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Flood risk management in historic centres: A scalable typological framework integrating GIS, BIM and VR

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ABSTRACT

The increasing frequency and severity of climate-related disasters underscore the need for reliable and adaptable risk management solutions, especially in complex environments such as historic city centres, where structural and functional characteristics pose unique challenges. To address this issue, the paper proposes a workflow that integrates GIS, BIM, and VR technologies to enable seamless informative integration and effective assessment of key factors related to hazard, building vulnerability, and user exposure in flood prone historic towns. The approach adopts a multi-scalar logic – connecting the macro-scale analysis of the urban built environment with meso-scale modelling of selected blocks and open spaces – alongside a typological framework that abstracts real-case features into representative, idealized clusters. The objective is to build a digital ecosystem capable of identifying priority areas and scenarios based on construction characteristics and occupancy patterns and serving as a foundation for more specialized studies in hazard modelling, evacuation simulation, and virtual training and communication. The proposed workflow is tested on a historic centre in Central Italy exposed to fluvial flood risk, demonstrating its potential to integrate and operationalize data and processes that have typically been addressed separately in the current practice. Ultimately, the aim is to support a guided and accessible technology transfer to technical and administrative stakeholders involved in risk decision-making.

1. Introduction

In recent years, urban built environments have been exposed to critical conditions in view of the frequency and severity of flood events worldwide [1–5]. On the one side, global warming is contributing to the intensification of extreme weather phenomena such as heavy rainfall, heatwaves, along with recurring disruptions in atmospheric patterns [6–11]. Recent studies have shown a significant rise in the concurrence of floods and heatwaves, closely linked to the global average temperature increase, which has now exceeded 1.5 °C above pre-industrial levels [12]. This shift in climate conditions has led to a doubling in the occurrence of extreme flood events, amplifying the risks faced by both populations and infrastructure [13]. On the other side, anthropic factors, such as urban expansion, increasing population density in cities, and land-use transformation, play a critical role in multiplying hydraulic vulnerability across

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many regions [14–16]. Rural depopulation is a continuing and marked trend, with a yearly decline of 0.1 % in rural areas across Europe, accompanied by a 0.4 % annual rise in urban populations [17]. According to recent projections, by 2050 approximately 83.7 % of the EU population will reside in urban areas [18]. This process of urbanization leads to the expansion of impermeable surfaces and often takes place without adequate infrastructure planning, leaving cities increasingly exposed to flood hazards [19–21]. The lack of effective rainwater drainage, due to outdated or insufficient systems and the widespread presence of non-permeable surfaces, contributes to the intensification of flood peaks.

Within this context, historic urban centres are particularly prone to flood risk due to a combination of physical, spatial, and social factors that increase their vulnerability and exposure [4,22,23]. First, these historic areas are often located near rivers or in zones historically susceptible to flooding, which further exacerbates their exposure to hazard [24,25]. These key issues represent fundamental factors of flood hazard, as the combination of the physical characteristics of flooding specific to the site and the probability of occurrence [26]. On these bases, the morphology of open spaces and the nature of surface materials significantly influence flood dynamics [27]. The compact urban fabric, characterized by a dense layout of buildings, with narrow streets and a limited number of wider open spaces, such as urban squares, tends to reduce the proper outflow of rainwater, along with factors related to urban and surface porosity, as well as sewerage system efficiency. Established hydrological and hydraulic models can be applied to urban environments to simulate flood scenarios, generating key outputs such as flood extension, water depth and flow velocity depending on the typology of flood to be considered (e.g. riverine, coastal, pluvial) [28–32].

The hazard factors should be then associated with the physical vulnerability of the built environment, which also affects the potential building damage [33]. Considering that building heritage, typically composed of aging structures, is highly susceptible to water damage, previous research pointed out that relevant related indicators include facades configuration (the number, size, and orientation of openings relative to the flood direction), number of floors, material properties, conservation status, and heritage value [27, 34–38]. Furthermore, technical infrastructure, such as sewerage networks and drainage systems, are frequently inadequate compared to current needs, especially when faced with extreme weather events [39].

Finally, hazard and physical vulnerability should be also combined with the human factors, which mainly relate to the users' exposure and vulnerability and are essentially assessed in terms of the number of individuals located in flood-prone areas and their capacity to respond to flood events [33,40]. Human factors are hence shaped by a combination of socioeconomic and demographic variables, such as age, gender, mobility, risk awareness, and knowledge of the built environment, along with their dynamics in urban built environment use [34,41,42]. Moreover, the possible high population density, often combined with the presence of tourist flows, complicates emergency operations and risk management [29,43].

A comprehensive understanding and joint analysis of these elements are essential for accurately assessing flood risk in historic urban areas, thereby laying the groundwork for effective and sustainable mitigation strategies. Hazard and building vulnerability are typically treated as static parameters, since they depend on fixed physical and structural conditions. In contrast, users' vulnerability and exposure are dynamic, fluctuating over time and space. The number of people exposed in a risk area changes throughout the day and week, influenced by urban mobility patterns with substantial impact on both flood risk evaluation and emergency response planning [44]. Despite advances in flood risk assessment, many current approaches still focus primarily on hazard and the physical vulnerability of the built environment [24,29,37], sometimes integrating static data on population exposure [43]. In view of the increasing availability of simulation models [19,45,46], tools are indeed available to assess human-environment interactions and emergency behaviour during flood events and the related evacuation process [19,47,48]. The literature highlights that individual responses during emergencies, even seemingly minor actions such as hesitation or attachment to personal belongings, can significantly increase exposure to danger, affecting mobility, the ability to select safe routes and evacuation times, ultimately influencing the overall outcomes of flood events [49–53].

Nevertheless, traditional risk management approaches seem to be often insufficient, as they are generally based on simplified representations of urban space and fail to account for human exposure and behaviour [24,29].

In historic urban centres, the interaction between spatial configurations, physical vulnerability, and pedestrian mobility requires multidimensional tools that can offer a detailed and updatable risk overview [54]. Therefore, it becomes essential to promote methodologies that synthesize the multiplicity of spatial, structural, and social data into accessible and dynamically adaptable decision-making models [55]. In this context, the implementation of Geographic Information Systems (GIS) [28,34,38,56,57], Building Information Modelling (BIM) [58,59], and Virtual Reality (VR) [60,61] technologies presents a strategic opportunity. Several studies leverage 3D environments and immersive interaction to display informational content and explore digital models related to flooding, such as vulnerability maps [38,62] or damage scenarios [62–64], while others concentrate on risk and safety training, involving instructions on egress paths [65] or identification of protection elements [66].

If properly designed, these tools not only support technical and planning decisions but also serve as communication interfaces to improve risk awareness among citizens and local stakeholders [38,61]. For example, immersive visualization of flood scenarios can significantly improve public understanding of risk dynamics, encouraging more informed and prudent behaviours [60]. At the same time, simulating alternative scenarios in digital environments allows decision-makers to evaluate the effectiveness of different mitigation strategies before their implementation [67].

Despite the ongoing and rapidly evolving scientific debate on the use of digital technologies for risk assessment and communication, their methodological and operational integration into coordinated data-driven processes (through the development of standardized ontologies and interoperable information flows) remains a significant research challenge [38,68]. However, this integration is particularly effective in addressing key requirements of risk analysis and management strategies, especially in historical contexts, by mainly considering scalability and typological classification [63].

First, scalability refers to the ability to harmonize assessment methods and results considering the different levels that constitute the urban structure/system/organism, by mainly linking the macro-scale with the meso-scale as reliable scale levels for risk assessment and urban form resilience [38,69–71]. In particular, the macro-scale level refers to the whole urban area or to a specific urban district, relying on its consolidated morphological, infrastructural, and functional configuration. The meso-scale levels, indeed, move towards building blocks and their surrounding open spaces, analysed in terms of their constructional features and usage patterns, thus by considering the aggregation of individual buildings (which represent the micro-scale level). Such multiscale alignment enables the identification of critical scenarios and the prioritization of interventions, allowing for progressively more detailed analyses as the granularity of available data increases. For instance, the macro-scale classification of urban block geometry and layout, building density and height, the location and orientation of entrances, internal courtyards, the degree of connectivity between public and private spaces, or proximity to watercourses, enables the development of analytical models useful for risk prediction and management, even in the absence of detailed local data [72,73]. Considering the urban form and its features [31,74], the spatial configuration of historic centres directly influences not only hydrodynamic patterns but also pedestrian evacuation patterns during flood events. These patterns can be incorporated into risk assessment frameworks to produce more realistic scenarios that reflect the interplay between urban morphology and human response [54,75]. In addition, meso-scale building data (regarding construction components, state of conservation, and functions hosted on different floors, whether derived from statistical surveys or on-site assessments) can support a more detailed identification of building vulnerability. Moreover, they allow for a refinement of user-related vulnerability and exposure assessments, by enabling the precise identification of activity types and, consequently, the estimation and profiling of the number and characteristics of the users involved.

Typological classification refers to the possibility of linking multiscale analyses conducted on real-world cases to schematic and idealized typological configurations that are representative of recurring conditions [31,73,76,77]. Typological scenarios go beyond a purely geometric classification, representing operational tools to simulate hazard, vulnerability, and exposure dynamics more accurately. This approach also allows knowledge transfer between case studies, reducing the need for context-specific analyses and supporting the development of scalable and adaptable mitigation strategies. By contributing to the abstraction of the built environment, it also helps avoid potential over-sensitization of local populations. Moreover, it lends itself particularly well to digital solutions for risk visualization and communication targeted at stakeholders, especially within immersive and interactive environments, by reducing computational loads and enhancing the intuitiveness of the user experience [61].

The considerations outlined above provide the rationale for this study, which seeks to develop the methodological framework and testbed demonstration of an integrated GIS-BIM-VR digital ecosystem, discussing its potential to support flood risk assessment and management in historic urban contexts. The research, as part of the broader ReACT project, within the Italian Extended Partnership RETURN, follows a scalability logic (from GIS to BIM), encompassing multiple dimensions, data types, and levels of detail for hazard, vulnerability, and exposure assessment, and a typological approach (from BIM to VR) aimed at communicating data, maps, and relations in a flexible and transferable manner.

The manuscript is therefore structured as follows: Section 2 generally presents the theoretical framework of the methodology. This relies on the logical organization of a GIS database containing building-vulnerability indicators derived from the literature, as well as user-occupancy indicators, which are useful for identifying typological clusters of the built environment. These clusters are then represented in a BIM environment for ready-to-use VR visualization, together with outputs from hazard and evacuation simulations. Section 3 applies the general framework to a testbed in order to demonstrate the methods for acquiring and processing real data in geographic and building information systems, to perform cluster analysis for the identification of typological environments, to illustrate the creation of emergency timelines and scenarios under representative hazard and evacuation conditions, and to provide operational details for the BIM-VR implementation of the various vulnerability, hazard, and exposure maps produced. Section 4 offers a discussion of the main considerations emerging from the demonstration, supporting broader reflections on the impacts and implications of this type of solution.

2. Theoretical framework of the methodology

The development of an integrated GIS-BIM-VR digital ecosystem to support flood risk management in historic urban centres is composed of four main phases, encompassing: (1) GIS-based data collection, (2) cluster analysis for definition of typological built environments, feeding hazard and evacuation modelling, (3) BIM-based modelling and (4) VR-based visualization (Fig. 1).

In detail:

(1) GIS-based data collection (Section 2.1) is proposed to be applied in a real historic centre at the macro-scale and it aims at the harmonization of heterogeneous factors involved in flood risk assessment and mitigation, both static (e.g., building vulnerability) and dynamic (e.g., user occupancy influencing evacuation dynamics and exposure levels). This enables the collection and analysis of information related to morphological urban layout, material-constructional-conservative characteristics of buildings, and intended use of indoor and outdoor spaces, according to a standardized framework toward the following cluster analysis.

(2) Cluster analysis (Section 2.2) of the main building vulnerability and user occupancy factors from the GIS database, along with the urban morphology, aims at the identification of built environment typologies at the meso-scale, thus referring to a schematic and idealized system of blocks, streets and squares. This typological model, which incorporates vulnerability and occupancy attributes, directly informs the sub-sequent BIM-based parametric modelling of building blocks. It also serves as the basis for the simulation of: (i) hazard, aimed at estimating water velocity and depths; and, in turn (ii) evacuation, aimed at predicting interactions between pedestrians and hazard from floodwaters' velocity and depth, based on number, type and position of

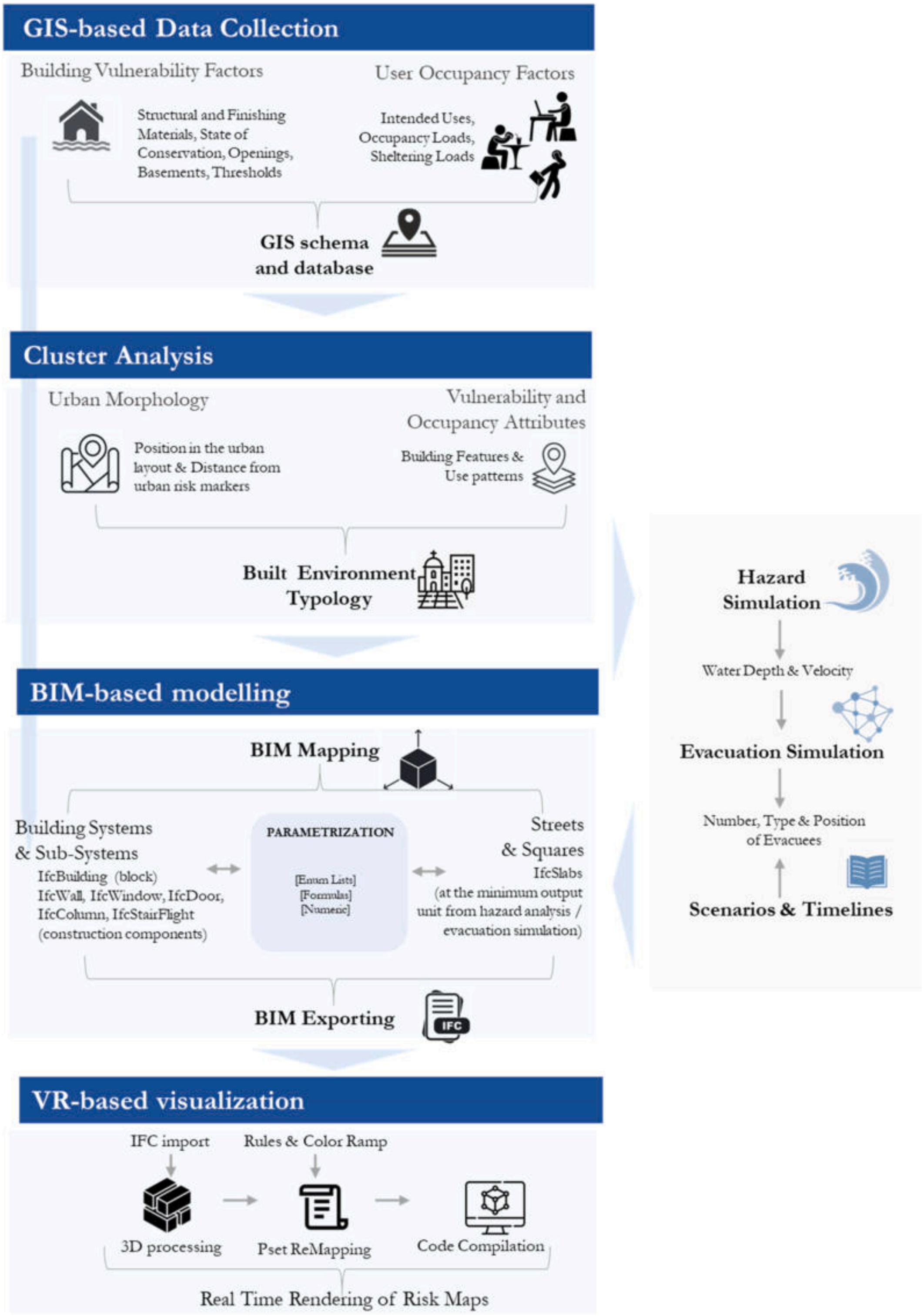

Fig. 1. Methodological workflow.

evacuees, and according to targeted scenarios and storytelling (Section 2.2.1). Moreover, the results of both the hazard and evacuation simulations also feed back into the same BIM model for streets and squares.

(3) BIM-based modelling (Section 2.3) aims at representing the typological built environment. This involves a systematic model breakdown into its physical components - building blocks, and their construction elements, as well as streets and squares - which must be discretized to match the minimum unit of analysis from building vulnerability and user occupancy assessment (blocks and construction elements), and from hazard and evacuation assessments (streets and open spaces). Each component is to be enriched with unified parameters, defined through predefined descriptor lists and governed by calculation formulas. This structure ensures the semantic coherence across different models (facilitating comparative analyses), and the unambiguous exportability of both the geometric and informational content for VR animation.

(4) VR-based visualization (Section 2.4) relies on the automation of the BIM-to-VR workflow for the direct visualization of the typological environment model and its associated content - hazard, vulnerability, and exposure parameters - within the VR environment. The system supports ready-to-use procedures for querying data from the model entities and mapping model parameters and descriptors through colour patterns pre-associated with risk variability ranges.

The following sub-sections provide a detailed description of the methods and tools proposed for each phase. It should be noted that the risk factors considered across the various areas of interest are based on existing literature, as explicitly referenced throughout the text.

2.1. Methods for GIS data collection

Data collection within the GIS environment aims to centralize all multi-scalar information relevant to flood risk assessment in an historic urban area, drawing from cartographic sources, institutional documents, statistical indicators, and direct field observations. Therefore, as previously mentioned, this phase is applied to the real-world context of one or more case study areas.

The primary goal is to integrate geometric data related to the morphological configuration of the urban settlement (e.g., block layout and orientation, building footprints and heights, street dimensions and slopes, presence of inner courtyards and public squares, access systems and connections between public and private spaces) with material-constructional-conservative characteristics associated with building systems and subsystems (e.g. construction techniques, size and type of openings, and level differences between interior and exterior).

To this set of static data - describing the physical consistency of the built environment and informing its vulnerability - are added

Table 1

SQL-supported GIS Attribute Schema for Building Vulnerability (BV) and User occupancy Factors (UF) – short version (Attributes marked with * are used in the building block clustering process - see Section 2.2.1).

Description	Data Type	Calculated [Yes/No]	Code
Building Vulnerability - state of conservation	String	No	BV_sc*
Building vulnerability - structural material	String	No	BV_sm
Building vulnerability - finishing material	String	No	BV_fm
Building vulnerability – type and condition of opening frames	String	No	BV_wd*
Building vulnerability - ground floor openings	String	No	BV_og*
Building vulnerability - existing basement	String	No	BV_eb*
Building vulnerability -door threshold	String	No	BV_dt*
weight of BV_sc	Integer	Yes	BV_sc_w
weight of BV_sm	Integer	Yes	BV_sm_w
weight of BV_fm	Integer	Yes	BV_fm_w
weight of BV_wd	Integer	Yes	BV_wd_w
weight of BV_og	Integer	Yes	BV_og_w
weight of BV_eb	Integer	Yes	BV_eb_w
weight of BV_dt	Integer	Yes	BV_dt_w
Building Vulnerability Index - Normalized weight of BV indicators	Real	Yes	BVI
Primary intended use at ground floor	String	No	UF_iu1*
Area of ground floor	Integer	No	UF_iu1_a
Primary intended use at upper floors	String	No	UF_iu2
Area of upper floors	Integer	No	UF_iu2_a
Occupancy load of ground floor (daytime) – All intended uses open – Residents and Non-Residents	Real	Yes	UF_ol_g
Occupancy load of ground floor (evening) – All intended uses open, except from schools, institutions, and offices	Real	Yes	UF_ol_g_ev
Occupancy load of ground floor (night) – All intended uses closed, except from Residential – Only Residents	Real	Yes	UF_ol_g_ni
Occupancy load of upper floors (daytime) – All intended uses open – Residents and Non-Residents	Real	Yes	UF_ol_up
Occupancy load of upper floors (evening) – All intended uses open, except from schools, institutions, and offices	Real	Yes	UF_ol_up_ev
Occupancy load of upper floors (night) – All intended uses closed, except from Residential – Only Residents	Real	Yes	UF_ol_up_ni
Intended use at the ground floor extended at the upper floors	String	No	UF_iu_ex
Area of UF_iu_ex	Integer	No	UF_iu_ex_a
Sheltering load from ground floor toward upper floors	Real	Yes	UF_sl

informational layers on indoor space use, disaggregated by building and floor level. In fact, the second goal is to derive expected occupancy loads under both ordinary and emergency conditions, further disaggregated by time slot (e.g., daytime, evening, nighttime), and user type (residents vs. non-residents). This enables the construction of a dynamic condition profile to support exposure assessments through behavioural simulations of evacuation processes.

The result is a structured system of indicators and descriptors, elaborated from available literature and encoded as a SQL-supported GIS attribute schema for building units (Appendix A), which systematically identifies the key risk data associated with a given area of interest (Table 1) [28,75].

In more detail, the GIS schema involves data collection on:

- Building vulnerability (*BV_xy*) factors, which were derived, in terms of attributes, descriptors, and weights, from some recent studies [20,28,29], developed by expert panel consultation and validated on Mediterranean historic centres prone to flooding. Here, their adoption is intended for demonstrative purposes and is motivated by the fact that the selected factors are referred to a broad range of building components, thereby enabling a full exploration of the data-driven process of digital modelling, which remains applicable to alternative combinations of attributes, descriptors, and weights, provided that their underlying logical structure is preserved. In particular, the literature studied report seven attributes that collectively define the susceptibility of structural and non-structural components to flood-induced damage and water infiltration, thereby contributing to the overall risk profile of a building. Some pertain to construction characteristics, such as the state of conservation (*BV_sc*) reflecting the physical condition of the building, where deterioration reduces resistance and facilitates infiltration; the structural material (*BV_sm*) considering the porosity and water sensitivity of load-bearing components; and, the finishing material (*BV_fm*) evaluating the ability of the outer cladding to act as a barrier against moisture. Others relate to water access points, such as the type and condition of window and door opening frames (*BV_wd*) that influence permeability; the ground floor openings (*BV_og*) representing potential entry paths for water; the presence of basements (*BV_eb*) that significantly heightens flood sensitivity due to their low elevation and likelihood of rapid inundation, and the height of the door threshold (*BV_dt*), relative to the plinth, affecting protection against shallow flooding. Each attribute is associated with four possible descriptors representing different vulnerability levels. For each descriptor alternative, a corresponding weight (e.g., *BV_sc_w* for *BV_sc*) is assigned by the above-mentioned literature studies [28] based on its relative contribution to overall vulnerability. The weights rank vulnerability from lowest to highest by weights of 10, 40, 70, and 100 respectively (e.g. *BV_sc_w* is equal to 10 for 'No damage/cracking', 40 for "Slight cracking/moisture', 70 for 'Generalized cracking/settlement/erosion', and 100 for 'Deformation/serious material decay). In the GIS environment, they are determined using SQL CASE WHEN-THEN statements and further elaborated in a composite Building Vulnerability Index (*BVI*), by computing the weighted average of all seven indicator weights, which is then normalized to produce a standardized index value.
- User occupancy factors *(UF_xy)* at the building level are collected, beginning with the identification of the primary intended uses (i.e., residential, office, school, hospital, commercial, institutional, religious, museum, theatre, hotel, bar, restaurant, sport) both on the ground floor (*UF_iu1*) and upper floors (*UF_iu2*), along with their respective areas (*UF_iu1_a*, *UF_iu2_a*). Based on these, the occupancy load (persons, pp) is calculated for each level (*UF_ol_g* for the ground floor and *UF_ol_up* for the upper floors) by applying the occupancy load rate (persons per square meter, pp/m^2) associated with each intended use under ordinary conditions [75]. These data provide an overall picture of the people potentially involved in an evacuation process. Nonetheless, considering that the aforementioned occupancy loads correspond to a daytime frame when all uses are operational, the same calculation is also carried out for the evening (*UF_ol_g_ev* for the ground floor and *UF_ol_up_ev* for the upper floors), assuming that schools, institutions, and offices are closed and for the nighttime (*UF_ol_g_ni* for the ground floor and *UF_ol_up_ni* for the upper floors), when only residential buildings are occupied. Nighttime occupancy loads can also be used as a proxy for the number of residents.

Furthermore, during evacuation, the presence of public functions on the ground floor extending to the upper floors can be relevant, as evacuees may seek relocate by moving upward rather than exiting the building. Based on this assumption, additional occupancy parameters are calculated for all building units. *UF_iu_ex* refers to an intended public use at the ground floor with corresponding area *UF_iu_ex_a* on the upper floors. Thus, *UF_sl* - the number of people sheltering from ground floor toward upper floors - is derived as the difference between an emergency occupancy load of 1 person/m^2 and the ordinary occupancy load determined by the intended use, assuming the upper floors offer additional capacity to accommodate people from the ground floor, without exceeding a crowding threshold that remains non-critical [75]. This value makes it possible to adjust the actual number of people who must evacuate the building from the ground floor to open spaces, as they are unable to activate shelter-in-place strategies on the upper floors. An evacuation ratio might also be introduced between the sheltering occupancy load (*UF_sl*) and the ordinary occupancy load on the ground floor (*UF_ol_g*) of buildings that enable the sheltering.

All the factors mentioned, in addition to contributing to the knowledge framework at the macro scale of the real-world case, guide the typological clustering at the meso-scale (Section 2.2).

2.2. Cluster analysis

According to the whole framework shown in Fig. 1, cluster analysis methods are used to define typological conditions of built environments (Section 2.2.1), which are then associated with hazard, evacuation and emergency timeline modelling (Section 2.2.2).

2.2.1. Definition of typological built environment

The clustering process is applied to define typological features for the building blocks and the street network. This process relies on unsupervised classification techniques aimed at identifying groups of buildings and streets sharing morphological and functional characteristics [78,79]. The construction of the typological model is grounded on the analysis of the real-world dataset that informs the selection and organization of the methodological GIS-based survey (Section 2.1). To this end, three steps are provided:

The first step involves the identification of a sub-set of descriptive indicators. According to previous approaches applied to built environments typologies identification [76], indicators are categorized into:

- active, meaning they are directly employed in the clustering procedure, and
- supplementary, which are herein used exclusively in the interpretative phase, considering, for instance, those characterized by very high frequency of limited ranges of values and/or consistent presence of outliers, which could contribute to possible distortions in the definition of the groups.

For the building blocks, the clustering process adopts the attributes marked with * in Table 1 as active indicators, along with the following further parameters to capture the urban context and emergency response capacity [80]:

a. (the position of each building block within the urban layout, in respect to relevant urban risk markers (e.g. the source of risk, such as the riverfront for riverine or coastal urban contexts);
b. the typology of facing public open space (street or urban square);
c. the capacity of the buildings to support shelter-in-place toward the upper floors.

Input data refer to individual structural units, as discussed in Section 2.1, and thus an aggregation process is performed to shift the analysis to the building block level. For the street network, according to previous works [31,74], the active indicators considered are:

a. the dimensions of building block areas, assumed to be non-floodable and idealized as rectangles with base b [m], assumed parallel to the river, and length l [m], assumed perpendicular to the river;
b. the b/l ratio, which indicates a shape ratio of the rectangle, and thus can distinguishes if building blocks are mainly oriented among parallel (if $b/l > 1$) and perpendicular (if $b/l < 1$) direction in respect to the river;
c. the average street width [m], used to represent streets as open channels, considering each building side along direction b and l.
d. the slope of each street, in respect to the river [5], for streets perpendicular and parallel to the river [74].

As the second step. given the objectives of the study, either hierarchical and non-hierarchical approaches are employed [81–83] to ensure the reliability of the clustering process. The process takes into account the following steps:

1. hierarchical clustering using the single-linkage method to identify outliers, defined as observations most distant from the dataset centroid. The resulting dendrogram highlights those elements that only cluster in the final stages of the process and are thus excluded from subsequent analyses. This step improves the robustness and reliability of the segmentation [76,84];
2. main clustering through the k-modes for building blocks, working on categorical active indicators, using Hamming distance as a similarity metric and identifying actual representative objects within the dataset [78]. The algorithm is initialized with a random selection of initial modes and iteratively updated until cluster assignments stabilize.
3. main clustering for the street network, using the k-means algorithm, as it is more suitable for numerical active indicators [81].

To determine the optimal number of clusters, two statistical indicators are computed across a partition range from two to ten clusters: the coefficient of determination (R^2), which measures the proportion of variance explained by the model, and the pseudo-F statistic, which evaluates the between-group variance relative to the within-group variance. Through the identification of inflection points and peaks in their respective plots, the combined analysis of these metrics supports the selection of the most appropriate number of clusters [76].

Once the final segmentation is obtained, results are finally organized into typological built environments to be implemented in the BIM model [85]. To this end, statistical analyses are performed:

1. for each cluster, to derive its frequency on the GIS-based data from the case study. This allows to consider the variability of typologies of building blocks and streets s within the urban layout;
2. for each active indicator in each cluster, to describe additional variations within each typological condition. The modal value is adopted for categorical indicators, while the mean (also ideal for normal distribution) and median (also ideal for non-normal distribution) values are considered for numerical indicators.

2.2.2. *Hazard, evacuation and emergency timeline modelling*

The typological built environment is then used as input for hazard and evacuation modelling, as well as for emergency timelines and scenarios definition [32,86–88]. Flood hazard conditions [29,30,32,74,89] are modelled using a typological approach, focusing on the fluvial flood scenario. Reference hydrographs from similar context are assumed. Then floodwater spreading is simulated assuming that building blocks are non-permeable areas, and thus that waters can only flow along the street network [77]. Water velocity V [m/s] and depths D [m] are provided as main simulation outputs, to inform both the BIM model and the evacuation simulation tools. The product DV [m^2/s] is then used as leading direct parameter for hazard assessment, since it can be used to estimate limit conditions for stability of users and vehicles in floodwaters, related occurrence of casualties, and possible damage levels for buildings [32,90]. In particular, DV effects on users are evaluated depending on the individual age class, to better link the user vulnerability factors with the effects of floodwaters [53]. DV values are calculated considering the average conditions of each component of the street network or each subpart [77] that constitute the minimum informative unit for the following BIM description.

Evacuation modelling is considered to assess evacuation timings, detect critical interactions between hosted users and the built environment, and then couple results with those of flood hazard assessment [19,45,46]. Evacuation models are informed of the number and typology of users present in the urban layout, and they consider the movement of people before or during the flood. To this end, an agent-based approaches is herein used since it can take into account the specific features of each simulated individuals (including initial position, age, gender, awareness, risk perception, adopted behaviours) and of the local flood hazard conditions (in terms of V, D and DV) [45]. These factors affect the way users move in the urban built environment, and thus allow to derive evacuation outputs per simulated individual, including: path selection; evacuation timings; interactions with other individuals and critical floodwaters conditions; probability to be involved in casualties; final position in safe or unsafe areas of the urban layout. According to previous works, main risk performances indicators, indices and metrices include [19,48,89,90]: the impact of stability conditions and the number of casualties or trapped users [persons]; the distance from the hazard sources and the user travelled distance [m]; the evacuation timing [s] and flows [persons/s]. Similarly to hazard modelling, these indicators are aggregated at the scale of the minimum informative unit for the following BIM description of the street network.

Hazard and evacuation modelling is used to assess risk levels depending on the scenario conditions, and, thus, on one or more specific flood emergency timelines, the related paths of events identified within these timelines and the resulting possible risk scenarios [86,87]. Emergency timeline modelling mainly considers:

- the built environment use conditions, which can then refer to different times of the year, week, and day to consider, also using event tree representations [32]. The main varying parameter are hence the number, typology and position of the exposed users, thus being correlated with UF parameters collected according to Section 2.1 procedures;
- the presence of early warning scenarios [32,91], considering whether alerts can be addressed or not towards the population, as well as whether users follow or not them by activating or not proper emergency procedures.

In particular, concerning warnings, three levels are assumed in this work, involving specific recommended actions and safety behaviours in view of the possible flood event impacts.[1] The evacuation process activation depends on: (1) the rapidity of the event evolution, which can be assessed through the hazard model, and on (2) the quantity, quality and adopted behaviours of exposure users, which can be assessed through the evacuation model. In this way, risk levels per minimum informative unit of the BIM model (thus, the component of the street network) are calculated for each path of events within a given emergency timeline, offering valuable insights for informed decision making.

2.3. Methods for BIM implementation

The typological clustering of the historic urban built environment at the meso-scale (see Section 2.2) can be integrated into a BIM environment through the implementation of a standardized data model. This model is based on a hierarchical taxonomy of physical components (e.g., building blocks, construction elements, squares, streets), consistently with the principles of BIM data schema structure. Such a system enables enhanced spatial and semantic discretization, prioritizing the minimum information units provided by hazard and evacuation analyses (component of the street/square network or subpart of it) and building vulnerability investigation (attributes and descriptors of construction elements and buildings), also in view of their VR-based visualization (Fig. 2).

Increasingly adopted in the context of urban and architectural digitalization, this paradigm emphasises that the information model should not only represent the built environment geometrically but also be structured to support specific operational, analytical, and communication objectives [92]. For these reasons, the BIM authoring phase, as proposed in this work, is conceived as a true meta-representation activity [93] aimed at managing the complexity and heterogeneity of the urban context, while preserving semantic and functional consistency for the processing and subsequent mapping of risk factors and indices within VR simulation environments.

In particular, for both building blocks and open spaces, the integration between geometric and semantic data is achieved through the assignment of *Property Sets (PSets)* parameterised on; descriptive lists (enum datatype), as in the case of the four alternatives corresponding to each of the seven Building Vulnerability factors (*BV_xy*) for the construction elements (e.g. openings, basements, thresholds) in typological blocks; pre-established rules and formulas, through the use of visual scripting, as in the case of the attribution of weights for the above-mentioned alternatives or for the calculation of the composite *BVI* for each block; or numerical values, as in the case of output data from hazard simulations – e.g., water velocity (*V*) and depths (*D*) – and evacuation modelling – e.g., risk indices – mapped onto open spaces for selected risk scenario and flood emergency timelines.

By structuring the informative description of the model and its entities, this approach enables a machine-readable representation that better supports automated, interactive simulations.

These approaches are well-documented in the literature on simulated 3D urban models [94], where coding, often based on

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[1] e.g. in reference to this work application context, see Italian Civil protection body guidelines https://www.iononrischio.gov.it/it/preparati/alluvione/# (last access: 25/07/2025).

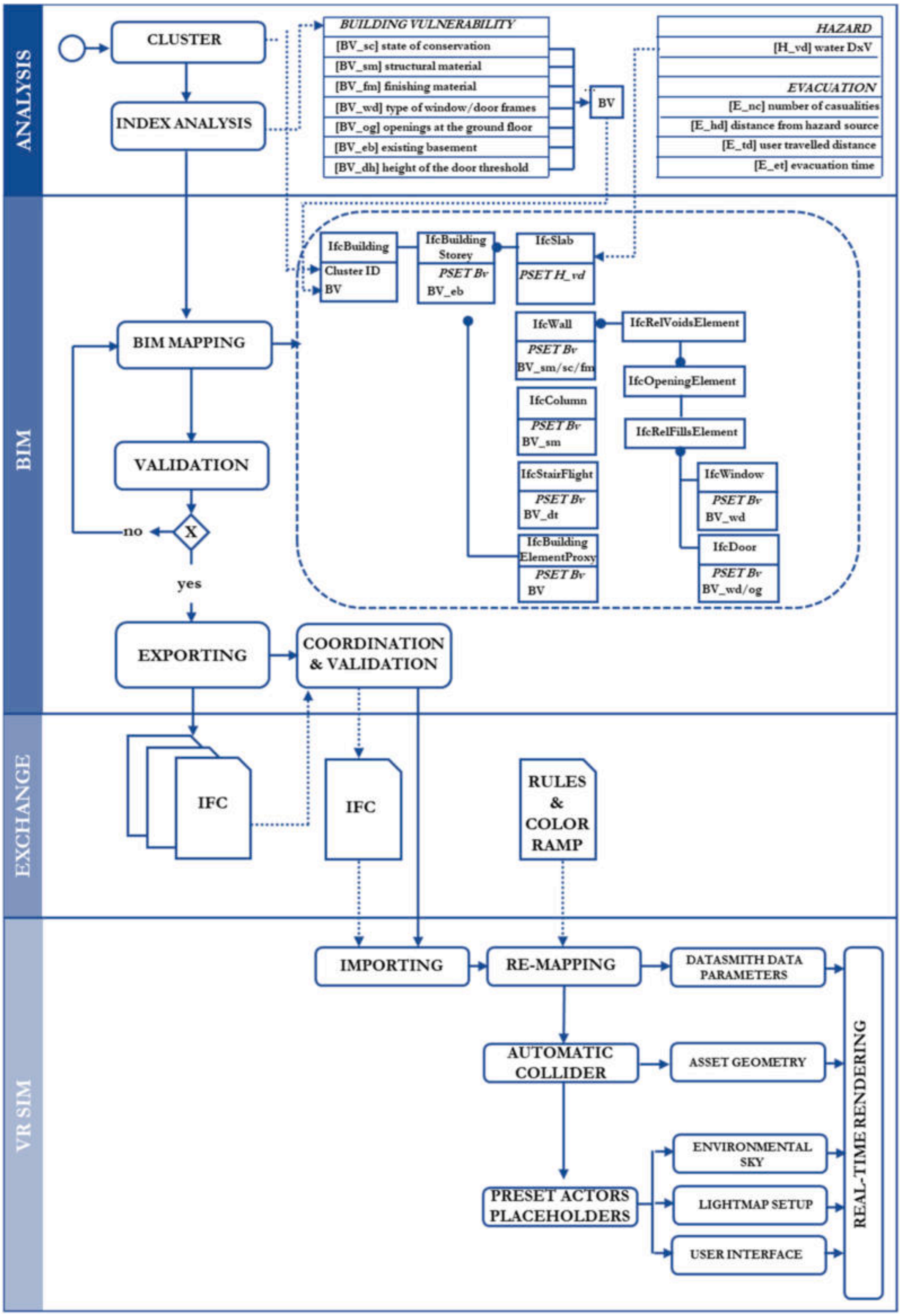

Fig. 2. BIM-VR pipeline.

standards such as CityGML or the more recent CityJSON, enables the representation of urban entities through multi-level structures. These are no longer conceived as mere geometric containers, but as intelligent objects capable of supporting processes of visualization, analysis, simulation, and customised interaction.

In this context, since the proposed methodological flow entails the description of risk factors related to entire blocks, specific construction components, and open spaces, the first modelling issue concerns the typological clusters, considered as information aggregators while maintaining their distinct geometric identity. This aggregation can be developed according to two alternative operational strategies.

The first method involves the use of a single BIM file in which all typological clusters and their corresponding construction details are modelled. In this scenario, the entire urban system is conceived as a unified model, enabling centralised information management, immediate semantic consistency among modelled entities, and greater fluidity in defining hierarchical and functional relationships between entities.

This structure enhances integration across construction elements and facilitates the assignment of shared properties and aggregated indices, particularly effective when the model's extent is limited or when a unified representational logic or governance framework is preferred.

Within this first configuration, the mapping of attributes and indices is accomplished through the introduction of symbolic geometries, typically represented by volumetric masses encoded as generic *IfcBuildingElementProxy* entities. These are appropriately parameterised to serve abstraction and synthesis purposes. Acting as conceptual containers, these masses represent both the typological affiliation of buildings within a cluster, and, through customised PSets, host aggregated risk indicators (e.g., *BVI*), supporting subsequent visualization in simulation environments.

The second method, is based on the development of separate BIM models for each cluster, later federated within a coordinated environment. This approach is particularly effective in more complex urban contexts or where distributed modelling by several users is desired. In this case, each model represents an autonomous and semantically homogeneous entity, whose federation requires the adoption of a shared spatial reference. It is therefore essential to define a common geometric datum or a Unique Reference System (URS) that guarantees spatial consistency between the different models created, ensuring spatial consistency within the virtual urban space.

In the second configuration, the aggregated BVI indices can be associated with the *IfcBuilding* entity, which, assumes an aggregative rather than unitary role. The geometric representation of this attribution is thus delegated to the simulation phase, potentially through the real-time generation of symbolic geometries.

Subsequently to the typological clustering, the modelling activity focuses on individual construction elements of building blocks by a symbolic normalization process, designed to render the specific entities for each attribute and descriptor more recognisable and distinct. This phase entails a morphometric definition conceived as a synthesis of symbolic rules and representational codifications, aimed at maximising expressive clarity while minimising topological complexity.

Following the three-dimensional generation of each entity, a *PropertySet* assignment phase is carried out to construct a structured, coherent, and functionally oriented representation of the Building Vulnerability factors (Table 2). This step is crucial to ensure effective functional interoperability between BIM authoring environments and VR simulation platforms.

The parametric mapping process is not limited to a simple formal enrichment of geometric entities but consists of a true computational structuring of the model, based on the use of controlled dictionaries and domain ontologies. This formalization guarantees the syntax and semantic consistency of the entire information system.

The information attributes associated with IFC classes define the relational structure that links data to construction entities. During the subsequent VR mapping phase, these entities can act as geometric containers, visually conveying the parametric variation of specific parameters and making explicit the relationships between morphological characteristics and risk values.

From this perspective, most of the construction elements (surface finishes, openings, window and door frames), already visible in the building envelope, can still be described using customized geometrization rules, aligned with shared levels of detail, based on objectives of stylistic recognizability or typological discretization.

A different case concerns the identification of construction components, such as underground or semi-underground floors, which often lack clear morphological evidence on the façade. To address this, simplified modelling strategies should be adopted to convey

Table 2
Association between IFC entities and Building Vulnerability factors (BV_xy).

IFC entity	Description	Property
IfcBuilding o IfcElementProxy	Cluster	Cluster ID BV
IfcBuildingStorey	Building levels	BV_eb
IfcWall	External walls	BV_sm BV_sc BV_fm
IfcColumn	Columns	BV_sm
IfcWindow	Windows	BV_wd
IfcDoor	Doors	BV_wd BV_og
IfcStairFlight	Threshold	BV_dt

latent spatial and functional information not directly inferable from the building envelope, yet crucial for the analytical and applicative goals of this study. In this application, a base strip was introduced by modelling a string course, used as a visual marker to suggest the possible presence of underground spaces not clearly visible from the façade (*BV_eb*).

Finally, the modelling activity of linear elements, such as street networks, and spatial elements, such as squares, is carried out using the generic *IfcSlab* entity, rather than the more specific *IfcRoad*, whose adoption is currently limited to the IFC 4.3 schema, still not fully supported by most mainstream software environments for building information management. This choice, although stemming from a functionally adaptive approach, ensures broader interoperability and greater compatibility with established modelling, authoring, and virtualization workflows. At the same time, it preserves the ability to associate structured information relevant to hazard and evacuation, thereby expanding the analytical potential of the model without compromising its operational efficiency. The topological definition of these elements is based on a geometric decomposition aligned with the selected level of information granularity. This allows for the identification of minimum representational units that can be associated with the analysed data, effectively constituting a parameter of informational resolution within the simulation process. In this case, the minimum units are derived from the typical positioning of gauging points in hazard modelling [74] and the organization of human factors and evacuation data according to urban public open spaces as referring elements for the meso-scale analysis (i.e. dividing into homogeneous areas which also consider the layout variations of the urban spaces) [32,34,90]. This work proposes: quarter areas for squares; street sections from corner to corner of the block if parallel to the river; and street segments from intersection centroid to intersection centroid if perpendicular to the river.

2.4. Methods for VR development

Concerning the following VR implementation, the use of high-fidelity virtual environments, developed using real-time graphics engines, represents an advanced methodological opportunity for the functional use of BIM information models within simulation domains, which are more oriented towards exploratory analysis and decision support.

However, the use of such environments requires the geometric reconfiguration of entities, often based on topological arrangements that prioritise form over informational mapping (Fig. 2).

To this end, a workflow is integrated that enables the import and interpretation of information containers encoded in the IFC schema, ensuring the preservation of position, geometry, and, critically, the associated information attributes.

In this phase of domain transition, from BIM to VR, the three-dimensional typological model of the built environment undergoes a phase of controlled abstraction, in which the geometric simplification envisaged during the modelling phase is further configured into dynamic levels of detail (LODs), maintaining the information and relational structure implicit in the IFC model. In particular, the conversion workflow not only enables the automated transformation of IFC entities into static geometric representations, but also includes the three-dimensional re-engineering of IfcSlab and IfcWall entities into dedicated collider components, aimed at accurately defining and constraining the physical behavior of the simulated environment.

Furthermore, the Property Set (PSet) attributes defined within the IFC objects are translated into instance-level parameters for each StaticMeshActor, thereby ensuring their accessibility and usability within the simulation framework. These parameters are subsequently remapped through a configurable, parametric ColorRamp, implemented via parametric materials whose chromatic properties dynamically adapt to real-time visualization and representation requirements.

The proposed workflow also preserves the attributions defined within the BIM environment, enabling the configuration of a mapping system that links attribute lists to shaders optimized for real-time rendering. This enables the visualization, through false-colour mapping, of all qualitative and quantitative descriptors of the information model for the various clusters, building blocks, streets, and squares, at the minimum descriptive scale derived from hazard, vulnerability, and exposure analyses.

With a more general reference to the user experience for VR interaction with the models and informational content, the choice falls on a First-Person Point of View (First-Person POV) exploration mode with six degrees of freedom (6DoF), enhanced by interactive pointing systems activated via input devices such as a mouse or motion controller, depending on the hardware configuration and level of immersion.

This configuration allows for a sort of logical decoupling between the visual axis and the centre of operational intention [95,96], expanding the possibilities for semantic interaction with objects in the scene and allowing direct queries on the information content associated with the modelled elements.

The user operates within a three-dimensional environment where spatial perception is enhanced by selective and context-aware interaction. The navigation interface, inspired by video game interaction paradigms, relies on established control schemes implemented through combined input devices (keyboard, mouse, gamepad), and can be extended to immersive VR systems, fostering intuitive and natural engagement with the simulated space.

This combination of perceptual immersion and informational access helps to strengthen the empathetic dimension of the experience, fostering deeper cognitive engagement and enhancing the effectiveness of risk-related content communication.

3. Testbed demonstration

The case study focuses on the municipality of Senigallia (AN), located along the Adriatic coast in Central Italy. Originally founded by the Romans, the city is built on a flat coastal plain crossed by the Misa River, which flows through the historic centre before reaching the Adriatic Sea. The urban layout of the historic centre retains its original orthogonal grid, derived from the roman cardo and decumanus scheme. The city's specific geographic configuration, between a river system and the coastline, results in a structural condition of high hydraulic risk. During the summer, tourism increases significantly due to both coastal activities and the presence of major national and international events, leading to a substantial increase in temporary population. This seasonal anthropic pressure introduces distinct challenges for urban safety management, positioning Senigallia as a relevant context for analysing integrated risk mitigation strategies in fluvial and coastal environments with high demographic variability.

3.1. *GIS-based macro-scale investigation*

The historic centre of Senigallia (AN) was analysed according to Phase 1 of the methodology (see Section 2.1) over a significant portion comprising 280 buildings distributed across 61 urban building blocks (Fig. 3).

The data were implemented by the open-source software QGIS v3.42.0, based on information gathered from cartographic sources, institutional documents, and statistical indicators, as well as from direct on-site observations and remote assessments via Google Maps.

With regard to Building Vulnerability (*BV*) factors, the area exhibits a substantial degree of homogeneity in terms of a good state of conservation (*BV_sc*: 76 % No damage/cracking, 22 % Slight cracking/moisture), the prevalence of traditional structural and finishing materials (*BV_sm*: 88 % Masonry structures, *BV_fm*: 98 % Brick/plaster/regular dressed stone) and the low door threshold (*BV_dt*: 81 % Level with the outside, 13 % Less than 2 steps). In contrast, the data show greater heterogeneity (Fig. 4a-4b-4c) with respect to windows and doors type (*BV_wd*: 38 % Metals, 58 % Wood), opening at the ground floor (*BV_og*: 65 % Window and door openings, 25 % Large openings), and existing basement (*BV_eb*: 54 % No basement, 42 % Basement with windows, no direct access). Overall, the normalized building vulnerability index *BVI* (Fig. 4d) shows a mean value of 0.41, with a standard deviation of 0.08, within a range between 0.14 and 0.62.

Concerning the User Factors (*UF*), the primary intended uses at the ground floor (Fig. 4a) are mainly commercial (53 %) and secondarily for dwellings (12 %), restaurants (9 %) and offices (6 %). There are also several public complexes, including 5 museums, 2 schools, 2 theatres, and 2 institutional buildings, which generate significant occupancy loads during daytime (Fig. 5b), compared to evening (Fig. 5c) and especially night-time (Fig. 5d), when the total number of people decreases from about 30.000 to about 28.000 (−6.7 %) and about 300 (−99.0 %), respectively (Fig. 5). Nonetheless, some of the public complexes contribute to provide sheltering capacity on the upper floors, along with commercial activities, whenever they extend their use from the ground floor, with a total reduction of about 42 % of people evacuating toward open spaces during daytime.

3.2. *Clustering for meso-scale typological environment*

The typological urban model was developed through the clustering process defined in the second phase of the methodology (see Section 2.2).

The analysis encompassed the urban layout components of the historical city centres, according to the QGIS data sources defined in Section 3.1. Three clusters for the street network and four clusters for the building blocks, as reported in Appendix B, were identified to respectively trace the general morphology of the model, and the typological composition of the building blocks and their use conditions. The outcoming typological urban layout comprised fifteen building blocks and one square, arranged along a fluvial axis that serves as the main morphological reference, being also able to depict the case study layout organization. The street network configuration followed a regular grid of streets, with $b = 33\text{m}$ and $l = 66\text{m}$, assuming the modal value of the related indicators, and thus a homogenous characterization of the building layout. The slope of streets in the case study was close to zero (as modal and median

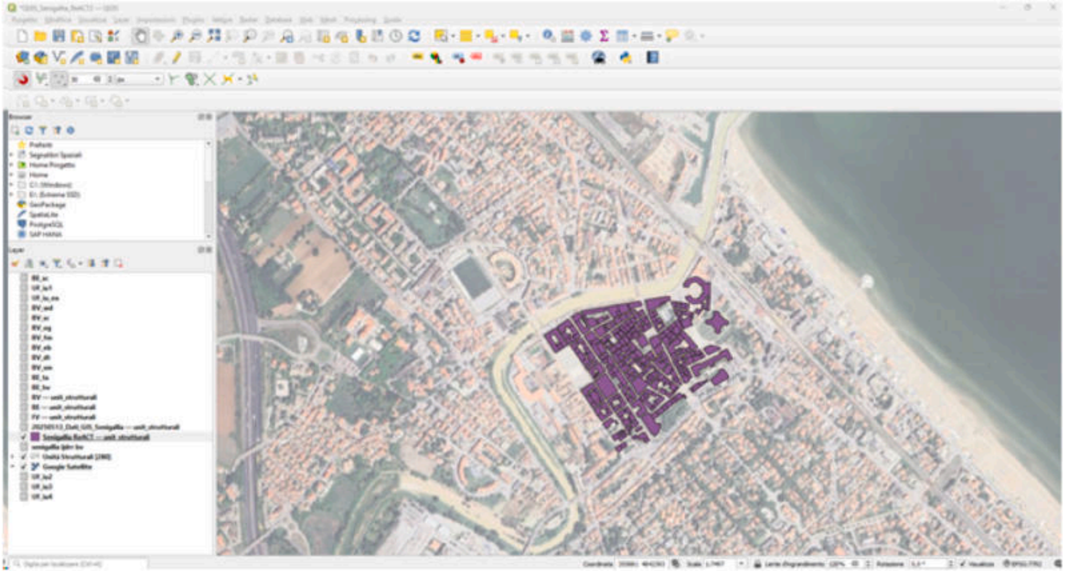

Fig. 3. Area under investigation.

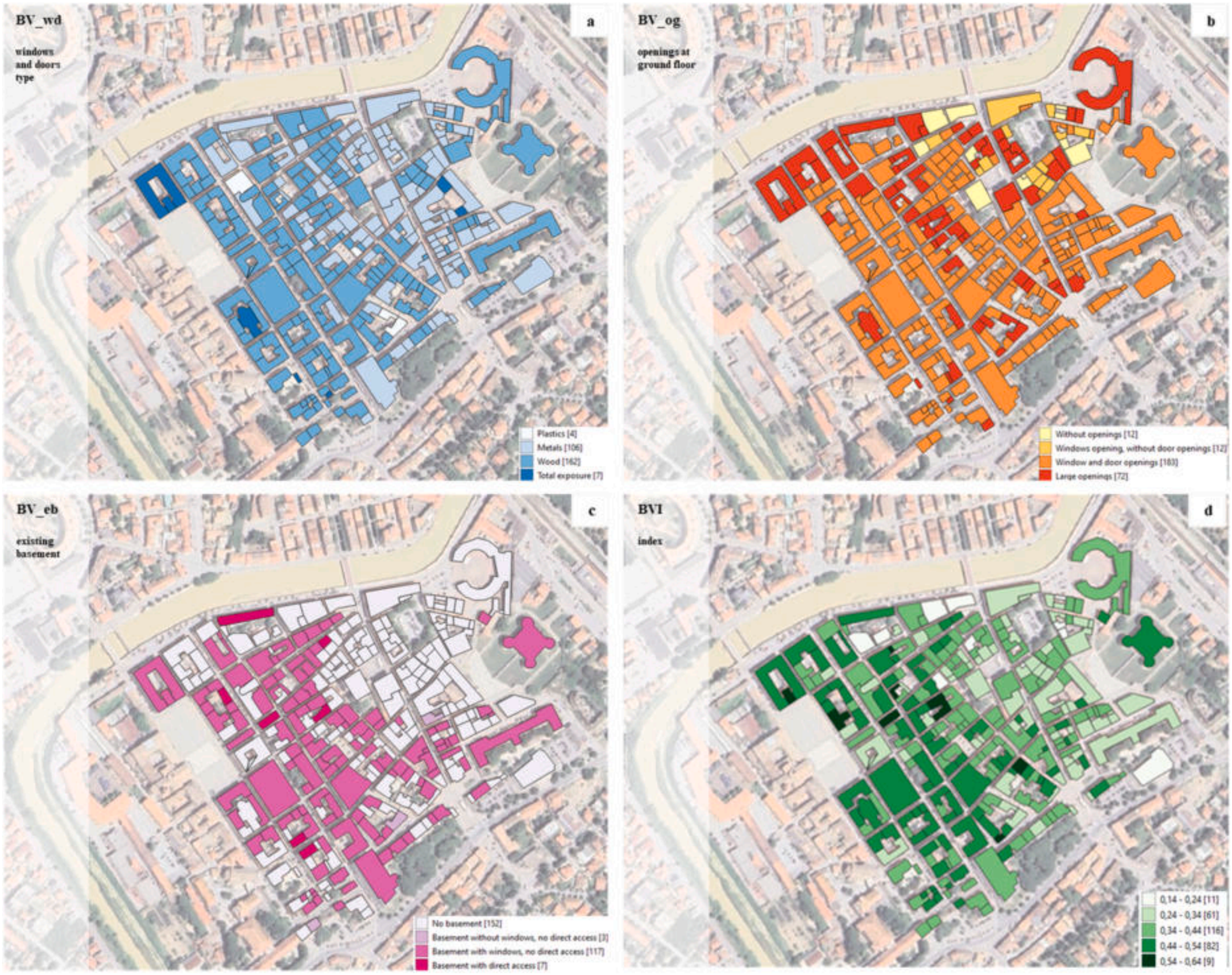

Fig. 4. QGIS maps of main building vulnerability factors and index: from top left clockwise: a. BV_wd, b. BV_og, d. BVI, c. BV_eb.

value), thus assuming almost level ground. Therefore, the building blocks were oriented with their longer sides perpendicular to the river ($b/l < 1$). An additional urban square, conceptualized as an empty block, was positioned adjacent to the riverfront, to additionally consider that this open space can collect fluvial floodwaters and thus induce critical conditions for facing users and building. Furthermore, street sections were defined by two distinct widths, reflecting the internal road hierarchy of the study area: 4 m for streets running parallel to the river and 6 m for those running orthogonally.

Regarding the typological clusters of the building blocks, representative groups of elements were defined for each building cluster, associating results with the analysis of statistical frequencies, and considering that related indicators were composed of categorical data. This approach captured both the dominant characteristics (as the modal value) and the internal variability of each configuration (assuming additional values depending on their statistical frequency in the sample), allowing for the assignment of coherent typologies to each building block in the model, as an essential step for subsequent BIM-based modelling.

To ensure consistency between the simulated model and the actual distribution of typologies in the historical centre, the percentage of building blocks belonging to each cluster in the real sample was calculated and proportionally assigned to the 15 building blocks in the model. Specifically, the four identified clusters were representative of the entire sample of analysed building blocks. In general terms, all of them considered good or adequate maintenance conditions (also associated with BV_sc), with absence or slight visible damage levels. Most of buildings hosted a basement level with windows, and openings (including large ones) at the ground level, affecting possible floodwaters intrusion. The four also clusters were essentially distinguished considering UF parameters, along with the shelter-in-place capacity of the buildings. Blocks were then mainly composed of (a) buildings hosting commercial areas at the ground level and residential areas at the upper levels, without effective vertical connection and thus limited possibility for the activation of shelter in place procedures (cluster 1, 56.6 % of blocks; cluster 3, 26.4 % of blocks; cluster 4, 13.2 % of blocks) and, conversely, (b) multi-storey public buildings (cluster 2, 3.8 % of blocks).

The spatial assignment of building block typologies was also guided by the position of each building block within the urban layout, in respect to the river (as source of hazard) and the typology of facing public open space (street or urban square), which was adopted by

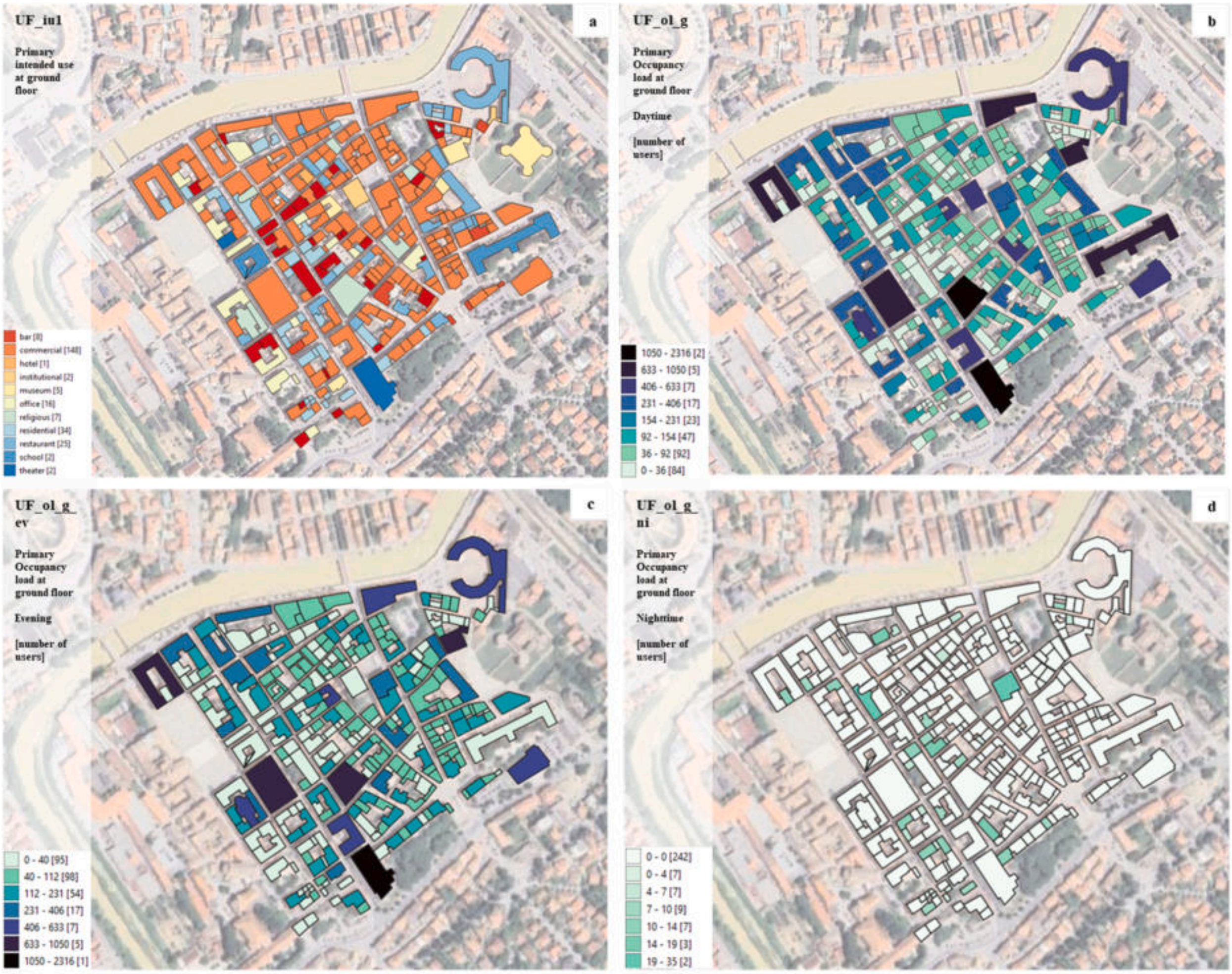

Fig. 5. QGIS maps of main user factors at ground floor. from top left clockwise: a. UF_iu1, b. UF_ol_g, c. UF_ol_ev, d. UF_ol_ni.

providing guidance without imposing a strict constraint. The final arrangement of building blocks within the environmental model, as shown in Fig. 6, thus reflected a balanced integration of cluster distribution, morphological coherence, and the inherent urban logic of the historical context, resulting in a configuration that is both representative and proportionally faithful to the original urban fabric. In the sake of completeness, the clustering-based description of each building block in Fig. 6 is detailed in Supplementary Material S1.

Following the definition of the typological urban model, the analysis incorporated the simulation of emergency scenarios related to flood risk, using a methodology based on paths of events within emergency timelines in reference to warning levels of the Italian Civil Protection Bodies. The response of the urban system was then assessed under two occupancy conditions: (a) the Baseline Occupancy Scenario, which essentially reflected a winter condition characterized by typical population density and absence of massgathering events; (b) the Maximum Occupancy Scenario, which represented a peak condition involving large-scale events (e.g. in a summer and holiday season), resulting in a significant increase in temporary population and urban load.

According to the Municipal Civil Protection Plan of Senigallia [97], three hydrogeological alert levels were associated with specific operational protocols:

- *Caution Phase (Yellow Alert):* triggered under potentially adverse weather conditions with limited risk. No restrictions are applied to mobility or public events. The users are mainly required to stay informed regarding official communications and potential hazards.
- *Pre-Alert Phase (Orange Alert):* associated with moderate risk. All massgatherings should be suspended, and residents are advised to remain indoors. Non-residents, particularly those attending temporary events, are hence required to leave the urban environment (as for the activation of evacuation procedures without floodwaters presence), also assuming to move toward safe areas according to the emergency procedures.
- *Alarm Phase (Red Alert):* activated in case of severe risk or an ongoing event. Residents located in risk areas must evacuate, either toward designated safe zones or to upper floors of buildings. Non-residents should have already been evacuated during the previous phase, however, potential latecomers in the evacuation process are considered. Two sub-scenarios are foreseen: without flooding

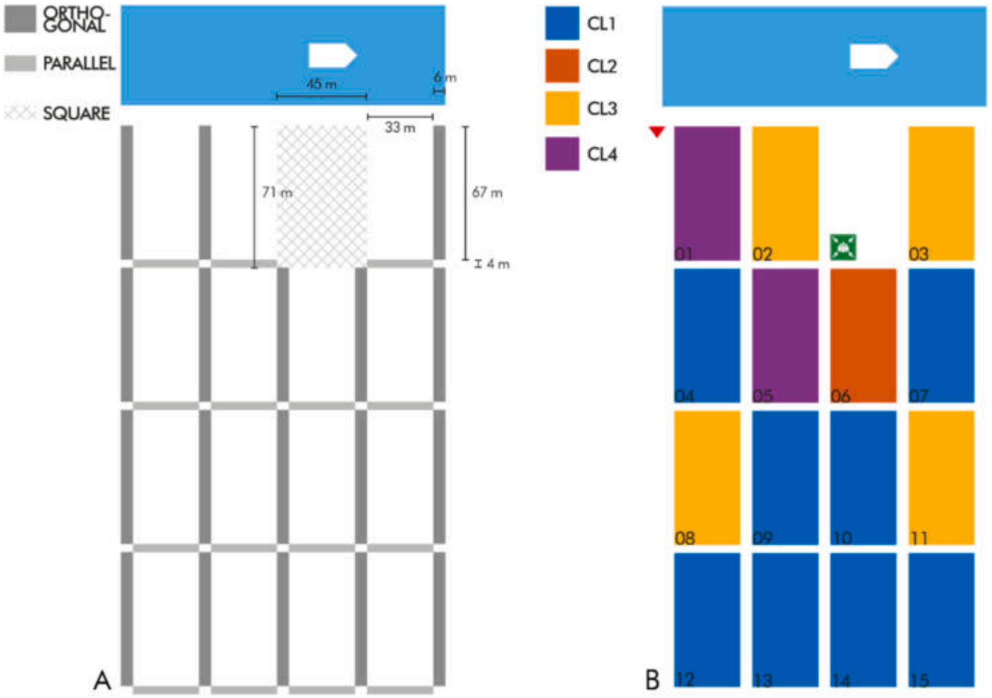

Fig. 6. A) typological environment, B) Placing of the four typological clusters in the environment model.

(preventive evacuation) and with flooding event, the latter involving increasing levels of risk. Different hazard levels were considered in case of flooding events, considering floodwaters D and V levels according to previous works on the flood effects on buildings and users [28]. In such cases, if autonomous evacuation is not possible due to hazardous conditions, assisted evacuation by emergency services becomes necessary.

This work assumed that the emergency conditions increase over time in terms of warning levels, and that alerts were properly addressed by users. Therefore, most of the hosted population was able to apply shelter-in-place procedures, when building blocks can host users at the upper floors thanks to the presence of adequate public areas, or leave the typological environment in a dry scenario (thus without interacting with floodwaters). In addition, a limited number of users were considered as latecomers, moving in flooded scenarios to leave the initial position and reach a safe area. Details of possible paths according to the timeline modelling are reported in Appendix B.

3.3. BIM-VR tool development

The application, following Phase 3 (Section 2.3) and Phase 4 (Section 2.4) of the methodology, involved the development of a three-dimensional information model by Autodesk® Revit® (BIM) environment. The modelling activity was conceived in accordance with Level of Development B (LOD B), as defined by UNI 11337–4:2017, ensuring a controlled balance between geometric abstraction and informational content. With reference to the two operational strategies discussed in Section 2.3, the experimental implementation adopted a unified BIM model, while still allowing, at the process design level, for the potential integration of federated IFC models, supporting future scalability and incremental updates of the system.

Starting from the definition of building levels and topographic composition, an *IfcSlab* entity was generated in compliance with the relevant elevation specifications. This entity was subsequently decomposed into minimum information units, functional to the assignment of hazard and evacuation indices. In detail, the public square was subdivided into four semantically consistent sub-regions and the streets into segments (from corner to corner of the block if parallel to the river; and from intersection centroid to intersection centroid if perpendicular to the river).

In the modelling of building-related components, particular attention was given to the representation of windows, which were typologically classified according to *BV_wd*. Wooden windows were modelled with shutters, conceived as symbolic elements emphasizing their traditional character and visual permeability, while metal-framed windows were represented with double-leaf frames lacking external shading. External doors were modelled following a recurring symbolic representation, using double-leaf configurations, with or without arches, differentiated in scale according to *BV_og* and *BV_fm*. The door threshold, defined by *BV_dt*, was modelled through the virtualization of an external step, as a symbolic indicator of elevation discontinuity between the public space and the access level. The presence of basements, *BV_eb*, not clearly visible from the façade, was represented as a base strip, defined by a string course and possibly characterized by openings at street level.

Upon completion of the information modelling phase, the model was exported in the open IFC format, according to the IFC4 Reference View Model View Definition (MVD). This MVD was selected for its ability to ensure an interoperable, simplified, and semantically interpretable information structure, without requiring support for complex parametric geometrization or editing functions.

The transition from the BIM authoring environment to the VR simulation environment was implemented within the Unreal Engine 5® platform.

The process began with the import of the IFC model, involving a parsing phase in which IFC entities were regenerated as geometric objects, while preserving their topological properties. The information attributes of each component were remapped into a customized enumerative structure using the Datasmith module, and were further enriched through predefined data dictionaries. Simultaneously, an automated module generated physical colliders for each geometry using simplified polygonal interpolation, enabling realistic navigation and interaction within the virtual environment. The generated elements were then associated with predefined actor placeholders, which handle their interactive behaviour during navigation and exploration, thereby enabling the programming and

Fig. 7. VR mapping of construction elements based on BV attributes and descriptors (top) and output of false colour visualization of BV_eb (bottom left) and BV_wd (bottom right).

control of the user experience.

The ability to read IFC parameters associated with each element within the VR environment enabled the implementation of interactive thematic visualization functions. These can be activated via dedicated keyboard commands or through interaction with contextual menus, allowing users to visualize risk indices either at the level of individual construction components (Fig. 7) or in aggregated form within defined clusters (Fig. 8).

This functionality is based on a predefined colour mapping system corresponding to the specific risk classes. These classes can be customized in both range and colour, and may refer either to a normalized scale or to a dataset-relative local scale. The association is established through a correspondence map between classes and materials, enabling the dynamic colouring of individual geometric components. This approach facilitates a functional, layered, and immediately interpretable reading of simulated risk conditions. The same approach is applied to open spaces, where it is possible to map hazard indicators and risk indices onto the minimum analysis units. In this case, the ability to switch between ground-level and top-down views allows users to achieve either a detailed or an overall perspective, depending on their needs (Fig. 9).

Given that the simulation is designed for medium-large-scale urban environments, a geometric streaming strategy was implemented through the synergistic combination of two main systems: World Partition and HLOD (Hierarchical Level of Detail), each playing a complementary role in optimizing the geometric data load.

The World Partition system automatically divides the scene into a spatial grid of cells. As the user navigates the virtual environment, Unreal Engine 5 dynamically loads only the cells within the camera's view or vicinity, progressively unloading those farther away. This process occurs in real time during execution, reducing the number of objects held in memory and thereby improving project scalability. The HLOD system operates at a higher level, generating simplified, aggregated versions of object groups that automatically replace original models when the distance from the camera exceeds a predefined threshold. This mechanism further optimizes performance in scenarios where users move quickly through space or large portions of the scene are simultaneously visible.

The environmental sky system and lightmap baking settings were configured according to principles of perceptual neutrality, ensuring that the virtual scene remains free from lighting or material interferences that are not aligned with the simulation objectives. This design choice prioritizes the informational hierarchy of relevant objects, while also improving the scene's computational stability in terms of frame rate and real-time performance.

The result is an immersive environment specifically designed for computational risk analysis, where geometries, attributes, and descriptive parameters can be easily accessed and queried based on integrated simulation and assessment workflows.

This mode of interaction not only enhances the communicative effectiveness of the model but also allows users to toggle specific informational layers on and off without interrupting navigation. This supports comparative analysis and personalized exploration of the modelled urban system.

The workflow thus conceived results in a semantic–informational transposition of the physical environment into an immersive computational space, where virtualization goes beyond mere geometric replication to become a tool for cognitive modelling. In this framework, spatial data is made intelligible through interactive, perceptual, and narrative dynamics.

The final debugging and compilation phase, conducted in the Windows environment, constituted a crucial step in the transition from the digital project to the executable application. It serves as a formalization process in which the model, previously structured through graphical assets, interactive logic, and informational architecture, is transformed into a performative artefact, accessible in real time.

From a technical perspective, compilation involves a cooking process, i.e. the conversion of project assets such as meshes, textures, blueprints, materials, and metadata into native formats optimized for execution in a 64-bit Windows environment.

This compilation is carried out in Development Build mode, enabling advanced debugging operations. Through this mode, it is possible to monitor variable states in real time, trace events, and diagnose system anomalies. This phase also holds theoretical

Fig. 8. VR mapping of blocks according to BVI.

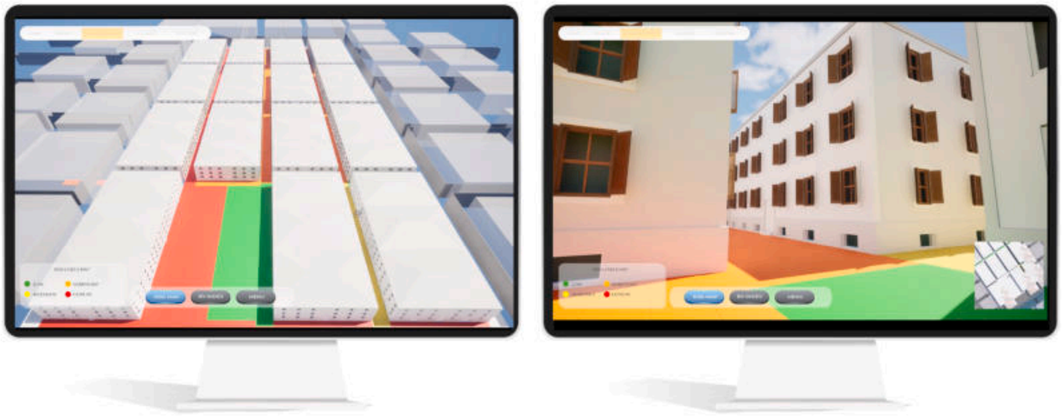

Fig. 9. VR mapping of open spaces according and hazard index D*V: top-down (left) and ground-level views (right).

significance, as it exposes the computational processes underpinning the simulation, revealing the interdependencies between data structures and visual form.

4. Discussions

4.1. Key findings

The GIS-based data collection of building vulnerability and user occupancy factors – while also serving as the foundation for the cluster analysis of recurrent typologies – provides a comprehensive overview of the most critical areas in terms of physical flood sensitivity and crowding, thereby supporting informed decisions on priorities and intervention strategies. In the Senigallia case study, the analysis highlights a comparatively higher level of building vulnerability in some sectors, particularly the south-eastern compartments (Fig. 4d). This condition is mainly associated with the presence and external accessibility of basements (Fig. 4c) and with the prevalence of wooden window frames, which are more permeable than metallic ones (Fig. 4b). In addition, buildings with wide ground-level openings are consistently concentrated along the riverfront strip (Fig. 4a), which forms the primary zone exposed to the initial inflow of floodwaters. Similarly, the analysis of intended uses and their diurnal fluctuations shows the substantial presence of commercial and recreational activities on the ground floor (Fig. 5a) that significantly increases population exposure during daytime (Fig. 5b) and afternoon hours (Fig. 5c), compared with nighttime (Fig. 5d), when only residents are present – fewer in number and generally more familiar with the local environment. The dataset also highlights specific buildings that warrant closer attention due to their high occupancy loads, as well as structures that could serve as potential shelters. Although sheltering is here conservatively assumed to benefit only the occupants of the same building, such capacity could, in principle, be extended to neighbouring structures. Altogether, these observations support the design of targeted structural and non-structural measures. Examples include mobile barriers to protect basement entrances and large openings, the installation of internal screens or double frames for windows, and the development of differentiated emergency instructions tailored to macro-categories of building use or specific time slots – guiding occupants either toward “leaving” the area or toward “sheltering” within designated buildings.

Furthermore, concerning the results of the cluster analysis, the typological model of the urban built environment describes an archetype for holistic flood risk assessment, where hazard and evacuation models can be applied according to different risk scenarios and paths of events within the possible emergency timelines. On the one hand, although simplified, this archetype traces basic common features of the Senigallia case study (Fig. 6) that can be also shared by other similar riverine sites. The definition of the dimensions of building blocks and streets, as BIM minimum informative units, ensures the rapid evaluation of the layout where hazard simulation on floodwater spreading are performed. Combining these data with the typological conditions of use by building blocks allows to estimate the quantity and position of exposed people. Then, the description of the possibility to perform shelter in place procedures ensures the proper application of evacuation models, estimating the number of evacuees per open space, and thus related evacuation indicators calculated from simulation outputs. Evacuation simulations should be carried out under the selected path of events traced in Appendix B, which can comprise baseline and maximum occupancy conditions, and the activation of procedures when pedestrians can move on dry surfaces or in floodwaters. This can then inform VR mapping of risk conditions at the open space level (Fig. 9).

Concerning the BIM-VR implementation, the results show a realistic simulation environment generated directly from IFC files, in which classes, entities, semantic relationships, and their associated PSets are automatically translated into parametric geometries through a rule-based mapping process. In the pilot case, the mapping rules were calibrated on specific IFC entities and properties (Fig. 7), reflecting the adopted literature analytical framework for the building vulnerability assessment [28], as well as the minimum spatial units used for hazard and evacuation analyses to represent risk conditions in urban open spaces. At the same time, the BIM-to-VR pipeline can accommodate different attributes, descriptors and weights of building vulnerability factors for the same elements, as well as additional construction and open-space components (e.g. foundation type, number of floors, building surroundings) [37], provided that coherent entities, attributes, and computational rules are defined within the information model.

Finally, in the test bed demonstration, the integration of IFC-based semantic mapping with an optimized rendering pipeline proves essential to support the interactive exploration of the simulated urban environment without compromising performance (Figs. 8 and 9). The adoption of geometric streaming strategies, combined with controlled levels of detail and perceptually neutral visual settings, ensures stable frame rates and high real-time responsiveness, even at the scale and complexity of the model. This performance stability enables users to seamlessly navigate between different spatial scales and analytical layers, while continuously accessing contextual data and visual feedback directly derived from BIM parameters throughout the navigation process.

4.2. Scalability and generalizability

The GIS-based data collection integrates and benefits from geospatial information on the urban morphology, as well as potentially from building-specific records and open-space inventories, which are increasingly managed through geoinformation platforms. As such, it offers a solid and complete basis for integrated – both static and dynamic – risk assessments that take into account the complex interactions between spatial configurations, physical vulnerability, and pedestrian mobility.

Moreover, the use of structured attributes and descriptors – supported by standardized nomenclatures and relational rules – ensures replicability in other contexts, allowing for result comparability. The inherently scalable nature of GIS also makes it possible to input and query data at varying levels of spatial detail. Observations can focus on single buildings or entire blocks in an associated form, and can be extended to portions of the urban fabric (e.g., architectural landmarks), entire homogeneous urban compartments, or functionally distinct areas of the historic city (ancient core, consolidated fabric, transitional margins). This flexibility in data granularity – both in terms of spatial coverage and aggregation level – makes it possible to tailor risk assessments to the intended purpose, context-specific conditions, and available resources. At the same time, relying on this granularity and flexibility issues, the approach also includes the definition of scenarios based on flood emergency timeline modelling concepts, which allows for the integration of temporal variability in population exposure, response and evacuation process results, introducing dynamic occupancy as a critical parameter in risk assessment.

The macro-scale database also enables the identification of typological reference models that play a key role in risk assessment and management, offering generalizable results in the form of scenarios and strategic guidelines with potential transferability to other application contexts. By abstracting recurring structural and functional characteristics observed across multiple real cases, the typological approach reduces context complexity and leads to a limited and finite set of representative typological models, each associated with key performance descriptors, discriminating parameters that clarify model behaviour under specific conditions. In this way, the classification of a new real case into an existing type can, in the long term, be carried out without repeating the full analysis, only by recognizing those key descriptors, thus enabling fast, replicable, and information-rich classification.

The above considerations align well with the BIM-based approach, which is herein demonstrated on a uniquely defined typological environment, but is potentially extendable parametrically to a set of geometries and variable attributes. Within this methodological workflow, BIM is proposed as a structured semantic information environment in which components are not only geometrically represented but are also described according to shared formal logics. Furthermore, BIM can evolve into a generative-computational logic within a typological framework, transitioning from a static output to a dynamic system through the explicit definition of morphological, functional, and performance-related parameters (e.g., building height, number of floors, openings at ground level, elevation of thresholds, types of windows and doors). These parameters, embedded into the model structure, support the controlled development of internal variations within the reference type, turning the model into a configurational matrix capable of describing a range of possible states rather than a single instance.

Finally, the development of VR environments that, in an interoperable way, render thematic mappings of data and indicators from the BIM model proves highly relevant as a management tool. The BIM-VR workflow, as conceived, enables the semantic and informational transposition of the physical environment into an immersive computational space, where virtualization extends beyond geometric replication to become a tool for cognitive modelling – making spatial data intelligible through interactive, perceptual, and narrative dynamics. The thematic data and indicator mappings constitute a core layer upon which more complex and diverse content (typical of virtual reality and simulation tools) can be added and customized based on: target groups (non-expert vs. expert), purpose (training, awareness campaigns, technical meetings), degree of visual fidelity (realistic vs. typological), level of interactivity (passive vs. active), and cognitive complexity (intuitive vs. high-density information).

5. Conclusions

5.1. Implications for decision makers

The proposed digital ecosystem is designed to combine technical rigor with operational accessibility, facilitating technology transfer toward stakeholders involved in decision-making processes, including local authorities, civil protection agencies, and cultural heritage bodies. In particular, the framework is structured to maintain a clear balance between low-tech and high-tech phases. It is particularly designed to consolidate the GIS and BIM systems into a coherent and manageable framework, maintainable by medium-skilled personnel – potentially within the managing authorities – who increasingly adopt such tools and can be directly involved in data population, querying, and analysis. The use of structured guidelines and ontologies in geographic and building information systems, combined with guided routines for managing and updating data flows, is intended to ensure that the proposed solutions are not only versatile and easily adoptable by decision-makers, but also technically consistent with advanced hydrological and hydraulic simulations, agent-based behavioural analyses, and the development of innovative VR environments managed by highly specialized professionals typically external to the managing authorities. This configuration may also activate virtuous mechanisms of capacity building within administrations, enabling training on digital technologies and the potential creation of local innovation hubs that integrate public, academic, and entrepreneurial expertise across different levels of specialization.

Moreover, the ability to query predefined typological or real scenarios – made accessible through interactive environments and immersive experiences – provides decision-makers with a useful tool for prioritizing actions and communicating transparently and effectively with citizens and stakeholders. In this way, the system becomes a decision support tool capable of translating risk complexity into actionable knowledge, promoting resilient and participatory planning. Furthermore, in terms of ex ante assessment of mitigation policies, the proposed tools allow for the development of graduated action plans, differentiating between structural interventions (e.g., physical mitigation of flood risk) and non-structural ones (e.g., communication, alert systems). They also support the integration of flood risk into urban and architectural design, avoiding ineffective or short-sighted solutions.

5.2. *Limitations and future works*

This study presents some limitations, which also provide valuable directions for future development, including the potential application to a larger number of cases to strengthen the general validation of the developed processes and outputs.

First, GIS-based data collection on construction and use characteristics of buildings was conducted manually through the analysis of available documentation and on-site surveys. This can be particularly time- and resource-intensive, potentially affecting the overall feasibility. In this regard, a promising development lies in the use of image-based automated object recognition procedures [98,99] trained to identify descriptors corresponding to risk-related attributes, thus expediting the classification process.

Concerning clustering methods, this work focuses on a single riverine case study to inform the typological model. On the one side, exploiting with different real-world scenarios sharing some basic similarities could improve the overall representativeness of the final archetype in additional contexts. Future work can move in this direction, boosting the application of typological models for preliminary application in risk assessment and mitigation procedures. On the other side, the organization of the model in respect to the source of risk could be adapted, e.g. assuming riverfront in riverine cities and seaside for coastal urban environments. The clustering approach relies on a simple “cardo-decumano” configuration for building block orientation, implying the definition of b as parallel to the river/coastside and l as perpendicular. Nevertheless, additional solutions in terms of basic morphology and sides could be adopted [76]. In addition, this work relies on a simplified street network modelling, deriving standardized building block sizes and street widths (depending on their spatial orientation), reflecting the hierarchy and spatial organization of the real urban fabric. As a primary result, a quite unified urban morphology is derived, implying a uniform distribution of building blocks dimensions. Conversely, a set of typologies for the selected clusters is used in the building blocks modelling to realistically reflect the diversity found in real-world data, offering a solid basis for further analysis and BIM applications. This choice ensures semantic consistency among typological components and allows for clear export of both geometric and informational content to virtual reality environments, supporting integration with BIM and VR workflows. Nevertheless, future applications could focus on more complex typological models, including different values for street width, length and slope which can be derived using the statistical analysis adopted for the building block use definition. Accordingly, each cluster of building blocks and streets will be composed of different groups of elements, each characterized by different combinations of indicator values. This step hence allows to define a set of possible typologies for building blocks and street components, which could be indeed represented by a single or multiple clusters, in combination with the procedure described above.

The hazard and evacuation simulations did not account for the physical configuration of buildings (e.g., permeability of facades and ground-level/basement openings), but only occupancy patterns linked to intended uses and the morphological configuration of the urban space, specifically its built-open space relationships. A further development could involve refining evaluations of the indoor environment's capacity to resist or admit water, and thus its potential to serve as a shelter during evacuation [100]. Moreover, future research should move to expand logics in hazard modelling, comprising also specific events (e.g. pluvial, riverine, coastal) in real-world contexts, and using cluster analysis to derive common features for modelling purposes. Concerning timeline modelling, the current work limits the analysis of the assessed path of events to a linear increase of warning levels, as shown by Appendix B. Nevertheless, loops in the selected events (and thus in the risk scenarios) can be indeed included, to increase the reliability of the approach over time, and thus the inclusion of different sub-conditions.

This aspect also points to the opportunity of extending the methodology outlined in this study to retrofitting scenarios, where building vulnerability may be reduced through targeted interventions on the building stock. These may include repairing facade damage, implementing protective devices such as flood skirts or barriers, sealing entry points, or replacing non-resistant doors and windows. This would contribute to a more holistic flood risk management strategy that addresses both existing and future urban conditions [101,102].

Finally, it is worth emphasizing that all proposed digital tools have been developed as prototype testbeds. As such, they require functionality testing and user acceptance evaluations in terms of robustness, alignment with operational needs, and perceived efficacy, usability, and utility. For this reason, future sessions of testing and feedback collection – also based on varying degrees of VR immersion – are necessary to guide iterative refinement and performance validation [67].

CRediT authorship contribution statement

Mariella De Fino: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriele Bernardini:** Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Caterina Alighieri:** Writing – original draft, Visualization, Resources, Investigation, Formal analysis, Data

curation. **Riccardo Tavolare:** Writing – original draft, Visualization, Software, Methodology, Data curation. **Enrico Quagliarini:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Fabio Fatiguso:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2026.106031.

Data availability

Data will be made available on request.

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