Systemic Modeling of Amazigh Dwellings. Complementarity Between HBIM and the Cognitive Model

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Abstract. Facing contemporary eco-social changes, preserving the vernacular architectural heritage of traditional Amazigh dwellings represents a crucial challenge to ensuring historical continuity and cultural sustainability in southern Tunisia. As witnesses to a centuries-old territorial identity, these dwellings are now facing both physical and symbolic degradation, thereby threatening their transmission to future generations. The present work proposes a theoretical framework for a hybrid modeling method, grounded in a systemic analysis of Amazigh habitats. The objective of this study is to complement conventional digital heritage modeling techniques, especially Heritage Building Information Modeling (HBIM), with a cognitive model that enables architectural systems modeling by focusing on knowledge construction. In contrast to HBIM, which relies on quantitative data, the cognitive model's emphasis is on intangible dimensions, including collective memory, duality logic (male/female, interior/exterior), and the symbolic and spiritual meaning of place, which are characteristic of Amazigh houses. The cognitive model is based on the systemic triangulation tool and is structured around three axes: (1) the structural axis involves morphological analysis of dwellings (volumes, materials) and synthesis of their spatial organization into a coherent system; (2) the imaginal axis focuses on the interaction between material aspects (stone, earth, wood) and immaterial aspects (symbols, rituals, memory). The proposed workflow follows a sequential structure in which tangible data are first modeled through HBIM, then semantically formalized using an ontology, and finally interpreted through the cognitive model to integrate symbolic and imaginal dimensions. The integration of HBIM with the cognitive model yields a knowledge-based digital representation, enriched with semantic data related to social practices and cultural symbolism. Despite its potential, this approach is encumbered by limitations, including the complexity of modeling abstract concepts and managing cultural interpretations. Ultimately, this hybrid modeling strategy enhances heritage preservation by providing a culturally enriched digital representation that captures both the material and immaterial dimensions essential to the continuity of Amazigh architectural identity.

Keywords: HBIM · Cognitive model · Systemic analysis · Amazigh dwellings

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1 Introduction

The Amazigh villages of southern Tunisia are a distinctive case study in vernacular architecture, illustrating a remarkable degree of adaptation to the local environment and socio-cultural context over the course of several centuries. These dwellings, often carved into rock or nestled in mountainous terrain, demonstrate remarkable constructive ingenuity. The interpretation of traditional houses must be considered in terms of their function as shelters, as well as their role in constituting tangible expressions of Amazigh culture. These expressions reflect collective values, symbolic logics and a way of life that has been adapted to arid climates, rugged topography and limited resources [1–3]. As new modelling tools continue to emerge with the aim of documenting and digitally preserving heritage, approaches such as Heritage Building Information Modelling (HBIM) are being adopted with increasing frequency. However, as HBIM is fundamentally based on quantitative data, its capabilities are inherently limited when attempting to model complex architectural systems, such as Amazigh dwellings, which are deeply rooted in intangible dimensions, including collective memory, ritual, and spatial symbolism [4]. Regardless, current HBIM approaches remain insufficient to represent the symbolic, ritual, and cognitive logics that structure Amazigh dwellings, leaving a methodological gap between geometric documentation and culturally meaningful interpretation.

In this context, the present article aims to develop a hybrid modeling approach that combines HBIM with a cognitive and semantic model [5–7]. These limitations justify the integration of a complementary cognitive model capable of addressing non quantifiable dimensions such as dualities, symbolic orientations, and collective memory which are central to understanding Amazigh domestic space.

The objective of this study is twofold: firstly, to enrich the digital model with cultural and social data, and secondly, to use HBIM as a narrative tool capable of revealing Amazigh thought and worldview. The traditional houses are to be treated as microcosms in this study, with the aim of accounting for their historical and symbolic stratification. The integration of tangible and intangible data is achieved through a systemic and semantic workflow, culminating in the creation of a knowledge model. The process involves the reconstruction and validation of the HBIM model, followed by its conversion into semantic structures through ontology alignment and reasoning. Furthermore, the participation of the local community of Toujane plays a key role in the collection and interpretation of qualitative data, ensuring that cultural knowledge and lived experiences are faithfully represented. These qualitative data are then verified and validated by an expert, guaranteeing both scientific rigor and cultural authenticity. The final result is a knowledge-based digital twin, in which geometric, spatial, and cultural information coexist within a unified model.

The article is structured into four sections: (1) a historical overview of Amazigh civilization is presented, followed by an examination of the characteristics of the village of Toujane and an analysis of the architectural configuration of its dwellings; (2) the methodology is outlined, including a definition of HBIM and a presentation of the cognitive model and its origins, with an in-depth analysis of the imaginal axis rooted in dualist logic; (3) the results are presented in the form of a hybrid approach combining both methods and converting semantic data to later enrich the digital model; (4) a discussion on the contributions and implications of this approach is provided. Finally, limitations and future perspectives are addressed in the conclusion.

2 Toujane: A Living Testimony of Amazigh Architecture

2.1 Characteristics of Amazigh Architecture

Amazigh architecture in southern Tunisia is a subtractive form of architecture, born from an ongoing dialogue between human beings and their natural environment. The mountain villages of the region are distinguished by shared architectural characteristics, ritual practices, beliefs, and traditions. Consequently, they exhibit a consistent spatial organization. In the topographical context of each village, a fortified collective granary is located at an elevated point. Such granaries are designated either a *ksar* (قصر) or a *galaa* (قلعة) which serves as the village's nucleus and oldest structure. This symbolic high point has been identified as a critical refuge for the population during times of danger, as well as a storage location for essential goods. Each family possesses a storage cell (*ghorfa*, غرفة) secured by a personal key an emblem of responsibility and belonging [1, 2, 8].

Traditional oil mills (*maassra*, معصرة) include several functional spaces corresponding to the stages of olive oil production: (1) a grinding area; (2) a pressing area; and (3) a temporary storage zone. In larger installations, draft animals were sometimes employed to facilitate the grinding process. Despite their unassuming exterior, these production spaces assume a pivotal function within the domestic and communal economy of the village [4].

Amazigh spatial thinking is rooted in symbolic dualities at both village and domestic scales structured by gender roles and sacred distinctions. The upper part of the mountain is designated for male use, marked by visible and monumental constructed architecture. It includes two subspaces: (1) profane space: the *ksar*; (2) sacred space: the mosque (*jamaa*, جامع). In contrast, the lower area, reserved for women, features subtractive architecture carved into the rock. It also comprises two subspaces: (1) profane space: traditional houses (*houchs*, حوش); (2) sacred space: mausoleums (*zaouïas*, زاوية), located at the mountain's base spaces of memory and spirituality.

The dualistic logic of the male/female, high/low, visible/carved, profane/sacred nature of this phenomenon has been shown to exceed the confines of a constructive framework, thus becoming an architectural and cultural language that has been codified over the course of centuries and firmly embedded in living collective memory [2]. The spatial configuration of the houses varies according to their architectural form carved, semi-carved, or entirely constructed demonstrating intelligent adaptation to the mountainous site and a deep-rooted Amazigh cultural identity. Each house features a village path in front, organically shaped in accordance with the natural topography. Where the slope is steep, steps are built to ensure integration with the natural ground. Two main hypotheses explain the emergence of these dwellings: one, a medieval origin linked to Arab-Muslim invasions, indicating a strategic and defensive function; the other, an adaptive response to the harsh desert climate, favoring the natural thermal insulation of caves [1, 2].

2.2 The Village of Toujane

Archaeological evidence suggests that the village of Toujane existed for millennia. This is indicated by traces of prehistoric settlement that have been discovered in the vicinity of the oued, near water sources and in a position that offers protection from enemies. The summit of Djebel Dahar, at an elevation of 715 m above sea level, is the highest point in the region. The official foundation of this Amazigh village was in the 12th century, with housing clusters forming the settlement. However, the caves are believed to date back to prehistory, suggesting that they may have been used for defensive purposes during Arab-Muslim invasions. The layout of the structure is horizontal, following the natural topography of the land [1] (for the spatial organization and topographic integration of the settlement, see Fig. 1).

Fig. 1. The village of Toujane.

The village is divided into two main clusters *El Fsil* (الفصيل) and *Taïcha* (طايشة) separated by the central oued, each with its own components (see Fig. 2). *El Fsil* is further subdivided into two areas along the main road: *El Haf* (الحاف) at the top and *Essahfa* (الصحفة). As in all Amazigh ridge villages, these entities share fundamental features: a founding ksar, religious spaces (mosques and mausoleums), traditional oil mills, and dwellings representing four distinct architectural typologies: (1) cave (*ghar*, الغار): the most primitive dwelling form in Toujane minimally arranged rock-carved cavities dating to prehistory; (2) semi-carved *houch* (حوش): present in the old village and on steep slopes, with rooms organized around a central courtyard whether carved or built; (3) constructed *houch*: found in the lower, flatter, more recent parts of the village, with rooms built around a central patio (*wast-eddar*, وسط الدار); (4) vertical-lateral *houch*: located east of the village, where the terrain is nearly flat, optimizing comfort suited to the local climate [1].

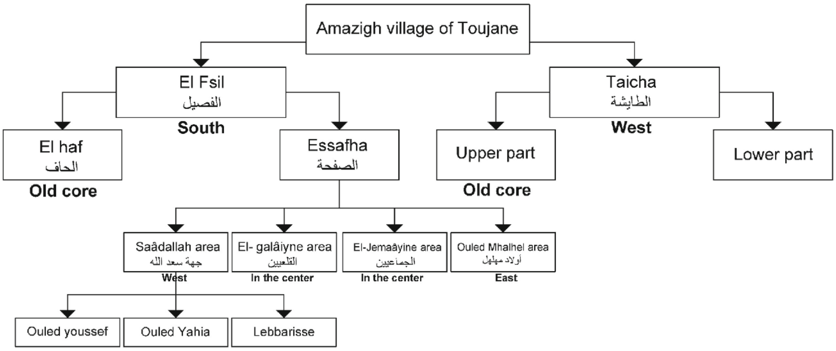

Fig. 2. The different clusters of Toujane [1].

2.3 Architectural Configuration of the Houses

The inherent geometry of caves naturally dictates the use of vaulted roofing in carved spaces, following the curvature of the rock. Conversely, built areas are characterized by flat roofs supported by transverse beams crafted from palm or olive wood. This constructive duality is indicative of innovative responses to spatial and material constraints. The stones extracted during the excavation are then utilized in the construction of the walls. The dry-stacked walls employed in this construction method are characterized by a specific arrangement, wherein larger stones are positioned at the base and smaller stones at the summit. This results in the formation of robust load-bearing walls, utilizing local materials in accordance with traditional construction techniques. Doors are typically crafted from palm or olive wood [1, 2, 4, 9]. In some cases, doors are reinforced with metal strips to stabilize floors or strengthen panels. Finally, walls are coated with lime or gypsum materials derived from local stone offering both protection and aesthetic value, revealing mastery in traditional Amazigh finishing techniques. In semi-carved Amazigh mountain villages, spatial organization follows a sequence of transitions reflecting hierarchical functions and deep symbolic values. The passage from collective village space to individual domestic space occurs through a transitional zone the central courtyard (patio) which serves as the distributive heart of the home. This spatial progression follows a functional scale: from the more public daytime space, through more intimate nighttime areas, to private and symbolic zones. The courtyard acts as a central node, connecting all architectural and social elements of the house [1, 2, 10, 11].

3 Hybrid Approach: HBIM–Cognitive Model

The hybrid workflow adopted in this study is articulated through six structured steps: (1) the acquisition and reconstruction of tangible data using HBIM; (2) the geometric validation of the resulting digital model; (3) the export of the validated model into IFC format to enable semantic processing; (4) the ontological structuring and alignment of IFC entities with the CIDOC-CRM standard; (5) the integration of qualitative and symbolic data derived from the cognitive model; and (6) the reinjection of these enriched semantic attributes into the HBIM environment, ultimately generating a knowledge-based digital twin that synthesizes both material and immaterial dimensions of the architectural system.

3.1 Quantitative Data from HBIM

Heritage Building Information Modeling (HBIM) is a digital modeling approach that involves creating models of built heritage based on accurate surveys (laser scanning, photogrammetry) and structuring the information into parametric objects. The aim of HBIM is to document, preserve, restore, and manage existing buildings, while ensuring the interoperability of the digital model among different stakeholders. It is essential to establish a state of the art of HBIM to define its process by retracing its origin, its stages, its outcomes, and its objectives. First, Murphy et al. [12] define it as a new methodology derived from BIM, which transposes the principles of interoperability and collaboration to existing historical buildings. It is structured in three stages: (1) acquisition of data through laser scanning and photogrammetry, as well as historical and architectural sources; (2) design and development of a parametric object library; (3) modeling the entire heritage studied in the form of a complete and shared digital model. Similarly, Dore et al. [13] propose a digitization process for heritage sites consisting of two major phases: (1) HBIM modeling, based on the creation of a library of parametric objects; (2) integration of these objects into a 3D Geographic Information System (3D GIS), compliant with the CityGML interoperability standard, thus facilitating the storage and exchange of 3D urban models. Barazzetti et al. [14] present a broader vision of HBIM by using augmented and virtual reality based on point clouds and heterogeneous data. Their objective is to make HBIM accessible not only to professionals but also to the general public, for cultural and touristic purposes, using the open Industry Foundation Classes (IFC) format.

Several studies have been conducted on HBIM, integrating new properties and characteristics depending on the user's objective. However, all these studies follow the same steps, regardless of the type of modeling (manual, semi-automatic, or automatic): (1) Acquisition of tangible data; (2) Post-processing; (3) Insertion into a BIM environment and analysis of the various components of the heritage studied, followed by classification into two groups (simple geometry and complex geometry); (4) Creation of the HBIM model; (5) Verification and validation (see Fig. 3) [4].

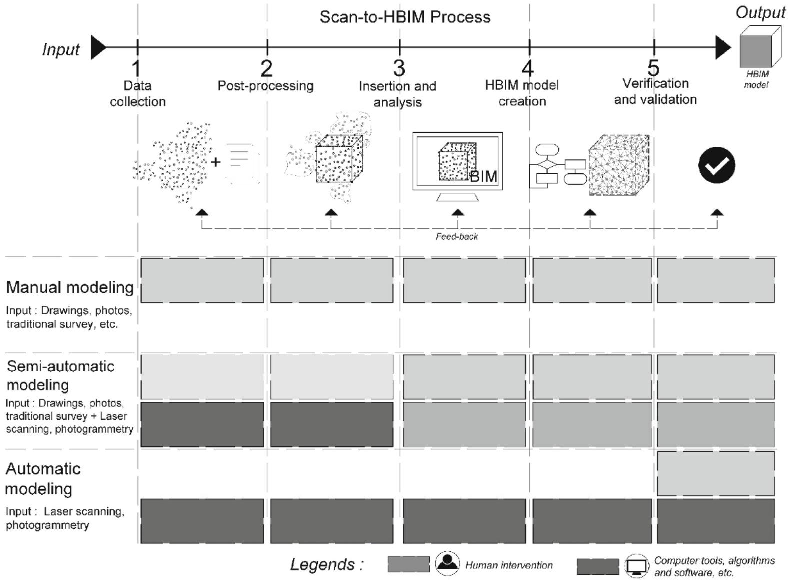

Fig. 3. HBIM steps and modeling types [4].

As part of the HERIT-IT project in Jordan, Cotella et al. [15] consider HBIM a cutting-edge digital tool to highlight successive historical and architectural migrations, both geometrically and semantically. They analyze the Qaqish House, which presents a complex geometry, using a Leica RTC360 TLS terrestrial laser scanner, requiring 56 scans to ensure complete spatial coverage. They then undertake the development of a library of parametric objects, integrating a social dimension into the data included in the modeling process. The digital model thus created is not only used to feed the platform and reproduce the existing geometry, but also to highlight the contributions of HBIM to the understanding of Jordanian cultural heritage, shaped by these migrations. The platform offers various objects related to Jordanian architectural styles, accessible to users, with the possibility for professionals to import their own libraries and download resources. Beyond the geometric complexity addressed, particular attention is paid to the integration of qualitative attributes (origins and cultural influences) to classify families according to their emergence contexts, while reinforcing the identity anchoring of the model, facilitating the tasks of experts and raising awareness among local and international communities. In their article, Simeone et al. [16] reveal the limitations of HBIM in representing and managing non-geometric heritage data. They therefore propose the integration of semantic web technologies to enrich the created model with qualitative data, which allows for improved understanding and interpretation of all aspects of heritage. This leads to a knowledge system supported by a platform that enhances semantic representation and multidisciplinary knowledge management within the conservation process. Their work is structured around three main points: (1) the use of semantic web technologies to represent an intangible dimension within HBIM; (2) the integration of all the knowledge necessary for understanding the heritage object, beyond the geometric data linked to physical components, including historical and contextual data; (3) the encoding and formalization of the social and historical dimension using algorithms, to later integrate them into the digital model.

HBIM proves to be a relevant tool for analyzing the historical stratification of buildings and identifying the cultural influences that shaped them. Thanks to the Scan-to-HBIM method, it is possible to generate an as-built digital model with a high level of geometric detail (LOD 500), capable of accurately reproducing the sometimes irregular and unique forms of heritage buildings. However, this visual richness often comes with a reduced level of information (LOI 200), limited to dimensions, or LOI 300 when data on materials or functional status is added. Although it presents certain limitations particularly in handling intangible data these can be optimally managed by integrating complementary tools, such as the semantic web, which provides a suitable framework for exploring the integration of intangible dimensions within heritage models. In this study, HBIM serves as both a modeling tool and a bridge to a more comprehensive system that includes both measurable and meaningful data [17].

3.2 Qualitative Data from the Cognitive Model

Originally, this cognitive model was proposed and developed by Mounir Dhouib between 2004 and 2013 [6]. It was later tested in the research conducted by members of the *Architecturology and Design Modeling* research team (ERAMC) at the National School of Architecture and Urbanism. The model is primarily inspired by systemic thinking and the theory of complexity. However, it distinguishes itself by integrating an imaginal and poetic dimension into the object of study. Qualitative data relating to symbolic dualities, rituals, and spatial practices were collected through field observations in Toujane, semi-structured interviews with inhabitants, and interpretative readings of ethnographic sources. These data were triangulated through expert validation to ensure cultural accuracy before their integration into the ontological and cognitive modeling phases.

In the context of architectural design studios, a consistent observation has been made: project methodology often suffers from a disconnection between the design and synthesis phases. This disconnection can be seen as a factor that encourages students to seek external references when inspiration is lacking. This situation is frequently the consequence of an omitted step in the design process, resulting in a methodological rupture. This echoes Koestler's observations in *les somnambules* [18] on the history of human thought, where he highlights a long-standing breakdown between reason and imagination, a rupture that hindered scientific progress for fifteen centuries. The goal is therefore to renew the alliance between these two approaches.

The methodology employed in this study is underpinned by systemic triangulation, a theoretical framework that involves the reorganization of its fundamental concepts to align more closely with the unique characteristics of the object of study: (1) the structural axis, combining functional and ontological poles to articulate the use and the nature of the system; (2) the historical axis, derived from the genetic pole, to reconstruct the temporal depth and evolution of the system; (3) the imaginal axis, introduced through a vertical line inspired by Arab-Muslim thought, representing the passage from the material to the spiritual and associated with the imaginaries it evokes (see Fig. 4) [5, 6, 18].

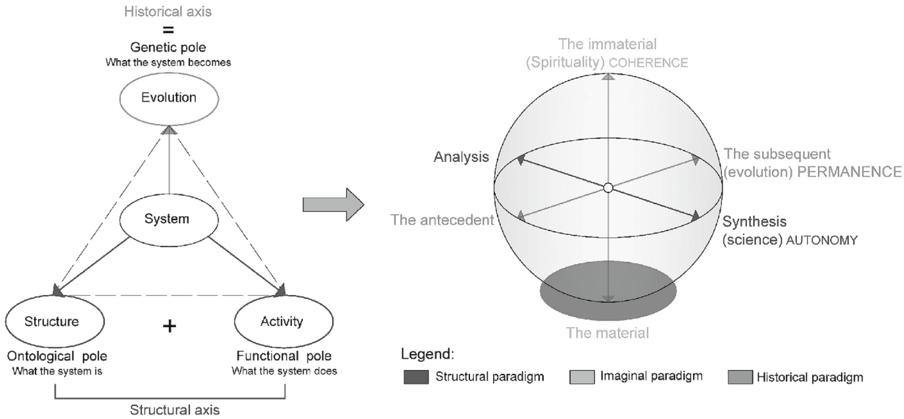

Fig. 4. The cognitive model [19].

According to Mounir Dhouib [6], to truly understand a building in its entirety, it must be approached through the cognitive model, which is structured around *three key paradigms*: (1) The structural paradigm is expressed through science, reality, and reason. It is defined by the axis of analysis and synthesis, and the movements of decomposition and composition. It integrates the dimension of horizontality, highlighting the autonomy of the whole and of the parts; (2) The imaginal paradigm is expressed through religion, poetry, and spirituality. Its axis is defined by the interplay between the material and the immaterial, and its movements are ascension and descent. It incorporates the vertical dimension, aiming for coherence and unity within multiplicity; (3) The historical paradigm is expressed through evolution and memory. Its axis runs from antecedent to emergent, with the movements of innovation and imitation. It integrates the dimension of depth, emphasizing the notion of historical progression [5–7, 20, 21].

The analysis presented in this article focuses exclusively on the imaginal paradigm (see Fig. 5) since the HBIM model already addresses the functional, material, and evolutionary dimensions of the object of study. The main interest of this method lies in its capacity to explore the Amazigh worldview, which reveals the symbolic and poetic dimension of architectural space. This methodological extension allows for a systemic approach that goes beyond materiality and historicity, in order to restore the cultural and immaterial depth of heritage. While HBIM yields geometric entities, material properties, and structural relationships (tangible outputs), the cognitive model produces symbolic spatial hierarchies, cultural meanings, and dualistic logics (intangible outputs). The ontology acts as the mediating layer that integrates both types of knowledge into a unified semantic environment.

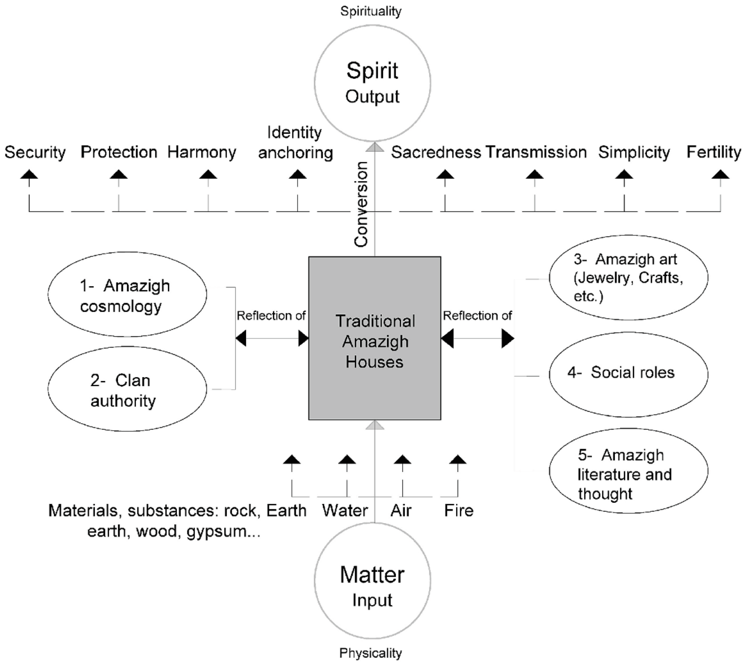

Fig. 5. The imaginal paradigm of Amazigh houses [5].

Applying the cognitive model requires *appropriate tools* for optimal deployment. Several tools are available for studying the structural paradigm, including: (1) the incidence matrix, which focuses on the interactions between elements; (2) component frequency analysis, which identifies patterns and variations; (3) the geometric ordering level, which addresses dimensions and proportions; (4) the physical level of materiality, which considers material quantities through the full/empty ratio and wall thickness; (5) spatial syntax, which reveals the relationship between topological space configuration and social-human behavior [5, 22].

In the context of the imaginal paradigm, the primary tool used is the "black box" [23]. Amazigh architecture is conceived as an opaque box, focusing attention on its inputs, outputs, and interactions with the environment. An abstraction of the material aspect of the dwellings (geometry, structure, internal organization, etc.) is made to concentrate on the immaterial and imaginal dimension (see Fig. 5). The goal is to understand the Amazigh vision of the universe and their belief system, emphasizing the movements from the material (matter) downward to an elevation toward the immaterial (spirit) [5, 6, 20]. Matter, representing the input of the black box, is composed of four fundamental elements (earth, water, air, fire), which interact and transform into the immaterial [18].

The spatial conception in Amazigh architecture is not only governed by functional or climatic logic; it also reflects a profound symbolic thought, structured around fundamental dualities that organize space based on social, cultural, and gendered codes.

In Amazigh vision, a clear distinction is made between gender roles and their associated spatial domains [2, 10, 11, 24]. The domestic space, interior and enclosed, is historically associated with women, while the exterior space agricultural land, oases, markets is reserved for men. This division of space is also reflected in the types of production: women are responsible for domestic crafts (weaving, food processing, care), while men take charge of agricultural production and external trade.

Amazigh houses embody this dual organization. They form the central node of a mythico-ritual system. According to Amazigh belief, the house is a microcosm where the cosmic order is recreated [11]: (1) The front part, exposed to light, is dedicated to living functions; (2) The rear part, darker and more embedded, is used for economic functions (food storage, oil jars, reserves). This opposition between light and dark follows a horizontal axis. A vertical axis adds complexity to this symbolic structure: (1) The right side of the house, generally oriented toward the mountain, is seen as an honor space; (2) The left side, associated with the sea, the lower realm, and the invisible, is considered a dishonor space [2].

These orientations reflect deeply rooted local cosmology. Spatial structuring follows strict social norms, where each subspace has not only a precise function but also a symbolic value. The absence of ornamentation is not a sign of austerity but an intentional form of purification, meant to highlight the functional and symbolic role of each architectural element. In this symbolic logic, the threshold (entrance door, raised slab, or simple passage) becomes a transitional device between different worlds: interior/exterior, male/female, sacred/profane. It acts both as a physical boundary and a symbolic barrier, marking the passage from one social register to another (see Fig. 6) [2, 8, 10, 11]. Other oppositions also structure space, as shown in the following table 1:

Table 1. Symbolic dualities in Amazigh houses.

Pole 1	Pole 2	Meaning
Masculine	Feminine	Sexual polarity, social complementarity
High (mountain, sky)	Low (plain, earth)	Spirituality vs materiality
Dry (summer, fire, sun)	Humid (winter, water, moon)	Natural cycles and elements (e.g., the year divided into two main seasons: *Tagrest* dry season, associated with the masculine; and *Taghrawla* humid season, associated with the feminine)
Right	Left	Beneficial vs potentially harmful (right is positive, active, blessed; left is passive, ambiguous, or sacred)
Cultural (house, village)	Natural (forest, desert)	Civilization vs wilderness
Day	Night	Consciousness vs unconsciousness, visible vs hidden
Order	Chaos	Role of society vs raw natural force

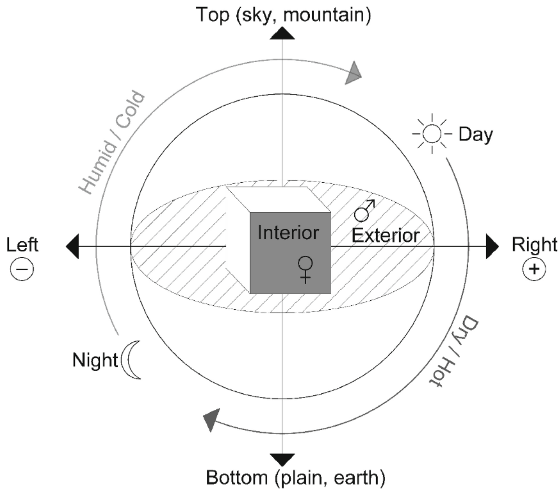

Fig. 6. Symbolic dualities in Amazigh houses.

4 Results: Hybrid Approach

The results follow the methodological sequence previously established: HBIM reconstruction (Steps 1–2), IFC conversion (Step 3), ontological alignment (Step 4), semantic enrichment and reasoning (Step 5), and reintegration of intangible attributes into the digital twin (Step 6).

The Semantic Web is an object-oriented approach aimed at developing an initial system to model the characteristics of built heritage elements and their interrelations. An ontology is a formal representation composed of three key components: (1) classes, which assign specific meanings; (2) properties of each element; (3) rules and relationships, which define the associations between classes (see Fig. 7).

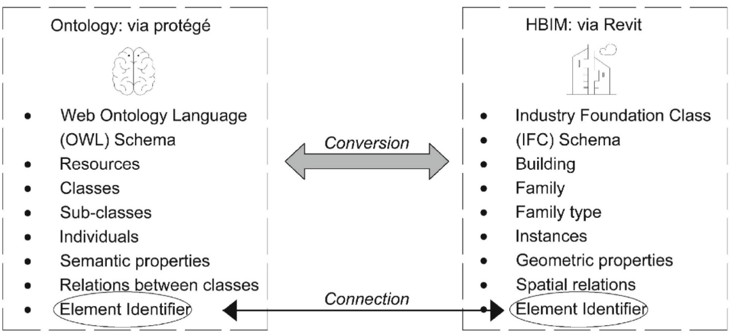

Fig. 7. Comparison of ontology and HBIM [25].

The choice of ontologies depends on the nature of the studied heritage (its style, etc.) and is based on the model provided by the International Committee for Documentation (CIDOC-CRM), a semantic reference model specifically dedicated to heritage [16, 17].

This approach enables the association of intangible data with each element such as symbolic or cultural values and the representation of the links that unite them. Beyond simple data categorization, the ontology structures complex cultural relationships such as symbolic orientations, ritual functions, and dualistic oppositions thus making explicit aspects of Amazigh spatial logic that remain invisible in conventional HBIM models. Within the HBIM framework, this method is distinguished by its advanced Level of Information (LOI 500), surpassing technical data (LOI 300) and historical data (LOI 400), and reaching the highest level of semantic enrichment required for a fine-grained understanding of vernacular spatial logic [17]. The proposed approach is based on the unique identification of each object, associated with a set of specific properties. This enables the establishment of a systematic link between the entities in the HBIM model and the elements of the ontological environment. This correspondence ensures a coherent connection between the two systems using shared labels [25, 26].

Ontology facilitates the establishment of a knowledge model for any case study, while the HBIM process provides the parametric reconstruction of its tangible components. To achieve a semantically enriched model, it is necessary to follow six main steps: (1) creation and validation of the HBIM model is achieved through the reconstruction and verification of the edifice through geometric analysis (cloud-to-mesh distance). This process ensures the accuracy and reliability of the digital mock-up; (2) export of the HBIM model in IFC format is a process that is intended to ensure the systematic and consistent conversion of architectural and heritage elements into an Industry Foundation Classes (IFC) file. The resulting dataset has been standardized and made interoperable, thus allowing seamless integration and data exchange across different platforms and applications; (3) integration of IFC data into the ontology environment is achieved by the importation of the IFC file into Protégé, thereby establishing a bridge between the geometric entities of the HBIM model and the corresponding semantic structures; (4) process of semantic structuring and alignment involves the conversion of IFC data into RDF (Resource Description Framework) format. The following steps are then taken: classes, relationships, and properties are defined and aligned with existing ontological standards, such as CIDOC CRM, with a view to ensuring interoperability with heritage information systems (see the example of the patio study using *protégé* software to integrate semantic data in Fig. 8); (5) generation of the knowledge graph is achieved through the application of semantic reasoning tools, which facilitate the inference of implicit relationships. This process culminates in the creation of a knowledge graph that integrates the spatial, functional and cultural dimensions of the built environment; (6) semantic feedback and model integration process involves the reintroduction of enriched semantic data into the HBIM model, thereby creating a knowledge-based digital twin in which material and immaterial information coexist and interact [17, 25, 26].

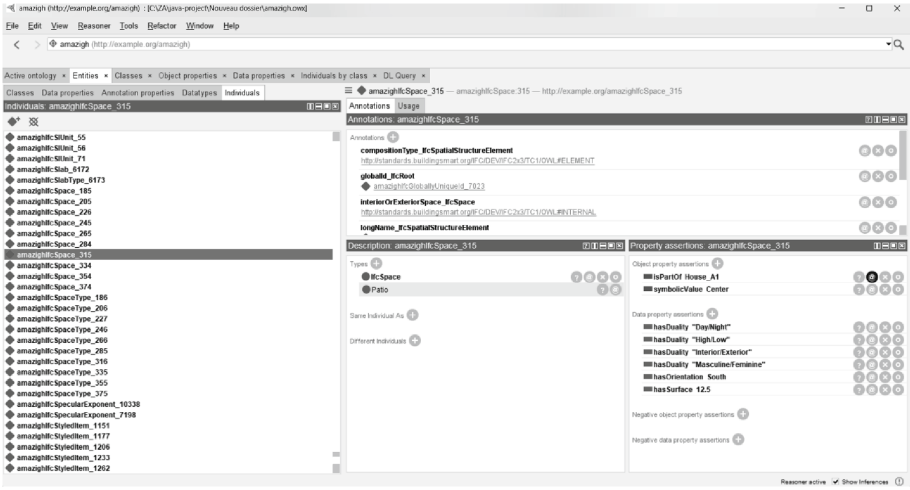

Fig. 8. Representation of the Patio Concept in the Ontology Using Protégé.

Compared to an HBIM-only model, which remains limited to geometric accuracy and material description, the hybrid HBIM ontology cognitive model substantially enhances interpretive depth. It enables the encoding of symbolic values (right/left, high/low), socio-spatial roles, and ritual uses of space, offering a culturally meaningful reconstruction impossible to achieve through HBIM alone.

5 Discussion

Similar integrations of HBIM and semantic frameworks have been explored in Italy, China, and Jordan, where ontologies and enriched HBIM models improved the representation of socio-historical layers and intangible heritage. These international precedents reinforce the external validity of the hybrid approach proposed for Amazigh dwellings. The use of this hybrid approach, which combines two different methods, is based on technological advancements, the principle of interoperability, and a purely systemic method aimed at providing a comprehensive reading of all aspects of the heritage object. This dual intelligibility incorporates both: (1) the material dimension, through the reconstruction of the geometry of the houses, their components, and all quantitative data; (2) the immaterial dimension, through the restitution of know-how, traditions, symbolism, and lived experiences of spaces. This approach has resulted in Amazigh dwellings being regarded as more than mere built structures; rather, they are now regarded as microcosms reflecting the Amazigh worldview. In this perspective, matter is transformed into spirituality through concepts such as security, harmony with the environment, identity anchoring, fertility, and more. Indeed, each architectural element carries symbolic and social qualities that influence the architectural design of traditional houses in the form of foundational dualities (high/low, interior/exterior, male/female) [1, 2, 5]. In practical terms, these dualities guide the segmentation of HBIM components, the assignment of semantic attributes, and the hierarchical organization of spaces within the ontology. They directly influence reasoning rules and the generation of the knowledge graph. Amazigh housing is thus considered a space of dialogue and continuity between nature and culture, between the individual and the collective, and between the tangible and the intangible.

The integration of digital tools goes beyond mere heritage documentation. It spans three temporalities: (1) the past, by restoring the original concepts of the spaces; (2) the present, by integrating recent modifications to the houses through 3D surveys; (3) the future, by enabling better heritage management and facilitating decision-making regarding restoration and conservation work. The combination of these two methods supports the valorization of both tangible and intangible heritage, demonstrating the capacity of digital tools to encompass the full complexity of traditional Amazigh dwellings.

6 Conclusion

This study aims to combine HBIM and the cognitive model to establish a hybrid approach capable of analyzing, deconstructing, and reconstructing Amazigh dwellings, while revealing their socio-symbolic characteristics and the potential for dialogue between memory, lived experience, and digital tools. The methodological contribution of this research lies in the systematic integration of HBIM, ontological structuring, and cognitive interpretation into a unified workflow capable of articulating both measurable materiality and symbolic immateriality (see Fig. 9).

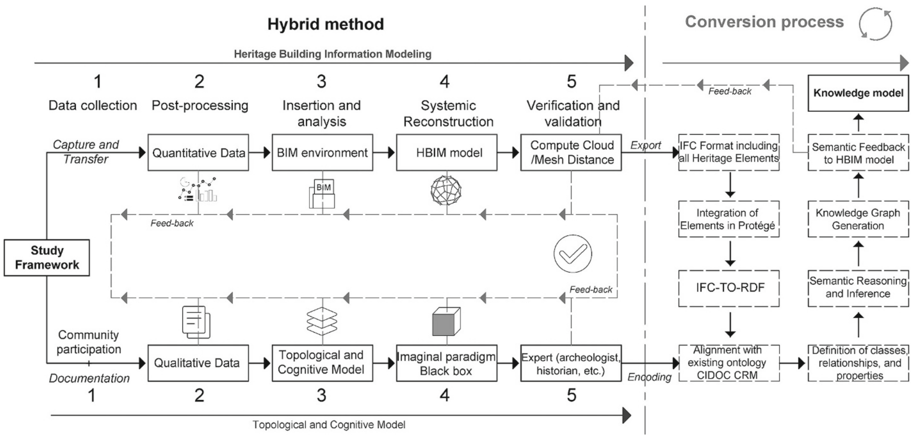

Fig. 9. Summary diagram of the methodology.

Despite the significant technical contributions of this approach to heritage enhancement, it still presents several broader limitations: (1) beyond the absence of automated tools for modeling qualitative data, the main challenge lies in translating cultural, social, and symbolic dimensions into digital form without reducing their meaning. The integration of intangible information such as values, rituals, and memories remains a complex interpretive process that requires interdisciplinary collaboration rather than mere technical refinement; (2) moreover, while HBIM models necessitate continuous updates for effective analysis and restoration planning, the living and evolving nature of heritage particularly that which embodies spirituality, identity, and memory demands a dynamic interpretive framework capable of accommodating social and cultural transformations. This hybrid framework can be generalized to other vernacular architectures whose spatial logics rely on symbolic systems, rituals, or collective memory, providing a robust tool for the preservation of culturally embedded heritage worldwide.

Nevertheless, this method offers promising perspectives in the field of heritage preservation: (1) The reverse-engineering of Amazigh houses has the potential to serve as a model applicable to other vernacular architectures. This approach, combining the technological capabilities of HBIM with the interpretive richness of the cognitive model, enables the generation of more accurate, comprehensive, and culturally respectful representations, mobilizing both digital tools and symbolic thought [4, 5, 20]; (2) It promotes educational and cultural transmission, ensuring historical continuity not only for tangible heritage, but also for Amazigh know-how, arts, and belief systems thus helping to bridge the generational gap and reinforce cultural identity and belonging.

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