ABSTRACT

Knowledge representation and management play a key role in built heritage field, deeply influencing decisions and actions of the different specialists involved in investigation, intervention, conservation and fruition processes. An accurate and complete representation and comprehension of architectural heritage artefact require a large amount of semantics related to its intangible aspects such as social and historical context. On these bases, the research presented in this paper investigates the potential impact of Building Information Modelling introduction in built heritage field in order to enhance knowledge management and, as a consequence, collaboration among specialists. To include in the artefact representation both tangible and intangible knowledge, the model has been conceived as the integration of a BIM environment with a knowledge base developed by means of ontologies. To test its features and capabilities, the model has been applied to the archaeological investigation of the Castor and Pollux temple at Cori, Italy.
INFORMATION MANAGEMENT AND BUILT HERITAGE INVESTIGATION

The Architectural Heritage investigation and conservation process is a system of multidisciplinary activities where each professional is both user and provider of a large amount of information. The accuracy and the completeness of the built heritage knowledge representation deeply affect the activities of the different specialists involved in the investigation, intervention, conservation and maintenance phases. Any decision made by the different actors is based on “what is known” of the object and any lack of knowledge or inconsistence can lead to errors and even irreparable damages. In this field, it is clear that the management of information is crucial to support collaboration and knowledge sharing at all the different levels of the investigation/conservation process of an architectural heritage artefact.

Differently from the construction industry, where buildings are very clearly modelled in all their components and features, in heritage field, any artefact is usually a blurred-outlined knowledge domain and any lack of documentation is almost equivalent to the destruction of a part of the discovered remains.

To gain a reliable and accurate understanding of the artefact, a large amount of knowledge related to different contexts (social, historical, geographical and technological, just to mention a few) is needed. Every heritage object can be seen as a unique historical archive; a precious source of primary information from which any research, investigation or conservation activity will retrieve new data (Letellier et al., 2007). In heritage processes, information is collected, documented and made virtually available by the different professionals. Nevertheless, this knowledge is almost inaccessible since it is spread among different professionals with their own sets of tools and jargons. At the same time, useful data related to the artefact and its contexts—potentially able to support the process of interpretation and intervention—are often buried in tons of different data repositories. As a result, all efforts to comply with recording and documentation requirements are wasted and intervention decisions are too often made without a full comprehension of the artefact and its multifaceted features.

The introduction of digital technologies to the built heritage field has left this problem unsolved: while several efforts have been made to develop virtual reality techniques oriented to building original appearance simulation or data acquisition technologies, a more general methodology for knowledge representation and management for historical artefact is missing (Kalay 2008; Tan et al. 2009). At present, information management in heritage processes is still mainly document-based and the representation of the artefact is just the sum of the documentation provided by the actors during the heritage process. As a consequence, built heritage representation usually suffers from these main deficiencies:

- Difficulty in checking the information stored and finding errors and inconsistencies within the documentation sets;
- Lack of integration, coherence and coordination among different documentation sets generated by the different activities of the heritage process;
- Poor information management with consequent lack or duplication of data;
- Actors’ difficulty to share knowledge and collaborate during the investigation and the restoration phases.

The research presented in this paper aims to introduce Building Information Modelling in the built heritage field, providing an innovative modelling approach potentially able to overcome these shortcomings and enhance collaboration among the several profiles operating in the heritage field.

Similarly to its effects on the Architecture, Engineering and Construction industry (AEC), BIM application to the representation of archaeological/historical artefacts provides a modelling environment able to improve information management ensuring unambiguity, consistency, coordination and coherence of all the knowledge needed to fully understand the artefact.

In fact, BIM approach is potentially able to provide a modelling environment where geometrical and not-geometrical data about an architectural artefact can be represented, managed, integrated, updated and shared among different actors (Eastman 2008, Crotty 2011). The proposed BIM environment behaves as a smart and up-to-date electronic dossier of the artefact during the investigation and conservation activities, integrating geometrical representation and not-geometrical data. To fully represent and comprehend a historical/archaeological artefact, it is necessary to include not only information directly related to the object or to its parts (both tangible and intangible such as material, dating, deterioration), but also a large amount of semantics about different context aspects (for example historical context, social information, environmental resources, other heritage artefacts information, etc.). For this reason, we have decided to integrate Building Information Modelling with a knowledge management system based on ontologies in order to enclose crucial information that would be difficult to represent in the component-based BIM approach.
In order to test the real effectiveness of the proposed modelling approach, we have chosen to apply the BIM+ontologies system to the process of investigation and documentation of the roman temple of Castor and Pollux in Cori, Italy (Figures 1) and (Figures 2).

FEATURES AND LIMITS OF CURRENT MODELLING APPROACHES FOR BUILT HERITAGE

Since the advent of CAAD, a wide number of researches has concentrated on the development of digital methodologies to support built heritage representation with particular attention to digital acquisition and virtual reconstruction and communication of historical/archaeological artefacts (Kalay 2004; Affleck 2005). The introduction of laser scanning and photogrammetry technologies allow to reach accurate reality-based levels of representation, both in CAAD and BIM environments (Garagnani et al. 2013). While the digital acquisition/representation topic is well-covered in literature, only recently some attention has been moved towards modelling approaches able to integrate geometrical representation and documentation of heritage artefacts (Pauwels et al 2008; Attar et al. 2010). Among the others, Virtual Reality GIS (VRGIS) is currently considered the most capable system able to integrate the geometrical representation of the artefact (i.e. data collected through laser scanner technologies) with the related semantics, allowing actors and users to interrogate virtual 3D model in order to gain data and information. Nevertheless, while this system can be useful in representing consolidated information about the artefact after the heritage process, several limits arise when it is applied to real time information management in heritage investigation and intervention activities. Current VRGIS systems are mere data storages, usually lacking in knowledge coherence and consistency, and they are not oriented to support collaboration and knowledge sharing among the different specialists; moreover, their coordinate-based approach does not allow inclusion of a large amount of semantics not geographically relatable but still crucial for the artefact representation and comprehension.

Despite the widespread adoption of BIM in the field of design and management of new buildings, only a few projects have looked at Building Information Modelling as a technology that can improve the representation of the relationships between tangible and intangible heritage knowledge.
BIM is not discussed in Robin Letellier’s Recording, Documentation, and Information Management for the Conservation of Heritage Places (2007), and it is not mentioned in the Metric Survey Specifications for Cultural Heritage proposed by Bedford et al. (2009) both considered key references for heritage documentation.

In spite of the apparent disinterest, the use of BIM in heritage conservation field is not without past instances: in 2007, Pentilla presented a case study that evaluates utilization of BIM for the retrofit of historical buildings by means of an “inventory model” as a database of both past and present of an existing building condition. Nevertheless, this and similar experiments have been focusing more on database creation and extension rather than considering BIM as documentation hub to support and enhance specialists’ activities and collaboration.

In built heritage field, the process of cataloging is often done through the creation of large databases mainly characterized by a vast heterogeneity of knowledge related to the typology of media and formats used, to their level of accessibility, and to their logical models of representation (Volk et al., 2014).

This methodology is only partially well-suited to the limited amount and level of semantics that can be attributed to the objects by means of current BIM platforms: in fact, the mere description of their features through the use of a list of properties generates information, which is often redundant or overly simplified inside many separate slots, highlights the inability of such data models to represent logical associations among entities with other sections of data related to different disciplines. This aspect clashes with the requirement that, as stated before, the information related to cultural heritage objects has a strong need for correlation in order to fully express their true worth.

For this reason, integration of BIM with information management techniques like semantic reasoning is essential to enhance representation of archaeological building knowledge, requiring a model in which data and entities are linked in a relational system, revealing some information that would otherwise remain “hidden”.

Such considerations lead to a possible solution in a modelling approach that meets the needs listed above and which plays a fundamental role in representing the semantics of objects. At present, ontology-based systems have been progressively introduced in AEC industry to support collaboration and knowledge sharing among the different actors involved in the design process (Beetz 2005; Carrara 2009) and allow the representation of entities not only through the description of their properties but also by formalizing the relationships among them (Di Mascio et al. 2013; Carrara et al. 2009). On these bases, we propose a BIM model integrated with a knowledge base developed by means of ontologies, in order to enclose a sufficiently accurate and computable formalization of the knowledge related to the artefact and its components, and to expand current BIM abilities of inference and rules-based reasoning on this knowledge structure.

The BIM-BASED PLATFORM FOR INFORMATION MANAGEMENT IN BUILT HERITAGE PROCESSES: BIM AND BUILT HERITAGE REPRESENTATION

In built heritage processes, professionals’ actions and operations are usually asynchronous and several years of investigation are needed to reach a sufficient and comprehensive documentation level. For this reason, a collaborative information management platform is crucial at all the phases of investigation and intervention in order to formalize and systemize the artefact-related knowledge as soon as it is collected and modeled by the operators.

The proposed BIM platform for built heritage aims at providing a unified representation of the artefact, where geometrical representation and the needed semantics can be set up and updated along the entire process, allowing actors to access, edit and manage such information in accordance to their role, tasks and expertise. To include both these kinds of knowledge in the artefact representation, the proposed platform has been conceived as an integration between a BIM environment and a knowledge base developed by means of ontologies. This approach supports the information management along the entire heritage process, providing a reference model of the artefact that unifies and coordinates the information resulting from the different specialists’ activities.

In the investigation process supported by Building Information Modelling, the first logical step consists of recognizing and identifying the different components of the artefact. This process of interpretation relies on actors’ knowledge and experience and it is crucial for the information management system, since each component is associated to a BIM class in order to be progressively enriched with data and information collected and provided by the operators.

Differently from the AEC industry where each element is defined and modeled in all its parts and properties, the different components in built heritage are often not clearly identifiable (especially at the beginning of the investigation process). To overcome this
problem, some classes have been developed in order to represent these unknown objects in terms of their geometric and material features, waiting for a later interpretation that will associate them to the identifiable class. In this way, actors can see which entities are still unidentified and, on the bases of their knowledge and experience, provide suggestions for their interpretation.

During the site survey, a wide amount of data is associated to the entities in terms of properties values and relationships. This part of the knowledge base (that we defined as Survey Knowledge Base–SKB) represents the information directly gained on site in accordance to the different disciplines considered (i.e. dimensions, morphology, topology, materials information, temperature, deterioration rate, carbon dating, etc.).

Once an element is associated to a class, it inherits its representation template with all the properties required to reach a sufficient level of representation, helping the operators to understand the information collected from the site and which data are still missing. BIM approach provides a central model with specific standard and protocols for collaboration and data sharing among different specialists, in order to always have an up-to-date representation of the artefact and, at the same time, a track record of the different investigation and interpretation activities.

In the presented case study, the temple of Castor and Pollux and its components were modeled in the Autodesk Revit environment; geometry was mainly derived through a survey campaign carried out in a traditional way (hand measuring and photogrammetry) but supported by an information manager. Although more accurate geometrical representations of the temple were created using usual 3D modelling software, for the purpose of this research we chose to simplify objects focusing more on the management of not-geometrical data and not-tangible knowledge (Figure 3).

Following survey activities have investigated other physical aspects of the artefact such as materials diagnostics and environmental data collection in order to provide information for the later restoring interventions. This information was modeled quite easily in BIM environment by developing classes for each element type (columns, walls, stairs, etc.) and adding as many properties and rules as needed. Although the potentials of BIM parametric features are limited by the uniqueness and context-dependence of each historical artefact, the representation templates generated for each component are still potentially reusable in investigation campaigns of similar artefacts. After modelling the current state of the temple, a historical investigation has been carried out in order to gain useful data from different archives and different configurations of the site have been modeled in accordance to the different historical periods.

In fact, built heritage usually bears with its history a lot of morphology mutations, use changes and even destructions or relocation of its parts. For instance, in this case study, some columns were moved from their original position during time and reused in the medieval age as part of new walls. This aspect deeply increases the complexity of the artefact and of its representation, since its different states need to be represented and visualized. For this purpose, a specific set of properties has been implemented in order to represent if the element is in place or not, the age, the period of realization, and the different phases of the heritage object life it was in (Figure 4).

THE ONTOLOGY-BASED SYSTEM TO INCLUDE SEMANTICS IN HERITAGE REPRESENTATION

Even when accurate data are collected during well-performed survey activities, the Survey Knowledge Base alone is not sufficient to provide a full, comprehensive representation of a built heritage artefact; it is necessary instead to include information about intangible aspects of the artefact such as its evolution during time, its historical, social and technological context, its intended use, materials caves and sources, etc.

This External Knowledge Base is derived from other knowledge domains and, when introduced and made accessible in the proposed model, it can support the actions of interpretation, investigation and intervention. For instance, in the case study of the temple of Castor and Pollux, information related to the historical periods and the pits available along the centuries helped in understanding of materials typology and construction techniques, while social context data provided useful information for the identification of possible uses of spaces. In order to include external knowledge in the artefact model, we have chosen to integrate the BIM environment with a knowledge management system based on ontologies.

An ontology, as defined in the ICT field, is an explicit specification of concepts that includes within the same descriptive system the concepts of a knowledge domain and the relations between them (Gruber 1993); and only recently those tools have been proposed as a method to formalize immaterial knowledge about cultural heritage (Pauwels 2008). In the proposed model, ontologies play the key role of structuring and managing concepts.
related to the intangible knowledge of the artefact and to any kind of data and documentation that can be useful for its interpretation such as external links, textual documents, images, modeled objects, bibliographic references, etc. (Figure 5).

In particular, we chose to rely on an ontology-based model oriented to the representation of entities in terms of three knowledge components defined as meanings, properties and rules. This template has been previously developed and tested by the research group to provide knowledge modelling environment–defined Building Knowledge Modelling–that allows actors to share not only data but also concepts and knowledge attached to any entity involved in new buildings design process (Carrara et al. 2009).

The first component–meanings–provides a domain-dependent description of the entity; properties, instead, represent all the descriptive aspects related to the concerned element (for example, geometrical, physical, historical, technological features); the rules represent the connections among entities, by expressing relationships or reasoning links. MPR model allows a dynamic and
recursive approach to the formalization of knowledge being as effective in the representation of simple entities as in those of greater complexity, focusing the description of concepts on the analysis of their structure, their effective representation and, therefore, referring to a model aimed at improving cooperation among the actors of the investigation process. This structure allows not only to efficiently define and manage the knowledge belonging to the built heritage modeled entities, but also to perform activities of reasoning about the concepts represented.

In the ontology-based system, an inference engine checks the formalized entities and the relationships among them assuring the consistency and the coherence of the information represented in the model. In addition, some data are automatically inferred by executing operations and algorithms on the introduced properties values, providing a complete knowledge base to support actors’ decisions and operations. This is very useful in the archaeological heritage field since many layers usually overlap, many elements are reused with different functions over time and several interpretation inconsistences can emerge at all times.

As well known in information management practice, the availability of large amount of information is not sufficient to assure collaboration among different specialists: integrating all this semantics in a single model could even be counterproductive, since the needed information can be hidden in this complex system of entities and data. For this reason, a semantic filter has been implemented in the modelling environment, letting each actor access, edit and visualize only the information that he/she actually needs in accordance to his/her field of expertise and its tasks in the investigation and conservation process.
In the temple case study, the knowledge base has been created by means of the ontology editor Protege [1], representing each entity through the Meaning-Properties-Rules representation template. The entities definition has been made by combining two approaches:

- Top-down–analyzing the domains of interest of the built heritage field and determining which knowledge and entities are required to represent the artifact.
- Bottom-up–identifying entities and defining, for each class, a set of properties, attributes, and relationships necessary for their definition and representation.

In the presented case study, the ontology-based part of the model allowed to include in the artefact representation other kinds of documentation such as paintings and pictures from the first excavation phase (1940–1950), paintings and drawings representing the heritage site in different times (as the one shown in Figure 4) and ancient texts about the temple and the city of Cori.

In order to connect the BIM environment with the knowledge base, particular accuracy is needed in creating a correspondence between the ontologies structure and the entities network in the BIM environment.
environment. In the presented case study, the coordination between the BIM environment and the knowledge base has been assured by using Revit DB-Link, a plug-in for external databases connections.

Differently from previously knowledge management models, the integration of the ontology-based model with the Building Information Modelling environment allows to integrate the geometrical representation of the artefact the semantics (tangible and intangible knowledge) managed during the different phases of the heritage process. This system comprehensively represents "what is known" of the object and "what is needed to know" for further proceed with the process of investigation, conservation and communication.

CONCLUSIONS

In this paper we have presented knowledge of Modelling approach aimed at enhancing artefacts' accuracy representation and information management in built heritage processes. At its bases, there is the necessity of providing a model that is able to successfully represent all the knowledge needed for a full comprehension of the artefact, including both tangible and intangible aspects such as its geometrical representation and its historical, social, geographical context. For this purpose, the model has been conceived and developed by integrating a BIM environment with a knowledge base developed by means of ontologies.

Similarly to its impact on the AEC sector, Building Information Modelling introduction in the Built Heritage field is able to support the management of the information collected, modeled, used and shared by the different actors involved in the investigation/conservation process. It improves availability and accessibility of all the knowledge related to a historical/archaeological artefact, making easier to interpret its nature, monitor its changes and document each investigation and intervention activity. As a consequence, intervention decisions will be made by relying on the knowledge accurately formalized in the proposed model, supporting the identification of emergency situations, the scheduling of intervention activities and the planning of routine management and maintenance.

NOTE

1 http://protege.stanford.edu

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**IMAGE CREDITS**

Figure 1. Simeone, Davide, Toldo, Ilaria and Cursi, Stefano (2013) Investigation of the Temple of Castor and Pollux in Cori.

Figure 2. Simeone, Davide, Toldo, Ilaria and Cursi, Stefano (2013) Metric survey and historic documentation of the Temple of Castor and Pollux in Cori.

Figure 3. Simeone, Davide, Cursi, Stefano and Toldo, Ilaria (2014) BIM and ontologies for built heritage.

Figure 4. Simeone, Cursi, Stefano and Toldo, Ilaria (2014) Historical stratification represented through BIM.

Figure 5. Simeone, Cursi, Stefano and Toldo, Ilaria (2014) Built Heritage knowledge modeled by means of ontologies

**DAVIDE SIMEONE** holds a PhD and a MSc degrees in Architectural Engineering from Sapienza University of Rome. He has been a visiting scholar at Technion Israel Institute of Technology and at University of California, Berkeley. His research focuses on modelling and simulation of users’ behavior in buildings, Building Information Modelling for built heritage, ontology-based systems for BIM collaborative environments.

**STEFANO CURSI** recently received a degree in Civil Engineering–Architecture at the University “La Sapienza” in Rome where is currently achieving a PhD in Architecture and Urban Planning Engineering. His research interests are oriented toward ontology-based systems, BIM and knowledge management in built heritage.

**ILARIA TOLDO** holds a MSc degree in Architectural Engineering from Sapienza University of Rome. She works as consultant in an international engineering firm, dealing with construction sites planning and management for infrastructural projects. Her research interests focus on the impact of BIM and of digital simulation on architectural design.

**GIANFRANCO CARRARA** is a former full Professor of Building Design at Sapienza University of Rome (1976–2013); director of several national and international scientific projects in the fields of knowledge-based computer assistants for architectural design, hospital design, building design; author of more than 150 scientific publications on knowledge-based support systems for integrated architectural design, and collaborative design.