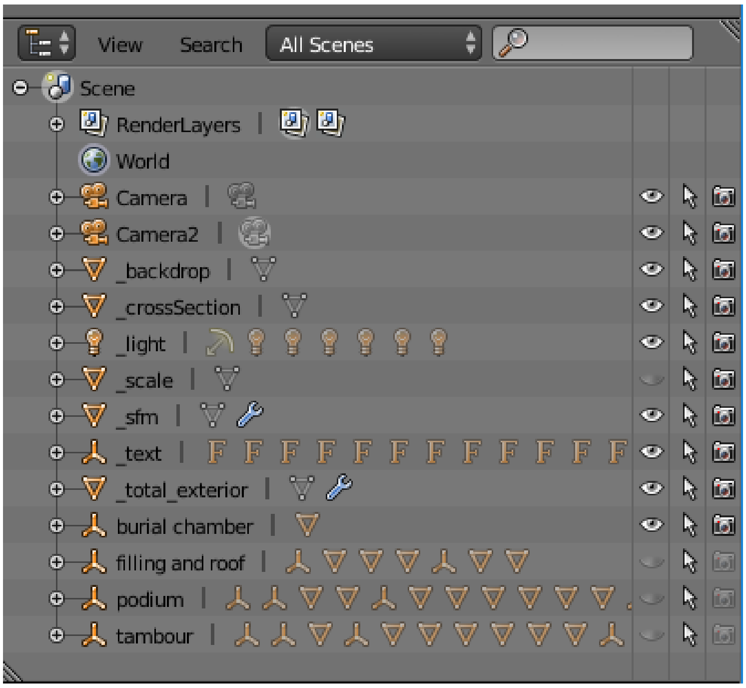

Figure 16: Hierarchy system of Blender and the project (Screenshot in Blender 2.79).

The little eye and camera enable the editor and renderer to turn the visibility on and off. They are important to hide or show only the requested parts in order to explicitly show or indicate, for example, the first building phase of the podium. Either the search field on top of the hierarchy can be used with the relevant key, or the "*Podium*" object is opened by a click on the small plus in front of it. After that one has to decide between the second and third nodes.

Colors

In order to inspect one of the objects, it has to be selected in the hierarchy or the 3D view. Now the property window on the right should show the material settings (fig. 17). If not, click on the circle icon. In this state one can see the uncertainty material for form, material and building technique. Simultaneously, the material should be opened in the "*Node Editor*" below the 3D view. The node editor allows one to trace back the emergence of a color (fig. 18), in this case the color for "*pdm_cs_bp3_frm*". Hereby, one can see that fieldwork at the monument and analogies were used for the interpretation. However, they are not equally reliable and responsible for the interpretation. The exact values are indicated in the relative uncertainty and the mixing ratios.

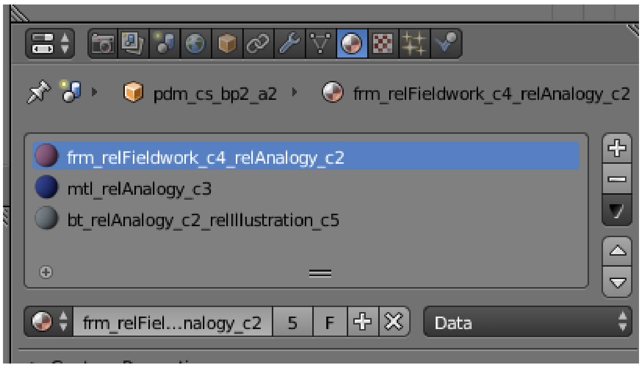

Figure 17: Material settings of Blender (Screenshot in Blender 2.79).

The nodes are colored according to the primary color of their source classification. Instead of a relative and stepped gradient, a smooth an absolute gradient can be chosen from the library. This would allow the direct use of the fuzzy data derived from one of the databases. In the current version, only additive color mixing is possible.

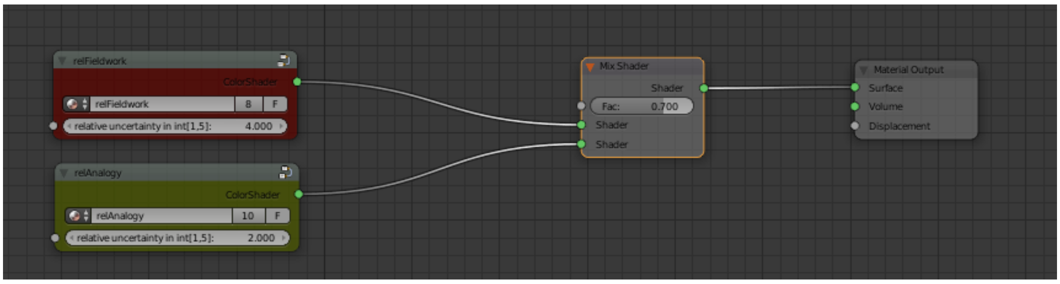

Figure 18: Node setup of the material "*frm_relFieldwork_c4_relAnalogy_c2*", which is used for the Podium (Screenshot in Blender 2.79).