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# Parametric Modeling and Heritage: A Design Process Sustainable for Restoration

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**Abstract:** Parametric design, algorithmic modeling, generative design, and associative design are only some of the keywords of a work paradigm that is becoming more and more popular, designed to respond to the complexities of contemporary architecture. Most commonly, such an approach is used for new buildings, but when algorithmic design meets heritage building information modeling (HBIM), the process can take on an even greater centrality—flexibility and control go hand-in-hand, ensuring precious tools for the planning of restoration interventions and management projects. This contribution, oriented to expand the use of these strategies to heritage, deals with the theme of parametric modeling of masonry vaults, a structural–architectural feature that in many forms and combinations characterizes most historic buildings. In particular, the connection of BIM software with algorithmic modeling software can allow the 'translation' of complex geometric shapes into elements with full Level of Detail elements (LOD 500) while preserving, at the same time, the algorithmic editing functions. In this paper, it is illustrated as this approach permits the finetuning of the vaults' details, from time to time, based on different survey strategies (e.g., direct measurements, experimental tests, laser scanners, etc.). In other words, using this new connection in real time, architects can design restoration interventions tied to shapes, geometries, and masonry peculiarities that would otherwise be impossible to manage. An updatable virtualization of the actual state of a heritage building thus becomes affordable for the wider public (LOD G). There is also a valuable benefit for the heritage stakeholders in terms of protection of the architectural value and conscious planning in the restoration practice, especially in the museum field.

**Keywords:** COVID-19; building information modeling; heritage; generative modeling; restoration



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## 1. Introduction

### *1.1. Contemporary Challenges in the Built Environment*

The pandemic caused by the new coronavirus and its social effects offered the opportunity to reflect on new methods of teaching and working aimed at ensuring interactions, even if only virtually. This healthcare crisis event constitutes a watershed and some of the topics that will engage each of us on the individual and collective level have already emerged: new forms of sociality and control, work organization, the relationship between public and private, rhythms of everyday life, the rediscovery of new morphological characters of urban space, and soft mobility. Indeed, the outbreak of COVID-19 caused an estimated 900 million people around the world to remain at home in 2020 to prevent the virus from spreading through the workplaces, among them architects, engineers, and designers. For most professionals, it was unfamiliar terrain. Moreover, even if the emergency has passed, it left its mark on the human race and the troubles in terms of safety and social issues are not over yet (e.g., as demonstrated by the recent events of the "zero Covid" revolt in China). Undoubtedly, the human relationship is irreplaceable, but the pandemic has accelerated socio-technical and digital transitions that were already in place, highlighting the influence that new work flows and social networks are earning in the contemporary world. "The current coexistence with Covid-19 is not acceptable" as claimed in a recent interview by Dr. E. Carafoli [1], a professor of the Zurich Polytechnic and member of the University of Padua and of the *Accademia dei Lincei*. In fact, it represents a sort of uneasy armed truce, and it does not exclude the onset of more pathogenic variants of the actual virus or of new ones [2]. The scientific research must respond not only on a medical level but also to the everyday needs that involve work and sociality. The very latest studies in this sense aim to put the virus out of action through the rediscovery of medicines previously applied in other fields and in recent times proven to be effective, no longer pinpoint-targeting the virus, but the human cells. This impressive scientific breakthrough, tracing promising new routes in off-patent drugs that could protect from new variants, was made by the Dr. Teresa Brevini, an Italian researcher at the University of Cambridge [3]. In the 'writers' opinion, the field of historical and museum heritage, and its reactivity to changes and health emergencies, must move in the same direction through strategies of general significance but be scalable in different contexts. For this reason, the creation of databases on historical heritage can be very useful not only for managing the well-known pandemic but also in the perspective of future ones (also involving the cases of seasonal influenza, known as the 'flu', which could be higher now than earlier in the COVID-19 pandemic).

The contribution analyzes the opportunities offered, in terms of the management of projects and resources, by the increasing use of BIM modeling and proposes its implementation though a strategy aimed at the restoration of heritage buildings. Even in the areas of restoration, structural consolidation, and administration of artistic and architectural assets, the current generation must be able to interpret the possibilities offered by the evolution of the aforementioned paradigms. The administrators and technicians who will be called upon to propose interventions will be unable to avoid reflections on the performance of historic buildings in terms of the limitation of different threats connected to natural and human factors, a necessity that must be conciliated also to the goals of safeguarding the artifacts from other risks, for example the ones deriving from seismic events. Furthermore, the way of living in the city has to change, and a review of the accessibility and usability criteria of public buildings, especially the museum-like ones, will be necessary. In particular, Italian architectural heritage tells the stories of the territory through the vital beat of the art cities in which an ancient and stratified past unfolds, mindful of a mystical relationship between nature, tradition, and art. In this regard, the preservation of historical heritage is not only about the safeguarding of our cultural identity but is necessarily related to the central themes of fruition and tourism; transforming the buildings of value from 'postcards' to new reservoirs/containers of spaces represents a mandatory condition to re-establish to tourism its role as an economic and social promoter [4,5]. These purposes require an inclusive and interdisciplinary approach that involves, among others, architecture, design, and engineering in order to ensure the safety and the functionality of the cultural poles through an administrative policy aimed at addressing the new problems of contemporary times and the management of the risks to human health.

Such observations must be associated with the creation of data culture. In fact, for the first time in history, man has more data available than he can manage. This disorientation has distanced the interpretative models from reality itself, the complexity of which can only be investigated through the construction of digital tools that allow the information, emerging from different forms of surveys and monitoring, to be effectively transformed into knowledge.

### *1.2. HBIM and Restoration*

In response to these new needs, this contribution, which is divided into two phases, proposes, through a peculiar approach to building information modeling (BIM), the development of a new parametric strategy to the modeling of different types of masonry vaults. This architectural–structural feature, very common in masonry buildings, makes heritage modeling a cumbersome and long process, with cases in which clusters of masonry vaults with one or two stories combine different heights and spaces inside the buildings

(Figure 1). Given these peculiarities marking the architectural heritage, and in order to assess the safety of their structural subunits, the geometrical and constructive features must be qualified in detail through an inclusive approach to numerical modeling. For this purpose, a single digital medium capable of integrating all the information pertinent to an edifice into a 3D model and to guarantee their exchange between the different 'players' that contribute to the process of protection and management of buildings is required. On this, the innovation of the BIM method, associated at the beginning almost exclusively to the design and construction of new buildings, moves on through an 'H' standing for heritage which, added to the previous acronym, connotes the HBIM applicability to ancient buildings [6,7].

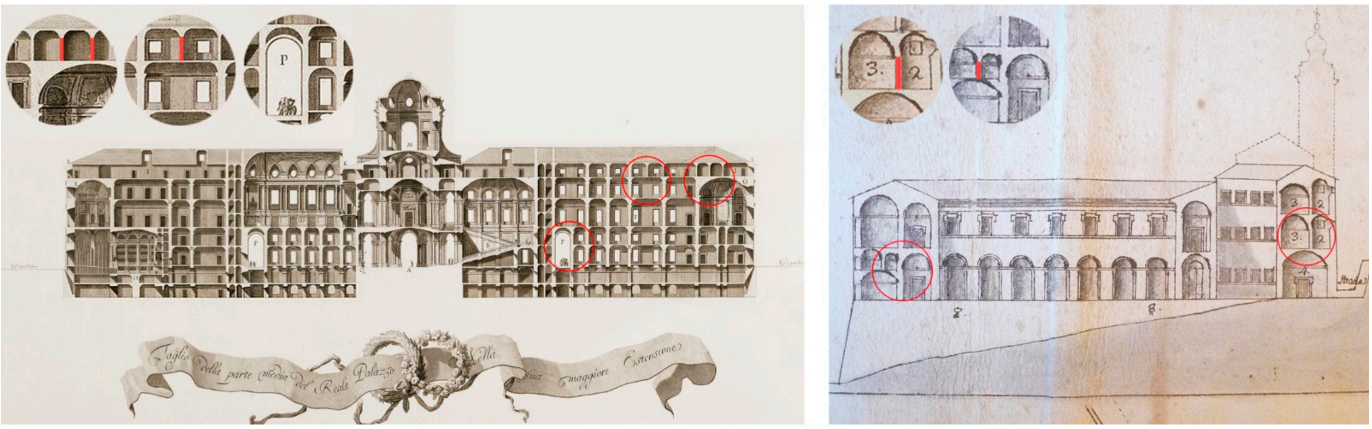

**Figure 1.** Examples of relevant heritage buildings marked by the presence of masonry vaults: on the left, edited transverse section of the Royal Palace of Caserta; Luigi Vanvitelli, Dichiarazione dei Disegni del Reale Palazzo di Caserta. 1756. Regia Stamperia, Napoli; on the right, re-elaboration of the cross-section of Murena Palace; Luigi Vanvitelli. 1739. Archivio di Stato, Perugia.

By analyzing the state-of-the-art in the field, it emerges that this vision is still not widespread in Italy even if the regulatory framework already includes the timeline and modalities of the progressive BIM adoption for public tenders with the 'BIM decree' of the Minister of Infrastructure and Transport, n. 560 of 2017 [8]. So, in a future perspective for Italy, but already at hand in other countries [9], the goal will be to reach an adequate level of adoption of the HBIM method, through a common file format that allows users to combine data and to carry out checks and queries on the models in order to manage the entire life cycle of the constructions. A key issue consists in the opportunity to highlight, through the modeling and simulation of different scenarios, the invisible relationships between architectural space, structural safety, managerial aspects, and preventive restoration interventions.

Speaking of 'serialization' of the design process may seem particularly difficult for the restoration sector, which stands out for being one of the most traditional still to exist. The built heritage is necessarily—and must be—perceived as 'unique'; from churches to residential buildings (structures that are closest to the concept of seriality), and in architecture production, each building will always have unique characteristics compared to others. It therefore does not seem possible to think and speak of 'replicability' of the method to be applied to thousands of case studies, as is what happens for the most classic production chains, or to think of construction as an assembly line that, starting from a prototype, allows replication of the same result for large numbers. However, we must not debate the wrong subject. Indeed, this new frontier concerns the design flow and the approach to heritage management and not the project's 'contents' in terms of cultural and formal values, that from time-to-time it is necessary to adapt to different needs. For example, in this regard, the process is enriched—apart from the specific case study—by 'ritual' cognitive development stages, such as surveys and documentation related to the existing buildings. Including traditional techniques of surveys or the use of innovative investigation technologies, e.g., point cloud techniques and thermography [10,11], the model of a building is in this manner considered as a complex 'box' in which adequate levels of accessibility and performances, which are mostly subordinated to the management of the substructures and the services that imply them, must be ensured. Thus, through the HBIM of the building, the professionals have at their disposal a structured database to analyze in order to plan strategically and, in a quick and flexible way, maintain and possibly intervene on the physical spaces or, at its end use, in both ordinary and emergency conditions. Indeed, thanks to the implementation of a common digital platform based on the interoperability of digital models, affordable in a cloud, it will be possible to design and achieve architectural–structural reconfigurations of the buildings in a more expeditious way compared to traditional timelines. Such an aspect also concerns the architectural re-use standpoint [12,13], since the construction sites can be organized according to the building's function, allowing in some cases to not interrupt the use/activity of places and to improve accessibility and safety requirements. The involvement of local institutions and companies will draw up a process that synergistically integrates the design, construction, and management of the public works, aimed at heritage safeguarding.

## 2. The Model

### *2.1. Parametric Modeling: A Tool for Restoration Design*

The present study proposes an integrated approach for architectural design and modeling useful in restoration purposes. It is in fact an architectural tool extension of computer-aided design programs (CAD), introduced in the last decade by different software houses. Indeed, algorithmic aided design and its opportunities for cultural heritage have been studied in recent years by different research groups via 3D virtual and augmented reality applications [14,15]. Moreover, similar programming approaches are currently used in different fields for blockchain systems [16] (e.g., in economy, concerning BTC value, bitcoin cryptocurrency, crypto trading, and more). In particular, Grasshopper®, a plug-in of the software Rhinoceros®, is a visual programming language that in recent years gained enormous popularity [17], not only for the project design of objects or interiors, but also the architecture, engineering, and construction industry (AEC) noticed all advantages coming from algorithmic aided design (AAD) (Figure 2). Furthermore, numerous applications of the Rhinoceros software can be counted concerning archaeological and museum sites and other applications for the re-use purposes of building complexes [18–20].

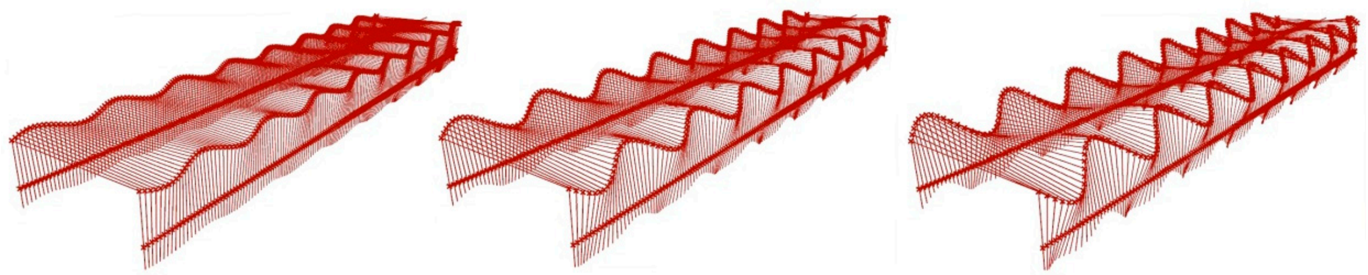

**Figure 2.** Parametrization of the TAV station designed by Santiago Calatrava in Reggio Emila. Three different models can be obtained only by varying the equation of the base curve making up the rooftop; all the geometry reconfigures itself Consequently. Elaborated from Wahbeh W. Parametric Waves_Reggio Emilia Station | Grasshopper, 2016, Youtube.

Anyway, the state-of-the-art about parametric modeling is constantly evolving, especially concerning heritage architectures [14]. It is a type of three-dimensional approach that differs from classical solid modeling because it is based on relating various components/parts of the geometry to each other or with numbers or characteristics that are precisely defined by parameters. This represents an interesting way to structure and create virtual models, as it allows one to chain a series of changes and automate processes every time the designer goes to act on a certain parameter to make a change. A well-structured parametric definition allows one to quickly and accurately make changes to the project or to study in a relatively simple way a series of possibilities or alternatives starting from the numerical (dimensional, quantitative) or formal assumptions assigned. This approach produces generative models, an adjective that refers to the fact that parametric modeling software uses mathematical algorithms to describe the processes and actions that result in three-dimensional models.

Moreover, parametric modeling can represent a tool for restoration design that is 'sustainable' from different perspectives. It is well known that contemporary paradigms are shifting in the construction industry and that there is a planetary call towards carbon neutrality, also involving heritage buildings and the circularity of interventions and materials used [21]. On such topics, the scientific research must cover a connecting role between technical demands and building aesthetics, and the outcomes obtained by different research groups indicate that the parametric approach offers opportunities to improve efficiency and support decision-making in early-stage design, as well as concerning the behavior of existing buildings in terms of seismic vulnerability [21,22]. The authors dare to compare the innovations due to BIM to the 'revolution' from handmade drawing to computer-aided design (CAD). There are lots of similarities in both transitions. Besides learning the new concept of thinking, it is crucial to learn how to implement effective tools, and that is the case of the potential live-link connection with parametric modeling. In particular, as mentioned, Grasshopper allows designers to create complex geometries based on input data or parameters and it is done by visually setting up logical and geometrical formal relationships in an algorithm. Take the example of a masonry tower building and the modeling of its multiple stories. If the extra level will have the same geometry and properties as the lower one, the change of just one parameter can be assumed, e.g., the number of floors. The rest of the structural elements (e.g., columns and beams) will be added automatically based on the previously defined relations. Indeed, instead of manually inserting the individual parts, the algorithm will do all the job leading to a way of working that can be highly efficient and consistent. In addition, already today it is conceivable that eventual HBIM data can be added or updated together with geometry changes devising proper procedures.

Starting from these assumptions, the present contribution focuses on the geometrical–parametrical approach aimed at the generation of digital 'copies' of heritage which will allow the user to grow a large number of benefits for the restoration and reconstruction process. Consequently, the use of parametric design for the prompt modeling of complex arched and vaulted masonry structures could be, in a future perspective, combined with the HBIM approach. Indeed, even if there are few valuable experiences [23,24], according to the authors, only sporadic examples of generative models specially designed for the masonry vaults and the variegated elements that compose them are reported in literature.

### *2.2. Vaults Geometry*

In this section, the first phase of the work is described, consisting of the theorization of a suitable parametric transposition of the vault's geometry based on the critical analysis of historical–iconographical research. It is important to point out that the aim of the successive modeling is to replicate a large variety of masonry vaults starting from the simple typologies and then leading to the complex geometry of groin vaults (also pointed). Those masonry technologies are based on the evolution of a simpler type of structure, the barrel vault, consisting of a semi-cylindrical surface which weighs on lateral bearing walls. A geometric operation to obtain the basic elements constituting the 'composed' vaults, e.g., dormer vault, trough vault etc., consists of dividing the primitive barrel vault with two vertical planes passing through the diagonals of the base edges, thus obtaining four equal two-by-two surfaces: a pair of concave patches of the cylinders and one of masonry 'nails'. The union of four nails conducts the creation of a regular square cross vault and, likewise, the ensemble of four identical concave patches produces a cloister vault with a regular shape [25]. Starting from the relations between the base elements and themselves—

which could also have different sizes—or with barrel vaults, a wide variety of shapes and typologies can be generated. Moreover, the varied 'line-up' is enriched by the peculiarities, such as decorations, and the non-canonical shapes, e.g., irregularities, constructive defects, non-semi-circular arches, etc., are always observable in architectural heritage.

In particular, the present contribution is focused on the aforementioned groin or groined vault (also known as double barrel or cross vault), also achievable in the geometric perspective by the intersection at right angles of two-barrel vaults (sometimes known as cylindrical vaults). The attribute groin refers to the edges between these intersecting vaults. Such a construction element was first exploited by Roman culture, but then fell into relative obscurity in Europe until the resurgence of quality stone buildings brought about by Carolingian and Romanesque architecture. When compared to the barrel vault, the groin vault provides benefits in terms of material economics, structural efficiency, and architectural composition. Indeed, the thrust is concentrated along the groins or arrises (the four diagonal edges where barrel vaults ideally intersect); the vault only needs to be abutted at its four piers/pillars, leaving the opportunity to open windows and doors in the lateral non-bearing walls [26]. Sometimes, the arches of groin vaults are pointed instead of round and both diagonal groins and lateral/transverse arches are usually reinforced with masonry ribs. Anyway, in each configuration, vaulted structures are difficult to construct, especially in modern times, because of the complex geometry—especially of the groins (elliptical if analyzed in cross-section)—which requires great skills. Indeed, the stone blocks must be cut by craftsmen to form a neat arris and the correct masonry texture. This difficulty, in addition to the formwork required to create such constructions, led to—at a later time in history—the rib vault superseding the groin vault as the preferred solution for enclosing a space, e.g., in the Gothic architecture.

These are the necessary premises to point out the basic geometrical assumptions used to devise the proposed modeling strategy (Figure 3).

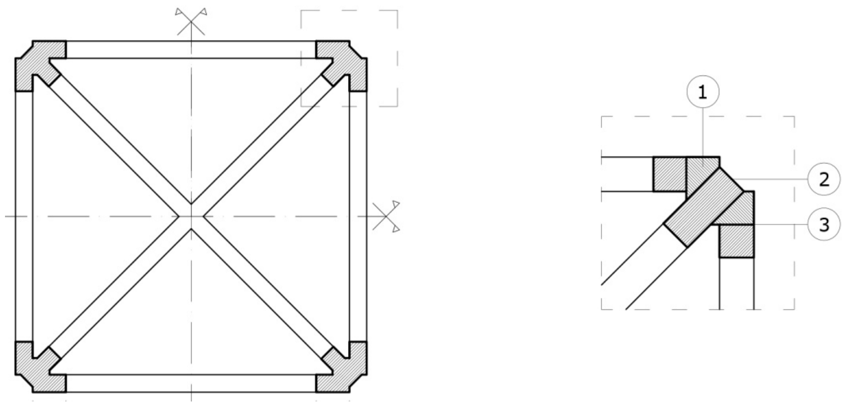


**Figure 3.** Scheme of a ribbed groin vaults intrados. On the right, its abutment is dived into the main geometrical features' imprint—taken into account in the successive modeling—governing the shape: (1) nail; (2) diagonal rib; and (3) lateral rib.

## 2.3. The Innovative Algorithms

In the literature, some examples of parametrization of masonry vaults' geometry are reported with different purposes and methods, but none of them are similar to the one proposed in this contribution in terms of versatility and ease of use [24,27,28]. As introduced in the previous section, the cross and cloister vaults can be geometrically defined essentially as curved two-dimensional surfaces, whose designs are based on the principle of the arch and on few parameters that characterize their shape with multiple possibilities of assembly. Both those structural systems are based on the evolution of the simpler barrel vault, which weighs on the lateral bearing walls. As mentioned, a geometric operation that is suitable to obtain their basic elements is to divide the primitive barrel vault with two vertical planes passing through its diagonals, connecting the base edges. This is the approach implemented in the following 3D parametric models. First, it was necessary to generate the thick barrel vault from the Boolean subtraction of two half-cylinder solids, the largest having an external surface coinciding with the extrados and the smallest instead representing the intrados. Those elements were previously generated, in turn, through extrusion of the two different parametric half-circumferences conveniently modelled as loft surfaces according to the characteristics chosen to be their generative parameters (Figure 3). Finally, the four concave patches of the half-cylinder were obtained, one at a time according to the desired partition, using Boolean subtractions between the solids, resulting this time from the extrusion of two planar surfaces, orthogonal to the horizontal plane, located on the square base's diagonals of the barrel vault. Then, the procedure, expressed though an algorithm, was designed to be entirely governed by only three parameters which regulate the shape, for example of the vault's nails, variable from case to case. In particular, those parameters, pertaining to the base barrel vault, are the distance between piers (i.e., the span's length), the thickness, and the rise of the arches on the borders. It follows that the union of four nails generates the desired groin vault geometry (Figure 4). Moreover, this model ensures that the aforementioned base arch—and consequently the entire vault—changes its curvature as a function of the parameters, also variable, if necessary, independently from one nail to another.

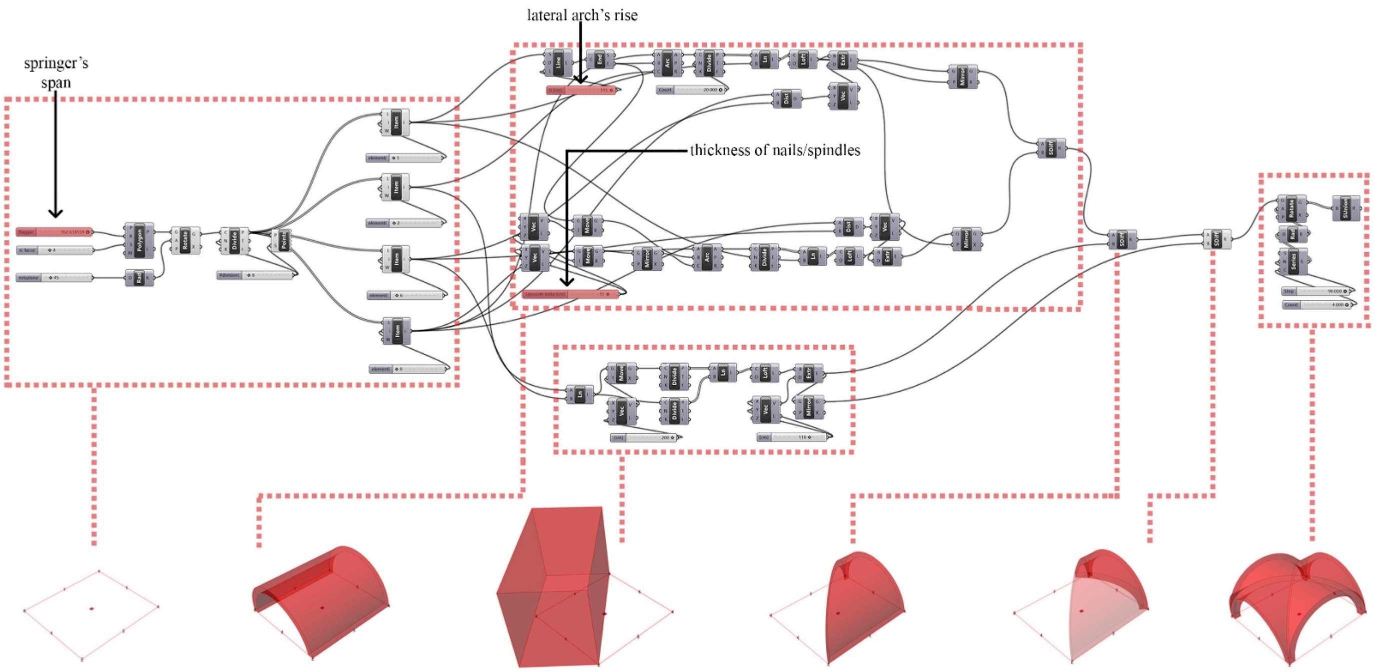


**Figure 4.** Algorithm proposed for the vaults modeling. Example of the phases generating the parametric groin vault. The input parameters that govern the entire shape are marked in red.

In the second step, and in order to model the wider variety of vaults, the proposed procedure has been improved adding new parts to the previous algorithm tied to the modeling of diagonal and lateral masonry ribs. On this, the challenge was to untie these new 3D elements from the previous parameters ensuring, at the same time, the maintenance of all the relationships established between the different elements that influence the vault's shape. This result was reached by interpreting the diagonal ribs in a parametric way, extruding the nail's limit surfaces and then freeing the thickness and width parameters of the latter from the rest of the geometry (Figure 5).

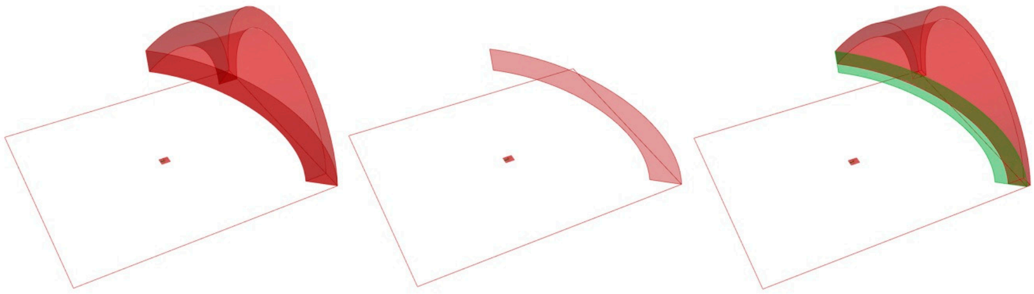

**Figure 5.** Modeling of the diagonal rib profile. From the base nail, the diagonal surface was extracted and then added to the previous geometry, against which is governed by different parameters.

The same procedure, but starting from the lateral arch, was used to obtain the transversal rib. It follows that the final assembly is composed by the union of the mentioned individual parts (arch, rib, etc.) and by nodal zones. The 3D model, designed according to a family of input variables that govern its shape and formal relations, allows the immediate generation of countless geometries, each one reconfigured in agreement to the changes of the input values in a specific range (Figure 6). To resume, the refined algorithm is governed by only seven parameters:

- Three variables consisting in the span between the piers, the rise, and the thickness of the lateral arch making of the nail;
- Four values, one pair for the lateral ribs and another pair for the diagonal ribs, concerning their width and thickness.

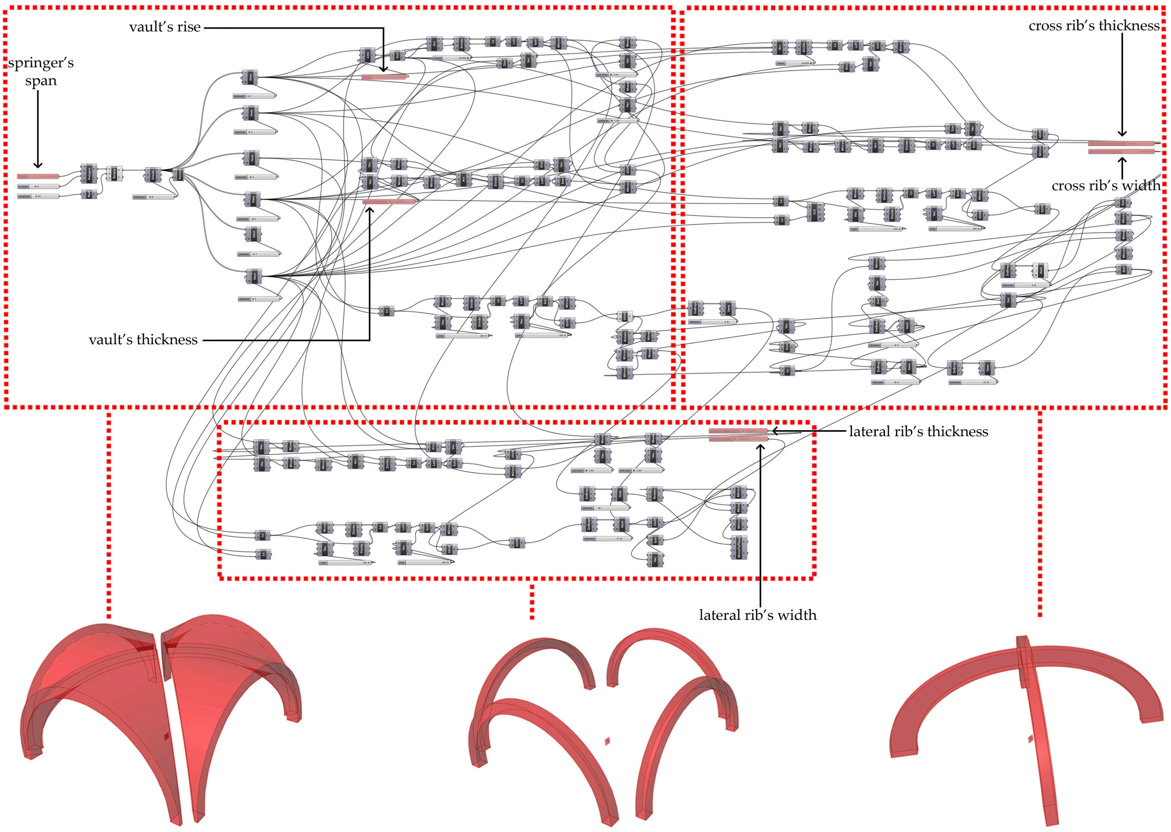


**Figure 6.** Scheme of the final algorithm. The parameters are shown in red and the command's groups are linked to the associated 3D modeling phases. In order: preliminary algorithm for the base elements' generation, with regular or irregular shapes and mixed features, additional commands concerning the side and diagonal stiffening ribs.

Depending on the case under analysis, this approach, through the operations of assembling and merging the different typological elements that can be generated, can be useful to realize an expeditious modeling of different types of vaults, also with irregular geometries.

## 3. Discussion on Results

The proposed approach, especially if combined with the HBIM method, opens opportunities for the design and management of restoration plans; in this section, some perspectives on this are presented. Undoubtedly, the first benefit is in terms of timing and the impact of the numerical modeling of complex heritage buildings. Indeed, the algorithm allows the expeditious modeling of different vaults only by the input of few geometrical and typological data obtainable from different types of surveys. In this way, a good fidelity to real architectural artifacts can be reached, also including irregular geometries (Figure 7). The latter aspect is not secondary in order to properly analyze the influence of geometrical irregularities on the performance of masonry vaults, or in the perspective of their reinforcement. As stated by numerous research groups [29–32], the presence of architectural–structural peculiarities and non-canonical shapes cannot be neglected since they often have penalizing effects regarding the load-bearing capacity of arched structures. Moreover, the 'roster' of masonry vaults replicable in a variety of environments is enlarged by the option to model add-ons to the basic structures, such as the aforementioned masonry ribs (Figure 8). This approach to modeling can be used for successive numerical finite element analysis or in building information modeling, involving different points of view. The HBIM method permits the use of families of objects; each BIM project consists of smaller blocks such as walls, windows, doors, etc., with precise connotations. These families can be very simple, where you just need to change the required information manually, or can be complex and detailed, where the data will be calculated automatically. This is the case of masonry vaults, for which to date no exhausting elements are available to adequately replicate the complexity of the architectural heritage, a mandatory aspect also in terms of its proper survey and documentation.

**Figure 7.** Modeling outcomes with reference to groin vaults' generation. In order, starting from a regular shape—with round arches—the rise and the thickness are changed maintaining the fixed span/springer features; the geometry reconfigures itself consequently.

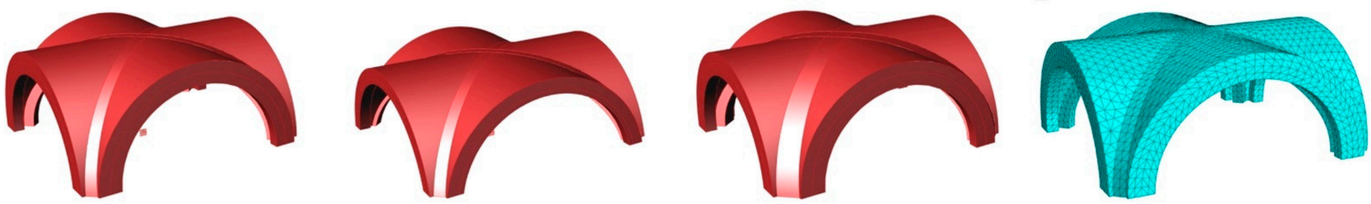

**Figure 8.** Modeling outcomes with reference to the generation of groin vaults with additional elements. As examples, not only the rise and the thickness of the nail composing the vault but also the width of the lateral and diagonal ribs are variable. Then, the desired geometry is suitable to be discretized for finite elements analysis (FEM) or HBIM modeling.

Additionally, it is no small thing to know that through the proposed method, each feature of the modeled vaults can be 'queried' to obtain precious data for the restoration intervention's design. For instance, the intrados' surface—often the object of interventions with composite materials—can be extracted from the model as a non-uniform rational basis spline (NURBS), an accurate mathematical method of representation for curves and surfaces. This opportunity permits the manipulation of the surfaces and to correlate relevant features such as area, curvature, etc., to the design of interventions that are sustainable not only in the economic perspective—by optimizing the project in a sort of parametric form-finding—but also at the architectural standpoint [33–35]. Indeed, they are mathematical representations of 3D geometry, which precisely define any shape from a simple line to a circle, an arc, or a curve, to the most complex solid or surface with free or organic 3D shapes. Thanks to their precision and flexibility, NURBS models can be used in a variety of processes, from illustrations and animations to fabrication. There are a variety of industry standard-based solutions that can swap NURBS geometries; for instance, the entire surfaces with a curvature containing the solid 3D geometry of the vaults can be unrolled/developed in one direction to a planar surface. As a result, customers can use their important geometric models in various engineering modeling, animation, and analysis software [17]. All these discussed aspects were put into practice concerning the seismic assessment and the restoration interventions—still in development—concerning a relevant heritage building, the Murena Palace of Perugia from the 18th century, designed by the prominent architect, Luigi Vanvitelli. The procedure proved that different 3D models of masonry structures such as cross and barrel vaults (with square or rectangular shape and with or without coves) or ribbed vaults can be created only by changing the values of the input parameters deriving from surveys. So, starting by the combination of only five types of architectural elements, also involving an external wall and the internal ones, it was possible to obtain in a short time a finetuned model of a substructure of the building (Figure 9). It must be pointed out that without the proposed algorithms, the modeling process would have required the manual 3D 'sculpting' of about fifteen vaults all different from one another [13,36].

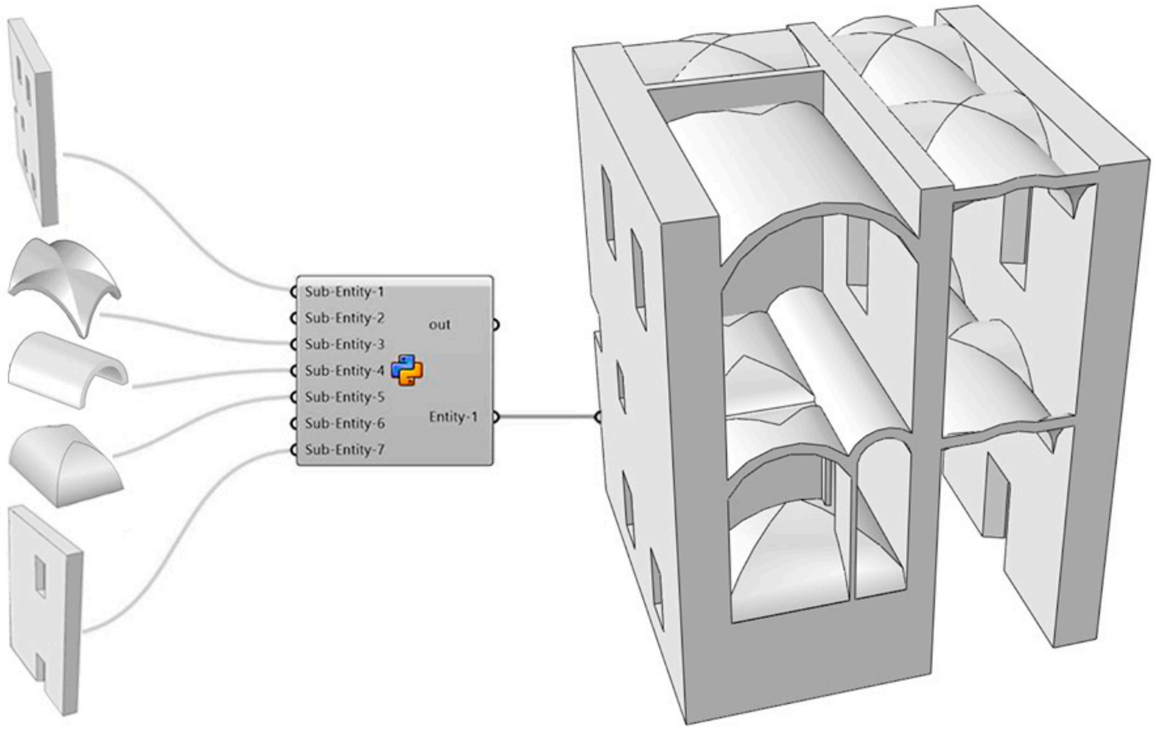


**Figure 9.** Application of the proposed method to the modeling of a real Italian heritage building. The model was used for the parametrization of barrel vaults, cloister vaults, and groin vaults; defined then from time-to-time through the data of different types of surveys. Finally, also including the simple parametrization of two types of walls, an accurate model can be obtained in a short time.

## 4. Theoretical and Practical Implications

Starting from the above-mentioned objectives, the ongoing research aims to reduce the gap between academia and the building industry to address the contemporary challenges in cultural heritage safeguarding. The work identifies in the academic field the common ground to meet different disciplines for the optimization of restoration processes. In particular, concerning the use of natural materials, the proposed approach shows its utility for the design of innovative applications of composites that, not only in terms of strengthening performances but also of aesthetic and cultural impact, are strictly influenced from the shape of masonry elements, always peculiar and irregular [37–39]. The possibility to limit through modeling the times and uncertainties of the different design phases is precisely the main scientific contribution of the present paper. Obviously, and above all, this 'conscious' approach is also appliable on a bigger scale to those heritage buildings that are characterized by very complex features.

Going back to the theoretical perspective, the parametric method is designed and proposed ad hoc for applications on ancient masonry buildings, a great 'plot twist' if considering that the generative modeling has been, until now, mainly used for the ideation of newly built architecture. However, it does not stop here. This contribution introduces the integration of the parametric approach in the HBIM and FEM framework (Figure 10). Indeed, these objectives appear to be topical issues of great importance in the contemporary construction sector on a planetary level. Italy is no exception in this panorama and in 2011, the Built Heritage Information Modeling/Management (BHIMM) project, which involved six research units led by Professor Stefano Della Torre of the Politecnico of Milano, was funded by the Italian Ministry of Education and Merit as a research project of national interest. At the time, the available bibliography on the application of digital information models to historic buildings was very limited. Now, just ten years later, research developments on the subject are nothing short of amazing. BIM applied to cultural heritage have become increasingly attractive for academic research [40]. It is, after all, a real means of technological transfer from the universities to the construction industry. Indeed, research, entrepreneurial, and institutional worlds are looking for an effective strategy to manage the entire life cycle of existing buildings though specific digital tools. The time has now come for a coherent, coordinated, and programmed management of conservation and enhancement activities. According to this approach, the focus of the research is focused not only on the evolution of BIM for heritage buildings, but also in the methods of an easy interchange between the various specialized software that can be used in the conservation and design processes. Additionally, it is not just an idea but is already a reality through 'tailor made' scripting languages such as VB and C# to help develop custom codes (e.g., the Python component is integrated as showed in Figure 9). This actual limitation of the algorithms is hoped to be totally solved in the near future, since it is already within reach [41]. Indeed, linking the architectural models of heritage buildings to structural analyses and BIM environments enables designers to include analyses of complex objects within the same cloud. A benchmark using the tool on a museum heritage building, as described in the previous section, proved its utility for a security assessment and collaboration between disciplines. Now, to better clarify the results and their discussion, two crucial questions must be addressed.

The first: why use Rhino and Grasshopper inside other software? First of all, Grasshopper allows users to unlock the full power of parametric design. Tasks that were impossible to perform in other software are now achievable. Designers can automate repetitive design tasks, build customized workflows, and handle complex geometries. Basically, the parametric design expends significant software capabilities and, instead of waiting for the next software update/patch or new release, it is possible to develop personal features. The second question: why work with Grasshopper in BIM? Grasshopper allows technicians to create geometries based on input data (parameters). This can be done by visually setting up logical and formal relationships through an algorithm, as described in Section 2.1. Then, instead of manually inserting the individual parts of the architecture, all BIM data can be added or updated together and will automatically follow the geometry changes. This way of working can be highly efficient and consistent, thus ensuring a modeling process that can be significantly faster than a traditional one, together with assured accuracy. For example, in terms of the design of restoration interventions, the live link of Grasshopper with other software allows the manipulation of native objects. This functionality is crucial to the great success of these types of connections, since together and according to the geometry, various reinforcements can be created through the algorithms. All data that define interventions in BIM or FEM software can be manipulated starting from the geometry level (e.g., including reinforcements in tapered or curved shapes).

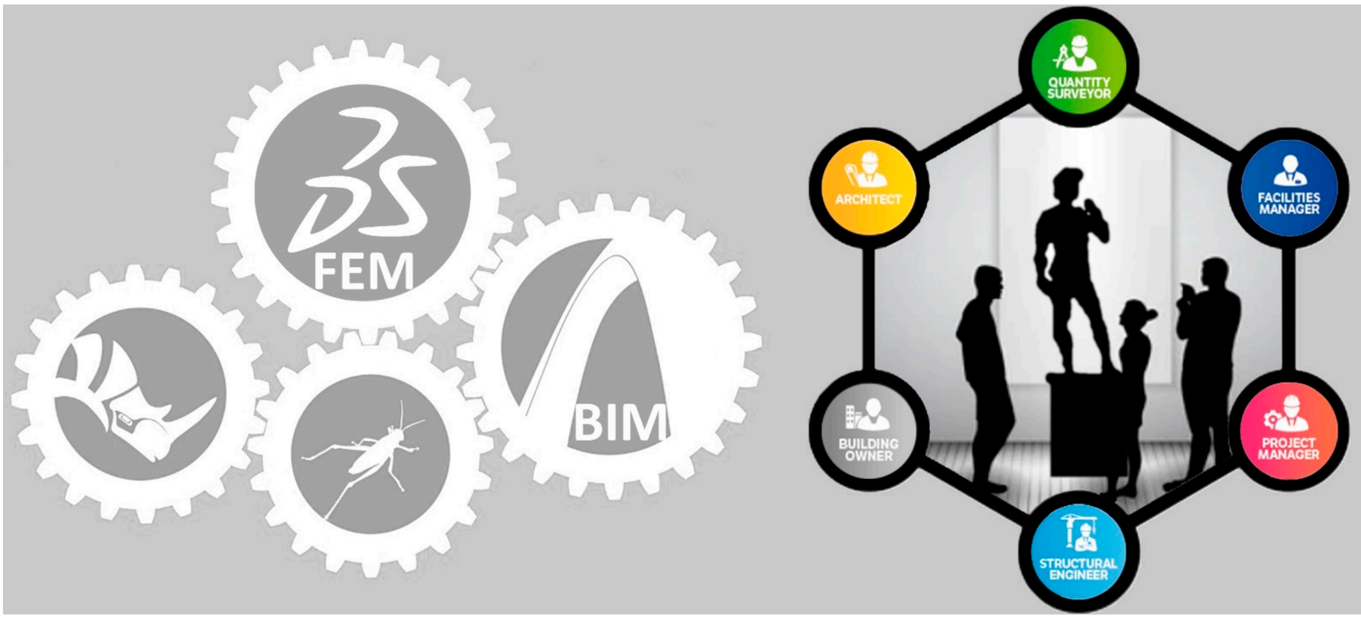


**Figure 10.** The first diagram reports the symbols of the connected tools to develop a common strategy, systematize resources and competencies, and set out schedules and intervention priorities in heritage museum sites (as summarized in the second mind map).

These objectives represent mandatory conditions for the efficient management of museum sites. The strategy, in a future perspective, is to refine an 'all-in-one' tool that can be provided to technicians and stakeholders and which is properly structured (too many channels will mean information is too disparate and will become lost and ineffective). Finally, the last aspect will be to move the creative and management process entirely to the cloud, in favor of a real interoperability between different competencies; different platforms already allow for the free storing and sharing of information in a secure way.

## 5. Conclusions

The management of heritage architecture requires increasingly efficient, simple, and shareable tools, aimed at its documentation and safeguarding. In this environment, with reference to the masonry vaults, a suitable procedure was developed to transform the survey data into parameterized objects. For this purpose, two algorithms were developed in Grasshopper to allow for an approach to vault modeling that could be more sustainable in terms of replication of their architectural features, the design of interventions aimed at their safeguarding, and time and efforts tied to their 3D crafting. In particular, on the basis of the literature analysed regarding the construction techniques and the typological characterization of masonry vaults in heritage, the development of the procedure was divided into two phases:

(1) A first generative algorithm was created to replicate the base elements (e.g., the nails) that make up simple and composed vaults;

(2) The previous algorithm was enhanced with the opportunity to model ribs, and transverse arches, elements often marking these masonry structures.

The model proves to be versatile for the fast realization of accurate 3D solids that, by varying few input parameters, can be easily—and instantly—reconfigured in order to replicate the irregular geometries of real case studies. An important result when considering that the so-called families for buildings and other models in HBIM software are actually not enough to replicate the complexity of heritage buildings.

So, in a future perspective, the integration of the proposed design tool with the latter method could guarantee a two-way transformation of the objects between the modeling environment and the HBIM software, thus having a database always updated according to the needs (e.g., after seismic events). As a result, any changes to the model made in a generative algorithm can be automatically made in the HBIM model and vice versa—an unprecedent 'sustainable' opportunity for technicians and stakeholders for the design of eventual restoration plans and, in general, the study and management of the entire life cycle of heritage architectures [41–43]. It follows that, for restoration purposes and for museum reconversions, the tools proposed will allow the mapping out of the development of contents and ideas, permitting each team member to understand what stage each project is at. In architectural practice, communication and file sharing are funneled through as few avenues as possible. This will minimize confusion and miscommunication and enhance productivity, also making emergency situations more 'sustainable'.

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