DigitMan
Occupant-based DIGITal predictive MANteinance to improve the built environment

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WP 4 – Safety predictive module development

T.4.1 – Relevant safety KPIs definition
T.4.2 – Safety data acquisition and post-processing
T.4.3 – Safety method development

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Abstract

Fire Safety is one of the most relevant topics in building safety. Well-established regulatory framework implies requirements on "deemed-to-satisfy" solutions to be easily and quickly checked by decision makers. In particular, evacuation-related topic surely represents a fundamental issue, being widely interconnected with building layout and occupancy alternatives, and being thus relevant for "how-to" (current scenario) and "what-if (design alternatives) tasks. Due to the complexity of buildings and their occupancy, modeling tools are needed to collect and manage these fire safety features and input data, and then assess regulation compliance using rapid Key Performance Indicators (KPIs). This report aims at defining simple, regulation-based KPIs for building safety assessment, mainly oriented towards "what-if" tasks. KPIs are implemented in BIM to Building Performance Simulation tools (i.e. Building Safety Model - BSM), and then applied to relevant DigitMan case study. KPIs trace geometrical issues under alternative scenarios, quickly supporting decision makers since they are associated with specific building levels, from micro (space, building component in the mans of egress) to macro (whole building/compartment) scale.

Keywords

Fire safety, Key performance indicators, predictive module, BIM, Building Performance Simulation, Building Safety Model

Approvals

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Summary

Introduction

Building safety issues are widely defined in respect to fire safety regulations, which have significant impacts in the process of design, adaptation and transformation of architectural layout and intended use [1, 2]. Spatial constrains about the types of spaces and the means of egress exist, also comprising the occupants as main reference issues for required basic verifications, implying complex analysis of different scenarios under design alternatives [2]. Providing tools to support decision makers in quick analysis of critical issues for each planned scenarios can boost the assessment process in a "what-if" perspective, while additional indicators could be used in the "how-to" process to check the current "health" status of the building, mainly using a user-centered approach [3, 4].

Approaches relying on Building Information Models (BIM) have been defined in this operational context, to manage safety in buildings, especially in respect to possible fire risk conditions also implying the activation of evacuation process [5–8]. In fact, they can support a data-driven approach to risk assessment, supplying data to facility managers about the current use and status of the spaces, as well as of equipment and systems, in case they are connected to Building Automation Systems (BAS) and to Computerized Maintenance and Management Systems (CMMS) [3]. The features characterization for sensitive building components (e.g. doors), systems (e.g. alarm, fire suppression), and spaces (e.g. corridors, staircases, safe areas) as well as for the occupants (in terms of number, position and typology over time), can ensure the development of integrated emergency evacuation frameworks to support risk assessment through Building Performance Simulation (BPS) approaches exploiting deepened simulations [7–9], and also manage the evacuation process in a quasi-real time manner (also by including remote control of dynamic BIM-based signage systems) [10, 11]. In this sense, data are hence linked to Building Safety Model (BSM).

Although previous works demonstrated the capabilities of BIM-based tools and methods, current approaches seems to be still limited in supporting decision-makers in simply and rapidly evaluate the impact of their operation choices (to improve the scenario, in an "how-to" standpoint), and of possible alternatives in building transformation (in a "what-if" perspective), especially in correlation to the building spaces and its occupants, and to basic verifications requested by fire regulations [12]. In this sense, the connection with common BIM-based modeling issues is fundamental to ensure a multi-purpose approach with other facilities management pillars, as those related to energy efficiency, occupancy optimization, and maintenance management, which can take advantage of multicriteria analysis [3].

In view of the above, this report aims at:

- Defining Key Performance Indicators (KPIs) for safety-related analysis in "how-to" and "what.if" scenarios (according to T4.1 activities),
- And defining the process of input data collection and calculation to derive the KPIs, to provide a BIM-to-BSM tools to support decision makers (according to T4.2 and T4.3 activities).

1 Phases and methods

According to the work aims, the current work is organized into two main phases. The first phase concerns the KPIs definition (Section 1.1), while the second one concerns the data acquisition and post-processing within a BIM-to-BSM tool, and thus involves the related calculation method development and tool development (Section 1.2).

1.1 Criteria for Key Performance Definition

KPIs are defined according to the "how-to" and "what-if" perspectives defined in WP1 activities of DigitMan project, and take into account their relevance to solve calculation requirements from fire safety standards [1].

From a general perspective, KPIs should follow the SMART assessment approach [13], which have been also successfully adopted by previous works on safety assessment of occupants in the built environment [14]. KPIs should be:

- **S**pecific: Targeting a specific safety issue for the building, mainly focusing on fire safety regulation, on architectural layout elements and on means of egress affecting the occupant safety in evacuation;
- **M**easurable: Quantifying fire safety conditions of the building, while being comparable in terms of output range. For instance, normalization of KPIs should be encouraged to make them varying between maximum and minimum safety conditions, or describing the fulfilment of regulation requirements in the same interval;
- **A**ssignable: Assigning to one or more risk-prone element of the building, mainly considering those correlated to architectural layout elements in view of the impact of building current scenarios (in "how-to") and transformation activities (in "what-if") on them;
- **R**ealistic: Establishing objectives related to fire safety regulation, mainly comprising those related to occupant's behavioural issues and involving specific actions of the decision makers on occupancy-related factors (i.e. comprising the intended use of the building and its layout);
- **T**ime related: Focusing on quick and timely analysis of safety conditions without needing additional advanced calculation steps which can move towards assessment procrastination.

In greater detail, safety SMART KPIs related to the Italian Fire Safety Code are correlated with requirements on verifications for "deemed-to-satisfy" solutions [1]. In fact, the Code introduces the concepts of "risk profile concerning human life safety" R_{life} [-], which is associated with each compartment composing the building. R_{life} is based on occupancy as one of the main leading factors to tailor specific solutions by fire safety strategy, fire hazard conditions. In this sense. Then, it is used to establish the Assignment criteria, and thus specific "deemed-to-satisfy" solutions, along with general building features and other operational conditions. DIGITMAN main focuses on the evacuation strategy (S.4) as the main goal for evaluation and thus for KPIs definition, since this strategy is one of the most important in correlation with the occupant number, position and typology, and thus it has direct consequences and correlation with the basic assumptions on "how-to" and "what-if" scenarios.

KPIs are hence classified by relevance in respect to the building layout and components themselves (S-1. GEOMTERY), in respect to the space risk (S-2. RISK) and to the intended use of spaces (S-3. USE). Then, they are associated with the specific type of space and architectural components to which they are applied, and calculation methods are defined to make them range between 0 and 1 (introducing a cap for values higher than 1 to consider all the not "deemed-to-satisfy" values), or to make them Boolean. Priority of KPIs is then defined according to the general rationale of WP5 microservices, preferring the implementation in BIM to BMS tools for "what-if" indicators adherent with explicit regulatory requirements.

Although they are derived for the Italian context, due to DigitMan national application scenario, the KPIs are applicable also in other international contexts which essentially adopts the same parameters to described occupant safety conditions (e.g. NFPA).

1.2 Data acquisition and methods implementation in a BIM to BSM perspective

1.2.1 Overview

The proposed methodology for data collection in digital models is organized into several phases and is interrelated with other WPs' activities. In particular, the general development phases are:

1. Topological BIM (addressed in WP1);
2. BIM-to-BEM (addressed in WP3);
3. BIM-to-BSM (addressed in this WP4's report);
4. Multicriteria analysis (to be addressed in WP5).

The first, conducted in WP1 and briefly summarized below for ease of reading, involves semi-automatically creating the BIM of some case study buildings, enriched with all the information necessary for energy and safety analyses, also called Topological BIM (TBIM). These models are semi-automatically generated with the objective of being compliant with BPS and BSM.

The second step comprised the automated BIM-to-BEM (Building Energy Model) conversion (described in the WP3's report "*D3.1 - KPIs and predictive methods for operation tasks*").

Similarly, the third step consists of the transformation of the BIM into a BSM (Building Safety Model).

In the final phase, simulations will be run, and the results will be interpreted in an integrated manner using project-defined KPIs to identify the optimal management strategies regarding space use, energy needs, and occupant safety.

The first and third phases are presented in this report, while the last, under development, will be the subject of future reports (WP5).

1.2.2 Topological BIM

The BIM process was conducted leveraging the TBIM process, documented in WP1's report (*D1.1 - "Definition of an occupant-centric conceptual framework and correlation methodology"*), which allowed us to semi-automatically generate a BIM rich with all the information needed for safety verifications. The process is briefly summarized below.

3D modeling

The initial substep is to model the building's geometry. This is done by creating a closed 3D BRep object for each building space by retracing the administrators' CAD drawings in a 3D modelling environment. This volume, representing the gross shape of the space boundary, is then transformed into a Topologic "cell", serving as the foundational spatial unit in the digital model.

Topology modelling

The topology modelling substep establishes the topological relationships between the model's core elements. Thanks to Topologicpy, the cells are combined into a higher-level spatial entity known as the "cell complex", a digital model consisting of topologically interconnected spaces and binding surfaces ("Collector Model") to transform the geometric cells into topological cells. Although the cells do not contain any data at this point, they are prepared to be populated with information. For this reason, they are called "Informational Collectors," serving as the primary data aggregators in the modelling process.

Information enrichment

In this subphase, conditional modelling is used to assign information to the elements within the Collector Model.

First, functional data is added to the Collectors by attributing "Informational Load Dictionaries" (ILDs) to them. ILDs are JSON dictionaries, each representing a specific space occupancy type (e.g., office, classroom, corridor, etc.) and containing relevant operational and safety data (e.g., thermal setpoints, electricity loads, area per occupant, etc.). To enrich a Collector, a space occupancy type is assigned to it, choosing between the occupancy types modelled in the ILDs, and the corresponding ILD is transferred to the corresponding cell, enriching it with the ILD's embedded data. The relevant data added to the spaces concerning safety evaluations are reported in Table 1.

Table 1. Safety properties added to the spaces of the topological model in the information enrichment step

Property Name	Description	Quantity	Unit
*pr_OccupancyDensitySafety***	*Number of people required per area for the activity assigned to this space according to fire safety regulations.*	*Occupancy Density*	*pp/sqm*
*pr_OccupancyDensityPeak***	*Number of people estimated to be in an area of the facility in occupancy peak hours.*	*Occupancy Density*	*pp/sqm*
*pr_OccupancyNumberPeak***	*Maximal number of people required for the activity assigned to this space in peak time.*	*People Count*	*pp*
pr_IsOccupied	*Indication whether the space is permanently occupied (TRUE) or not (FALSE) according to energy modeling purposes. For examples, offices and classrooms are permanently occupied, while circulation spaces or storage spaces not.*	*Bool*	-
*pr_OccupancyType**	*Occupancy type for this object. It is defined according to DigitMan's classification system.*	*Text*	-

*** The data on occupancy types was provided by the building administration and verified through on-site inspections. Subsequently, it was aligned with the OmniClass notation (Table 13); see WP1's report (DELIVERABLE NAME).*

** The data on the maximum occupancy capacity of the spaces, on the other hand, was derived, occupancy type by occupancy type, from the guidelines outlined in the Italian fire prevention code. For certain special spaces, such as classrooms, this data was adjusted to reflect the actual maximum number of occupants established by the owners.*

Next, after adding data to the cells, ILD information is transferred to the adjacent faces, binding the cell by executing topological queries. For instance, a partition wall is informed of the occupancy types of the spaces it delimits (e.g., "corridor-office") and respective data (e.g, "unheated-heated").

The faces then undergo additional data enrichment using the "Informational Rulesets" (IRSs), mainly containing construction data about envelope components (e.g., thickness, material, and thermal properties of walls, floors, roofs and openings). These key-value dictionaries contain "conditions" and "styles" applicable to faces. The conditions specify the property values a face should have for applying the IRS to it, while the styles define the new data to be assigned to the face if it meets the conditions. The assignment of IRS data is also carried out through topological queries. Each IRS is applied iteratively to each face within the Collector Model. The condition values are accessed and compared to the face's properties for each face. If a match occurs, the dictionary containing the style data is added to the face; if not, the iteration proceeds to the next face. The outcome is the so-called "Style Model", a Topologic cell complex containing the ILDs' data (operational data) and IRSs' data (construction data).

Relevant safety properties added to the doors thanks to topological and conditional modeling are reported in Table 2.

Table 2: Safety properties automatically added to the doors of the topological model

Property Name	Description	Quantity	Unit
pr_TopologicalType	*Describes the interface element from a topological perspective (internal vertical, external vertical, internal horizontal, top horizontal, bottom horizontal for surfaces, door, hole, or window for openings)*	*IfcLabel*	-
pr_IsExternal	*Indication whether the element is designed for use in the exterior (TRUE) or not (FALSE). If (TRUE) it is an external element and faces the outside of the building*	*IfcBoolean*	-
pr_Width	*Total outer width of the window lining.*	*IfcPositiveLengthMeasure*	*m*
pr_Height	*Total outer heigth of the window lining*	*IfcPositiveLengthMeasure*	*m*

BIM modelling

To finalize the BIM, the apertures are created. They include doors, holes, and windows. Doors represent apertures allowing for horizontal passage between adjacent cells on the same storey, while holes for vertical passage (e.g., between staircases). Windows, instead, links the cells to the external environment. Such apertures are modelled as face elements in Topologicpy, based on the IRS data associated with the faces hosting them.

Subsequently, the Style Model is converted into a Topologic graph to perform graph analysis and detect and correct any errors in the topology modelling process. The outcome is the TBIM, a Topologic cell complex semi-automatically populated with data relevant to BPS analysis, i.e. using BSM. The components in this model (i.e., cells, faces, and apertures) form a network of interconnected objects suitable for direct transformation into BEM and BSM.

As the last substep of the BIM phase, using pyRevit and aligning Topologic's class hierarchy with Revit's and IFC's element classes, the Topologic TBIM is transformed as an Autodesk Revit model. Following this, minor manual adjustments are made to specific instance objects in Revit and direct IFC export is performed. For example, TBIM's apertures, by default placed at the centre of faces, are repositioned as needed, and any errors in construction data assignments to faces and apertures are corrected.

Moreover, the properties that cannot be represented in the ILDs on a functional basis and need to be assigned space by space are added to spaces (such as for some specific safety attributes). All these modifications are synchronized with the Topologic model. The outcome is a streamlined BIM model, available in Revit, IFC, and Topologic JSON formats, containing all the essential information for energy and safety analyses.

Relevant data added to the spaces for fire safety evaluations are summarized in Table 3, while properties added to the doors are reported in Table 4.

Table 3: Safety properties manually added to the spaces of the BIM model

Property Name	Description	Quantity	Unit
pr_IsProtected	*A qualification of an activity space making up a fire compartment. It is TRUE when the space represents a specific compartment (e.g. stairways, room, route)*	*Boolean*	-
pr_IsSmokeProof	*indicating the ability of a compartment to limit the entry of smoke generated by fire that develops in a communicating compartment. It is TRUE when the space represents a specific compartment (e.g. stairways, room, route)*	*Boolean*	-

Property Name	Description	Quantity	Unit
pr_IsFireStaircase	*Indicates whether the space is a fire staircase (TRUE) or not (FALSE). A fire staircase is a stairway belonging to the evacuation system.*	*Boolean*	-
pr_IsFilterSpace	*Indicates if the compartiment is a filter space (TRUE) or not (FALSE). A filter space is a fire compartment in which the probability of fire ignition and development is considered negligible, in particular, due to the absence of fire ignition points and to the low specific fire load qf admitted.*	*Boolean*	-
pr_IsFireGap	*Indicates whether the space is a fire gas space (TRUE) or not (FALSE). A fire gap space is intendend as a detachment space, appropriately sized for aeration, ventilation or disposal of combustion products, delimited above by open outdoor space and longitudinally delimited by perimeter walls (with or without openings) belonging to the structure served and by embankments or walls from other structures, having an equal fire resistance.*	*Boolean*	-
pr_IsSafeSpace	*A place where the risk of fire for the occupants stationed there or passing through it is permanently negligible; this risk relates to a fire in the activity. It is TRUE when the whole related area is safe (e.g. outdoor gathering areas; indoor gathering areas; other spaces where users can remain safe all over the event time)*	*Boolean*	-
pr_IsTemporarySafeSpace	*A place where the risk of fire for the occupants stationed there or passing through it is temporarily negligible; this risk relates to a fire in specified areas of the activity other than the area in question. It is TRUE when the area remains safe during a given time span (recommended to define the temporal extension of the safe status)*	*Boolean*	-
pr_IsRefugeArea	*Temporary safe area where occupants may wait for assistance to complete their evacuation to a safe area. It is TRUE when the area remains safe during a given time span (recommended to define the temporal extension of the safe status), while users are waiting for rescuers' arrival (e.g. users with motion disability)*	*Boolean*	-
pr_AverageHeight	*The weighted mean of the heights h_i of a room with the plan view projection of the portion of floor area A_i of the floor area at the height h_i, according to the equation: $\sum(h_i \times A_i)/\sum A_i$*	*Lenght*	m
*pr_Lenght**	*The distance each occupant must travel along an evacuation route from the point at which they find themselves to reach a temporary safe area or a safe area. The evacuation route length is assessed with the straight-line method without considering furnishings.*	*Lenght*	m

Table 4: Safety properties manually added to the doors of the BIM model

Property Name	Description	Quantity	Unit
pr_IsFireExit	*Indication whether this object is designed to serve as an exit in the case of fire (TRUE) or not (FALSE). Here it defines an exit window in accordance to the national building code*	*IfcBoolean*	-
pr_IsStoreyFireExit	*Indication whether this object is designed to serve as an exit in the case of fire (TRUE) or not (FALSE). Defines if the opening (door) is an emergency exit for the floor it is located on.*	*IfcBoolean*	-

1.2.3 BIM-to-BSM

The BIM-to-BSM process was then applied on the TBIM to generate the models needed for safety verifications. The process, depicted in Figure 1, is further explained in paragraph 2.2 with direct application on the project's case study.

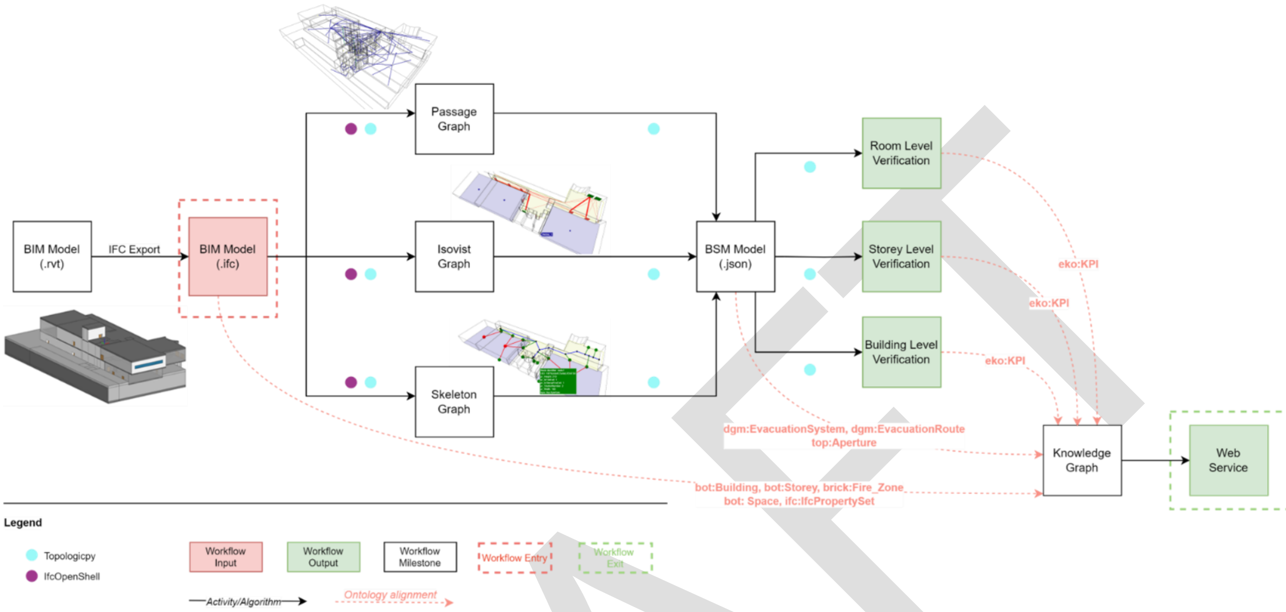


Figure 1. BIM-to-BSM workflow.

2 Results

2.1 Key Performance Definition

Figure 2 summarizes the main developed KPIs, by stressing their correlation with the Fire Safety Code, and providing boundary for application and calculation in both "how-to" and "what-if" conditions. In particular, three main categories of KPIs could be provided referring to: geometry, which are essentially based on Code-based verification on width, length and number of escape routes (including door features); risk, which relates to differences in fire loads; use, which directly relates to occupant number and typologies. In particular, considering input data sources shown in Figure 2, risk and use KPIs could be directly derived from emergency plans and procedures and fire evaluation/control documents.

According to criteria shown in Section 1.1, for each category, numerical and Boolean KPIs are considered. Numerical ones are calculated as ratio, thus allowing to obtain values >0. Final checks by KPIs are threshold-based, essentially evaluating the final value of each KPIs and preferring lowest (tending to zero) values in a conservative manner. In fact, it is assumed that 1 is the safety maximum threshold: when the KPI>1, values are unacceptable according to their definition, representing critical conditions for occupant safety. Boolean KPIs are indeed acceptable when they are true.

Moreover, since geometry KPIs relies on Fire Safety Code basic calculation about evacuation strategy (S.4), they also allow to implicitly perform regulation checks for "deemed-to-satisfy" strategies. By this way, decision makers could avoid perform fire safety engineering analysis using the BIM-based data. As remarked by the application schematization in Figure 2, three levels of calculation could be performed:

- Space-level calculation (section 2.1.1),
- Storey-level calculation (section 2.1.2),

- Compartment/building-level calculation (section 2.1.3).

	KPI	reference (Fire Safety Code chapter)	application						goal		calculation	check
			space					interface				
			room	floor	compartment	building	corridor / staircase	door	HT	WI		
S-1_GEOMETRY	S-1.1_width ratio	S.4.8.8; Tab S.4-27; Tab S.4.28	s	x	x	x	x	x		X	ratio between "Deemed" value and current or designed value	≤1 ; lowest is better
	S-1.2_length ratio	Tab S.4-18; Tab S.4-20; Tab S.4-25; S.4.10 (Tab S.4-38)	s	x	x	x	x			X	ratio between "Deemed" value and current or designed value	≤1 ; lowest is better
	S-1.3_ independent exits & redundancy	Tab s.4.14; Tab S.4-15; S.4.8.6	x	x	x	x				X	number of exits & redundancy verification (boolean)	>1 when needed, or true
	S-1.4_door opening	Tab s.4-6	x	x	x	s	x	x		X	opening type/verse in correct VS needed conditions	true
S-2_RISK	S-2.1_fire load rate	S.2.9	s	s	s				X	X	difference in fire load [MJ or %] or ratio between "Deemed" value and current or designed value	almost the same or %<0 for risk reduction
S-3_USE	S-3.1_ occupancy rate	S.4.6.2	s	x	x				X	X	ratio between occupancy current or designed value and maximum or previous value	≤1 ; lowest for risk reduction is better
	S-3.2vulnerable users' rate	n.a.	s	s	s	s			X	X	ratio between occupancy current or designed value and maximum or previous value	≤1 ; lowest for risk reduction is better

Figure 2. Main assumed DIGITMAN KPIs for safety pillar, organized with respect to basic classes, and correlated with the Fire Safety Code sections, the application spaces in the Topological model ("x" for primary, "s" for secondary), the application purposes ("how-to": HW; "what-if": WI), and basic for calculation and checks.

2.1.1 Space-level calculation

Basic verifications at the space level, that is considering specific rooms composing the fire compartment, refer to the minimum number of independent exits and width. References to the Fire Safety code section are provided in Figure 2. Therefore, the verification on each space first consider each room and its horizontal means of egress (i.e. space door/exits).

Two door/exits are independent if, in the room, points exist where the view angle between straight routes ≥45° and/or they are separated by fire-resistant elements (at least, IE30). The minimum number of independent door/exits depends on R_{life} and on the crowd size, as shown by the Figure 3.

The minimum width of each exit, to prevent localized overcrowding effects of doors as bottleneck, is derived by the occupancy assessment in number of persons in the given space as shown by Figure 4, according to Fire Safety code. This value is compared with the effective width of a given exit coming from the BIM model, for each door/exit of space. If all the exits provide positive validation of this comparison, being larger than required, the minimum width by overall room occupancy is then calculated. Minimum required width of all the exits of the room is calculated as the number of occupants in the room multiplied by the unity width per person, depending on R_{life}. Then, the sum of the effective width of each exit coming from the BIM model is compared with this minimum required width of all the exits to create S-1.1 as shown by the general rationale of Figure 4.

The workflow in Figure 4 should be also applied in redundancy conditions. Redundancy check aims at verifying the minimum width compatibility by considering an exit unavailable at a time.

Additional verifications on the door handling typology and opening direction, asking for UNI EN 1125/UNI EN 179 opening devices and opening direction in the direction of evacuation depending on occupancy >5 persons and any specific risk in the room. Finally, minimum height of escape routes ≥2 m must be also verified.

R_{life}	Crowd size in the area served	Minimum number of independent exits
Any	> 500 occupants	3
B1 [1], B2 [1], B3 [1]	> 150 occupants	
Other cases		2
If dead-end corridors are permitted in accordance with the provisions of paragraph S.4.8.2		1
[1] Areas with an occupant density > 0.4 p/m²		

Table 94: Minimum number of independent exits from a room or open-air space

CHECK

If effective number > minimum number: S-1.3 = true

Figure 3. Minimum number of independent exits and correlation with KPI S-1.3. Red circles remark main limitations for the application in the context of educational buildings as relevant application context for DigitMan. Elaboration from [1].

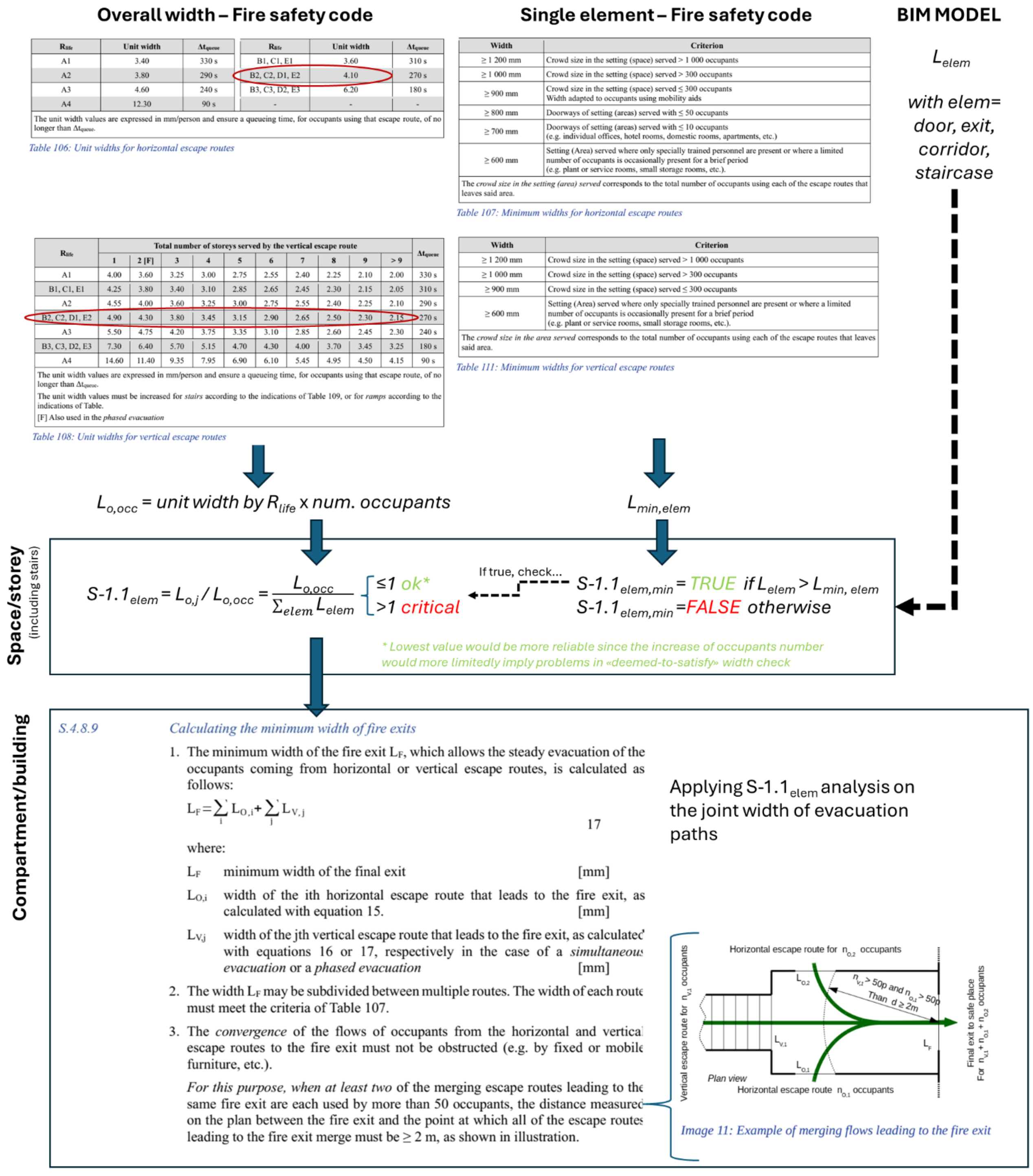


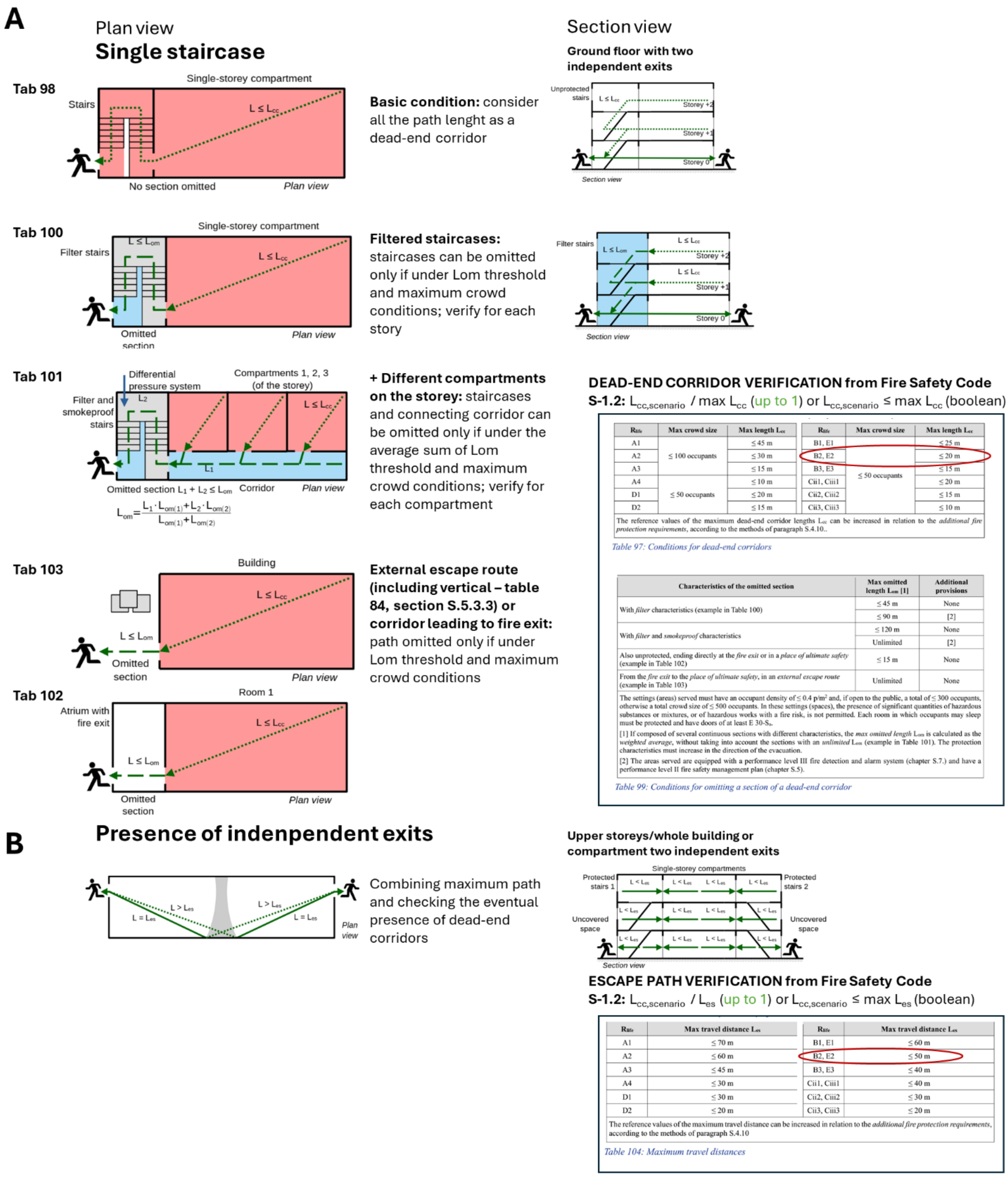
Figure 4. Width analysis and correlation with KPI S-1.1. Red circles remark main limitations for the application in the context of educational buildings as relevant application context for DigitMan. Elaboration from [1]. The scheme can be applied to the space/storey level as well as to the compartment/building level.

2.1.2 Storey-level calculation

Verifications at the storey level are based on the ones of the space level, thus requiring minimum width and number of horizontal escape routes (i.e. rooms, corridors and doors placed along them, until the staircases), as well as minimum height. Since occupants can enter the escape routes from different initial rooms, the occupancy is evaluated as occupants' sum by route section. In case two independent routes and final storey exits are present, redundancy check must be performed according to the same rationale of space-level calculation.

For dead-end route section, maximum length must be verified depending on R_{life} and maximum crowd size, as shown by Figure 5-A. Dead-end route sections could be omitted in the verification in case their length is under given threshold and additional fire safety-increasing characteristics are present.

Finally, in case of vulnerable occupants, an area of rescue assistance in accordance with ISO 21542 should be provided.



$$L_{om} = \frac{L_1 \cdot L_{om(1)} + L_2 \cdot L_{om(2)}}{L_{om(1)} + L_{om(2)}}$$

R_{life}	Max crowd size	Max length L_{cc}	R_{life}	Max crowd size	Max length L_{cc}
A1	≤ 100 occupants	≤ 45 m	B1, E1	≤ 50 occupants	≤ 25 m
A2		≤ 30 m	B2, E2		≤ 20 m
A3		≤ 15 m	B3, E3		≤ 15 m
A4	≤ 50 occupants	≤ 10 m	Cii1, Ciii1		≤ 20 m
D1		≤ 20 m	Cii2, Ciii2		≤ 15 m
D2		≤ 15 m	Cii3, Ciii3		≤ 10 m

The reference values of the maximum dead-end corridor lengths L_{cc} can be increased in relation to the *additional fire protection requirements*, according to the methods of paragraph S.4.10..

Table 97: Conditions for dead-end corridors

Characteristics of the omitted section	Max omitted length L_{om} [1]	Additional provisions
With *filter* characteristics (example in Table 100)	≤ 45 m	None
	≤ 90 m	[2]
With *filter* and *smokeproof* characteristics	≤ 120 m	None
	Unlimited	[2]
Also unprotected, ending directly at the *fire exit* or in a *place of ultimate safety* (example in Table 102)	≤ 15 m	None
From the *fire exit* to the *place of ultimate safety*, in an *external escape route* (example in Table 103)	Unlimited	None

The settings (areas) served must have an occupant density of ≤ 0.4 p/m² and, if open to the public, a total of ≤ 300 occupants, otherwise a total crowd size of ≤ 500 occupants. In these settings (spaces), the presence of significant quantities of hazardous substances or mixtures, or of hazardous works with a fire risk, is not permitted. Each room in which occupants may sleep must be protected and have doors of at least E 30-S_a.

[1] If composed of several continuous sections with different characteristics, the *max omitted length* L_{om} is calculated as the *weighted average*, without taking into account the sections with an *unlimited* L_{om} (example in Table 101). The protection characteristics must increase in the direction of the evacuation.

[2] The areas served are equipped with a performance level III fire detection and alarm system (chapter S.7.) and have a performance level II fire safety management plan (chapter S.5).

Table 99: Conditions for omitting a section of a dead-end corridor

R_{life}	Max travel distance L_{es}	R_{life}	Max travel distance L_{es}
A1	≤ 70 m	B1, E1	≤ 60 m
A2	≤ 60 m	B2, E2	≤ 50 m
A3	≤ 45 m	B3, E3	≤ 40 m
A4	≤ 30 m	Cii1, Ciii1	≤ 40 m
D1	≤ 30 m	Cii2, Ciii2	≤ 30 m
D2	≤ 20 m	Cii3, Ciii3	≤ 20 m

The reference values of the maximum travel distance can be increased in relation to the *additional fire protection requirements*, according to the methods of paragraph S.4.10

Table 104: Maximum travel distances

Figure 5. Lenght analysis and correlation with KPI S-1.2 for: A-dead-end corridors; B-overall path length (including thus independent extis). Red circles remark the main limitations for the application in the context of educational buildings as relevant application context for DigitMan. Elaboration from [1].

2.1.3 Compartment/Building-level calculation

In case staircases are present, verification on the minimum width are performed using the same rational of horizontal escape routes and doors, and also applying redundancy check in case of more than one staircase. In this sense, the operational workflow is the one of Figure 4. Nevertheless, unit width per person depends on evacuation method, which varies the maximum number of occupants simultaneously considered in the staircases. The value is equal to the "total number of occupants using the vertical escape route, coming from all of the storeys served" for simultaneous evacuation, and to the "total number of occupants using the vertical escape route, coming from two of the storeys served, taking into account the two storeys, including if they are not adjacent, with a larger crowd" in case of phased evacuation. Additional correction coefficients depending on staircases slope are included. Indeed, the minimum width calculation for staircases doors follow the horizontal routes verification described above, as well as the final evacuation exit width and number.

Finally, overall verifications on the whole maximum evacuation route length, comprising all the horizontal and vertical lengths of composing section, and the dead-end ones, must be performed comparing values with occupancy-based and R_{life}-based thresholds. The general workflow is the same reported in Figure 5. Maximum values could be also increased by a ratio depending on the geometric features of the building (i.e. average net height of escape routes) and technological systems (i.e. fire detection, alarm, smoke and heat control).

Finally, since a building could be composed of one or more compartments, such verifications are referred to the compartment level too. In fact, exits refer to exits from each comportment, or toward open-air spaces/public road (in this case, calculation on minimum area by occupant typology are also included), or outdoor staircases. In this case, verifications must be performed for each composing compartment.

2.2 BIM to BSM implementation: algorithms and methods

The conversion of the BIM into a BSM is achieved through a Python algorithm, which employs an approach similar to the BIM-BEM conversion (see WP3 report) but aligns IFC's element classes and properties with those of Topologic and the Italian fire prevention code.

The BIM-to-BSM algorithm was tested on the two case study buildings belonging to POLIMI, i.e. the "Building n.9" and "Building n.10", whose BIM model were generated in WP1.

2.2.1 Ontology for BSM

Since neither Topologic nor the Italian fire safety code has an explicit ontology, the first step in the BIM-to-BSM conversion was to create a project-specific ontology, aligned as closely as possible with the definitions of the fire safety code and the Topologic class hierarchy [15].

The ontology for modeling aspects related to safety is shown in Figure 4. This is part of a larger ontology used in the DIGITMAN project to map digital objects within graph databases (see WP1's report D1.1). In summary, within the ontology the building's evacuation system is defined as 'dgm:EvacuationSystem'. The system consists of a network composed of a set of edges and nodes that form one or more 'dgm:EvacuationRoute'. The nodes can be spaces ('bot:Space'), apertures ('top:Aperture') or open spaces ('dgm:OpenAirSpace)'. The edges are parts of the path that connect each node. The set of edges and nodes related to a single path within the evacuation network forms a route (for example, the path that leads from one space to another space), identified as 'dgm:route'. The set of multiple routes thus forms the evacuation network.

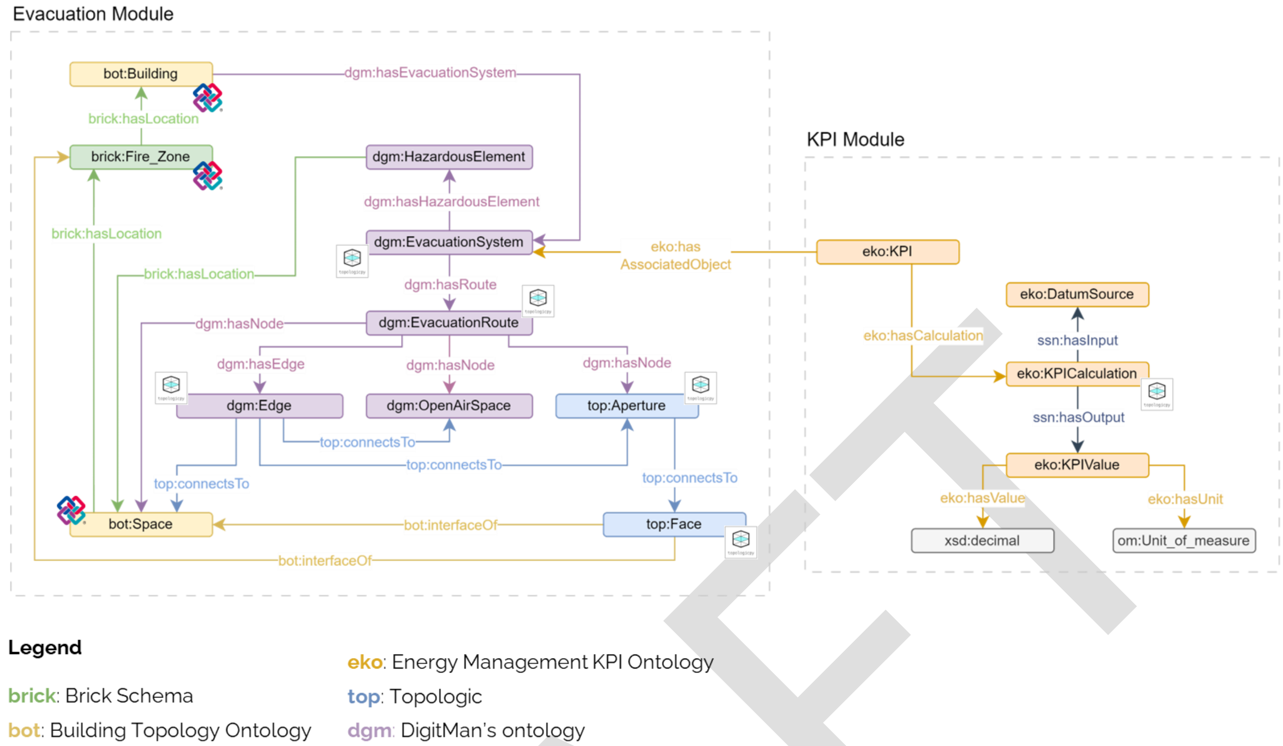


Figure 6. DIGITMAN's ontology (safety module).

Once the ontology was defined, three distinct Topologic graphs were automatically generated for each building to perform the checks required by the fire safety code on IFC models. Then, graphs of adjacent buildings sharing the evacuation network were merged (e.g., POLIMI's case study).

The three types of graphs, each serving different purposes, are:

1. **"Passage" graph;**
2. **"Isovist" graph;**
3. **"Skeleton" graph.**

Topologic Graphs are graph structures composed of nodes and edges, which can represent various objects (e.g., spaces and openings) and the relationships between them. Furthermore, semantic information (e.g., class membership in the ontology) and attributes (e.g., the number of people in a space or the width of a door) can be assigned to nodes and edges.

The three graphs, enriched with all necessary information, are used to perform the checks described below, which comprise basic fire safety verifications according to Italian Fire Safety Code about "Deemed-to-satisfy" solutions [1]. Nevertheless, the same rationale could be easily extended to other national and international contexts encompassing the space occupancy and typology (e.g. see https://codes.iccsafe.org/content/IBC2021P2/chapter-10-means-of-egress).

In particular, verifications depend on the risk profile concerning human life safety Rlife [-] assigned to each compartment/building, since it implies different levels of Assignment criteria for evacuation routes performance, and thus specific "deemed-to-satisfy" solutions. Additional verifications about variation of occupancy rate and presence and rate of vulnerable users (e.g. with motion/sensory disabilities), as well as the fire load rate, could be also overlapped to vary Rlife, and thus evaluate the effectiveness of solutions under building alternative use conditions without layout variation. Finally, it is worth noting that the Fire Safety Code relies on considering a unique fire ignition point, thus excluding arsons with multiple ignition points.

2.2.2 Passage graph

The “Passage Graph” is a graph that maps the relationships of passage between the various spaces that make up the building (Figure 7, Figure 8).

The “Passage Graph” maps the relationships of passage between the various spaces in the building (). It is an “ageometric” graph where nodes represent spaces or doors and edges connect spaces to adjacent doors, following the sequence “space-door-space”.

To construct the graph, IfcSpaces are converted into Topologic cells using IfcOpenShell and Topologicpy. Then, adjacency relationships between the IfcDoors and the Topologic cells are computed by executing geometrical and topological operations in Python.

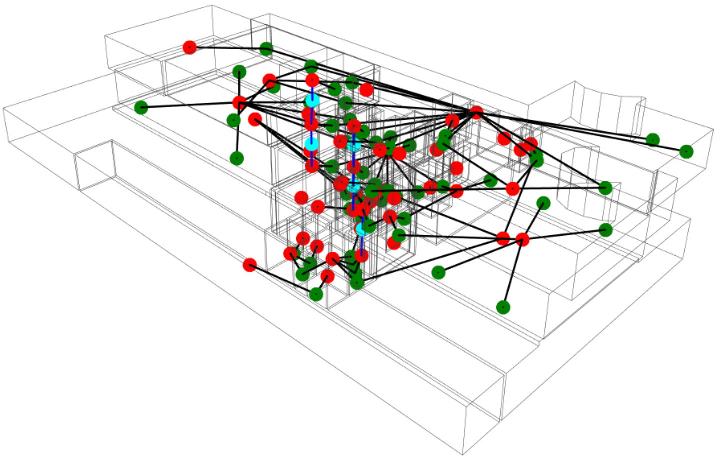


Figure 7. Passage graph of Building 10 (POLIMI).

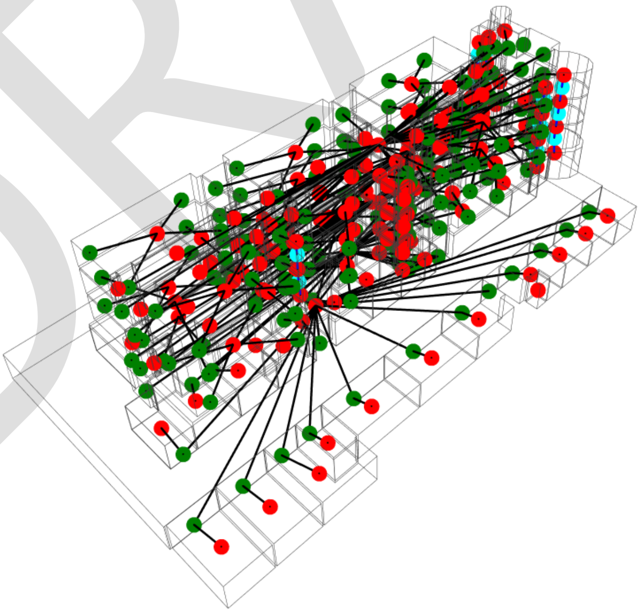


Figure 8. Passage graph of Building 09 (POLIMI).

2.2.3 Isovist graph

The “Isovist Graph” helps determine the shortest path connecting occupied spaces (e.g., classrooms) to the nearest emergency exits on the storey (Figure 9). It is called “Isovist” because its underlying algorithm is the isovist algorithm [16], which corresponds to the “straight-line” method required by the Italian Fire Safety Code for calculating evacuation route lengths (without considering furnishings, but fixed seatings if present).

For each “IfcBuildingStorey” in the IFC, the isovist algorithm is iterated from every internal door to every emergency door. The process continues until a direct line connecting the occupied door to the emergency door is found, or until a polyline passing through the occupied door (the emergency door) and all intermediate points of concavity is identified. The resulting lines are grouped in a new Topologic graph that, once constructed, can be processed by the shortest path algorithm to find the shortest route between the occupied door and the emergency door and store such relationship following the sequence “space-door-route-door”.

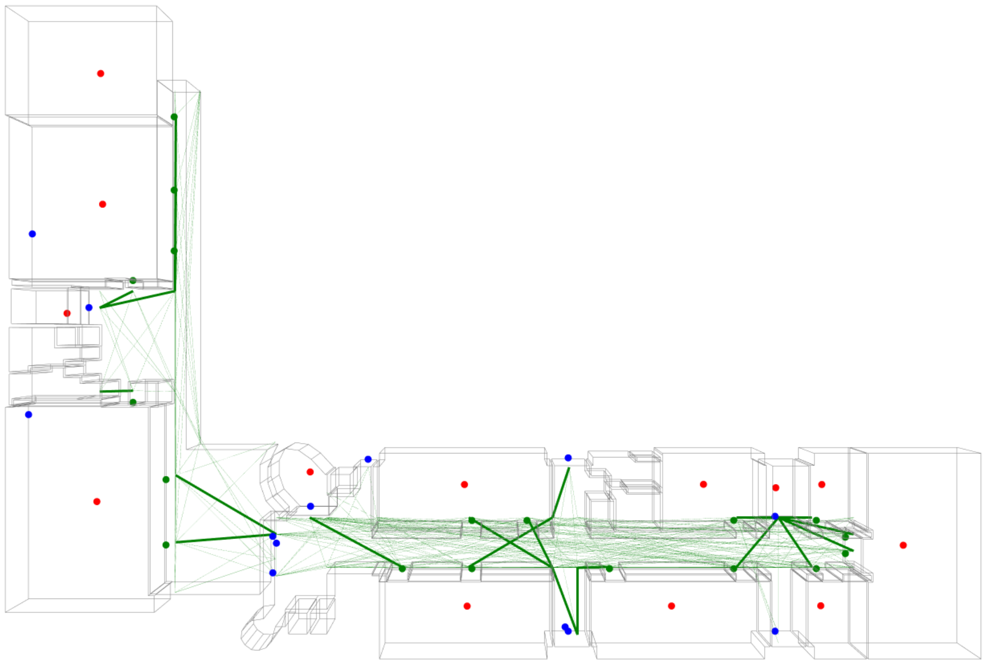


Figure 9. Combined isovist graph of Building 09 and Building 10 (POLIMI), shortest routes (first floor).

The graphs resulting from the application of the isovist graph algorithm on DIGITMAN’s case studies are depicted from Figure 10 to Figure 15.

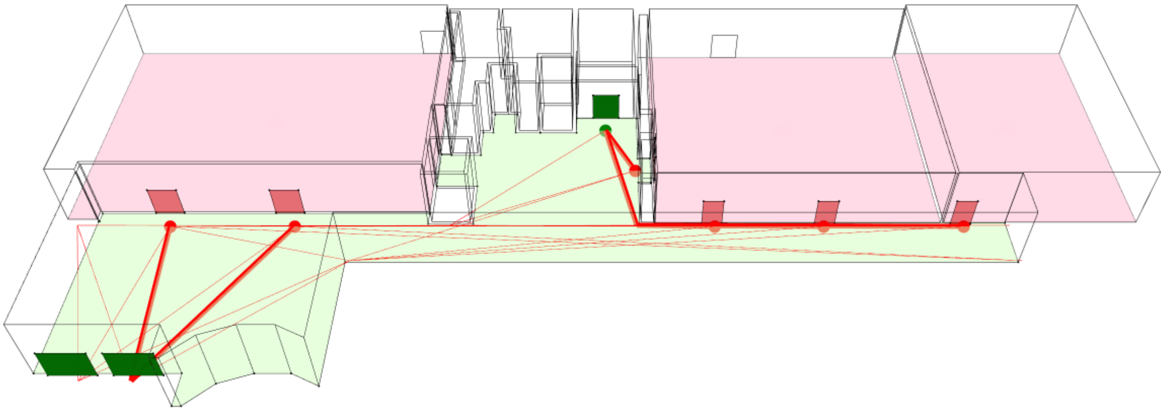


Figure 10. Isovist graph of Building 10 (POLIMI), first floor (elevation 5.17 m).

Figure 11. Isovist graph of Building 10 (POLIMI), ground floor (elevation 0.05 m).

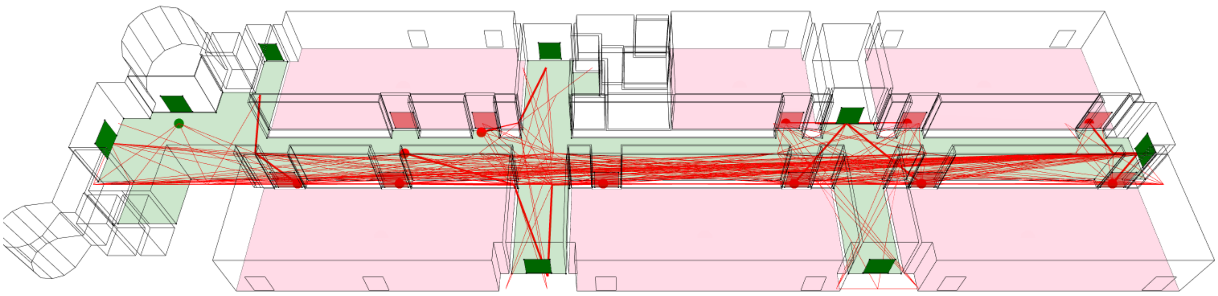


Figure 12. Isovist graph of Building 09 (POLIMI), second floor (elevation 10.29 m).

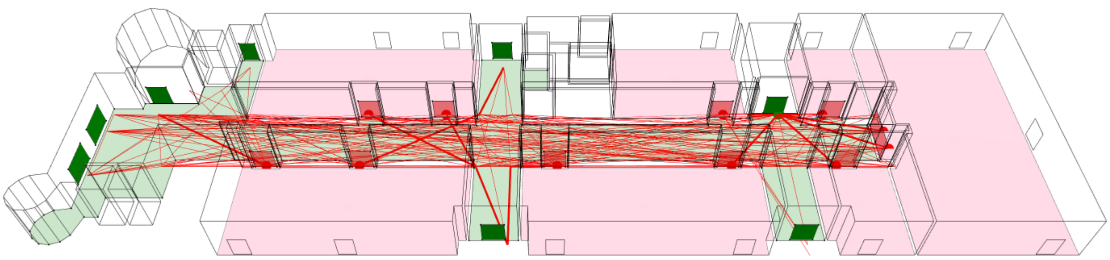


Figure 13. Isovist graph of Building 09 (POLIMI), first floor (elevation 5.17 m).

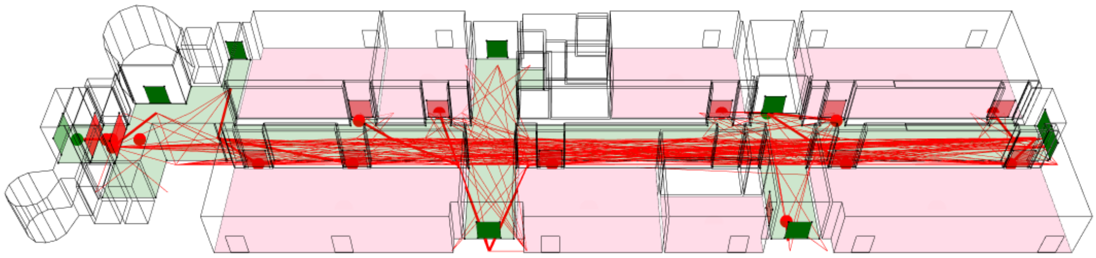


Figure 14. Isovist graph of Building 09 (POLIMI), ground floor (elevation 0.05 m).

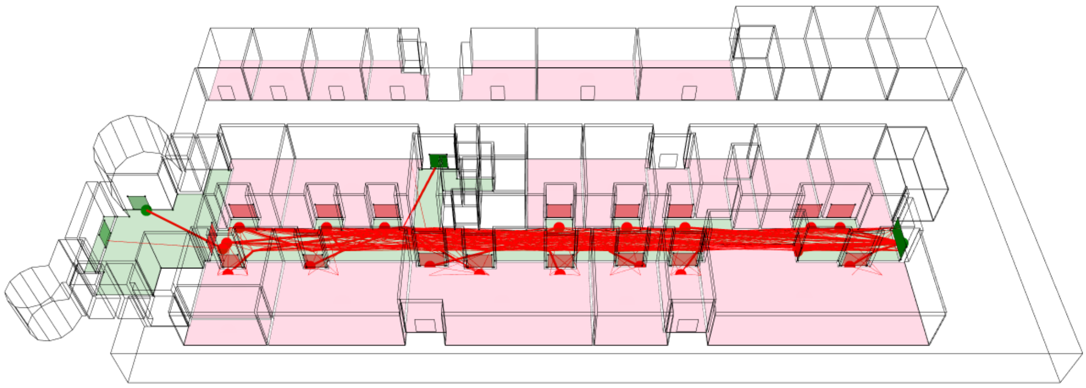


Figure 15. Isovist graph of Building 09 (POLIMI), underground floor (elevation -5.95 m).

2.2.4 Skeleton graph

The "Skeleton Graph" is finally used to map the flow of people through the building's evacuation routes and to perform necessary checks (Figure 16), such as verifying corridor widths based on the number of people using them. Like before, this graph is named according to its underlying algorithm: the skeleton algorithm [17].

This graph is generated for each circulation space in the IFC model. The process involves converting the circulation space into a Topologic cell, extracting the lower face of the cell, and applying the skeleton algorithm to it to generate the skeleton wire the skeleton wire undergoes further processing: 1) non-ridge wires (not on the skeleton's ridge line) are removed, 2) the ends of the skeleton are extended to reach the boundaries of the IfcSpace, 3) internal and emergency doors are connected to the nearest vertex of the skeleton wire (assuming a shortest path approach in path identification). At the end of this process, all resulting edges are grouped into a Topologic graph for each circulation space. These space-level graphs are then merged storey by storey, and finally, connections between floors are added through staircases.

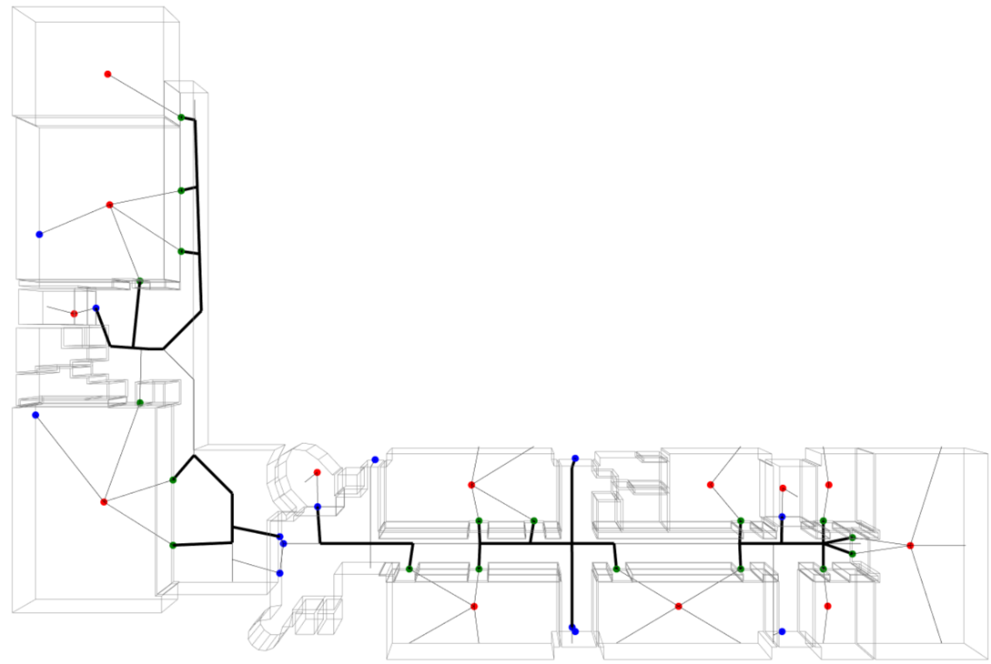


Figure 16. Combined skeleton graph of Building 09 and Building 10 (POLIMI), shortest routes (ground floor).

The graphs resulting from the application of the skeleton graph algorithm on DIGITMAN's case studies are depicted from Figure 17 to Figure 25.

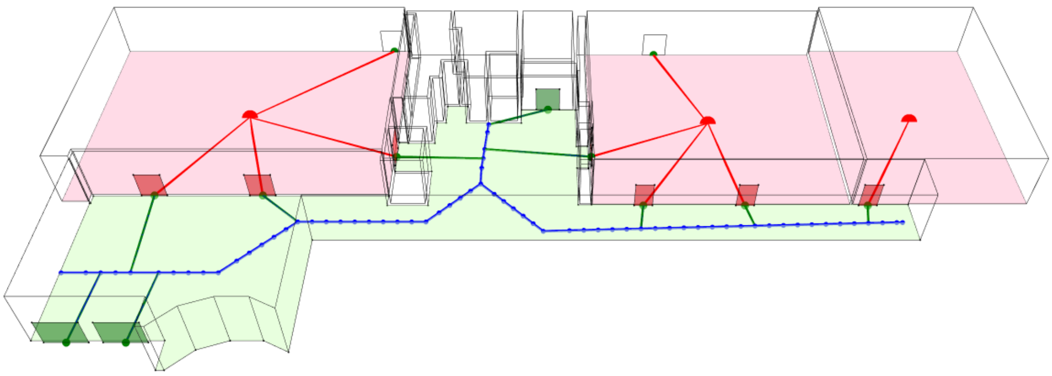


Figure 17. Skeleton graph of Building 10 (POLIMI), first floor (elevation 5.17 m).

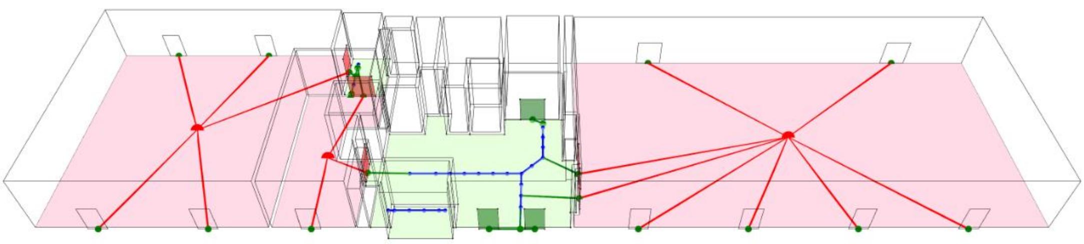


Figure 18. Skeleton graph of Building 10 (POLIMI), ground floor (elevation 0.05 m).

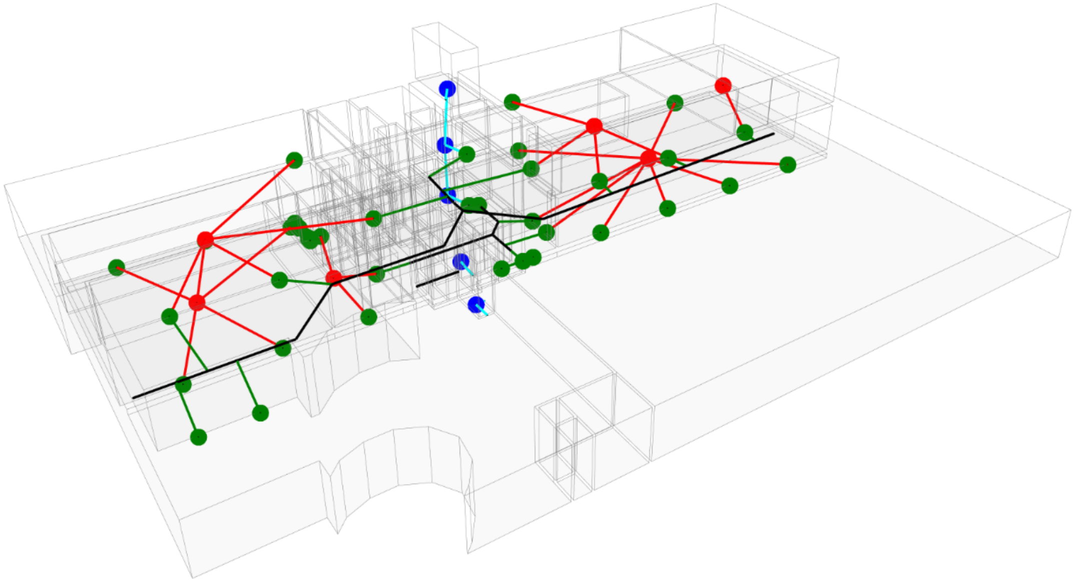


Figure 19. Skeleton graph of Building 10 (POLIMI), 3D view.

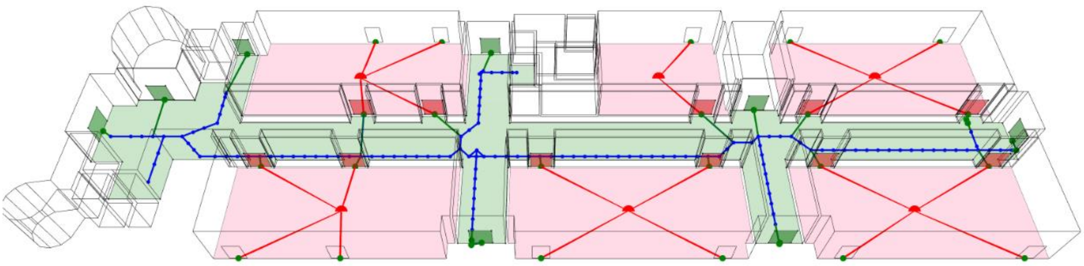


Figure 20. Skeleton graph of Building 09 (POLIMI), second floor (elevation 10.29 m).

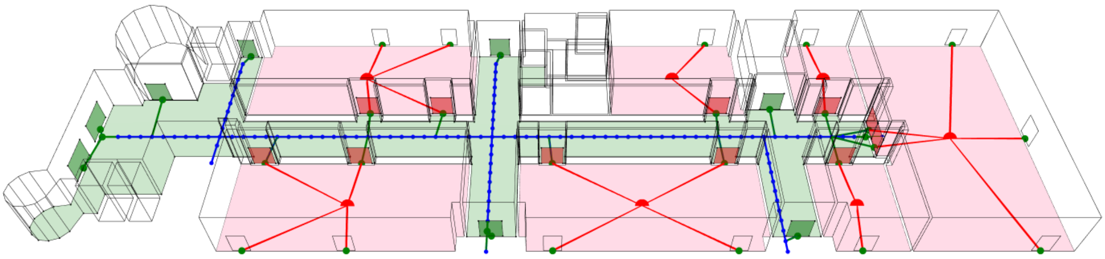


Figure 21. Skeleton graph of Building 09 (POLIMI), first floor (elevation 5.17 m).

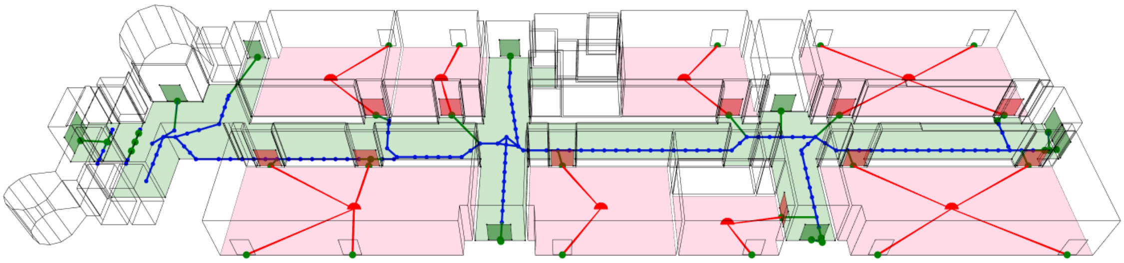


Figure 22. Skeleton graph of Building 09 (POLIMI), ground floor (elevation 0.05 m).

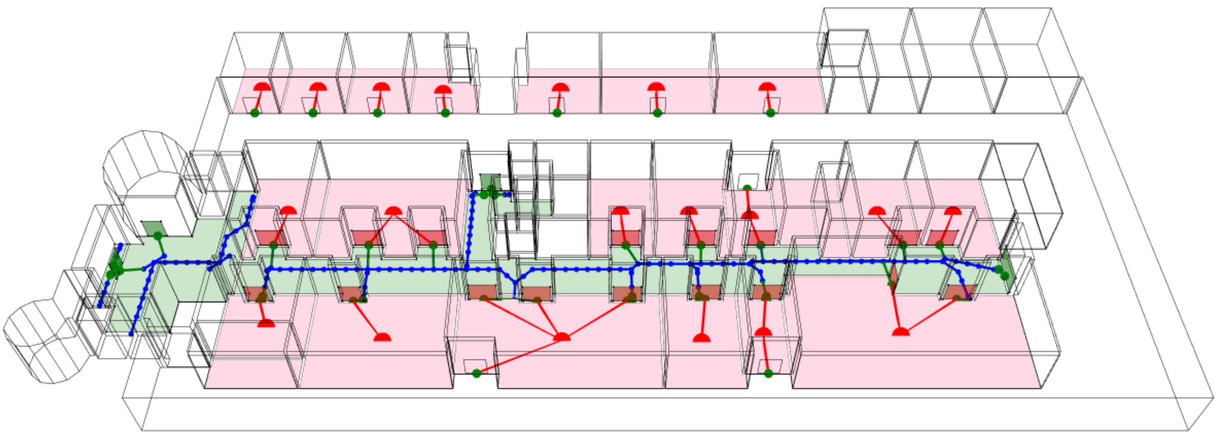


Figure 23. Skeleton graph of Building 09 (POLIMI), underground floor (elevation -5.95 m).

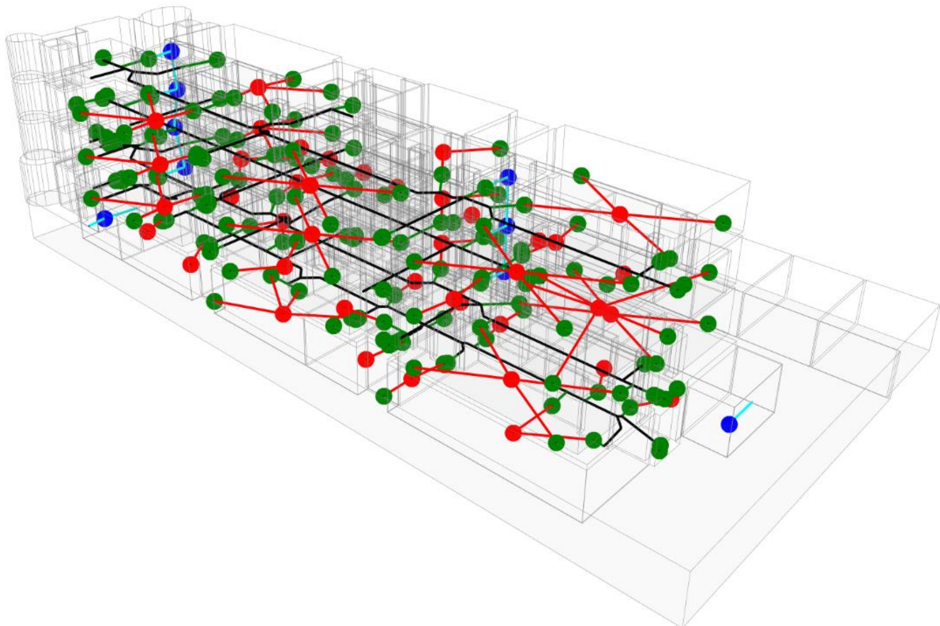


Figure 24. Skeleton graph of Building 09 (POLIMI), 3D view.

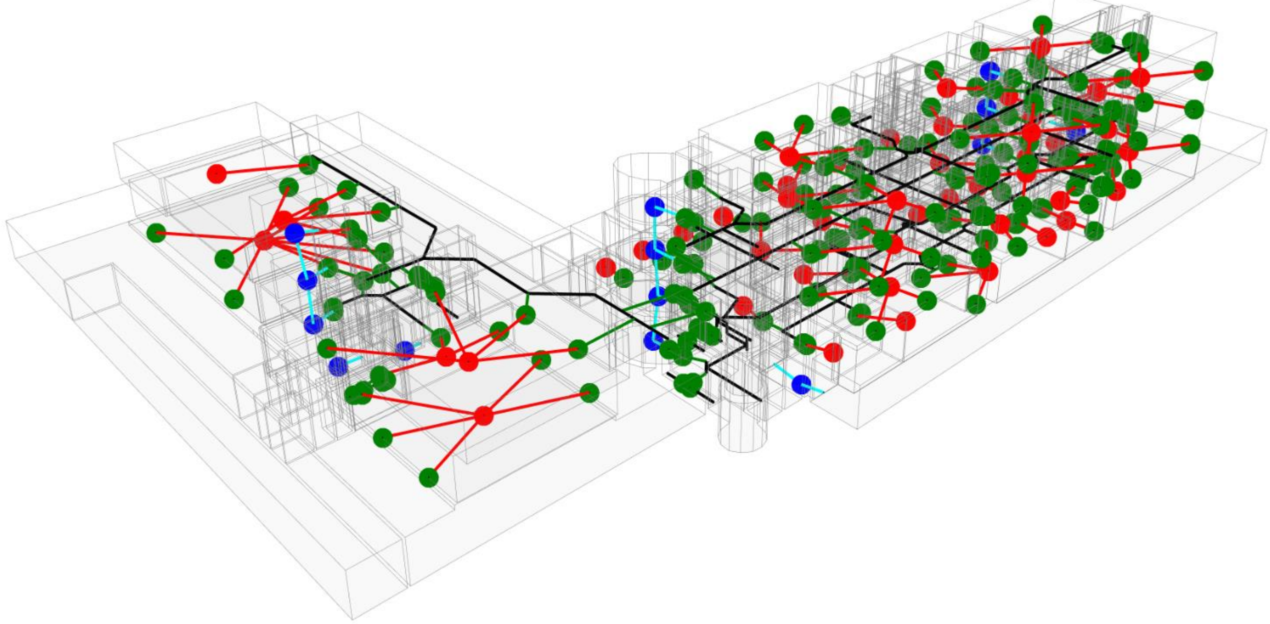


Figure 25. Combined skeleton graph of Building 09 and Building 10 (POLIMI), overall 3D views.

In the following paragraphs, the results of applying the previously presented methodology to the project's case study are reported. The application aimed to calculate the Safety KPIs, as indicated in Section 2.1, to perform safety assessments at the space, storey, and compartment/building levels. To facilitate readability, the assessments are presented separately as checks on the width of elements and checks on the length of evacuation routes. However, all assessments are conducted using the same models in an integrated manner.

2.2.5 Application to the room

The first verification algorithm was applied to automatically verify the compliance of individual occupied spaces (e.g., classrooms) in the pilot buildings. For each building, by processing the passage graph, the algorithms checked whether each space met the fire safety code's criteria including the width ratio and length ratio of the travel distance, the number of independent exits of the space, and door opening specifications including the opening device type and the opening direction, as reported in paragraph 2.1.1. The process generates visual reports to aid in identifying potential safety issues (see example in **Errore. L'origine riferimento non è stata trovata.**).

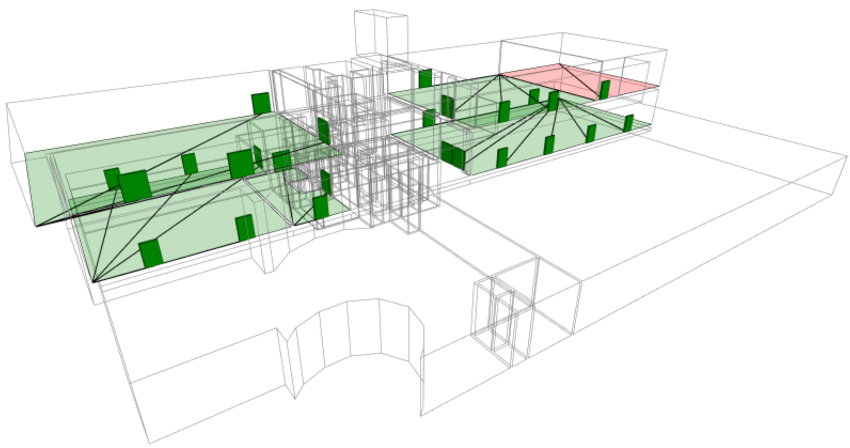


Figure 26. Room-level verifications conducted on Building 10 (POLIMI). On the left, 3D view: Green spaces are verified, red spaces are not verified. Green doors are verified, while red doors are not verified. The black lines in the spaces represent those with maximum travel distance for each space. On the right, report of the most significant parameters considered in the evaluation for a space.

2.2.6 Width ratio verifications

The width assessments were carried out following the methodological workflow proposed in Figure 4. To apply the workflow, two preliminary steps were required for the preparation of the BSM:

1. **Conversion of the Topologic graphs into NetworkX graph**. This step was necessary to speed up shortest path calculations since NetworkX proved to be about faster than Topologicpy;
2. **Identification of the shortest paths in the skeleton graph**, identified as the shortest routes leading from each door adjacent to an occupied space (e.g., classrooms) to the closest storey exit, using the lines of the isovist graph;
3. **Distribution of the number of evacuees from occupied spaces along the shortest routes in the skeleton graph**, as determined in the previous step.

2.2.6.1 Identifying the shortest routes along the skeleton graph

To identify the shortest routes on the skeleton graph, the following procedure was applied:

a. **Selection of start doors**: All doors adjacent to both an occupied space and a corridor (start doors) were identified by executing topological queries on the skeleton graph.
b. **Identification of end doors**: For each start door, the closest storey fire exit (end door) was determined by applying the shortest path algorithm on the isovist graph.
c. **Calculation of evacuation routes**: For each start door, the shortest path to the corresponding end door (evacuation route) was identified within the skeleton graph by applying the shortest path algorithm.

The results for the POLIMI case study are displayed in the following figures (Figure 27-Figure 31Figure 32).

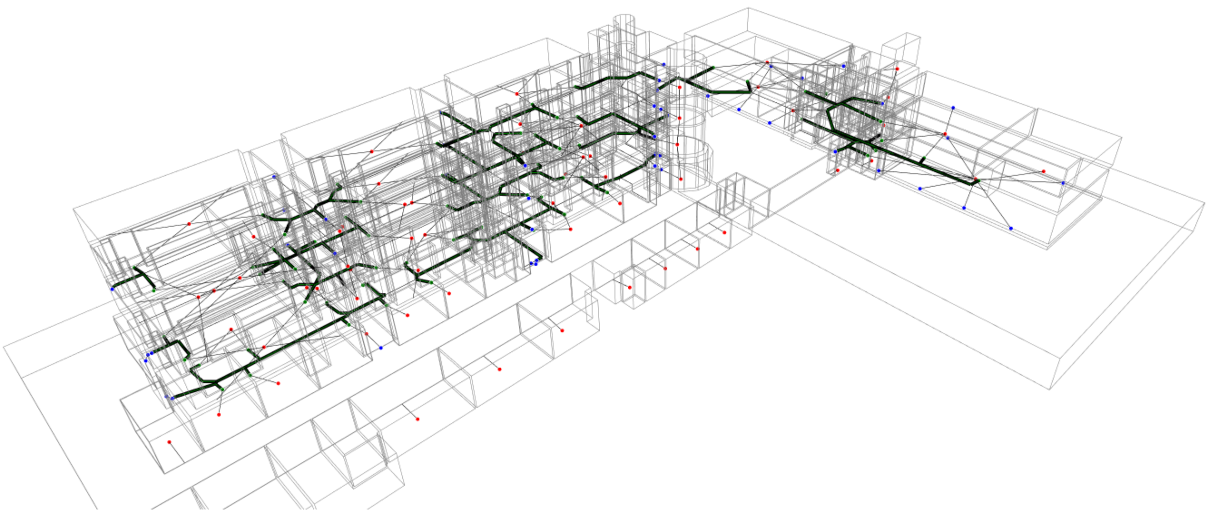


Figure 27. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with shortest routes highlighted.

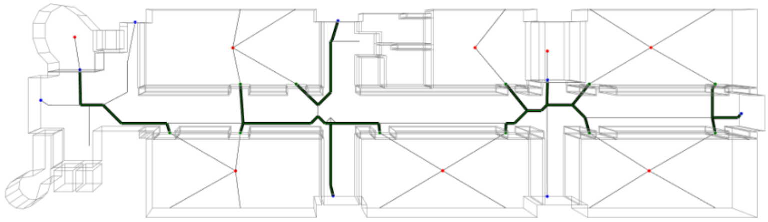


Figure 28. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with shortest routes highlighted. (elevation 10.29 m).

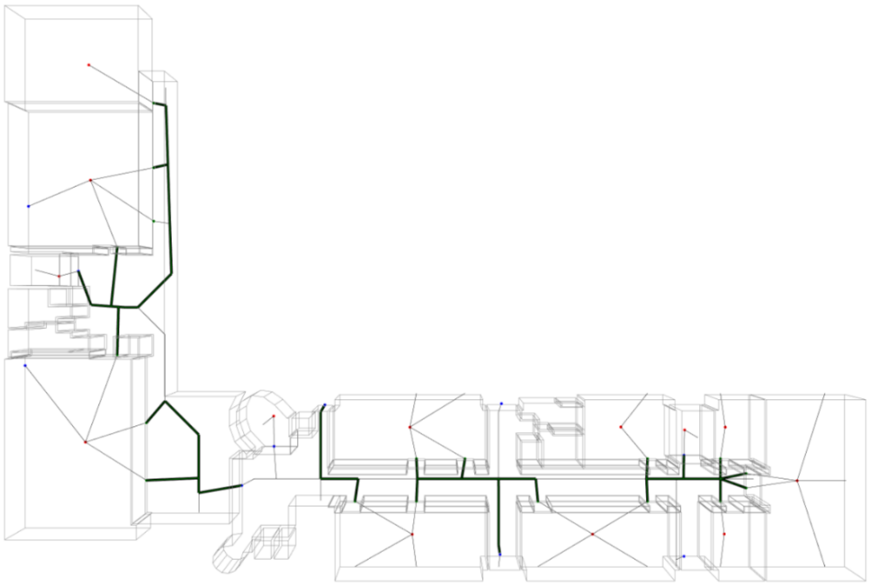


Figure 29. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with shortest routes highlighted. (elevation 5.17 m).

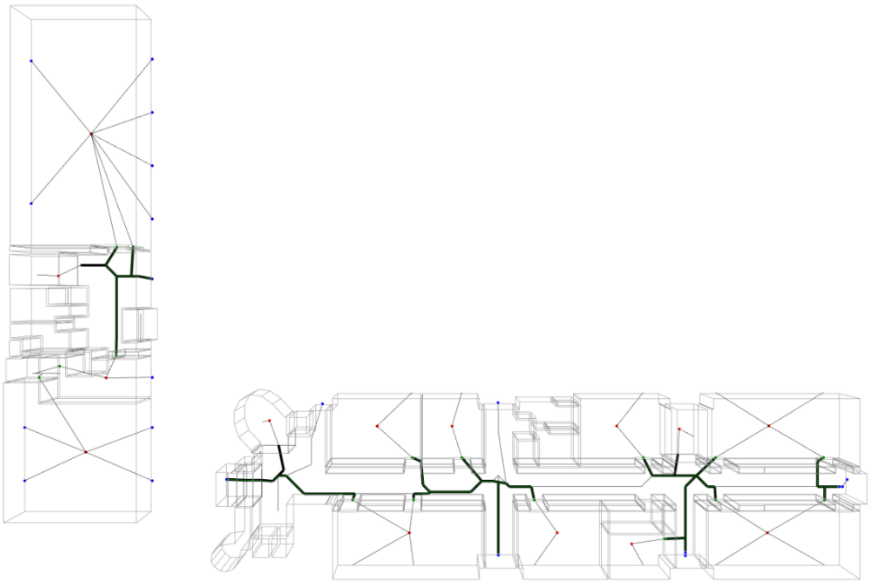


Figure 30. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with shortest routes highlighted. (elevation 0.05 m).

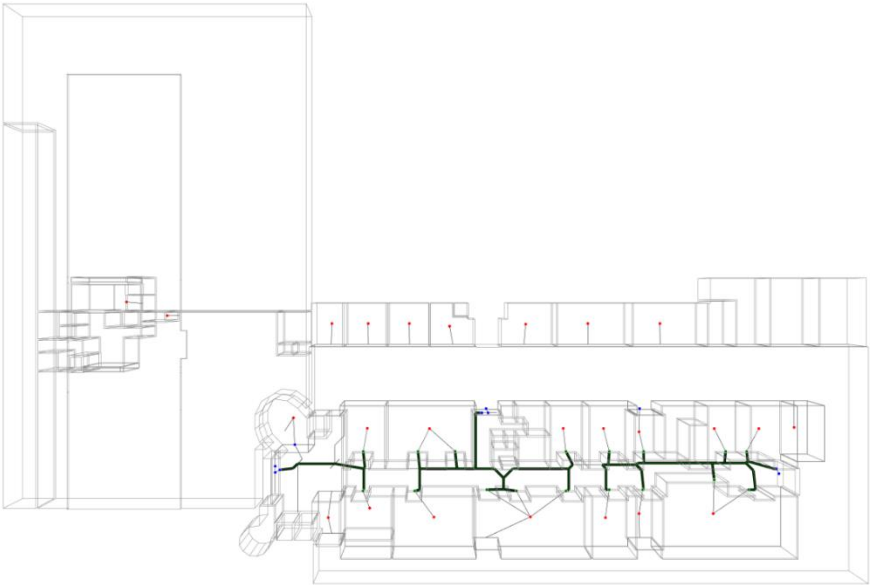


Figure 31. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with shortest routes highlighted. (elevation - 5.95 m).

2.2.6.2 Distributing the number of people along the evacuation network

Then, evacuees were distributed along the shortest path within the evacuation network, represented here by the skeleton graph. The algorithm followed these steps:

a. **Determination of evacuee numbers per start door**: For each start door, the number of evacuees passing through was determined by taking the peak occupancy of the adjacent occupied space and distributing it evenly among the space's start doors.
b. **Selection of evacuation routes**: The evacuation route from each start door to its corresponding end door in the skeleton graph was identified.
c. **Identification of ground-level evacuation paths**: At the ground level, for each door adjacent to the stairs, the shortest path from this door to the closest storey exit door was determined, following the same methodology as in the previous step.
d. **Assignment of evacuees to evacuation routes**: For each evacuation route, at each node along the route, the number of evacuees exiting from the start door was assigned to the corresponding node in the evacuation network. The edges of the skeleton graph were subdivided to allow assessments at every meter and at each intersection between different edges.
e. **Distribution of evacuees on the ground floor**: On the ground floor, evacuees descending from upper floors via staircases were distributed along the shortest routes intersecting the evacuation paths leading from the staircases to the nearest storey exit.

The results of this process for the POLIMI case study are displayed in the following figures (Figure 32-Figure 36).

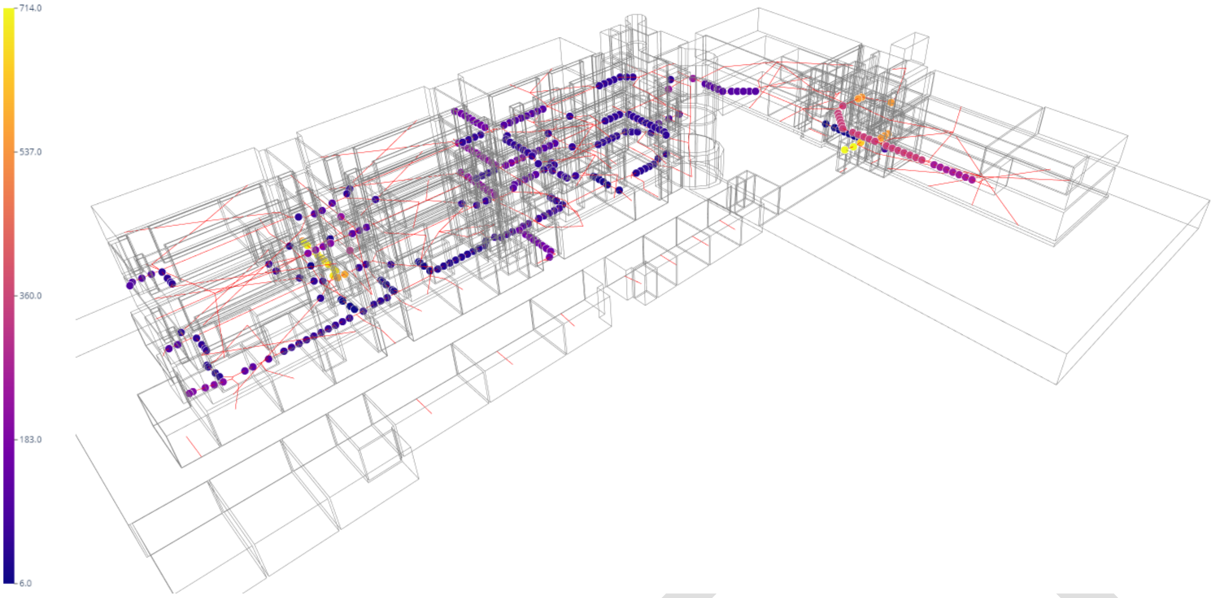


Figure 32. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with number of people distributed along the routes.

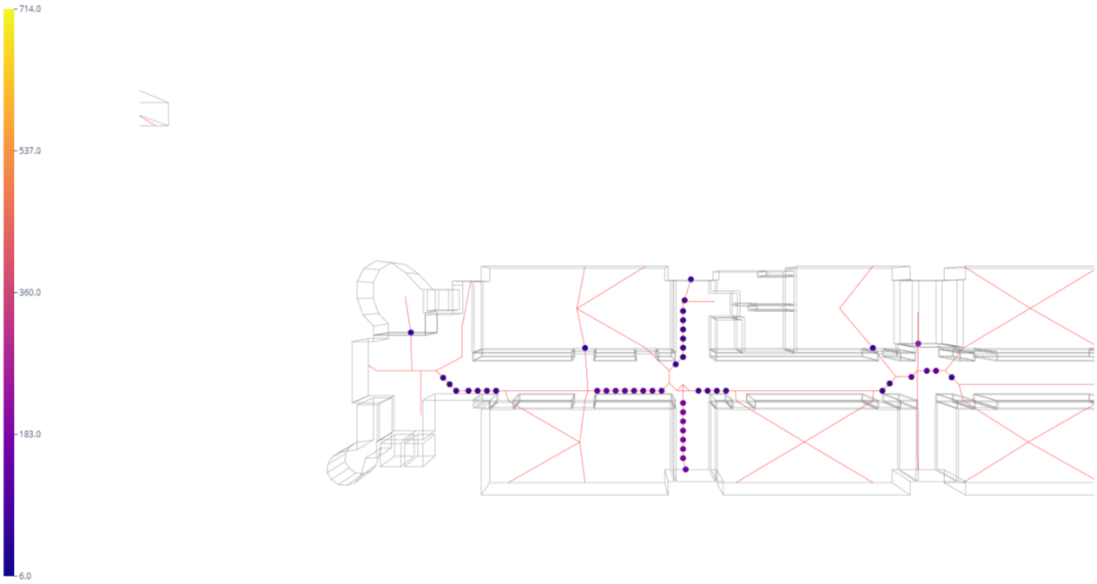


Figure 33. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with number of people distributed along the routes. (elevation 10.29 m).

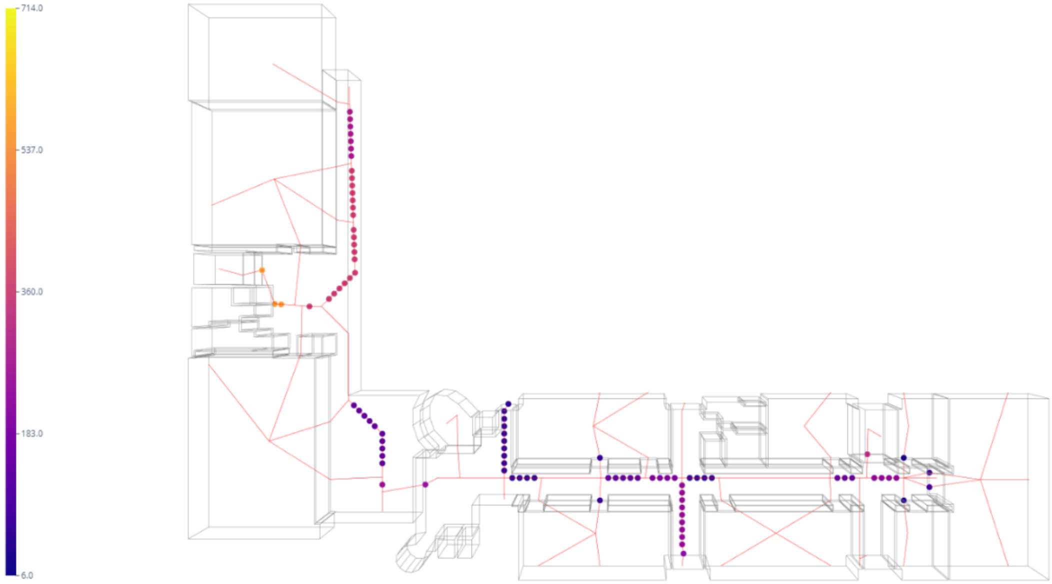


Figure 34. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with number of people distributed along the routes. (elevation 5.17 m).

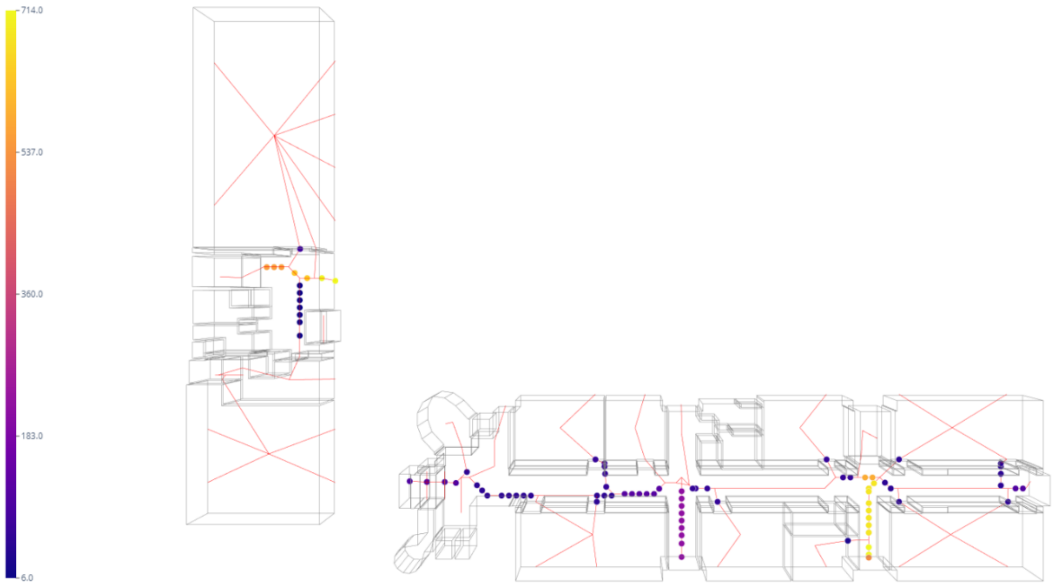


Figure 35. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with number of people distributed along the routes. (elevation -0.05 m).

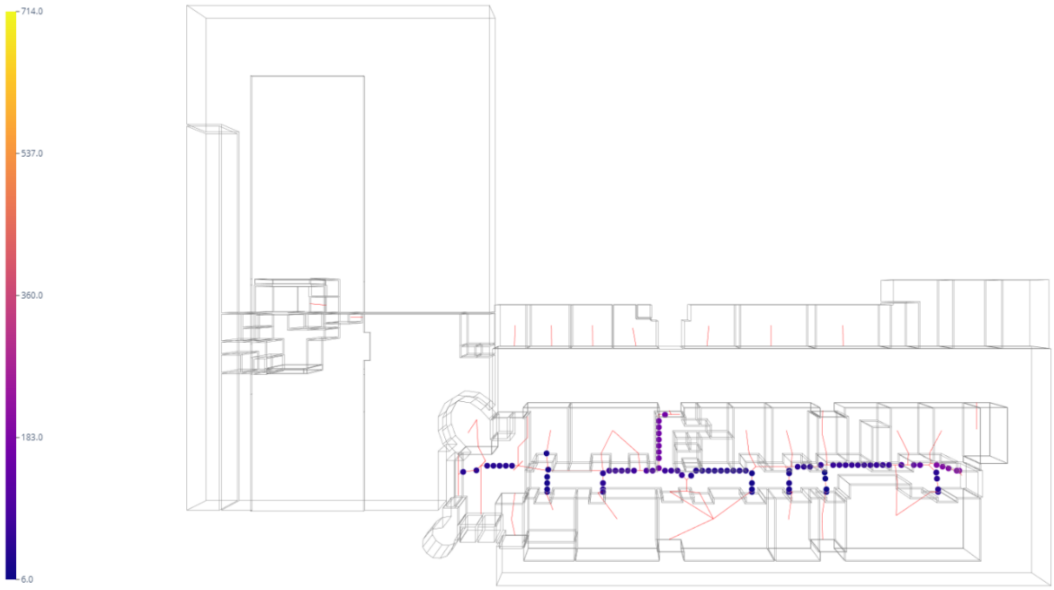


Figure 36. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with number of people distributed along the routes. (elevation -5.95 m).

2.2.6.3 Calculating the minimum width of horizontal escape routes (single element)

The second algorithm applied enables the verification of horizontal escape routes at the level of individual elements (i.e., doors or corridors). This algorithm follows these steps:

1) **Calculation of effective passage width (L_elem) for each corridor vertex in the evacuation network**:
   - Using functions from the TopologicPy library, the effective width of each passage is computed.
   - Specifically, for each vertex, the circulation space in which it is located is identified using the Vertex.IsInternal() method.
   - A line orthogonal to the edge of the skeleton graph, on which the vertex lies, is then constructed.
   - This line is intersected with the Brep of the IfcSpace containing the vertex using the Topology.Intersect() function.
   - The distance between the two vertices intersecting the Brep is taken as the corridor width at that vertex.
2) **Assignment of effective width for each door in the evacuation network**:
   - The effective width (L_elem) of each door is set equal to the pr_Width property of the door.
   - This width is assigned to the node in the skeleton graph representing the door.
3) **Comparison of effective width with the minimum required width** from the Fire Safety Code (Table 107):
   - For each vertex, the computed width is compared against the minimum width requirement specified in Table 107 of the Fire Safety Code.
4) **Additional verification based on occupant load**:
   - If the first verification is passed, the effective width is further compared with the required width from Table 106 (which defines the minimum width as a function of the number of occupants by multiplying the unit width per occupant).
5) **Final verification and KPI assignment**:
   - The element is considered compliant if both verifications (Table 107 and Table 106) are satisfied.

- Each element is assigned a KPI representing the width ratio, defined as the ratio between the minimum width required by the Fire Safety Code and the actual effective width of the door.

Figure 37 visually represents the results applied to the project's pilot site.

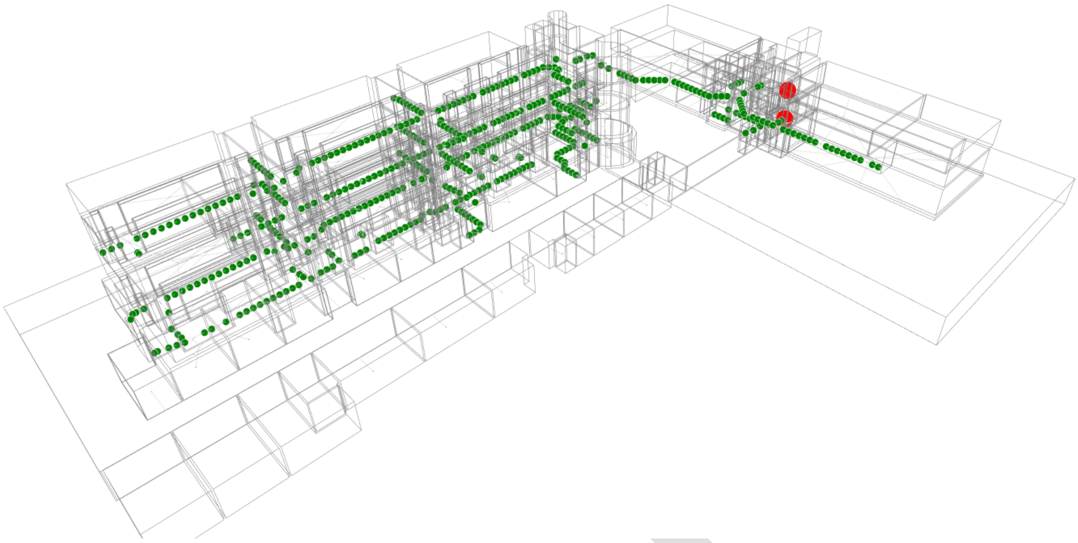


Figure 37. Verification of the minimum width of horizontal escape routes on the combined skeleton graph of Building 09 and Building 10 (POLIMI). Green vertices are verified, while red vertices are not verified.

2.2.6.4 Calculating the minimum width of vertical escape routes (single element)

A similar algorithm is applied to verify the minimum widths of staircases according to Tables 111 and 108 of the Fire Safety Code. The verification process follows these steps:

1. **Identification of vertical circulation spaces in the building**:
   - Stairways are identified as subgraphs of interconnected spaces classified with the function "*Stairway*".
2. **Calculation of the number of occupants using each stairwell**:
   - The number of evacuees assigned to each stairwell is determined based on the evacuation method, which can be either "*simultaneous*" or "*phased*", following the prescriptions of the Fire Safety Code.
3. **Definition of staircase width**:
   - The width of each staircase is set equal to the width of the virtual door leading from the corridor to the stairwell. This virtual door was specifically modeled in the BIM environment with a width equal to the staircase ramp width.
4. **Verification against the minimum width required for stair ramps (Table 111)**:
   - The effective staircase width is checked to ensure it meets or exceeds the minimum width specified in Table 111 of the Fire Safety Code.
5. **Verification against the occupant-based minimum width (Table 108)**:
   - If the first verification is passed, the effective width is further compared with the required width from Table 108, which specifies the minimum required width based on the number of occupants.
6. **Calculation of the width ratio and assignment to the skeleton graph**:
   - For each stairway, the *width ratio* (ratio between the minimum required width and the actual width) is computed.

- This ratio is assigned to the corresponding node in the skeleton graph.

The visual representation of the results is shown in Figure 38.

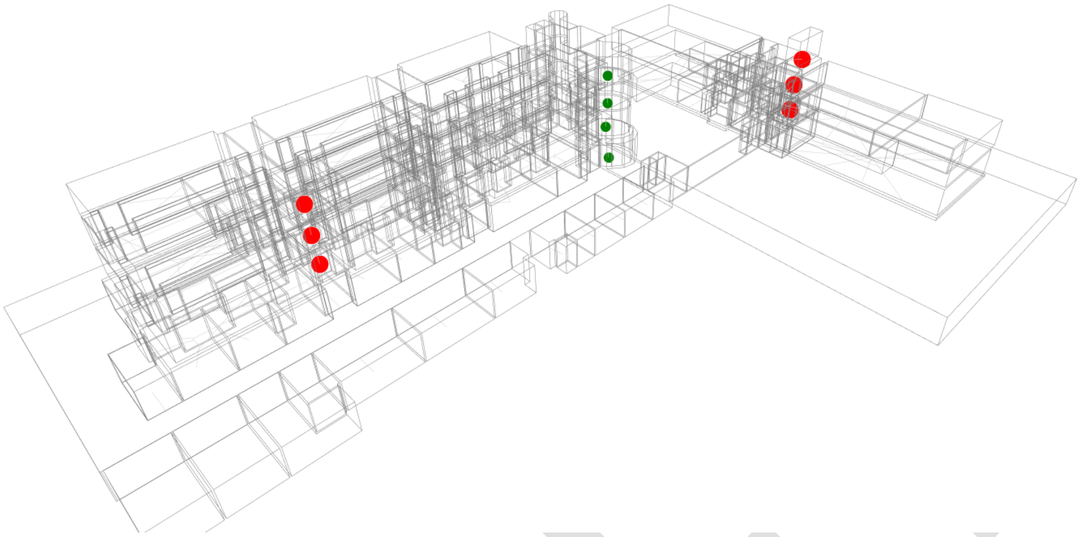


Figure 38. Verification of the minimum width of vertical escape routes on the combined skeleton graph of Building 09 and Building 10 (POLIMI). Green vertices are verified, while red vertices are not verified.

2.2.6.5 Calculating the minimum width of horizontal escape routes (storey-level)

The KPIs for width ratios of horizontal escape routes are aggregated at the storey level following these steps:

1. **Identification of storey exits within each compartment**: Storey exits are identified, including both exits leading to safe/exterior areas and exits from corridors to internal staircases.
2. **Summation of effective widths of storey exits**: The total effective width of all storey exits is calculated by summing the actual widths of all identified exits.
3. **Summation of minimum required widths of storey exits**: The total minimum width requirement for all storey exits is determined using the same calculation method as in previous steps.
4. **Calculation of the storey-level width ratio KPI**: The ratio between the sum of the minimum required widths and the sum of the actual widths is computed. This width ratio at the storey level serves as the KPI for horizontal escape route capacity on each storey.

Figure 39 visually represents the results of this process applied to the project's case study.

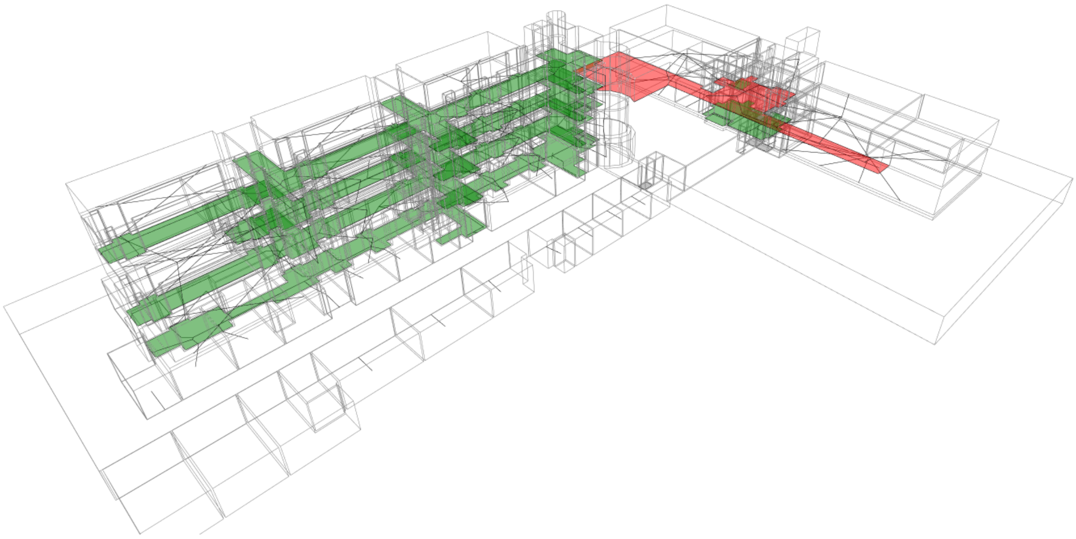


Figure 39. Verification of the minimum width of horizontal escape routes at the storey level for Building 09 and Building 10 (POLIMI). Green storeys are verified, while red storeys are not verified.

2.2.6.6 Calculating the minimum width of fire exits (compartment level)

The final width verification is performed at the compartment level for the building's final exits located on the ground floor. This verification considers not only horizontal evacuation flows but also vertical flows coming from the staircases.

The verification process strictly follows Formula 17 of the Fire Safety Code, as previously outlined in Section 2.1.3. This ensures that the cumulative evacuation capacity of all final exits is sufficient to accommodate the total number of evacuees from both horizontal and vertical escape routes.

Figure 40 depicts an output of this process applied on the project's case study.

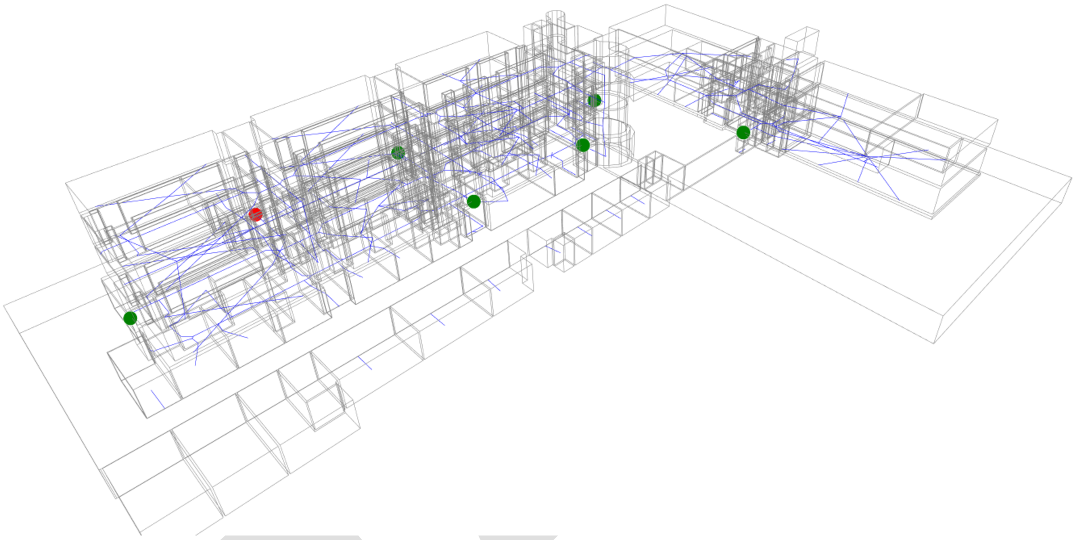


Figure 40. Verification of the minimum width of final exit doors the compartment level for Building 09 and Building 10 (POLIMI). Green exit doors are verified, while red exit doors are not verified.

2.2.6.7 Redundancy

A redundancy check was finally applied to all width verifications to ensure minimum width compatibility under failure conditions. This check evaluates the evacuation capacity by considering one exit unavailable at a time. The objective is to verify whether the remaining exits can still accommodate the required evacuation flow, ensuring compliance with safety regulations even in case of an exit blockage or failure.

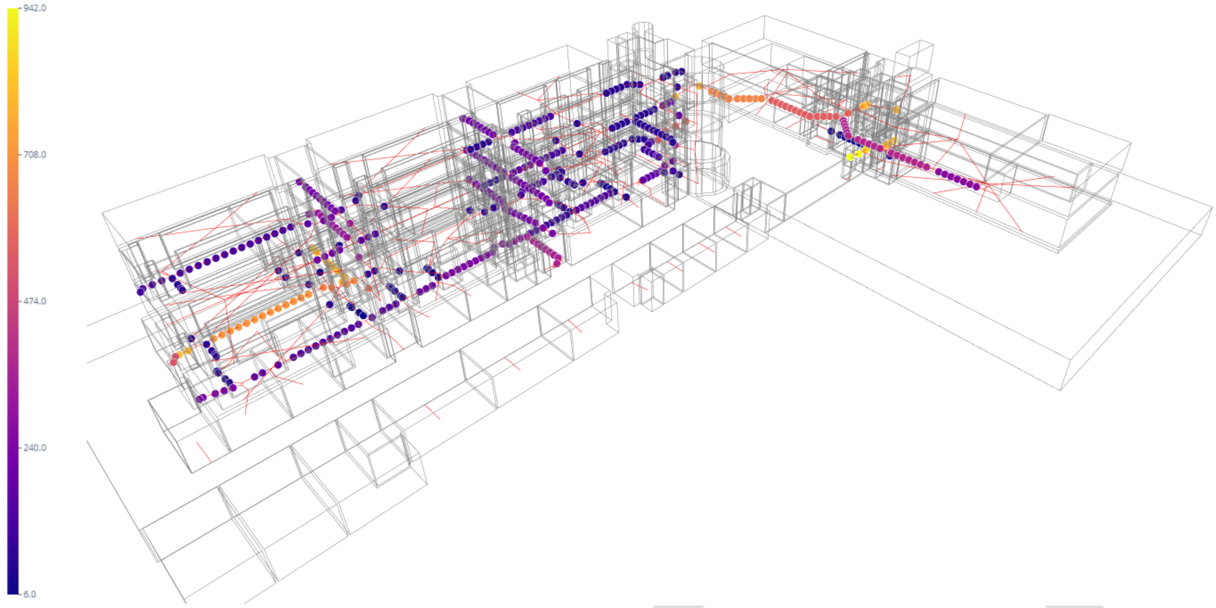


Figure 41. Combined skeleton graph of Building 09 and Building 10 (POLIMI) with number of people distributed along the routes after applying redundancy.

2.2.7 Length ratio verifications

The length assessments were carried out following the methodological workflow proposed in Figure 5. Similar to the width verifications, implementing this workflow required two preliminary preparation steps for the BSM:

1. **Conversion of the topological graphs into NetworkX graphs**. This conversion was necessary to enhance computational efficiency, as NetworkX significantly outperformed Topologicpy in calculating the shortest paths.
2. **Integration of vertical circulation paths into the isovist graph**. Specifically, edges representing vertical evacuation routes (e.g., staircases) were added from the skeleton graph into the isovist graph to reflect vertical movement within the model.

2.2.7.1 Identifying the shortest routes along the isovist graph

To identify the shortest routes on the isovist graph, the following procedure was applied:

a. **Selection of start doors**: All doors adjacent to both an occupied space and a corridor (start doors) were identified by executing topological queries on the isovist graph.
b. **Identification of end doors**: For each start door, the closest storey fire exit (end door) was determined by applying the shortest path algorithm on the isovist graph.
c. **Calculation of evacuation routes**: For each start door, the shortest path to the corresponding end door (evacuation route) was identified within the skeleton graph by applying the shortest path algorithm.

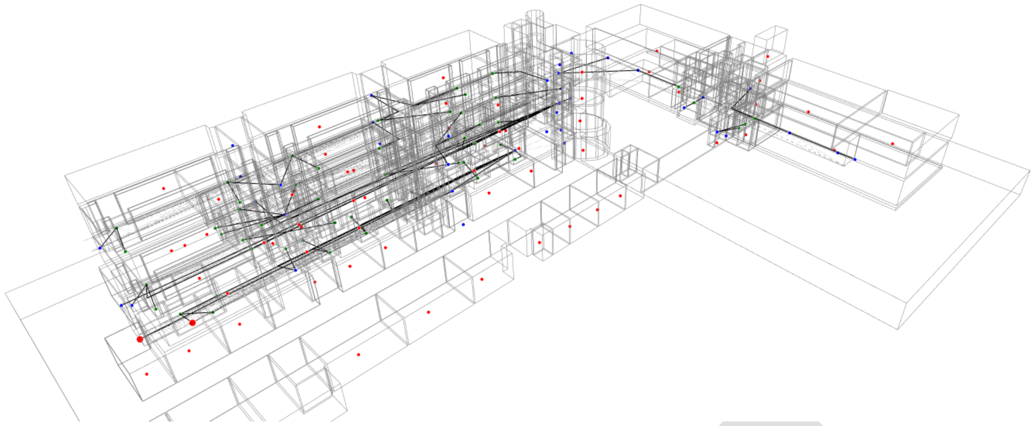


Figure 42. Shortest routes on the isovist graph of Building 09 and Building 10 (POLIMI).

2.2.7.2 Calculating the actual length of the evacuation routes

The actual lengths of the evacuation routes were then calculated as follows:

1. **Routes from occupied spaces to the start door**: These were calculated using the same algorithms applied at the room level as described in paragraph 2.2.5.
2. **Horizontal routes**. The actual length of the horizontal evacuation paths corresponds to the sum of the lengths of the edges in the isovist graph that are traversed from the start door to the end door.
3. **Vertical routes**. The actual length of the vertical evacuation paths was determined by accounting for the height of the staircase shafts and applying trigonometric relationships to compute the hypothetical length of a flight of stairs with a 30 cm tread and 15 cm riser (50% slope). In addition, the lengths of the landings were included, considering them to be as wide as the doors adjacent to the stair shafts and assuming two flights of stairs per floor by default. This approach was necessary because the TBIM model used for the BSM does not provide specific information regarding stairs.

The total effective length of the evacuation path was then obtained by summing the length of the routes from occupied spaces to the start door and the lengths of all elements belonging to horizontal and vertical routes. This approach allows for the automatic evaluation of dead-end and non-dead-end corridors.

2.2.7.3 Calculating the maximum length of the evacuation routes

The maximum length of the evacuation routes was calculated, depending on the specific case, following the guidelines provided by Table 104 of the fire safety code (maximum travel distances), according to the R Life category. Adjustments were considered to increase the maximum travel distance from Table 104 by applying factors from Table 117, which account for additional fire protection requirements for the compartment served by the escape route.
The final KPI was calculated for each space by considering the shortest available evacuation path and dividing its actual length by the maximum allowed length defined by the code.

3 Final remarks

The definition of KPIs on the safety issues and the development of the BIM to BSM tools incorporating their assessment first contribute to the analysis of "deemed-to-satisfy" parameters according to Fire Safety Code. In view of the KPI structure, decision makers can:

- Simply and quickly check if current/designed conditions of the building are compliant with basic assessment related to means of egress;
- Evaluate how alternatives in "what-if" scenarios involving different interventions on the architectural layout and on the spaces intended use (including modifications in the number of occupants) can increase or decrease the main numerical KPIs (i.e. S-1.1 and S-1.2);
- Then select the best alternative as the one that could maximize the allowed value of KPIs (optimization of the operative conditions in the given scenario) or that could minimize them (optimization in case of future changes, i.e. for S-1.2 related to an increase of occupancy and for S-1.1 related to an increase complexity of means of egress and space tortuosity);
- Quickly understand the structure of the means of egress by composing elements, having each KPI associated with the related element and thus a direct and clear association of possible "hot-spot" on the building layout.

The future implementation of KPIs into assessment metrics could mainly rely on S-1.1 and S-1.2 as numerical leading KPIs. Basic assumptions for combination could be based on possible balanced weights related to width ratio and length ratio then using the resulting vector to determine the overall safety level of a given configuration of the building. In this sense, modifications affecting fire safety would also act towards operational tasks (see WP3), in view of the combination of effects of alternatives in building layout definition on these performances.

Finally, the proposed approach selects a limited but reliable number of KPIs, focusing on geometrical ones for the implementation into the BIM to BSM approach. Risk and use-related ones could be comprised by future works, being correlated with data collection from CMMS and BAS, to verify the operational issue in safety at the space level or at the whole building (e.g. to incorporate data for intelligent and dynamic wayfinding and alert systems) [4, 10]. Further advanced logics could be also addressed in the BIM model, incorporating evacuation simulators too [5–9]. Nevertheless, the reliability of the model applicability should consider the automatic assignment of input conditions, excluding time-consuming steps which can be performed by fire safety designers but not by stakeholders. Morevoer, final results should be easy to use by decision makers, and thus based on clear association of simulation outcomes to simple indices.

4 References

1. Ministry of Interior (Italy): DM 03/08/2015: Fire safety code (testo coordinato dell'allegato I del DM 3 agosto 2015 - codice di prevenzione incendi) - in Italian, (2020).
2. Chen, Y., Jiang, H.: Optimizing automated compliance checking with ontology-enhanced natural language processing: Case in the fire safety domain. Journal of Environmental Management. 371, 123320 (2024). https://doi.org/10.1016/j.jenvman.2024.123320.
3. Burak Gunay, H., Shen, W., Newsham, G.: Data analytics to improve building performance: A critical review. Automation in Construction. 97, 96–109 (2019). https://doi.org/10.1016/J.AUTCON.2018.10.020.
4. Dong, B., Yan, D., Li, Z., Jin, Y., Feng, X., Fontenot, H.: Modeling occupancy and behavior for better building design and operation—A critical review. Building Simulation. 11, 899–921 (2018). https://doi.org/10.1007/s12273-018-0452-x.
5. Yakhou, N., Thompson, P., Siddiqui, A., Abualdenien, J., Ronchi, E.: The integration of building information modelling and fire evacuation models. Journal of Building Engineering. 63, 105557 (2023). https://doi.org/10.1016/j.jobe.2022.105557.
6. Tang, S., Shelden, D.R., Eastman, C.M., Pishdad-Bozorgi, P., Gao, X.: A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. Automation in Construction. 101, 127–139 (2019). https://doi.org/10.1016/j.autcon.2019.01.020.
7. Mirahadi, F., McCabe, B., Shahi, A.: IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling. Automation in Construction. 101, 1–16 (2019). https://doi.org/10.1016/j.autcon.2019.01.007.
8. Siddiqui, A.A., Ewer, J.A., Lawrence, P.J., Galea, E.R., Frost, I.R.: Building Information Modelling for performance-based Fire Safety Engineering analysis – A strategy for data sharing. Journal of Building Engineering. 42, 102794 (2021). https://doi.org/10.1016/j.jobe.2021.102794.
9. Zhang, J., Jiang, S., Qi, X.: Enhancing fire safety with Improved Risk Index and BIM in building evacuation. Engineering, Construction and Architectural Management. (2024). https://doi.org/10.1108/ECAM-09-2023-0923.
10. Yenumula, K., Kolmer, C., Pan, J., Su, X.: BIM-Controlled Signage System for Building Evacuation. Procedia Engineering. 118, 284–289 (2015). https://doi.org/10.1016/j.proeng.2015.08.428.
11. Galea, E.R., Xie, H., Deere, S., Cooney, D., Filippidis, L.: Evaluating the effectiveness of an improved active dynamic signage system using full scale evacuation trials. Fire Safety Journal. (2017). https://doi.org/10.1016/j.firesaf.2017.03.022.
12. Malagnino, A., Corallo, A., Lazoi, M., Zavarise, G.: The Digital Transformation in Fire Safety Engineering over the Past Decade Through Building Information Modelling: A Review. Fire Technology. 58, 3317–3351 (2022). https://doi.org/10.1007/s10694-022-01313-3.
13. Doran, G.T.: There's a S.M.A.R.T. way to write managements's goals and objectives. Management Review., 70(11). 35–36 (1981).
14. D'Amico, A., Sparvoli, G., Bernardini, G., Bruno, S., Fatiguso, F., Currà, E., Quagliarini, E.: Behavioural-based risk of the Built Environment: Key Performance Indicators for Sudden-Onset Disaster in urban open spaces. International Journal of Disaster Risk Reduction. 103, 104328 (2024). https://doi.org/10.1016/j.ijdrr.2024.104328.
15. Jabi, W., Chatzivasileiadi, A.: Topologic: Exploring Spatial Reasoning Through Geometry, Topology, and Semantics. Advances in Science, Technology and Innovation. 277–285 (2021). https://doi.org/10.1007/978-3-030-57509-0_25.
16. Hosseini Alamdari, A., Daneshjoo, K., Yeganeh, M.: New algorithms for generating isovist field and isovist measurements. Environment and Planning B: Urban Analytics and City Science. 49, 2331–2344 (2022). https://doi.org/10.1177/23998083221083680.
17. Saha, P.K., Borgefors, G., Sanniti di Baja, G.: Skeletonization and its applications – a review. In: Skeletonization. pp. 3–42. Elsevier (2017). https://doi.org/10.1016/B978-0-08-101291-8.00002-X.