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OPEN HBIM: IFC-BASED VIRTUALIZATION OF ARCHITECTURAL HERITAGE

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Abstract

The widespread usage of BIM for the study (HBIM) of architectural heritage (AH) advocates for a critical consideration of how models are built, in relation to information sharing and the need to carry out multiple disciplinary analyses from a single model. This Open HBIM is made possible by shared and standardized ontologies, such as Industry Foundation Classes (IFC). IFC, originally thought for new buildings, is a well-known open standard, currently used as a sharing format in BIM authoring software. The paper proposes a virtualization (model definition) procedure of AH organized in 'semantic segmentation' (modular and systematic decomposition) and 'semantic enrichment' (relation definition and property attribution) entirely based on IFC and open-source software (Blender-Bonsai, Python programming language). The resulting Open HBIM of a simple heritage building appeared as a data rich environment, easily shareable and ready for disciplinary analyses.

Keywords

Semantic segmentation, semantic enrichment, open-source software, ontology, data modeling

1. *Introduction*

Building information modelling (BIM) is currently spreading as a tool for the study of architectural heritage (AH), as Heritage BIM (HBIM). BIM is a technical innovation that allows for centralized storage, management and query of building-related data in a single platform that can be understood as a 3D model with a database attached. The potential and versatility of HBIM for the unification of knowledge about AH are widely recognized (Pocobelli et al., 2018), but the conceptual implications opened by such system on conservation practice are still little explored (Napoleone, 2015).

Some suggestions may come from exploring the relations between the real world and its model (Attenni & Rossi, 2022; Cutarelli, 2024; Di Luggo et al., 2020). Models are increasingly involved in documentation or assessment procedures of AH, but, rather than being used for visualization, the information they convey is assuming a crucial role. However, although the procedures for obtaining raw data are now settled (ICOMOS-ISCARSAH, 2003; MIC, 2010), there is little sharing on virtualization (UNI, 2017a), i.e. the process that makes geometric and informative contents available through a model for further processing. Indeed, the results achievable with the model strongly depend on this process, which far from being automatic (Roman et al., 2023), requires some interpretation (Bianchini et al., 2016) to transform raw data into information (i.e., knowledge) and to make it shareable and, consequently, improvable.

Information is the core of (H)BIM and it should be modelled alongside the geometry, not only for storage purposes, but also to infer data-driven decisions on diagnostics and design (UNI, 2017a). The normative framework (PCM, 2023; UNI, 2017a) advocates for BIM as a process, aiming at the maximum transparency and transferability of information and geometry among operators. This implies that information is clearly structured and modelled according to open formats, independent from specific modelling software, such as Industry Foundation Classes (IFC), developed by buildingSMART International and recognized as an international standard (ISO, 2024). The resulting model is known as Level 3 BIM or open BIM (Antonopoulou & Bryan, 2017). go

A completely IFC-based HBIM has never been attempted but is attractive enough thanks to the worldwide diffusion of IFC as a standard and its open specification, that would make it highly shareable. However, IFC is an ontology for new buildings and to make it suitable for describing AH, its specifications must be compared with the expected features and selected according to the rules commonly accepted in conservation practice. The acceptance of this system impacts on the way a model is created and edited, what can contain, in terms of information and geometry, and which interoperability allows. Starting from a review of the current approaches to HBIM (Section 2) The paper proposes an IFC-based data model for AH (Sections 3.1-3.4), a feasible workflow (Section 3.5) depending on the available tools and an application to a heritage building (Section 4).

2. *State of the art*

HBIM must face geometric and information modelling, which both concur to the Level of Development (UNI, 2017b) of a model and its suitability for the studies on AH (Sbrogiò, 2024). In geometric modelling, two contrasting approaches, i.e., regularized parametric modelling (Rosignoli et al., 2021) or meshing point clouds (Antonopoulou & Bryan, 2017; Attenni et al., 2022), are possible. In the former case, actual elements are traced back to their geometric primitives and to the assembly rules by means of a reverse engineering (Attenni, 2019). This process implies the decomposition of a building according to architectural rules and modules, or 'semantic segmentation' (Bianchini & Potestà, 2021), which is followed by the identification and attribution of properties, or 'semantic enrichment' (Quattrini et al., 2017). The semantic translation, from the real to the digital environment, can be supported by ontologies, which are systems used in computer science to represent in a formal way a field of knowledge, its concepts and their relationships.

Despite contributing to understanding the building process, regularized models, are deemed as oversimplified of historical building features and potentially misleading when interventions are planned (Brumana et al., 2018). In the latter case, point clouds are interpolated with surfaces, either mathematically described (e.g. NURBS) or not (mesh) to obtain a model which are the closest to the actual shape of the element. Although such models are geometrically accurate and do not require forceful adaptation of model items, they are limited to the external surfaces of elements and offer minimum added knowledge on their structure (Attenni et al., 2022).

These different approaches reflect also on how information is made available, i.e. through the geometry (3D model) or its description (database), since also the composition of building elements conveys information by itself. In mesh models information can be associated to model items externally, by tags or placeholders (Antonopoulou & Bryan, 2017) that describe textually things and their relations, whereas in regularized models it can be partially incorporated. Building elements (e.g., columns, arches, walls) are indeed systems that can be decomposed in subsystems (e.g, base and capital of a column, plaster and loadbearing part of a wall) and assembled according to specific rules. Virtualization should consider these rules not only as the 'parametrization' of a model (Scianna et al., 2020), i.e. the set of geometrical rules implemented in a building, but also as its 'granularity' (Stanga, 2023), i.e. the assembly rules of individual components to obtain the final work. However, mainstream BIM software (Revit, ArchiCAD) adopts pre-defined and parametric assembly rules that are suitable for new buildings but are deemed as a limiting factor in case of AH.

To overcome such issue in HBIM, descriptive, custom properties and graphic representation of parameters and rules are opted for, but this limits structuring and sharing of the obtained knowledge, as this is bound to the software in which it was created (see e.g. Lo Turco, Caputo and Fusaro (2016), Mol et al. (2020) for applications on material degradation surveys; Borin et al. (2020) for construction phases).

Information-oriented procedures try to adapt AH ontologies to BIM (Acierno et al., 2017; Cacciotti et al., 2013). However, mainstream software implements only IFC and user-defined procedures are required to map that system into another (Acierno et al., 2017; Maietti et al., 2020; Quattrini et al., 2017; Yang et al., 2019). In such a context, infrasite 3D geographic information systems can implement any preferred ontological scheme while avoiding the constraints of current BIM authoring software (Cutarelli, 2024). Similarly, data can be stored separately from the mesh or parametric model and then linked to it (N. Bruno & Roncella, 2019; Cursi et al., 2022). The database is generally relational and remotely stored, so that it can be accessible from multiple platforms and users, while the model is shared through the IFC standard. Thanks to their structure, these systems also enable inferencing for cause detection and proposal of interventions (Barontini et al., 2022; S. Bruno et al., 2020, 2021). Despite its flexibility, the architecture of these systems is still user-defined, as item properties are. In these applications, information although related, is not embedded in the geometry and it exists separately from this latter.

An attempt to manage information and geometry at the same time was made by Diara and Rinaudo (2018). They proposed an open BIM approach to AH based on parametric open-source software (FreeCAD), that although compatible with IFC and freeing from modelling restrictions (Diara, 2022), is still unsatisfactory, as it advocates for the creation of AH-specific IFC classes (Diara & Rinaudo, 2020), that do not exist in international specifications, thus impairing the validity and the shareability of the model created. IFC-based procedures with an outlook on usage of information and geometry for automatized assessment of have ultimately been proposed for material degradation survey and crack analysis (Zanni, Sbrogiò, et al., 2024; Zanni, Zanchetta, et al., 2024).

2.1 IFC

IFC is a platform-neutral and open file format specification that describes the built environment (building elements, their relationships and their properties) thanks to an object-based system (Li et al., 2016). IFC descriptions are formatted according to EXPRESS language and are stored as plain text in a .ifc file; however, for explanation purposes they can be also graphically represented (EXPRESS-G). Mainstream BIM authoring software (e.g., Revit, ArchiCAD) can only export proprietary formats into .ifc files but two pieces of open-source software, Blender, thanks to the Bonsai plugin, and FreeCAD, can work directly on .ifc files. In addition to being imported by proprietary ones, IFC files can be visualized and queried by free pieces of software such as BIMVision, Solibri and usBimViewer+.

In IFC, building elements with the same function (e.g., walls, slabs, foundations) are grouped into types, called classes. Informatically, these are objects, a collection of items (instances) that allow specific behaviors (attributes) and features (properties). Classes are identified by the Ifc prefix, attributes and properties by italics and predefined property values by small caps; camel case writing is adopted in the nomenclature.

The classes that reproduce physical elements (walls, beams) are all children of an abstract class (IfcObjectDefinition). Logical or physical relations between objects according to assembly rules, hierarchy or composition/decomposition (e.g. the action of connecting a girder and a slab) (Temel & Başağa, 2020) are objectified and stem from *IfcRelationship* (Li et al., 2016). Attributes depend on the relations that each class can create with other classes, so they are shared among the instances of the same class. Properties, which descend from *IfcPropertyDefinition*, describe, through free strings or predefined enumerations, physical or performance-related sets of features of each instance. They are gathered in homogeneous groups, which are distinguished in *Psets* (Property Set), when dealing with qualitative features, and *Qtos* (Quantity Take Off), when dealing with quantitative ones (e.g., area, volume, dimensions). IFC classes exist as digital objects independently from a representation in the 3D space; geometric items are children of IfcGeometricRepresentation, and they need to be related to other classes to give them a shape.

A very rough description of IFC schema, which actually is an object-relational database (Li et al., 2016), is the network presented in Fig. 1. In such a graphical representation, each object or IFC class (colored tags, Fig. 1) contains a list of instances whose behaviors (IFC attributes) do not exist until a relationship (empty small tags, Fig. 1) is created between two instances, creating the key of the relation. Properties are locally attached to single instances, picking them from the predefined lists. A proper database management of this system can be rather challenging using common relational rules to execute queries (Bock & Michaelis, 2019; Li et al., 2016), therefore the preferred way for code-like IFC editing and compiling is Python programming language through the IfcOpenShell library (Krijnen, 2024). This programming language is object-oriented, so it is compatible with IFC structure.

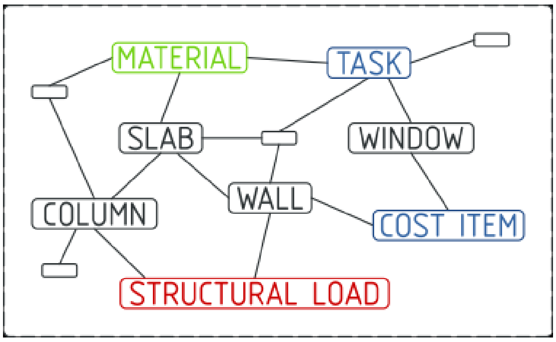

Fig. 1: Representation of an IFC model, the colored tags are the classes, while the small empty ones are the relationships; from https://docs.ifcopenshell.org/

3. Materials and methods

3.1. IFC classification of historical building elements

Cutarelli (2024) compared historical building elements to both Revit Families and IFC classes, showing that there are large overlapping uses (e.g. *IfcCovering* for flooring, plasters and roof coverings) and some deficiencies, especially in curved elements, such as arches and vaults. A similar comparison is shown in Tab. 1, though the intermediate step of Revit Families is omitted: IFC definitions already include many items that are capable to represent historical architecture and its features, including degradations and cracks.

A complex building (e.g., a castle, abbey but also clusters of residential buildings in historical centres) can be described as IfcBuilding with the *Type* attribute set to COMPLEX, instead the 'units' that compose it, from a structural (MIT, 2018) or constructive (Brogiolo & Cagnana, 2013) point of view, are also IfcBuildings, with the *Type*=PARTIAL. This class does not have a specific graphic representation, as it coincides with the assembly of the elements assigned to it. Internal rooms can be represented by the IfcSpace class.

Foundations correspond to the IfcFooting class, and in historical masonry buildings the most suitable *Type* is STRIP_FOOTING. Walls have the obvious representation IfcWall, but in IFC they are split among the storeys of a building; therefore, to represent the concept of 'façade', which is an assembly of walls spanning over multiple levels, the class IfcBuiltSystem (Type=OUTERSHELL) must be chosen. The construction phases of a wall, as stratigraphic contexts (SC) (Brogiolo & Cagnana, 2013), are described by IfcBuildingElementPart. IfcDoor and IfcWindows classes represent the elements (frame, glazing, etc.) that fill an opening which is a separate entity, instance of the IfcVoidingElement class. Finally, niches and chases that may be present in walls, locally weakening them, are represented by the IfcVoidingFeature class, using *Type*=CUTOUT. Lintels over doors and windows are described by IfcBeam (Type=LINTEL).

In historical buildings finishes can be as important as their host elements, since they may have relevant historical, artistic or documental value, conserving traces of the building process, decorations or peculiar craftmanship. In addition, they can be built in a different period than the host and more layers can be superimposed (Brogiolo & Cagnana, 2013). Thus, they are represented separately from the host wall, but in contact with it, so that they are not just a 'layer' of another element but can have an identity on their own. To that end, the class IfcCovering with the *Type* set to CLADDING can be used.

Tab. 1: historical building elements and IFC classes

Building element/feature	**IFC Class (*Type*)**
Building complex	IfcBuilding (COMPLEX)
Building unit	IfcBuilding (PARTIAL)
Internal room	IfcSpace
Wall	IfcWall
Wall part	IfcBuildingElementPart
Foundation	IfcFooting (STRIP_FOOTING)
Facade	IfcBuiltSystem (OUTERSHELL)
Plaster	IfcCovering (CLADDING)
Lintel	IfcBeam (LINTEL)
Window	IfcWindow
Door	IfcDoor
Opening	IfcVoidingElement
Niches / chases	IfcVoidingFeature (CUTOUT)
Joist	IfcBeam (JOIST)
Floor	IfcElementAssembly (DECK)
Floor substructure	IfcSlab (FLOOR)
Flooring	IfcCovering (FLOORING)
Suspended Ceiling	IfcCovering (CEILING)
Rafter/Purlin	IfcMember (RAFTER, PURLIN)
Roof Substructure	IfcRoof/IfcSlab (ROOF)
Vault	IfcRoof (BARREL_ROOF)
Dome	IfcRoof (DOME_ROOF)
Ties	IfcMember (TIEBAR)
Arch	IfcMember (ARCH_SEGMENT), IfcElementAssembly (ARCH)
Crack	IfcVoidingFeature (USERDEFINED) (IfcBuidlingElementProxy)
Degradation	IfcSurfaceFeature (DEFECT) (IfcBuildingElementProxy)

A proper representation of historical timber floor systems should virtualize the loadbearing elements as IfcBeams with *Type* attribute set to JOIST, and the substructure and finishes as respectively IfcSlab (*Type*=FLOOR) and IfcCovering (*Type*=FLOORING). The whole composition of these elements can be described through an instance of IfcElementAssembly (*Type*=DECK). IfcCovering represents also ceilings and faux vaults (*Type*=CEILING) and other decorative elements on a room (e.g. MOLDING, SKIRTINGBOARD).

In roofs, structural elements (rafters and/or purlins) are described by the IfcMember class, with the corresponding *Type* assigned, whereas the substructure of the roof is described by IfcRoof, whit the *Type* assigned according to the overall shape of the roof (e.g., FLAT, GABLE, HIP).

The class IfcRoof can represent also vaults and domes, using the *Type* BARREL_ROOF and DOME_ROOF respectively. Given such definition, other vault shapes (e.g., groin, cloister) can fall within the USERDEFINED *Type*. As IFC describes roofs as 'the covering of a building, that protects it against the effects of weather' (ISO, 2024), one may not consider this class suitable for intermediate floors. Therefore, the class IfcSlab can be also chosen to describe the structural part of a masonry vault, using the USERDEFINED *Type*.

IfcMember is a very versatile class that gathers linear elements that can be loadbearing or not but not necessarily horizontal or vertical. It can be used for representing tie rods (TIEBAR), parts of trusses (CHORD, COLLAR), bracing and supporting elements (BRACE, POST), the suspending elements of non-structural ceilings but also parts of arches (ARCH_SEGMENT). A complete arch is represented by IfcElementAssembly (Type=ARCH) that gathers many IfcMembers.

Cracks and degradations can be respectively represented by *IfcVoidingFeature* and *IfcSurfaceFeature* as they are described as modifications of either the body or a surface of an element, without changing its shape. In addition, IfcSurfaceFeature admits the *Type* DEFECT, that corresponds to material degradation. Both classes can be replaced by IfcBuildingElementProxy, which is a proxy class without a predefined meaning of the building elements it represents; this is the common choice in current HBIM practice (Bolognesi et al., 2023).

3.2. IFC classification of other AH related concepts

Architectural heritage also deals with concepts and items which either are involved in or affect the construction process (e.g. documentation, designer, builders) or are related to discipline-specific analyses. IfcDocumentReference and IfcDocumentInformation respectively capture the reference to the (physical or digital) location and metadata of the documents pertaining to a building. People and organizations are represented by IfcPerson and IfcOrganization, which are both comprised in the general class IfcActor, as human agents involved in the life cycle of a building, from its original design and construction (if they are known), up to the present diagnostic phase (e.g., visual inspections, lab and on-site tests) and the future restoration and maintenance operators.

Time is a key factor in analysing AH and planning its conservation. By means of the archaeological analysis of elevations, each building element can be traced to a unit of work, or task, in the past and each task can be inserted into a sequence, from the past to the present. In IFC this is managed through IfcTask class, that represents the activities for the construction, installation or demolition of the building elements described in Tab. 1, defining their duration and sequence. Specific events (earthquakes, floods, wars) that may trigger a building task (reconstruction, repairs, additions) or induce a response on a building (damage, deterioration) can be described in the IFC schema through the IfcEvent class. These classes are the IFC counterpart of Revit Phase tool, although it is much more than that, as this is a computer readable information and not just a label which can be filtered in a graphical representation.

3.3. IFC representation of relationships in AH

Real-world interactions between building elements are reproduced in the IFC schema as a set of classes for 'objectified relationships'.

There are five general types of relationships: Decomposes, Connects, Assigns, Associates, Declares, Defines, each with a few specifications. In any relationship, two (at least) items are created as respectively the parent (*RelatingEelement*, which receives the relationships) and the child (*RelatedElement*, which creates the relationship). Any child can have only one parent, but parents can have several children; it is also possible to nest relationships, so that children are parents of second-order subordinate elements and so on. The IfcRelDecomposes class expresses the concept of elements being composed of parts that are hierarchically subordinated to the whole. Its specifications are i) IfcRelAggregates, for the assembly of elements (e.g., wall and plaster, joists and slab); ii) IfcRelAdheresToElement, for degradations applied on a surface; iii) IfcRelVoidsElement for the voids generated by openings on a wall. IfcRelConnects expresses a 1:1 physical or logical connectivity between elements and its specifications include the concept of i) enclosing a space (IfcRelSpaceBoundary); ii) being connected structurally (IfcRelConnectsStructural-

Member); iii) being inserted in a building level (ifcRelContainedIn-SpatialStructure, IfcReferencedInSpatialStructure); iv) filling a void in another element (IfcRelFillsElement); v) being a part of temporal sequence (IfcRelSequence).

The remaining relationship classes deal with the link between building elements and external concepts. The IfcRelAssign class describes links between elements and services that use or produce them and IfcRelAssociate to link them to external sources of information. The specification IfcRelAssignToProduct traces tasks to elements, and IfcRelAssignToActor human agents to them. The latter, through IfcRelAssociatesDocuments, link objects to the associated documents.

By using relationships, the attributes of each IFC instance are automatically compiled referring to the instances to which they related. For example, IfcWall has the attribute *HasOpenings* that points to any IfcOpeningElement which is related to it through the IfcRelVoidsElement relationship.

3.4. IFC properties of historical building elements

The properties of building elements are collected in thematic sets called *Psets*. The items each *Pset* collects and the possible *Psets* associated to each class are fixed by ISO (2024), according to the type of building element. The Psets involved in AH are shown in Tab. 2, associated with the context in which they shall be used.

The *Condition* and *EnvironmentalConditions Psets* apply in assessing the state of conservation as they store information respectively about the procedure and results (e.g., date, description, method, frequency) and the environmental requirements for a proper conservation of an element (e.g., humidity, temperature, wind speed, solar radiation).

Tab. 2: Psets related to AH and reference context for their usage

Context	Pset
Assessment of state of conservation	*Condition*
	EnvironmentalCondition
Maintenance	*MaintenanceStrategy*
	MaintenanceTriggerCondition
	RepairOccurrence
Risk assessment	*Risk*
General	*Common*

EnvironmentalConditions can refer to both the internal spaces and the building elements that bound them (plasters and floorings) to define respectively the actual state, updatable in real time through web-connected room sensors (Jouan & Hallot, 2019) and the conservations requirements of the surfaces

MaintenanceStrategy defines the priority and importance of an interventions, whereas *MaintenanceTriggerCondition* gives the thresholds at which maintenance should occur and finally *RepairOccurrence* describes the contents and the date of maintenance activities. These bits of information can help in planning inspections and interventions, supporting the definition of a conservation programme.

The *Pset_Risk* deals with the exposure of each building element to hazard and the associated likelihood of damage and expected consequences in unmitigated and mitigated conditions. The Pset_*Common* stores general information on building elements (loadbearing capacity, external or internal placement, thermal transmittance), with slightly different contents depending on the type of object considered (i.e., wall, slab, etc.).

An overview of IFC ontology applied to AH is shown in Fig. 2 according to EXPRESS-G notation: blue boxes represent the classes, and yellow ones refer to the relationships; the connectors end with the dot, thus indicating the parent-child hierarchy tree of the system. IFC avoids redundancy and so, for example, once the aggregation is established between a building and its storeys and between one of these and the walls inside it, the dependency of the walls from the building is already set. However, each element can create different relationships at the same, although each with a different element: walls can aggregate plasters and be voided by openings as well.

3.5. Workflow

The virtualization procedure of AH, to obtain a IFC-based 3D semantic model, has two main steps: reverse engineering - semantic segmentation and semantic enrichment (Fig. 3). A distinction in the workflow should be made, depending on whether proprietary (Revit, ArchiCAD) or open-source software (Blender-Bonsai, FreeCAD) is used for modelling, but the tools for the consulting and visualization of the final 3D semantic model are the same.

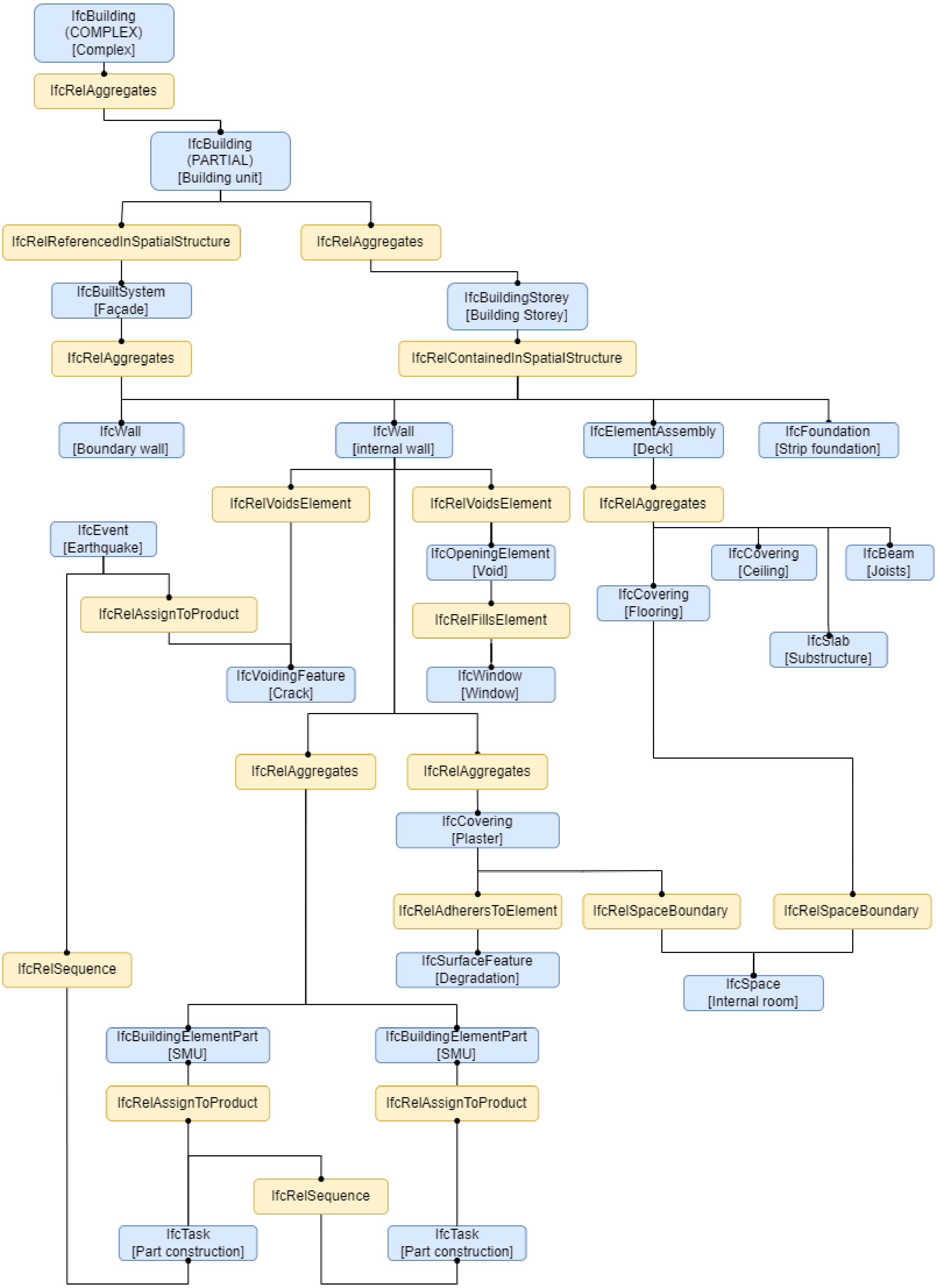

Fig. 2: Overall IFC-based ontological description of AH using EXPRESS-G notation; redundant relationships have been omitted

Starting from the data retrieved in the exploratory studies of AH according to well-known methods and criteria (ICOMOS-ISCARSAH, 2003; MIC, 2010), the 3D model of a building can be recomposed in any modelling software. In this phase, buildings elements are recognized and placed in the model (reverse engineering), and each one is decomposed in its subsystems (semantic segmentation) according to their function and research aims and the relevant information associated (semantic enrichment). The informative content and level of development of a model can be adjusted depending on its aims (e.g., assessment of the existing state, preliminary design) and the disciplinary analyses foreseen (e.g. material deterioration surveys, construction phases, structural safety or energy needs) (Sbrogiò, 2024). It is worth noting that, compared to Revit and ArchiCAD, Blender-Bonsai and FreeCAD free modellers from the restrictions generally encountered in parametric modelling of AH, as these pieces of software allow for freeform modelling and do not include family-based modelling.

Once geometric items are created, they are semantically enriched by assigning them to an IFC class and associating the required IFC properties and relationships, in order to avoid user-defined properties. A Revit- or ArchiCAD-based workflow requires that the model is now exported to .ifc, and then postprocessed as a code through Python and IfcOpenShell to assign the properties and create the relationships. Differently, Blender-Bonsai or FreeCAD directly create .ifc document and can assign any IFC class to any geometric item, so that in-place elements, which are often used in modelling of AH and are generally exported as proxy objects (IfcBuildingElementProxy), are avoided. In addition, Blender-Bonsai and FreeCAD both allow to create and edit IFC properties directly within the modelling environment. However, in both cases, relationships can only be created through the code.

At this point, the 3D model is semantically enriched both from a geometric point of view, so that building elements are represented in its subsystems and components, and informative one, since each item has its meaning, properties and links to other elements. As they are encoded in IFC, geometry, properties and relations can be visualized in free IFC viewers such as Solibri, Navisworsks, usBIMviewer+) which also allow some editing. In addition, .ifc documents can be easily shared, not requiring version compatibility, advanced hardware or storage pas they are plain text files. The enriched model can be imported in disciplinary pieces of software (e.g., for energy or structural analyses) or can be postprocessed, consulted or analysed directly through *IfcOpenShell*, writing an ad hoc code.

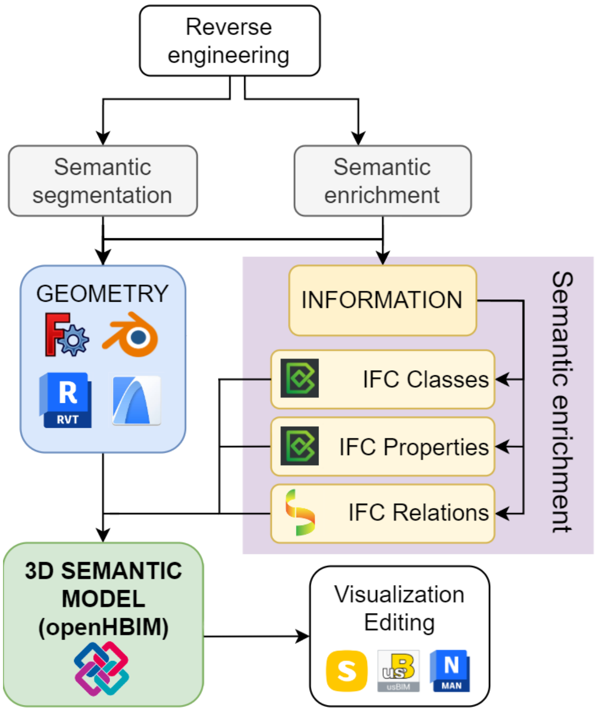

Fig. 3: Workflow for obtaining a open HBIM

4. Case study

The case study is the eastern *barchessa* of Villa Venier-Contarini (Fig. 4), in Mira Taglio (Venice) along the river Brenta. This villa is the seat of the Regional Institute of Venetian Villas (IRVV) since 2001. The complex includes the main mansion, another *barchessa* on the western side of it, a chapel and minor rural annexe, all overlooking a park. The year built of each building is not exactly known: the mansion is firstly mentioned in 1589 whereas the *barchesse* are recorded only since the beginning of the 17th cent., though it cannot be excluded that they have existed even before (Bassi, 1987). Differently from the western one, which was built by the Venier family starting from 1660 as a reception quartier and lavishly frescoed, the eastern *barchessa* kept its agricultural function, except for a room (Hall of Pysche, Fig. 5a) on the ground floor at its western end, which was frescoed by Daniel van der Dyck before 1657 (Conton, 1999).

Starting from the 18th cent., the complex changed the owner often and it was ultimately held, since 1953 to the late 1990s, by Dominican nuns who converted it into a girls' school. To accommodate the school, the nuns altered especially the eastern *barchessa*, using ground rooms as classrooms and the first floor as dormitories. Recently, IRVV converted the grund floor into exhibition spaces, except for the Hall of Psyche, whereas the first floor — dismantled the 20th cent. partitions —, still needs and end use.

Fig. 4: Villa Venier-Contarini, east *barchessa*: view of the south façade from east. The manor house is visible in background.

The eastern *barchessa* reflects architectural models of the late 17th century: the main façade shows a series of elliptical arches framed by doric pilasters and a tall entablature opened by small windows to light the attic (Fig. 4). At the ground floor, the rectangular plan is bipartite, with a series of rooms opening on a porch on the south side (Fig. 5b); at the first floor, the east end hosts the extrados of the faux vault of Hall of Psyche (Fig. 5c) and the rest is a vast attic space, interrupted only by the pilasters that support the roof rafters (Fig. 5d). The steps now visible were added by the nuns, who lowered the original timber floor on the north rooms and rebuilt it in reinforced concrete but were forced to keep the original floor over the porch. The Hall of Psyche is in poor state of conservation due to misuse as a classroom (scratches, traces of nails) and raising damp from the ground. The timber roof was restored in the early 2000s, keeping the original beams, and replacing rotten ends by means of new insertions. The assessment of the current condition was carried out in 2022 through visual inspections and on-site testing, encompassing resistance penetration drill tests on original rafters, infrared thermography and sonic pulse velocity tests[1].

5. Results and discussion

The model of Villa Venier-Contarini was created in Blender (v. 4.2)-Bonsai (v. 0.8.0). Blender has advanced modelling capabilities, that include geometric primitives, Boolean operations on them and free form editing of shapes. This is an advantage with AH, as irregular elements and shapes are possible. By using Bonsai plugin, the software can open and save .ifc files and displays the spatial structure of an IFC model (Fig. 6), showing as a hierarchy tree its decomposition in buildings, building storeys and spaces. For each item of the spatial structure, a list of objects inside is shown. Although a set of commands for creating the most common IFC objects (e.g., walls, slabs) appears as the plugin is enables, any 3D object created in Blender can be assigned to any IFC class (spatial, architectural or structural) thus overcoming the restrictions of the families and the parameters that are generally required for Revit objects. This helps in avoiding the use of 'generic masses' every time special objects are found in Revit, which are translated into the generic IfcBuildingElementProxy class. In addition, users can interact at deeper level with IFC than what is allowed in Revit: for example, windows are obtained in Blender-Bonsai by opening a void in a wall and then adding the frame, while in Revit, the void is automatically created as a window is placed on a wall. Given the features of the software, geometric deviations of building elements (e.g. out-of-plumb, beam sagging) can be directly included in their model. Notwithstanding, the preferred approach was to describe objects with their 'regular' shape and to represent any deviation as a (custom) parameter, so that its evolution can be monitored over time by comparing the model and the observations. Once the class is assigned, a modeler can edit the IFC properties of an item, selecting them from the available Psets; define its materials; assign a construction phase as explained in Section 3.

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[1] The tests were carried out by the students of the course of Restoration and Laboratory 2022-23 held at the University of Padua, as a part of their teaching.

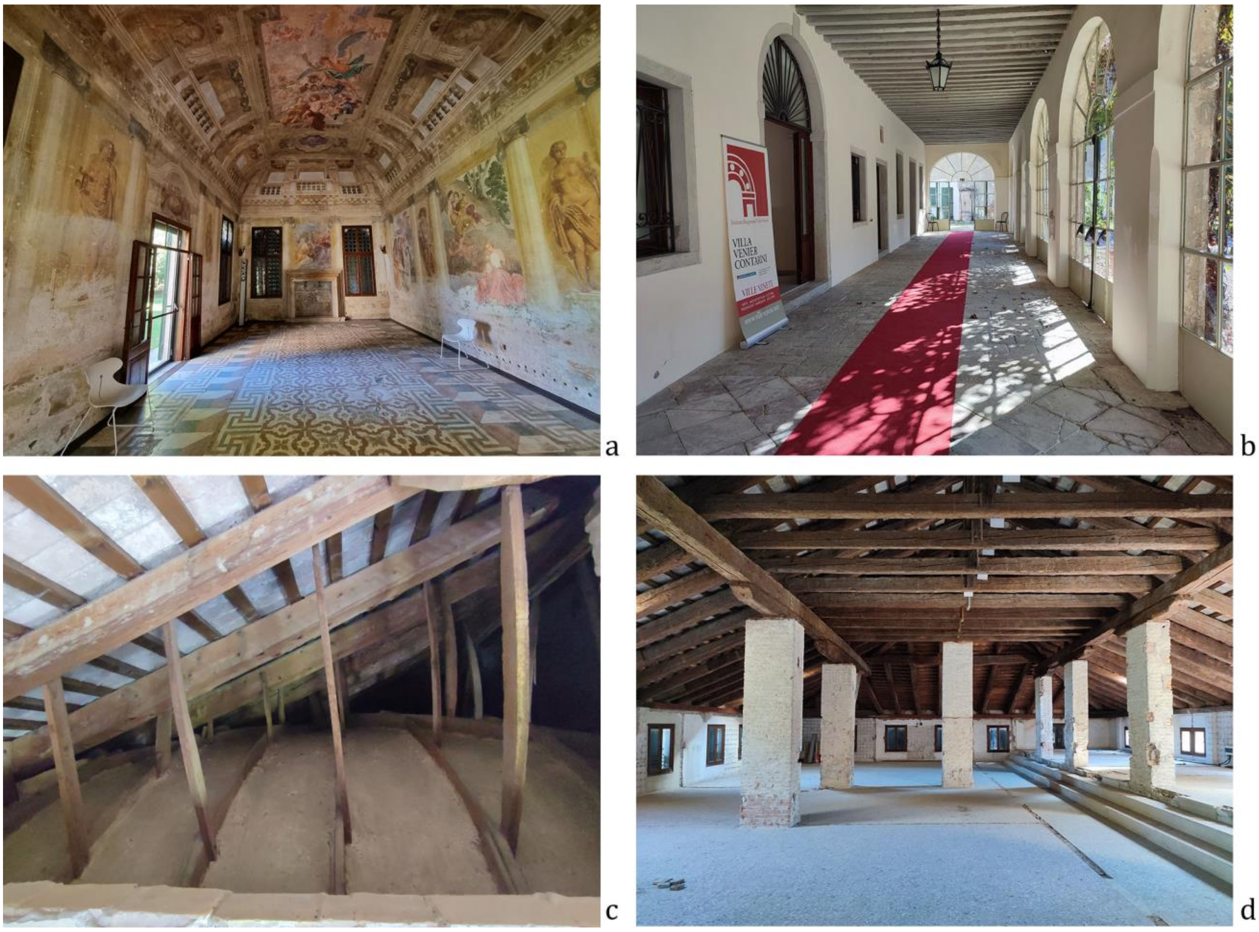
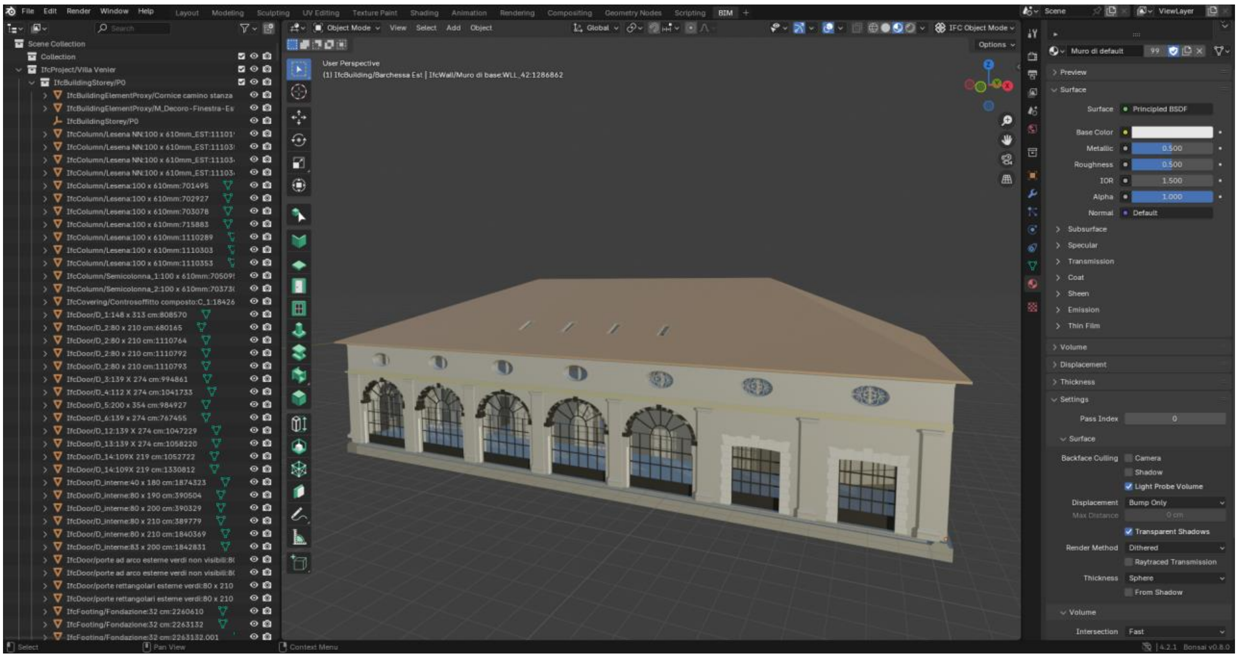


Fig. 5: Villa Venier-Contarini, interior views of the eastern *barchessa*: a) Hall of Psyche; b) porch; c) extrados of the faux vault of the Hall of Psyche; d) first floor, after the demolition of 20th cent. Partitions (north is on the left of the picture)



User Perspective
(1) IfcBuilding/Barchessa Est | IfcWall/Muro di base:WLL_42:1286862

Scene Collection
Collection
IfcProject/Villa Venier
IfcBuildingStorey/P0
IfcBuildingElementProxy/Cornice camino stanza
IfcBuildingElementProxy/M_Decoro-Finestra-Es
IfcBuildingStorey/P0
IfcColumn/Lesena NN:100 x 610mm_EST:11101
IfcColumn/Lesena NN:100 x 610mm_EST:11103
IfcColumn/Lesena NN:100 x 610mm_EST:11103
IfcColumn/Lesena NN:100 x 610mm_EST:11103
IfcColumn/Lesena:100 x 610mm:701495
IfcColumn/Lesena:100 x 610mm:702927
IfcColumn/Lesena:100 x 610mm:703078
IfcColumn/Lesena:100 x 610mm:715883
IfcColumn/Lesena:100 x 610mm:1110289
IfcColumn/Lesena:100 x 610mm:1110303
IfcColumn/Lesena:100 x 610mm:1110353
IfcColumn/Semicolonna_1:100 x 610mm:70509
IfcColumn/Semicolonna_2:100 x 610mm:70373
IfcCovering/Controsoffitto composto:C_1:18426
IfcDoor/D_1:148 x 313 cm:808570
IfcDoor/D_2:80 x 210 cm:680165
IfcDoor/D_2:80 x 210 cm:1110764
IfcDoor/D_2:80 x 210 cm:1110792
IfcDoor/D_2:80 x 210 cm:1110793
IfcDoor/D_3:139 X 274 cm:994861
IfcDoor/D_4:112 X 274 cm:1041733
IfcDoor/D_5:200 x 354 cm:984927
IfcDoor/D_6:139 x 274 cm:767455
IfcDoor/D_12:139 X 274 cm:1047229
IfcDoor/D_13:139 X 274 cm:1058220
IfcDoor/D_14:109X 219 cm:1052722
IfcDoor/D_14:109X 219 cm:1330812
IfcDoor/D_interne:40 x 180 cm:1874323
IfcDoor/D_interne:80 x 190 cm:390504
IfcDoor/D_interne:80 x 200 cm:390329
IfcDoor/D_interne:80 x 210 cm:389779
IfcDoor/D_interne:80 x 210 cm:1840369
IfcDoor/D_interne:83 x 200 cm:1842831
IfcDoor/porte ad arco esterne verdi non visibili:8
IfcDoor/porte ad arco esterne verdi non visibili:8
IfcDoor/porte rettangolari esterne verdi:80 x 210
IfcDoor/porte rettangolari esterne verdi:80 x 210
IfcFooting/Fondazione:32 cm:2260610
IfcFooting/Fondazione:32 cm:2263132
IfcFooting/Fondazione:32 cm:2263132.001

Muro di default 99
Preview
Surface
Surface: Principled BSDF
Base Color
Metallic: 0.500
Roughness: 0.500
IOR: 1.500
Alpha: 1.000
Normal: Default
Subsurface
Specular
Transmission
Coat
Sheen
Emission
Thin Film
Volume
Displacement
Thickness
Settings
Pass Index: 0
Surface
Backface Culling: ☐ Camera
☐ Shadow
☑ Light Probe Volume
Displacement: Bump Only
Max Distance: 0 cm
☑ Transparent Shadows
Render Method: Dithered
☐ Raytraced Transmission
Thickness: Sphere
☐ From Shadow
Volume
Intersection: Fast

Fig. 6: Blender-Bonsai graphical interface: the left pane shows the structure of the IFC project, the right one allows to edit objects, the model is shown in the center

The reverse engineering of Villa Venier-Contarini was helped by having a room on the ground floor and almost all the first floor stripped off the finishes, exposing the structure of building elements. The semantic segmentation was functional to the needs of the programmed disciplinary analyses, which focused on material degradation survey, assessing the timber roof and structural analysis. The segmented IFC model is shown in Fig. 7a and to check for its validity it was also opened in Solibri. The check was passed, as all the elements and their properties were displayed in the validator (Fig. 7b).

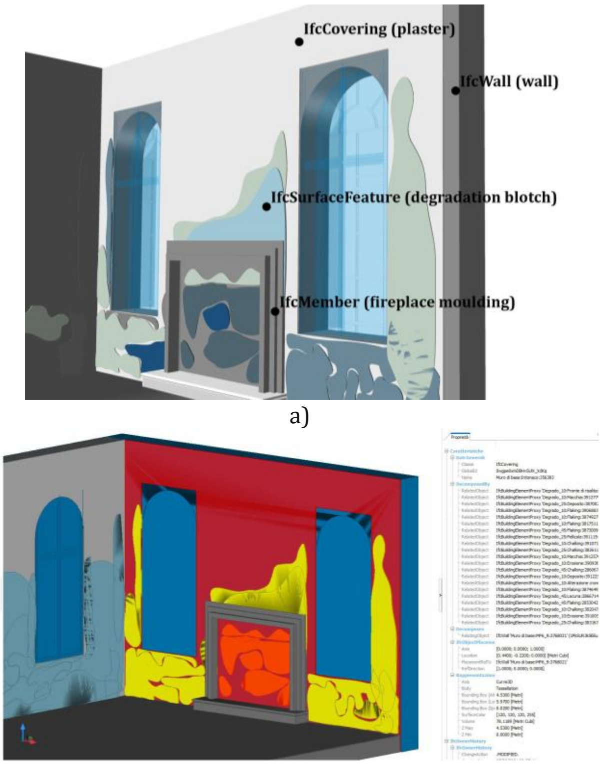
a)

b)

Fig. 7: IFC model: a) in Blender, with objects automatically coloured by class; b) in Solibri model viewer

Masonry strip footings (Fig. 7a) were modelled according to what was observed in a room where the floor had been removed. Brick walls were characterized by the loadbearing capacity and their external or internal position (respectively *LoadBearing* and *IsExternal* properties in *Pset_Common*). They did not show evident distortions, so they were modelled as perfectly vertical and orthogonal. The pillars in the loft were considered as IfcColumns, given their prevalent vertical dimension, and in addition to the properties of the walls, those relative to their condition (*AssessmentCondtion*, *AssementDate*, *AssessmentDescription*) were filled in with the data obtained by the sonic pulse velocity tests. In the Hall of Psyche, finishes were modelled separately from the supporting walls (IfcCovering) given the presence of the frescoes. Where wall finishes had been recently replaced or were generic, they were represented as a layer of the walls, except for the exhibition rooms, whose cladding in gypsum boards was again distinguished from the walls. Similarly, floor finishes, largely altered in the 20th cent. were modelled as layers, distinguishing just the timber or reinforced concrete joists. The timber roof was modelled in its individual elements: battens, rafters, purlins, posts and collars were converted into IfcMembers while principal horizontal beams in IfcBeams; a thin slab (*IfcRoof*) represented the flat clay tiles below the curved ones. Some members, forming trusses, were aggregated as IfcElementAssembly, using the specific tool in Bonsai. The faux vault of the Hall of Psyche was modelled as a thin shell assigned to IfcCovering, layered in the plaster and the slats above, whereas the ribs and the braces were modelled individually as IfcMembers.

In material degradation survey of the Hall, areas with degradation were represented by planar objects superimposed to the finishes (Fig. 8a) and then related to them, which, in turn, were related to their host wall (Fig. 8b).



a)

b)

Fig. 8: Material degradation survey: a) IFC model in Blender-Bonsai with IFC classes shown; b) relationships shown in usBIMViewer+, a plaster (child, in red) is related to its wall (parent, blue) and relates to its degradations (children of the plaster, yellow)

This reproduces the real-world behavior, as degradations affects only the finishes, which are applied on top of the loadbearing part of a wall, and not the structural element itself (Zanni, Sbrogiò, et al., 2024). In order to create relations, the database was firstly queried via Python to get the requested items (i.e., walls or plasters) and then intersecting objects (i.e., plasters or degradations respectively)were selected through IfcOpenShell bounding box[2] selection method (Zanni, Sbrogiò, et al., 2024). Once the relationships are established, custom parameters about the presence of degradation on a finish or a wall are unnecessary as this is already declared through the *RelatedElement* attribute that points to the children degradations. In some model viewers, like usBIMViewer+, hovering onto an element highlights all the related elements (Fig. 7b), displaying the relation. Thus, redundancy is avoided, and information is attached to its specific element: the overall condition of a finish or wall can be a function of the *AssessmentCondition* parameter of each degradation, according to the procedure defined by (Zanni, Sbrogiò, et al., 2024). However, compared to the methodology they presented, in the present model, IfcSurfaceFeature is used for material degradation, instead of IfcBuildingElementProxy.

Considering the assessment of the timber roof, resistance drill test reports were stored in a digital archive and then referenced to their specific element through IfcDocumentReference. The condition of rafters was implemented by compiling the *PSet_Condition* in Blender-Bonsai, and this information can be queried directly within the software (Fig. 9). The parameter related to midspan sagging of timber elements was stored in *PSet_Custom* in Bonsai, although it could be saved in a separate database and then traced back to IFC as a custom property of the *PSet_Condition* through a Python code.

The structural model was extracted from the overall one by selecting only the walls and the slabs of the first floor. The filtered .ifc file was then imported in DIANA (v. 10.9) finite element analysis software that accepted it as an input for the geometry. However, it was necessary to preliminarily pass through FreeCAD to make 3D objects importable in DIANA, as this latter uses a different definition of geometry than Blender (solids instead of surfaces). DIANA's import interface asked whether the reduced or solid geometry had to be imported, and the software rebuilt automatically the geometry described in the IFC database. The classes IfcWall and IfcCovering are imported by the software, whereas IfcStair is discarded. The reduced geometries were imported as shells, but the software automatically decided which external face of the 3D objects determined their shape and position.

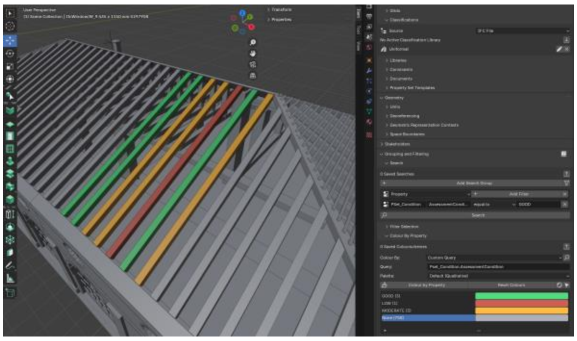
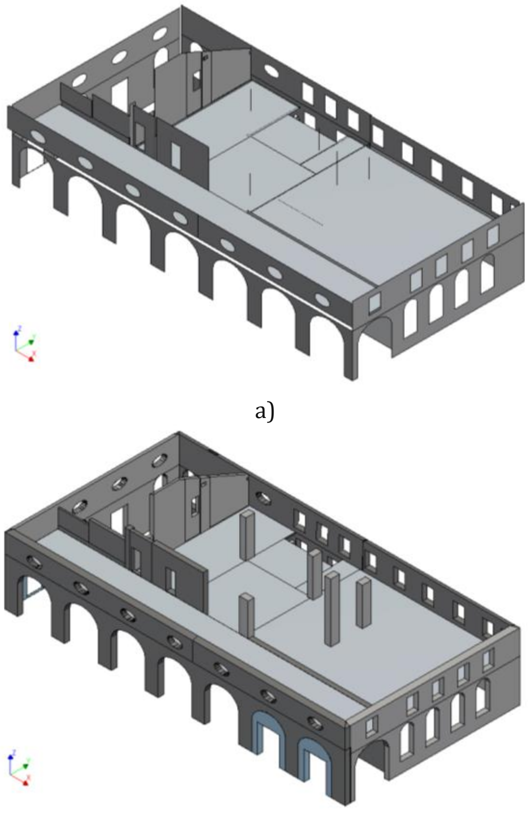


Fig. 9: Querying the *AssessmentCondtion* of *Pset_Condition* of the roof rafters in Blender


a)

b)

Fig. 10: Finite element model in Diana FEA using: a) shells; b) solid elements

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[2] The bounding box is the minimum 3D volume, oriented as the global system of the model, that encloses any IFC object.

Therefore, the shells did not meet at the ends and do not coincide with the mid plane of the walls as it is generally assumed (Fig. 9a) in structural models. Conversely, solid geometry was imported in its correct shape and position (Fig. 9b). However, in this case, overlapping or misalignment which were not evident in Bonsai prevented the direct conversion of the imported geometry into the mesh. Therefore, IFC models which can be ready for structural analysis require a level of accuracy which is still not reached by Bonsai. In both cases, any material property assigned in the modelling phase got lost and had to be inputted manually in DIANA.

6. Conclusions

The paper presents the implementation of an Open HBIM model of a heritage building through IFC ontology in the open-source software Blender with Bonsai plugin. The resulting model is a plain text file with a size of 21.2 Mb, features that make it easy shareable with other operators.

The implementation followed a three-step procedure organized in i) reverse engineering, ii) semantic segmentation, iii) semantic enrichment, to deliver a model ready for disciplinary analyses.

As a generic modeller, Blender managed also complex and non-standard geometries, which were created independently from parametric or typological definitions. Conversely, manual creation and editing of every object increased modelling time.

In the semantic phase, the definition of IFC classes and properties was contextual to 3D modelling, comprising both standard and user-defined properties. Relationship between model objects were created in post processing through Python code, alongside some custom properties. The properties and the relationships added and created in post processing were correctly displayed in a free BIM visualization software, as an example of public and stable access to the information stored in the model. However, programming as a preferential way to interact with the model prevents less experienced users to opt for the proposed system.

The information stored in the IFC model can be the input for disciplinary analyses in a purposely developed code, although most of them require proprietary software to obtain refined results. The test on interoperability of .ifc files with a structural analysis software showed that only the geometry was imported whereas attached information got lost, thus advocating for the development of a parsing code or the usage of IFC structural classes. In addition, different definitions of geometry in the modelling software (collection of faces, solid objects) affected the results of the import, and analysist should be aware of this.

Finally, it is worth noting that the proposed workflow considered only architectural elements whereas mechanical, electrical and plumbing as well as infrastructure systems, which also exist in IFC, were neglected. Conversely, they may be relevant respectively when the energy retrofit is foreseen (but not only) or when historical bridges or roads are considered.

It can be expected that BIM usage will increase in the future, for both new and conservation projects. Therefore, a viable shared solution for experts working in architectural heritage conservation should soon be found on the basis of a broad and open discussion. By adopting open standards such as IFC, heritage models can be shared and reused across public institutions, supporting the idea of an ‘open HBIM’ initiative that fosters collaborative research and conservation on a global scale. However, there is no need to adapt IFC to non-standard heritage elements but rather to ensure a balance between historical accuracy and data management to make this approach really suitable for conservation needs.

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