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Definition of a Risk Assessment Model within a European Interoperable Database Platform (EID) for Cultural Heritage

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Abstract

Nowadays, the topics related both to the safeguard and the valorization of cultural heritage and cultural assets are getting more attention in the political agenda. Innovative approaches to implement both the risk analysis and the resilience assessment are ever more required. This paper illustrates an original approach, concerning the development of a risk assessment model for cultural assets, with reference to fire, earthquake and flood. The proposed model includes specific evaluation tools, that are based on parameters and indicators related to the factors of hazard and vulnerability for the three considered types of risk. The multi-dimensional set of indicators is used to get synthetics indices, through a multicriteria approach. Furthermore, this evaluation is supported by specific questionnaires to include in the assessment model the opinion of different experts and stakeholders to introduce the indicators weights.
The results of this model are represented by specific evaluation tools which can be implemented in the risk assessment of cultural assets in different specific situations.

Keywords: cultural heritage; risk analysis; evaluation model; multicriteria analysis; architecture; indicators and indices

1. Introduction

The exposure of cultural heritage to extreme events caused both by natural events and man-made actions strongly increased in the last 20 years. Floods, fires, earthquake, volcano eruptions, wars and events related to climate change are arrecating irreparable damages to cultural heritage, including the loss of movable and immovable cultural assets. Despite different procedures related to the disaster management cycle are discussed both at governance and operative levels to protect and safeguard cultural heritage, no general and standardised procedures have been adopted yet.
Following the principle reported by Tabaroff J. [1], "the harm to cultural heritage further increases in the absence of adequate risk estimation, evaluation and minimization measures", this paper presents the work developed by the authors within the European research project named ResCult[1].
The ResCult project[1] [2,3] aimed at building an innovative European Interoperable Database platform (EID) to support decision makers, technicians, emergency operators, agencies and other relevant entities in the prevention and mitigation of the risk of cultural heritage. Starting from an in-depth literature review concerning the influences beween natural hazards and cultural heritage [4–8], one of the results of the project is a risk assessment model, made up of specific tools to evaluate the characteristics of the cultural asset in relation to specific hazards and risks. Furthermore, these tools can interact with GIS methods and 3D modelling techniques, on one hand promoting a complete visualization of the cultural asset at risk, from the urban context to the specific elements [9] and, on the other hand, supporting decision makers and technicians in the definition of policies and actions.
The present paper is organized into 5 sections. The "research aim" clarifies the challenge at the base of the paper. The "material and methods" section provides an overview of the relevant literature on the base of which the proposed model has been designed. The "theory" section deeply explains and clarifies the theoretical concepts, mainly related to risk, on which the proposed model is based. Specifically, the concept of risk is destructured in the components of hazard, vulnerability and exposure to which operative criteria and indicators presented in the following section are related. The "results and discussion" section is organized into sub-paragraphs according to the phases that constitute the model's structure. Each sub-paragraph explains, both theoretically and operatively, the proposed phases for assessing the state of a cultural asset, specifically

[1] **ResCult**, acronim for **"**Increasing Resilience of Cultural heritage: a supporting decision tool for the safeguarding of cultural assets", is an European project financed by DG ECHO that aimed at enhancing the capability of Civil Protection (CP) to prevent and mitigate impacts of disasters on sites of Cultural Heritage (CH) through the realization of an integrated European Interoperable Database (EID). The project ended in 2018 and involved many European partners. For any additional information please refer to the official project website: www.rescult-project.eu.

buildings according to three types of events, and the parameters that constitute the risk. A brief discussion about the proposed model and its limits is also presented in sub-section 5.3. Finally, in the "conclusions", future perspectives are identified for further studies and model's improvements.

2. Research aim

The research aim of this paper is to illustrate an original risk assessment model. Its challenge is to understand the relation between the risk components, i.e. hazard, vulnerability, value and cultural heritage [4] through operative decision tools. The proposed model is useful to assess the level of risk of cultural assets, in relation to fire, earthquake and flood. In particular, it allows to analyze the structural, functional, and formal elements of a heritage building, thus identifying its most vulnerable elements. In this sense, this approach is retained suitable to support technicians and experts in the definition of interventions to reduce and manage the risk of cultural heritage.

3. Materials and methods

3.1 International efforts in Disaster Risk Reduction

Disaster Risk Reduction (DRR) is a development strategy that is increasing attention in the political agenda, due to the current emphasis on various components of human and environmental security [3,10]
There are three different international frameworks for Disaster Risk Reduction (DRR) which have local actions as fundamental principle [11]:

1. *Yokohama Strategy and Plan of action for safer world* [12]. It is the first document providing guidelines at the international level for preparation, prevention and mitigation of disaster impacts [11]. Its great importance is related to the acknowledgement of the community involvement in DRR. Furthermore, it provides a set of principles to structure DRR strategies, suggesting an involvement of local actors in risk management practice;
2. *The Hyogo Framework for action 2005-2015* [13]. It represents the first document that described the processes required to reduce disaster risks in different sectors and at various scales. Its adoption established different tools and platform to implement the DRR at national, regional and local levels;
3. *Sendai framework* [14]. It is a voluntary, non-binding agreement which recognizes that the State has the primary role in reducung the disaster risk, but the responsibility should be shared with other stakeholders, including local government and private sector.

These frameworks recognize the importance of the involvement of local people in developing DRR for their own communities (Table 1).
The literature on Disaster Risk Reduction (DRR) establishes that the evaluation of possible hazards that could impact the community is the first step to implement risk reduction [12,15,16]. The UNISDR defines the risk assessment as a "process of determining the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend" [12].
Therefore, risk assessment requires a systematic use of information and data to determine the likelihood that a hazard might exploit a particular vulnerability within a community. Different applications of the disaster risk analysis are recognised in literature (Tab. 2).
In fact, risk assessment is applied to several fields, that implies the use of different evaluation methods, including also the combination with GIS methods. The main findings of this literature review (Tab. 2) can be summarized into two fundamental points. Firstly, several of the listed evaluation methods are often used to assess an asset considering one risk at a time (e.g. flood risk, fire risk). In fact, few methods are developed to consider different types of risk simultaneously [17]. Secondly, it reveals that risk assessment is mainly applied to urban and territorial contexts, thus revealing that the application to specific building is limited.

4. Theory

This section describes the concept of the risk on which the proposed risk assessment model is grounded.

The model aims to assess the status and the degree of vulnerability of unmovable cultural heritage assets, considering different events. The methodology is based on a deconstruction of the concept of risk in its main components, i.e. hazard, vulnerability and value. It integrates a multicriteria approach to assess the status of a cultural asset and its elements in relation to the risk components. The final aim of this model is to provide a sinthethic index to technicians and users, evaluating the status of the buiding at risk and of its most vulnerable elements.

4.1 The concept of risk

The concept of risk has many meanings. From the point of view of psychologists, sociologists and historians, the risk is generally considered as a social phenomenon [18,19]. From this perspective, understanding risk requires knowledge on social values, perceptions and interactions between different actors. However, geologists, geographers, economists, epidemiologists and engineers adopt an approach based on the hypothesis that risk can be objectively quantified or evaluated [20]. The concept of risk is grounded on the probability that a dangerous phenomenon may occur and several elements can be affected. Thus, risk reduction means also reducing the effects of future disasters. Risks are the combination of the consequences of an event or hazard and the associated probability of its occurrence [21]. The consequences are negative effects, that are expressed in terms of social, political economic and environmental impacts. In those situations, where it is possible to quantify the probability of occurrence of a hazard of a given intensity, this refers to the probability of occurrence p. In risk analysis, impacts are often expressed in terms of vulnerability and exposure. Vulnerability V is defined as the characteristics and circumstances of a community, system or resource that make it sensitive to the harmful effects of a hazard [21,22]. Exposure E is the totality of people, properties, systems or other elements present in the hazard areas which are therefore subject to potential losses [13,14].

$$Risk = f(p, E, V) \qquad (1)$$

Where p is the probability of occurrence, E is the exposition and V the vulnerability.
Measures and interventions to prevent and adapt sites and buildings can reduce vulnerability and consequently risk. Vulnerability reduction is closely related to the concept of resilience, which is the ability of a system, community or society exposed to risks to absorb, adapt to and recover from the effects of a hazard in a timely and efficient manner, including through the conservation and restoration of its essential basic structures and functions [13,14].

5. Results and discussion

5.1 The risk assessment model purpose

The risk assessment model developed in the ResCult project (www.rescult-project.eu), aims to provide a method to assess the state of unmovable cultural assets in relation to natural and antropic risks. This model was developed starting from an in-depth analysis of existing tools and methodologies. The aim is providing to the interested users (e.g. institutions, civil protection, experts, citizens, companies) a quick tool to assess the state of risk of buildings with high cultural interest.
The model identifies a set of parameters that aims to measure the risk of cultural heritage, by providing to the evaluator a specific methodology and estimation tools. The model proposes an original method to link general concepts of risk with specific assessments of vulnerability and hazard, concerning heritage buildings in their formal, functional, structural aspects and their urban context. Moreover, this risk assessment model can be also applied to strategic buildings (e.g. institutional buildings, schools, hospitals), whose functionality should be guaranteed to support citizens during and after a disaster. The structure of the model and the specific evaluation phases will be detailed in the following paragraphs.

5.2 Model structure and components

The proposed model is structured into four evaluation phases: (i) the AREC Cards (Asset Risk Evaluation Cards) in which the parameters and components indicators of hazard and vulnerability of the building and its site are defined, (ii) the SMARTER Ranking method [23,24] which aims to weight the system of cultural heritage indicators according to a rank order, (iii) the Factsheets, and (iv) the Operational Dashboard of Evaluation (Figure 1).
In detail, these techniques have been chosen for the following motivations:

1. AREC Cards are conceived as a theoretical frame which assumes the risk and its fundamental elements as cornerstones to develop the model;
2. Factsheets are characterized by easy usability and operative functionality for the analysis of different cultural assets;
3. SMARTER has been considered suitable between MCDA techniques because facilitates the experts to evaluate sets of criteria through a simple ranking.

Risk for cultural heritage ($Risk_{CH}$) is evaluated in relation to the components *p*, *E* and *V*, where the probability *p* is extended to the most comprehensive concept of hazard *P* (probability *Rp*, regional hazard *Rig*, local hazard *Ril*) and the exposure *E* is circumscribed in the value *Val* of the asset. The $Risk_{CH}$ is therefore defined as follows:

$$Risk_{CH} = f\,(P_{CH}, Vu_{CH}, Val_{CH}) \quad (1)$$

Hazard P_{CH} is an expression of the geographical and statistical components of the “risk” (the probability of a phenomenon occurring with a given return time and a maximum expected intensity, and the conditions of the site where the building is located in relation to the characteristics of natural risk) [25]; Vu_{CH} describes the intrinsic vulnerability of a building to the phenomenon considered (partial or total inability to counteract the effects of the phenomenon) [26,27]; Val_{CH} describes the economic, social and cultural value expressed by the asset [28].
Therefore, hazard P_{CH} is an expression of the *Rp* probability, the general characteristics of the territory (*Rig*) and of the local context in which the building is located (*Ril*):

$$P_{CH} = f\,(Rp, Rig, Ril) \quad (2)$$

The Vu_{CH} vulnerability describes the building characteristics that are sensitive to the damaging effects of an event. The Vu_{CH} vulnerability is function of the followings: the structural vulnerability (Vu_{str}) that is the ability to preserve the static properties of the building, the functional vulnerability (Vu_{fun}), that refers to the ability to preserve the functions of use of the building and the formal vulnerability (Vu_{for}) is the ability to maintain the peculiar aspects of form that characterizes the building (e.g. volume, style, decoration, interior and exterior architecture) [29–31].

$$Vu_{CH} = f\,(Vu_{str}, Vu_{fun}, Vu_{for}) \quad (3)$$

Finally, the *Val* value is defined by the equation (4). The economic value (V_e) indicates the estimated value of the building, related to a possible market value and the cost of its hypothetical reconstruction. The cultural value (V_c) is an expression of the importance of the building, also in relation to the context. The social value (V_s) can be defined as the importance given to the building by the local community, occasional users (e.g. tourists, scholars) or global admirers.

$$Val_{CH} = f\,(V_e, V_c, V_s) \quad (4)$$

A description of an asset based on these risk parameters is useful to determine the most vulnerable elements, what scenario could be generated by a disastrous event and what emergency measures should be taken by the emergency operators in the first intervention.

5.2.1 The Asset Risk Evaluation Cards (AREC)

The AREC Cards “Asset Risk Evaluation Cards” describe the building and the site where the asset is located, considering its significant relation with the risk indicators: parameters and components. In this version of the model only the parameters of hazard and vulnerability are considered. These indicators represent the site characteristics (P_{CH}) and the formal, functional and structural aspects of the building (Vu_{CH}).
The value of the building (*Val*) will be included in a subsequent model’s implementation [32].
A set of indicators has been defined and organized according to type of risk, factor, parameters and components. Its aim is to assign hazard and vulnerability values to a given asset.
As an example, Figure 3 reports some indicators related to the structural vulnerability of a building. A complete list of the indicators is given in Table A.3. Each component corresponds to a specific indicator that gives a detailed characterization of the building under investigation. These indicators are determined by experts using a 5 points scale, where 1 means a very low risk and 5 means a very high risk.

5.2.2 The SMARTER method for weights assignment

The Simple Multi-Attribute Rating Technique Extended to Ranking (SMARTER) is a type of Multicriteria Decision Analysis (MCDA) [33,34] finalized to rank a series of elements for elicitating the weights [23,24]. In this paper, the SMARTER method has been considered for its versatility and pratical usefulness in supporting the decision makers, in the field of cultural heritage. (see Figure 4).
It is a multi-step process (for more please see [23,24]) and the main steps applied to the risk assessment of cultural heritage are described below:
Step 1: Definition of the evaluation goal, that is the risk assessment of the cultural asset. This step is also dedicated to the identification of the decision-makers to be involved in the evaluation;
Step 2: Structuring of the value tree. The parameters and components within the AREC Cards are defined as a hierarchical system of indicators;
Step 3: Definition of the objects of the evaluation and formulation of the objects-by-attributes matrix. A set of cultural assets are chosen and evaluated using the indicators;
Step 4: Assignment of weights. A questionnaire has been proposed to a multidisciplinary panel of experts (Figure 5). Figure A.1 illustrates part of the questionnaire proposed to the experts. The rankings attributed by the experts are subsequently organized into a matrix and then substituted by the Rank Order Centroid weights that are typical of SMARTER;
Step 5: Calculation of the average value for parameters and components. Once having substituted the rankings with the ROC weights into the matrix, it is possible to calculate the average value between the ROC weights. We define the average value of the components as local weights, whereas the average value of the parameters as general weights;
Step 6: Calculation of the final priorities. Each local weight is multiplied for the weight of the belonging parameter thus obtaining the final priority, i.e. global weight. Tables from A.2 to A.4 detail the global weights as final priorities of the model;
Step 7: Calculation of the risk index: The risk index is obtained by aggregating the normalized Factsheets’ values and the global weights, thus obtaining a non-dimensional value that varies in the interval [0, 1], where 0 means lack of risk, whereas 1 means a very high risk for the cultural asset.

5.2.3 Factsheets

The Factsheets derive from the AREC Cards as operational tool (Figure 6a). They contain information of the building, from the architectural and construction state to the geographic-geological conditions of the site with respect to the hazard and vulnerability. Figure 6b illustrates the main characteristics. Specifically, the Factsheets are compiled by experts from various disciplines (geography, geology, construction science and technology, history of architecture, etc.), who estimate and assign value to each Factsheet representing a specific indicator. This means that Factsheets require specific expertises, even if the scientific competence could be compensated by experience when the information are uncertain and/or unavailable.

5.2.4 The operational dashboard of evaluation

The Operational Dashboard of Evaluation is a spreadsheet developed in Excel environment that combines the results of the above-mentioned tools to calculate a final synthetic risk index for the building under investigation (Figure 7). It is finalized to be part of the ResCult EID platform for entering information about the hazard and vulnerability of historic buildings for the EID Database [35] (Figures A.2 and A.3).The functioning of the dashboard is described below.

a) Weight of parameter and components: normalization

The first macro-column of the dashboard describes the general parameters and the local components, with the respective weights and finally the global weights as final priorities.
To obtain a homogeneous calculation of the weighed values comparable with the observed values (derived from the Factsheets and then normalized), general weights (*GW*) and local weights (*LW*) have been normalized (GW_N, LW_N) in the interval [0–1]; the weights of the local components (*i*) have been normalized considering the general parameter (*j*) of belonging:

$$GW_{jN} = \frac{GW_j}{max_{j=1}^{n} GW_j}, \qquad LW_{iN} = \frac{LW_i}{max_{i=1}^{m} LW_i} \tag{5}$$

The overall weights (GL_N) of the components are then calculated:

$$GL_{iN} = LW_{iN} \times GW_{jN} \tag{6}$$

where each local LW_{iN} weight is relative to its general GW_{jN} parameter.
Global weights have the purpose to refine the evaluation of the importance of local components, as they relate this evaluation with the weight of the general parameter to which they belong: the local normalized weight of the component decreases its value if the general normalized weight of the parameter to which it belongs is less than 1.

b) Observed values
The second macro-column of the dashboard describes the observed values resulting from the Factsheets: for each indicator component, the expert inserts the corresponding value measured or estimated. The values are normalized to allow their subsequent weighting with the previously described weights.
The observed values are graphically represented with histograms (with color gradations corresponding to the intensity of the value).
When it is impossible to attribute a value to an indicator, it is generally assigned the maximum value, as a precautionary measure.
When an indicator is not significant for the considered building, it will not be taken into account in the evaluation and without altering the final risk index.

c) Weighted values

The third macro-column of the dashboard describes the weighted values. The observed values (VN) are weighed with local weights (component weights, LWN) and global weights (parameter weights, GLN), to take into account the importance given to components and parameters simultaneously. In particular, local weighted values "adjust" the observed values to the importance of the indicators; global weighted values adjust the observed values to the importance of the indicators to the importance of the parameter to which the indicator belongs. The values evaluated with the local weights of a component "i" are given by:

$$VL_{wiN} = V_{iN} \times LW_{iN} \tag{7}$$

The same values evaluated with the global weights of a component "i" are given by:

$$VG_{wiN} = V_{iN} \times GL_{iN} \tag{8}$$

In this way, three types of refining of the observed values are carried out: a first order of refining tares the value observed on the importance of the indicator (local). A second order of refining tares the value observed on the importance of the indicator related to the importance of the class of the component of the parameter to which it belongs. Observed values, local weighted values and global weighted values are therefore three types of measurements that the expert can use to assess and describe the hazard and vulnerability of the building and identify any adaptation measures to reduce the degree of risk.
In summary, the observed values indicate the objective state of risk and deterioration of the building; the weighted values indicate which are the most significant components relating to hazard and vulnerability, those on which it may be more appropriate to intervene with actions of adaptation and protection, with a view to optimize costs/benefits. Observed values and weighted values can sometimes differ significantly.
A third degree of refining is characterized by the scenario analysis. It aims to increase the robustness of the risk indices by relating the i-th index obtained as final output from the dashboard, with a risk index calculated by hypothesizing a scenario of maximum risk. As it is possible to see in Figure A.3, from the relation between the risk index and the risk index of maximum scenario a very similar index is obtained. This means that the evaluation is stable.

d) Synthetic indicators

Starting from the values of the components, it is possible to obtain synthetic indicators, concerning the parameters of hazard and vulnerability for the three considered risks. Synthetic risk indices can be useful to have an overview of the status of the building that can be compared with the risk of other buildings in a given territory. This risk information can also be georeferenced in a GIS-WEB database and can be used by actors involved in disaster management, in the prevention, emergency and reconstruction phases.
Finally, the determination of synthetic risk indices allows to carry out a multi-risk assessment for the building and its parts, considering different events, possibly concomitant. In this sense, an assessment can be made of the interaction between different types of events, which sometimes could not lead to a simple sum of the individual effects, but can lead to more serious damage scenarios.
Regional hazard values, local hazard values, vulnerability values are calculated as the weighted average of the values of the normalized components, using the local weights (*LW*) of the components themselves. Regional hazard (*Rig*) and local hazard (*Ril*) for a given event are defined as:

$$Rig = \frac{\sum_{i=1}^{n} Rig_{(i)} LW_{Rig_{(i)}}}{\sum_{i=1}^{n} LW_{Rig_{(i)}}} \qquad Ril = \frac{\sum_{i=1}^{n} Rig_{(i)} LW_{Rig_{(i)}}}{\sum_{i=1}^{n} LW_{Rig_{(i)}}} \tag{10}$$

where the index "i" refers to each component of the parameter considered. Formal vulnerability (Vu_{for}), functional vulnerability (Vu_{fun}), structural vulnerability (Vu_{str}) are defined as:

$$Vu_{for} = \frac{\sum_{i=1}^{n} Vu_{for_{(i)}} LW_{Vu\_for_{(i)}}}{\sum_{i=1}^{n} LW_{Vu\_for_{(i)}}} \qquad Vu_{fun} = \frac{\sum_{i=1}^{n} Vu_{fun_{(i)}} LW_{Vu\_fun_{(i)}}}{\sum_{i=1}^{n} LW_{Vu\_fun_{(i)}}} \tag{11}$$

$$Vu_{str} = \frac{\sum_{i=1}^{n} Vu_{str_{(i)}} LW_{Vu\_str_{(i)}}}{\sum_{i=1}^{n} LW_{Vu\_str_{(i)}}}$$

Synthetic indicators of hazard (*TH*) and vulnerability (*TV*) for earthquake (*e*), fire (*f*), flood (*h*), can be defined as weighted averages of hazard and vulnerability values for each event, using parameter weights (*GW*):

$$TH_e = \frac{Rig_e GW_{Rig\_e} + Ril_e GW_{Ril\_e}}{GW_{Rig\_e} + GW_{Ril\_e}} \quad , \qquad TH_f = \frac{Rig_f GW_{Rig\_f} + Ril_e GW_{Ril\_f}}{GW_{Rig\_f} + GW_{Ril\_f}}$$

$$TH_h = \frac{Rig_h GW_{Rig\_h} + Ril_h GW_{Ril\_h}}{GW_{Rig\_h} + GW_{Ril\_h}} \tag{9}$$

$$TV_e = \frac{Vu_{for\_e}GW_{Vu\_for\_e} + Vu_{fun\_e}GW_{Vu\_fun\_e} + Vu_{str\_e}GW_{Vu\_str\_e}}{GW_{Vu\_for\_e} + GW_{Vu\_fun\_e} + GW_{Vu\_str\_e}}$$

$$TV_f = \frac{Vu_{for\_e}GW_{Vu\_for\_f} + Vu_{fun\_f}GW_{Vu\_fun\_f} + Vu_{str\_f}GW_{Vu\_str\_f}}{GW_{Vu\_for\_f} + GW_{Vu\_fun\_f} + GW_{Vu\_str\_f}}$$

$$TV_h = \frac{Vu_{for\_h}GW_{Vu\_for\_h} + Vu_{fun\_h}GW_{Vu\_fun\_h} + Vu_{str\_h}GW_{Vu\_str\_h}}{GW_{Vu\_for\_h} + GW_{Vu\_fun\_h} + GW_{Vu\_str\_h}} \quad (10)$$

5.3 Limitation and opportunities of the study

The proposed risk assessment model aims at being applied in different contexts of cultural heritage and risk. However, both further refinements and future opportunities should be considered. For what concerns the required improvements, the most important can be listed as follow:

- The necessity to verify the completeness and adequacy of the parameters and components, with a further study of the issues involved with the help of experts;
- The examination of the weights assignment to considered indicators, using other techniques in addition to the SMARTER method and through a further survey involving a larger pool of experts. The objective is verifying and recalibrating the set of weights;
- The concept of value of the asset should be implemented, in order to reflect the economic, social and cultural components, as an element of evaluation for strategies of adaptation and/or reconstruction.

The opportunies identified for this model are summarized as follow:

- The developed tools and the selected techniques allowed to evaluate the risk status of the considered asset in a simple and quickly way;
- This framework can support the definition of actions for the restoration or adaptation of both the building within its different part and the site in which it is located;
- The structure of this risk assement tool permits to extend its application both to other types of buildings, such as historical churches, considering their structural mechanisms and to other typology of risks (e.g. risks from industrial accidents or terrorist attacks), with the addition of dedicated AREC cards.

This risk assessment could be combined with adjustments and constructive interventions for the reduction of the risk and optimizing costs and benefits [10,36–38]. For instance, a MCDA could be performed to identify an optimised ranking of the interventions to adopt on a building to improve its response to risk, or to reduce its degree of vulnerability.

6. Conclusions

This paper illustrates the risk assessment model, developed for cultural heritage, with reference to disastrous events which could affect unmovable cultural assets [10]. The model allows to quickly describe the components of hazard and vulnerability based on expert assessments. The Arec cards allows to describe the building in relation to risk parameters, using specific criteria and indicators. The Facsheet contains the information useful to filling in the AREC Cards according to experts evaluation and description. Moreover, through the application of the Smarter method, indicators are weighted and, finally, the operation board of evaluation allows to calculate a final synthetic risk index for the building under investigation. Thus, it is firstly possible to easily compare the risk of different buildings in a territory. Secondly, it allows to define specific actions for adaptation and restructuring through more detailed assessments on individual buildings. A model with these properties is original in the European scenario. In fact, the model proposed through the specific application tools developed, can be useful in all phases of the disaster, to identify the best interventions in the prevention, emergency, reconstruction phases [39,40]. In the prevention phase, the model can help to choose the necessary interventions on the building and the site to reduce vulnerability and exposure. For example, it

is possibile to determine the interventions both on building and on its location through the analysis derived from the factsheets, e.g improving the resistance of the construction elements, hydraulic protection measures for extreme flood events.
In the emergency phase, the model can help emergency operators to establish the priority interventions, considering the state and vulnerability of the asset. The knowledge of hazard and vulnerability derived from the model can highlight which scenario could be generated in a disastrous event and therefore which emergency measures should be taken: for example, it can be estimated what damage may have occurred and to what extent.
After the event, the model can help to develop an effective reconstruction strategy, identifying the methods of recovery and reconstruction of buildings, based on previous vulnerabilities and the state of damage resulting from the event, and on the priorities of the reconstruction, with a view to cost-value-benefit optimization [10,36,38,41–43].
The evaluation model described in this paper has been positively applied in some case studies in Italy and Europe, in the framework of the European project ResCult. Thus, this model can contribute to apply robust techniques within the cultural heritage context, expanding their context of applicability and contributing to the improvement of the body of knowledge in the risk assessment of cultural heritage.

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Caption of Figures

Figure 1. Workflow illustrating the fundamental phases of the evaluation model.

Figure 2. Representation of the risk components P_{CH} and Vu_{CH} and the investigated parameters (Elaboration from [10])

Figure 3. The figure shows the Arec Cards relating to the three events considered. At the bottom, a detail of the structural vulnerability indicators for the earthquake is represented, which refer directly to the vulnerabilities of the corresponding construction elements [10].

Figure 4. Workflow illustrating the development of the SMARTER method (Elaboration from [10]).

Figure 5. Panel of experts involved in the survey (Elaboration from [10]).

Figure 6. AREC Cards and Factsheets (ResCult, 2017) Each component of the Arec Cards provides a Factsheet (a) with respect to the building under investigation (b) (Elaboration from [10]).

Figure 7. Integration of the tools into the operational dashboard of evaluation.

List of Tables

Reduction Risk Frameworks	
Yokohama Strategy, 1994	It is focused on improving mechanism in order to better cope with and recover from disasters' impacts. [44]
Sendai Framework, 2015	"The substantial reduction of disaster risk and losses in live, livehood and health and in the economic, physical, social cultural and environmental assets of persons, business, communities and countries" [45]
Hyogo Framework for Action, 2005 - 2015	"Reducing loss of lives and social, economic, and environmental assets when hazards strike". [13]

Table 1. Reduction Risk Frameworks and their principal outcomes (Source: authors processing)

Author	Field Application	Objective of the evalutation	Methodology
Vermaak et al., 2004 [15]	Flood disaster	To explore several initiatives for disaster risk reduction in South Africa	Interview with the stakeholders; Risk and vulnerability assessment; Hazard mapping to collect data.
Shivaprasad et al., 2017 [46]	Flood risk assessment	To evaluate the flood risk situation, integrating the flood hazard zonation, with social, infrastructures and land use vulnerability, in India	Integration of MCA and GIS for coupling spatio-multi-temporal historic satellite datasets, socio-economic data, infrastructure and land use with vulnerability parameters.
Guerra et al., 2019 [47]	Flood risk assessment	To quantify a flood hazard for an entire city and develop a city response plan	Integration of experts' knowledge with Arc GIS and multicriteria analysis
Schaefer et al., 2019 [48]	Water risk assessment in supply chains	To aggregate relevant indicators into an index score designed to assess suppliers' water risk based on their location.	Hierarchical evaluation framework, using Monte Carlo Analytic Hierarchy Process (MCAHP)
Sanchez-Silva et al., 2013 [49]	Seismic risk analysis and management of civil infrastructure systems	To find a methodology to assess seismic risk to bridges and other components of civil infrastructure networks	Integrated framework that combines Structure analysis with pattern recognition (clustering) and Hierarchical model of infrastructure networks
Trakas et al., 2018 [17]	Power systems	To Mitigate the impacts of such events on critical infrastructures	SRI: Severity Risk Index, which is an online risk spatial risk analysis tool, which considers the spatial and temporal evolution of the extreme event.
Ager et al., 2018 [50]	Trans-boundary Wildfire Exposure	To quantify and mapping trans-boundary exposure, in order to predict wildfire ignition location and fire perimeter	SPATIAL DATA: U.S. Census Berau and the SILVIS windland urban interface, and also window simulation tools.
Shortridge et al., 2018 [51]	Building Resilience	To address climate change risks to infrastructure	Robust decision-making analysis
Esnard and Lai, 2018 [52]	Interdisciplinary Approaches to Examining Post-disaster School Recovery	Assessing the post-disaster recovery	Mixed metod approach: Parallel, Concurrent, Sequential.
Ferretti et al., 2017 [53]	Environmental Multi-Impact Spatial Risk Analysis	Assess spatial risks, taking into account the multidimensional nature of spatial impacts	Multi-criteria decision Analysis and Spatial Analysis (GIS)

Guanquan et al 2008 [54]	Fire risk evaluation	Quantitative assessment on building fire risk	Stochastic analysis on occurrence probability of fire scenario
Anderson et al., 2016 [55]	Fire risk evaluation and prediction	Statistical models to predict the number and geographic distribution of fires caused by earthquake ground motion and tsunami inundation	Integrated approach combining generalized linear models (GLMs), generalized additive models (GAMs) and boosted regression trees (BRTs)
Andretta et al., 2017 [56]	Environmental risk of cultural heritage	Development of a risk assessment methodology for cultural heritage protection (NICHE) and application to a historical library	Analysis of the environment/artefact system, statistical processing, scenario analysis
Chiabrando et al. 2018 [9]	Building of a conceptual data model	Development of a conceptual data model for the risk assessment of cultural heritage as extension of the INSPIRE UML model.	3D Models and Level of Data (LoDs) Geographic Information Systems (GIS) - CityGML

Table 2. Some applications of risk analysis for built environment (Source: authors processing)

Supplementary Material

Type of risk	Factors	Parameters	Components (indicators)
Fire	Hazard	Regional hazard	Climatic conditions
			Weather conditions
			Territorial conditions
		Local hazard	Conditions of the architectural - urban context
			Urban fire prevention system
	Vulnerability	Formal vulnerability	Distribution type
			Furnishings, coatings, objects, non-structural elements
			Building fire prevention system
			Fire-fighting elements
		Functional vulnerability	Functional typology
			Staff for emergency intervention
		Structural vulnerability	Type structure of the building
Earthquake	Hazard	Regional hazard	Seismic conditions
			Geological conditions
		Local hazard	Conditions of the architectural - urban context
	Vulnerability	Formal vulnerability	Non-structural elements
			Planimetry configuration
			Height configuration
			Aggregated volumes
			Distribution type
		Functional vulnerability	Functional typology
		Structural vulnerability	Links between structural elements
			Horizontal structures
			Structural typology
			Wall quality
			Roof
			Arch and vault
			Foundations
			Resistant vertical elements
			Stairs
			Building context
			Deterioration
			Deterioration by recent earthquake
Flood	Hazard	Regional hazard	Weather conditions
			Geo-morphological conditions
			Regional hydrographic conditionsi
			Global territorial conditions
		Local hazard	Local hydrographic conditions
			Contrast of risk
			Conditions of the architectural - urban contex
	Vulnerability	Formal vulnerability	Building protection systems
			Distribution type
			Furnishings, Objects, of cultural value
		Functional vulnerability	Functional typology
		Structural vulnerability	Structural typology

Table A.1 Set of indicators organized in factors, parameters and components and according to the type of risk considered in the AREC Cards.

Fire risk				
Parameters	**Components (indicators)**	**Local weights**	**General weights**	**Global weights**
Regional Hazard *(Rig)*	Climatic conditions	0,2553	0,1787	0,0456
	Weather conditions	0,1832		0,0327
	Territorial conditions	0,5616		0,1004
Local Hazard *(Ril)*	Conditions of the architectural and urban context	0,3581	0,2459	0,0880
	Urban fire prevention system	0,6419		0,1578
Structural Vulnerability (Vu_{stru})	Type structure of building	1	0,1612	0,1612
Functional Vulnerability (Vu_{fun})	Functional typology	0,4122	0,2792	0,1151
	Staff for emergency interventions	0,5878		0,1641
Formal Vulnerability (Vu_{form})	Distribution type	0,0972	0,1350	0,0131
	Furnishings, coatings, objects and non-structural elements	0,1553		0,0210
	Objects of cultural importante contained in the building	0,1562		0,0211
	Building fire prevention system	0,3508		0,0474
	Fire-fighting elements	0,2405		0,0325
			Total	1,000

Table A.2 Fire Risk components and weights.

Earthquake risk				
Parameters	**Components (indicators)**	**Local weights**	**General weights**	**Global weights**
Regional hazard *(Rig)*	Seismic Conditions	0,5278	0,3167	0,1672
	Geological Conditions	0,4722		0,1495
Local hazard *(Ril)*	Conditions of the architectural - urban context	1	0,2222	0,2222
Structural Vulnerability (Vu_{stru})	Links between structural elements	0,1275	0,2544	0,0324
	Horizontal structures (slab)	0,067		0,0170
	Structural tipology	0,1557		0,0396
	Wall quality	0,0782		0,0199
	Roof	0,0463		0,0118
	Arch and vault	0,1178		0,0300
	Foundations	0,0438		0,0111
	Resistant verticals elements	0,0699		0,0178
	Stairs	0,0717		0,0182
	Building context	0,0252		0,0064
	Deterioration	0,0626		0,0159
	Deterioration by recent earthquake	0,1342		0,0341
Formal Vulnerability	Non structural elements	0,1011	0,1089	0,0110
	Planimetric configuration	0,315		0,0343

(Vu_{form})	Height configuration	0,1664		0,0181
	Aggregated volumes	0,2219		0,0242
	Distribution type	0,2219		0,0242
Functional Vulnerability (Vu_{fun})	Functional typology	1	0,0978	0,0978
			Total	1,0000

Table A.3 Earthquake Risk components and weights.

Flood risk				
Parameters	**Component (indicators)**	**Local weights**	**General weights**	**Global weights**
Regional hazard *(Rig)*	Weather conditions	0,1435	0,3674	0,0527
	Geomorphological conditions	0,3264		0,1199
	Regional hydrographic conditions	0,3056		0,1123
	Global territorial conditions	0,2245		0,0825
Local hazard *(Ril)*	Local hydrographic conditions	0,3982	0,2782	0,1108
	Contrast of risk	0,4167		0,1159
	Conditions of the architectural - urban context	0,1852		0,0515
Formal Vulnerability (Vu_{form})	Building protection system	0,3856	0,0831	0,0320
	Distribution type	0,3464		0,0288
	Furnishing, objects, etc.	0,268		0,0223
Functional Vulnerability (Vu_{fun})	Functional typology	1	0,1086	0,1086
Structural Vulnerability (Vu_{stru})	Structural typology	1	0,1626	0,1626
			Total	1,000

Table A.4 Flood Risk components and weights.

FIRE RISK / RISCHIO INCENDI

According to your opinion, which is the most important attribute with reference to the **Fire** risk assessment?
Please rank the following attributes from the most important to the least important (e.g., C > A > B)
Secondo la sua opinione, qual è l'attributo più importante in riferimento alla valutazione del rischio **Incendi**?
Per favore ordini i seguenti attributi da quello più importante a quello meno meno importante (es., C > A > B)

INDICATORS/INDICATORI

A — **Climatic conditions**/Condizioni climatiche
Climate, weather and average temperatures. Clima, meteo e temperature medie.

B — **Weather conditions**/Condizioni metereologiche
Areas interested by rainfalls. Aree interessate da precipitazioni.

C — **Territorial conditions**/Condizioni territoriali
Presence of fire risk elements. Presenza di elementi di rischio incendi

☐ > ☐ > ☐

A — **Conditions of the architectural and urban context**
Condizioni del contesto architettonico e urbano
Buildings density and relative distances. Densità del tessuto edilizio e relative distanze.

B — **Building fire prevention system**/Sistemi antincendio a livello di edificio
Availability of building fire prevention systems. Disponibilità dei sistemi antincendio a livello di edificio.

☐ > ☐

A — **Distribution Type**/Tipologia di distribuzione
Distributive routes that favor more or less the people evacuation.
Percorsi di distribuzione che favoriscono più o meno l'evacuazione di persone.

B — **Furnishings, coatings, objects and non-structural elements**
Arredi, oggetti ed elementi non strutturali
Fire resistance capability of elements.
Capacità di resistenza agli incendi degli elementi.

C — **Objects of Cultural importance contained in the buildings**
Oggetti di pregio all'interno degli edifici
Presence of cultural objects at risk of fire.
Presenza di oggetti di valore culturale a rischio incendi.

D — **Building fire prevention system**/Sistema di prevenzione incendi a livello di edificio
Presence of efficiency fire prevention systems in buildings.
Presenza di efficienti sistemi di prevenzione incendi negli edifici.

E — **Fire fighting elements**/Elementi antincendio
Presence of efficiency fire-fighting elements (e.g. fire fighting compartmentation of spaces).
Presenza di efficienti elementi antincendio (es. compartimentazione antincendio degli spazi).

☐ > ☐ > ☐ > ☐ > ☐

A — **Functional Typology**/Tipologia funzionale
The level of people affluency in both public and private buildings.
Livello di affluenza delle persone in edifici pubblici e privati.

B — **Staff for emergency interventions**/Personale per interventi di emergenza
Presence of trained emergency staff. Presenza di personale addestrato per interventi di emergenza.

☐ > ☐

GENERAL ASPECTS/ ASPETTI GENERALI
According to your opinion, which is the most important aspect with reference to the **Fire** risk assessment?
Secondo la sua opinione, qual è l'aspetto più importante in riferimento alla valutazione del rischio **Incendi**?

A — **Regional Hazard**
General territorial features.
Aspetti territoriali generali.

B — **Local Hazard**
Context of the building.
Contesto dell'edificio.

C — **Vulnerability (STRUCTURE)**
Static properties of the building.
Proprietà statiche dell'edificio.

D — **Vulnerability (FUNCTION)**
User functions of the building.
Funzione di utenza dell'edificio.

E — **Vulnerability (FORM)**
Peculiar aspects of shape.
Aspetti peculiari della forma.

☐ > ☐ > ☐ > ☐ > ☐

Figure A.1. Part of the SMARTER questionnaire submitted to the experts in the First User Forum, Venice (2017) (Authors processing within Rescult project 2017-2018).

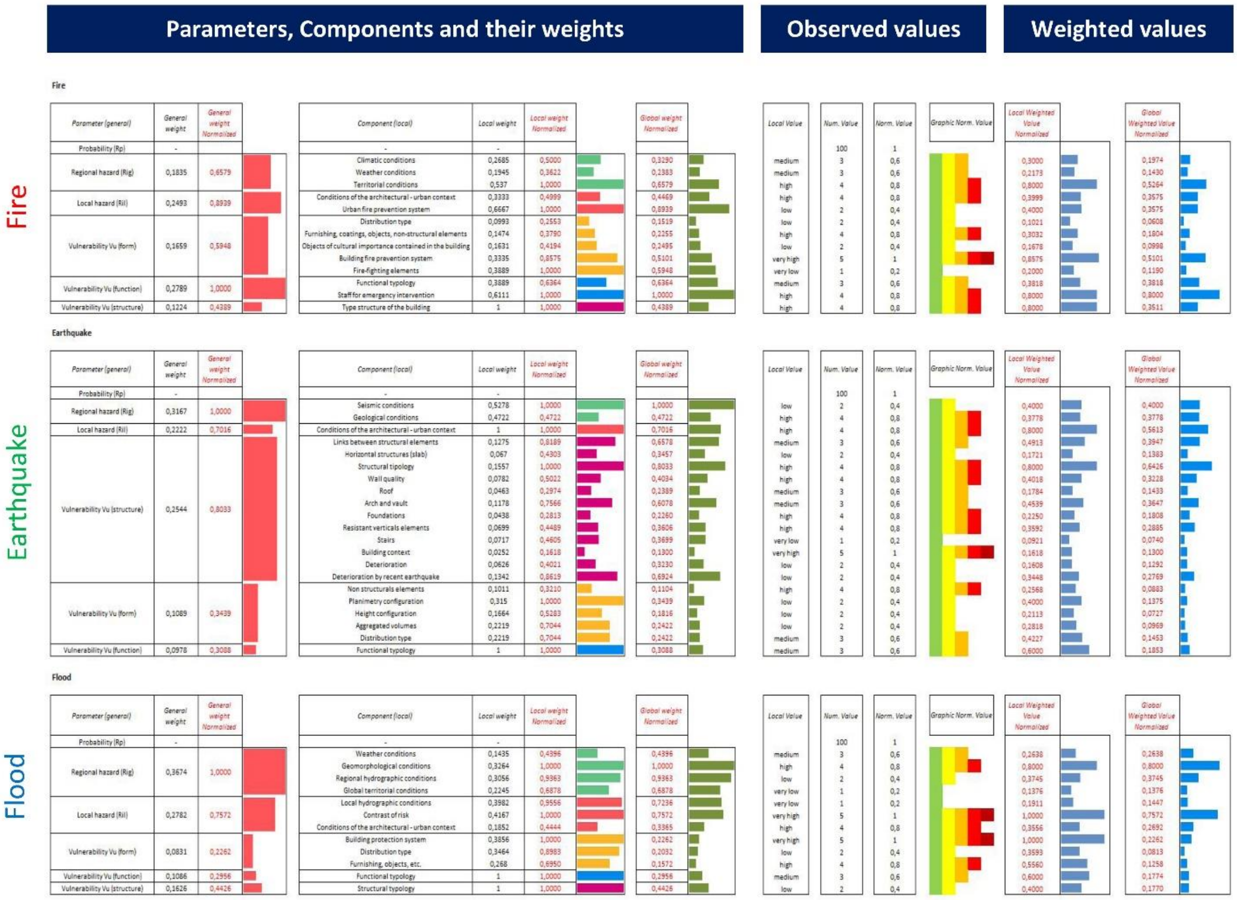

Figure A.2 The operative dashboard that includes the AREC Cards, the Factsheets and the SMARTER method in an integrated evaluation tool [10].

Evaluation of specific components of hazard and vulnerability - Maximum Scenario

Fire

Parameter (general)	*Component (local)*	*Local weight*	*General weight*	*Global weight*	*Local Value*	*Num. Value*	*Norm. Value*	*Graphic Norm. Value*	*Local W. Value*	*Global value*
Probability (Rp)	-	-	-	-		100	1			
Regional hazard (Rig)	Climatic conditions	0,2685	0,1835	0,0493	very high	5	1		0,2685	0,0493
	Weather conditions	0,1945		0,0357	very high	5	1		0,1945	0,0357
	Territorial conditions	0,537		0,0985	very high	5	1		0,537	0,0985
Local hazard (Ril)	Conditions of the architectural - urban context	0,3333	0,2493	0,0831	very high	5	1		0,3333	0,0831
	Urban fire prevention system	0,6667		0,1662	very high	5	1		0,6667	0,1662
Vulnerability Vu (form)	Distribution type	0,0993	0,1659	0,0165	very high	5	1		0,0993	0,0165
	Furnishing, coatings, objects, non-structural elements	0,1474		0,0245	very high	5	1		0,1474	0,0245
	Objects of cultural importancecontained in the building	0,1631		0,0271	very high	5	1		0,1631	0,0271
	Building fire prevention system	0,3335		0,0553	very high	5	1		0,3335	0,0553
	Fire-fighting elements	0,3889		0,0645	very high	5	1		0,3889	0,0645
Vulnerability Vu (function)	Functional typology	0,3889	0,2789	0,1085	very high	5	1		0,3889	0,1085
	Staff for emergency intervention	0,6111		0,1704	very high	5	1		0,6111	0,1704
Vulnerability Vu (structure)	Type structure of the building	1	0,1224	0,1224	very high	5	1		1	0,1224
										1,0219
										1,0000

Earthquake

Parameter (general)	*Component (local)*	*Local weight*	*General weight*	*Global weight*	*Local Value*	*Num. Value*	*Norm. Value*	*Graphic Norm. Value*	*Local W. Value*	*Global value*
Probability (Rp)	-	-	-	-		100	1			
Regional hazard (Rig)	Seismic conditions	0,5278	0,3167	0,1672	very high	5	1		0,5278	0,1672
	Geological conditions	0,4722		0,1495	very high	5	1		0,4722	0,1495
Local hazard (Ril)	Conditions of the architectural - urban context	1	0,2222	0,2222	very high	5	1		1	0,2222
Vulnerability Vu (structure)	Links between structural elements	0,1275	0,0978	0,0125	very high	5	1		0,1275	0,0125
	Horizontal structures (slab)	0,067		0,0066	very high	5	1		0,067	0,0066
	Structural tipology	0,1557		0,0152	very high	5	1		0,1557	0,0152
	Wall quality	0,0782		0,0076	very high	5	1		0,0782	0,0076
	Roof	0,0463		0,0045	very high	5	1		0,0463	0,0045
	Arch and vault	0,1178		0,0115	very high	5	1		0,1178	0,0115
	Foundations	0,0438		0,0043	very high	5	1		0,0438	0,0043
	Resistant verticals elements	0,0699		0,0068	very high	5	1		0,0699	0,0068
	Stairs	0,0717		0,0070	very high	5	1		0,0717	0,0070
	Building context	0,0252		0,0025	very high	5	1		0,0252	0,0025
	Deterioration	0,0626		0,0061	very high	5	1		0,0626	0,0061
	Deterioration by recent earthquake	0,1342		0,0131	very high	5	1		0,1342	0,0131
Vulnerability Vu (form)	Non structurals elements	0,1011	0,1089	0,0110	very high	5	1		0,1011	0,0110
	Planimetry configuration	0,315		0,0343	very high	5	1		0,315	0,0343
	Height configuration	0,1664		0,0181	very high	5	1		0,1664	0,0181
	Aggregated volumes	0,2219		0,0242	very high	5	1		0,2219	0,0242
	Distribution type	0,2219		0,0242	very high	5	1		0,2219	0,0242
Vulnerability Vu (function)	Functional typology	1	0,2544	0,2544	very high	5	1		1	0,2544
										1,0029
										1,0000

Flood

Parameter (general)	*Component (local)*	*Local weight*	*General weight*	*Global weight*	*Local Value*	*Num. Value*	*Norm. Value*	*Graphic Norm. Value*	*Local W. Value*	*Global value*
Probability (Rp)	-	-	-			100	1			
Regional hazard (Rig)	Weather conditions	0,1435	0,3674	0,0527	very high	5	1		0,1435	0,0527
	Geomorphological conditions	0,3264		0,1199	very high	5	1		0,3264	0,1199
	Regional hydrographic conditions	0,3056		0,1123	very high	5	1		0,3056	0,1123
	Global territorial conditions	0,2245		0,0825	very high	5	1		0,2245	0,0825
Local hazard (Ril)	Local hydrographic conditions	0,3982	0,2782	0,1108	very high	5	1		0,3982	0,1108
	Contrast of risk	0,4167		0,1159	very high	5	1		0,4167	0,1159
	Conditions of the architectural - urban context	0,1852		0,0515	very high	5	1		0,1852	0,0515
Vulnerability Vu (form)	Building protection system	0,3856	0,0831	0,0320	very high	5	1		0,3856	0,0320
	Distribution type	0,3464		0,0288	very high	5	1		0,3464	0,0288
	Furnishing, objects, etc.	0,268		0,0223	very high	5	1		0,268	0,0223
Vulnerability Vu (function)	Functional typology	1	0,1086	0,1086	very high	5	1		1	0,1086
Vulnerability Vu (structure)	Structural typology	1	0,1626	0,1626	very high	5	1		1	0,1626
										0,9999
										1,0000

Figure A.3 Operative dashboard representing the maximum risk scenario concerning the building under investigation (Authors processing within Rescult project 2017-2018).