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A cognitive approach for improving built environment and users' safety in emergency conditions

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Highlights

Cognitive Systems Criteria are applied to develop Building Components for individuals' emergency safety in architectural spaces. The System Architecture is defined to firstly monitor built environment conditions and human behaviors in emergency evacuation. Data are sent to a central unit and Key Performance Indicators (KPI) are developed to detect critical emergency conditions. Interactive Building Components change their status basing on KPI thresholds, to provide support to the evacuees (i.e. wayfinding). Significant applications to indoor and outdoor architectural spaces are provided to demonstrate the proposed approach capabilities.

Abstract

Cognitive Systems can be applied in architectural spaces to improve Built Environment performances basing on users' needs. They can: 1) jointly monitor environmental conditions and human behaviours through Cognitive Built Environment (CBE) components; 2) use human-environment interaction models and related Key Performance Indicators to detect critical situations; 3) adapt CBE devices status to inform users on how to properly behave. This approach is applied to safety performances of outdoor (earthquake) and indoor (fire) scenarios, by proposing and testing solutions to support evacuees while reaching safe areas and rescuers' support.

Keywords

Cognitive Built Environment, Human evacuation and emergency safety, User-centered design, Construction and Building Performance, Emergency wayfinding systems

1. INTRODUCTION

The actions performed by occupants in the Built Environment (indoor, outdoor) while using spaces and facilities can significantly influence the performance of the Built Environment itself, regarding all the related performances characterizing Building Operation and Maintenance (i.e. comfort, safety, management of spaces and flows) [1,2]. In fact, users are subjected to boundary conditions (physical, social, psychological) which can vary over time and space: they face such conditions by adapting their behaviours to increase their level of satisfaction. In this process, they can interact with the physical spaces and the building components, changing their state and, therefore, the overall (or local) environmental conditions and, finally, the performance of the whole

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considered space [3–6].

Architectural Spaces (indoor and outdoor) can adopt a "cognitive" approach to automatically allow the Built Environment to adapt itself to user needs, by considering the combination of environmental conditions and occupants' adopted behaviors, both in ordinary and emergency conditions [7–9].

Such approach is based on three benchmarks. Firsly, thanks to Internet-of-Thing (IoT) paradigms [10,11], which allow a widespread monitoring of the Built Enviroment both at the single building component and at the overall system level (also according to Building Automation System - BAS principles[12]), the Cognitive Built Environment (CBE) "measures" and "understands" the enviromental conditions, as well as the users' actions the according to the relative spaces use models, by additionally "learning" the relative changes over time and space [2,9].Then, at the level of the single component (in a simple IoT approach) or at the level of the central processing core (more common in centralized BAS-based spaces), the CBE "evaluates" (and "forecasts") the impact of boundary conditions on the level of performance for the occupants (e.g. comfort, safety, use) thanks to models of occupant-environment interactions (including simulation-based ones), and to user-centered evaluation metrics [3,4,13]. Finally, the CBE "interacts" with the occupants, by automatically adapting the status of the implemented components and technological systems (i.e., if "active", like for electrically powered ones), or by suggesting users the actions to be performed to effectively restore the required performance levels (by means of automated building components, e.g., visual, or the interaction with users' personal devices) [14–18]. In this perspective, the use of digital technologies for Building Information Modeling (BIM) and the organization of operational databases play a key role for coordinating system operations and design phase activities of engineers and architects [7,12,19,20].

These concepts can be adopted for the implementation of CBE in buildings as in urban spaces in order to [9,14,21–23]: 1) increase occupants' satisfaction in building use process (eg.: optimization of visitors' flows and users' activities); 2) plan management operations, such as control and maintenance; 3) optimize the management also in relation to the staff members' operations and their interaction with users (eg: positioning and specific skills of staff members); 4) improve the building operation and mantenance in relation to economic factors, pursuing an interaction perspective over time, space and methodologies ("where and how necessary"); 5) support people by limiting the adoption of occupants' actions that are not useful (eg, for energy, comfort, use) or that can be risky (i.e., in an emergency).

1. INTRODUZIONE

Le azioni compiute dagli occupanti nello spazio (indoor, outdoor) e le modalità di fruizione dello spazio e delle facilities possono influenzare significativamente la performance dell'ambiente costruito in tutti i campi di analisi prestazionale della Building Operation and Maintenance (i.e. comfort, sicurezza, gestione degli spazi e dei flussi) [1],[2]. Infatti, gli utenti sono sottoposti a condizioni al contorno (di tipo fisico, sociale, psicologico) variabili nel tempo e nello spazio, e che fronteggiano adattando le loro azioni per aumentare il proprio livello di soddisfazione. Così facendo, essi possono interagire con lo spazio fisico e i componenti edilizi, modificandone lo stato e quindi, di conseguenza, le condizioni ambientali e, infine, le performance dell'edificio [3]–[6].

Gli Spazi Architettonici (sia indoor che outdoor) possono utilizzare approcci di tipo "cognitivo" per permettere al costruito di adattarsi ai bisogni degli utenti sulla base della combinazione tra condizioni ambientali e comportamenti attuati dagli occupanti, sia in condizioni ordinarie sia di emergenza [7]–[9].

L'approccio si bassa su tre capisaldi. In primis, grazie ai paradigmi di intelligenza distribuita – Internet-of-Thing (IoT) [10],[11], che permettono un diffuso monitoraggio nell'ambiente costruito a livello anche dei singoli componenti edili e sistemi installati (anche in accordo ai principi del Building Automation System – BAS [12]), il Cognitive Built Environment (CBE) "misura" e "comprende" quali sono le condizioni cui sono sottoposti gli ambienti, e le azioni degli utenti secondo i relativi modelli di fruizione, per poi "apprendere" nel tempo e nello spazio i relativi cambiamenti [2],[9]. Quindi, a livello di singolo componente (in caso di intelligenza distribuita) o a livello di nucleo elaborativo centrale (più ricorrente nei sistemi BAS centralizzati), il CBE "valuta" (e "prevede") l'impatto delle condizioni al contorno sul livello di prestazione per gli occupanti (es.: comfort, sicurezza, fruizione) grazie a modelli di interazione uomo-ambiente, anche di tipo previsionale, e a metriche di valutazione di tipo "user-centered" [3],[4],[13]. Infine, esso "interagisce" con gli occupanti, adattando automaticamente lo stato dei componenti e sistemi tecnologici implementati (i.e., se "attivi", ovvero alimentati elettricamente, connessi ed integrati), o suggerendo loro azioni per ripristinare i livelli di performance richiesti (sia tramite componenti edili automatizzati, es., di tipo visuale, sia tramite interazione con personal devices degli utenti) [14]–[18]. In questa ottica, l'utilizzo di tecnologie digitali per l'informazione e la modellazione del costruito (es.: BIM) e la costruzione di database operativi svolge un ruolo di coordinamento sia nell'operatività di sistema che nella fase di progettazione [7],[12],[19],[20].

Questi concetti possono essere adattati per l'implementazione

The present study intends to apply the concepts of CBE to a significant research sector for the built environment: the emergency evacuation. The development and preliminary testing of cognitive components is aimed at improving occupant safety performance in indoor and outdoor significative scenarios, in two different types of disasters.

2. COGNITIVE BUILT ENVIRONMENT FOR EMERGENCY SAFETY

The occupants' safety in emergency is one of the most important areas for the application of the CBE, since, in these conditions, people adopt choices that can be critical in relation to the state of the surrounding Built Environment [8,14,16,18].

The evacuation phase is the most critical step for users' interactions with the Built Environment, especially for the SUdden Onset Disasters (SUODs) [24]. Regardless of the type of SUODs, the environmental conditions are modified in a short time by the disaster, leading people to face unpredicted scenario conditions while owning a (often) limited level of knowledge with layout and procedures to be adopted in emergences. Among SUODs, relevant examples are fire (indoor) and earthquake (outdoor). In such conditions, people must be assisted while reaching a "safe area", in the least risky way. In a fire, for example, people must be supported to minimize the interactions with smokes and flames along motion paths, according to a perspective of minimization of the time of evacuation process [18]. In an earthquake, on the other hand, users must be guided through the paths with the lowest level of risk, which is essentially linked to the vulnerability of the structures and the earthquake-induced effects on them [25].

According to literature and application practices review, the three main solutions for managing the evacuation process in the Built indoor and outdoor Environment and assisting the evacuees are: passive solutions, which are widespread and standardized [26,27]; active / interactive solutions [14,16,28,29]; cognitive solutions [14,18,30,31]. Figure 1 compares the main features of the three systems.

In particular, passive solutions become particularly ineffective in highly crowded environments (e.g. public buildings, outdoor events, massgathering events), where the logic of spontaneous group organization and the individuals' familarity with architectural spaces and procedures can lead to a significant difference between expected (planned) and effective emergency response conditions [25].

del CBE in edifici come in spazi urbani al fine di [9],[14],[21]–[23]: 1) aumentare la soddisfazione dell'utente nel processo di fruizione (es.: ottimizzazione di flussi e attività); 2) pianificare operazioni di management sul costruito, quali controllo e manutenzione; 3) ottimizzare la gestione tramite operazioni dello staff nell'interazione con le persone (es.: posizionamento e competenze specifiche dei membri dello staff); 4) tendere all'ottimizzazione dell'operatività del costruito in relazione ai fattori economici, perseguendo un ottica di interazione "dove e come necessario"; 5) assistere le persone limitando l'adozione da parte loro di azioni non utili (es., per aspetti energetici, di comfort, di fruizione) o rischiose (i.e., in emergenza).

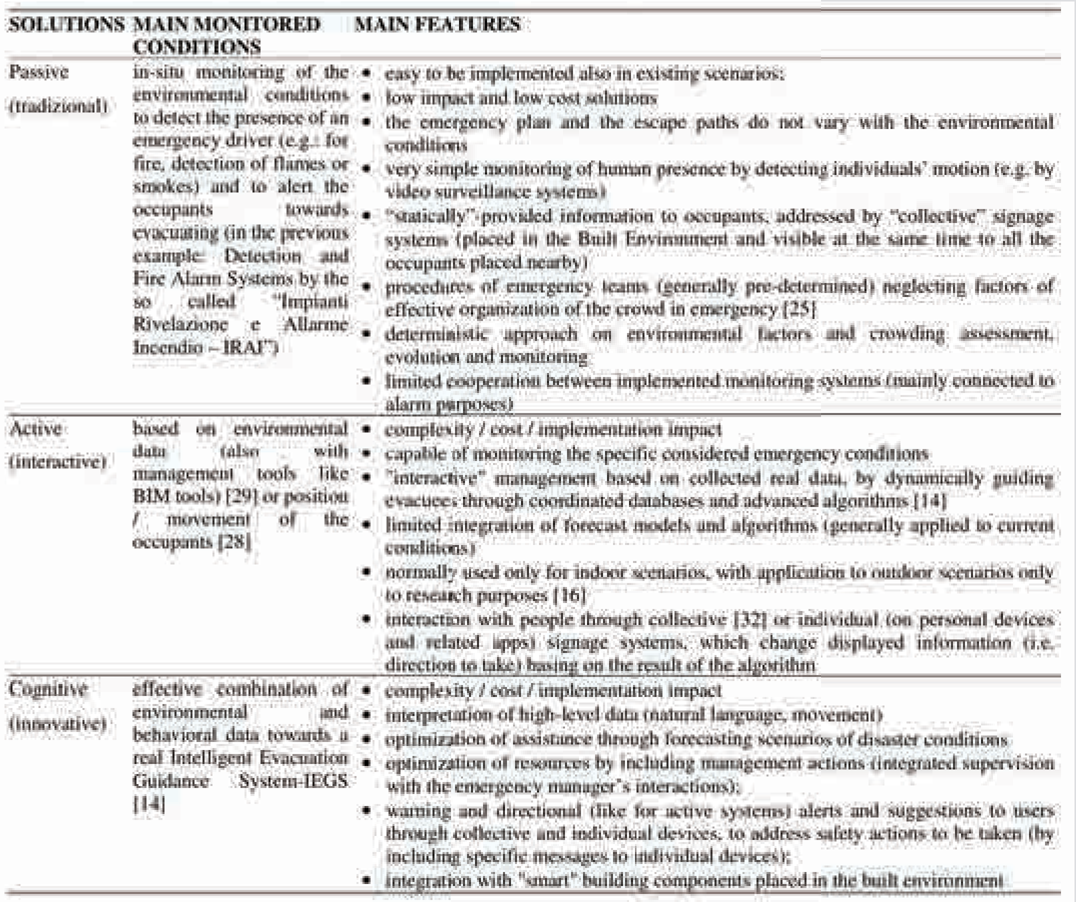
Il presente studio intende applicare i concetti del CBE ad un settore di ricerca significativo per l'ambiente costruito, quello dell'evacuazione d'emergenza, proponendo sviluppo e test preliminari di componenti per migliorare le performance di sicurezza degli occupanti in ambienti significativi indoor e outdoor, e in due diversi tipi di disastri.

2. IL COGNITIVE BUILT ENVIRONMENT PER LA SICUREZZA IN EMERGENZA

La sicurezza degli occupanti in emergenza, è uno dei settori di maggior rilievo per l'applicazione del CBE, poiché le persone adottano scelte che possono essere critiche in relazione allo stato dello spazio circostante e del loro livello di conoscenza (spesso limitato) con layout e procedure da adottare in emergenza [8],[14],[16],[18].

Il processo di evacuazione è il momento più critico per gli utenti, specialmente per i SUdden Onset Disasters (SUODs) [24], in cui, a prescindere dal tipo di emergenza, le condizioni dell'ambiente sono modificate in breve tempo dall'apparire del disastro. Tra questi, esempi rilevanti per l'ambiente costruito sono l'incendio (indoor) e il sisma (outdoor). In tali condizioni, le persone devono essere assistine nel raggiungere, nella maniera meno rischiosa possibile, una zona sicura. In un incendio, ad esempio, le persone devono essere assistite per minimizzare la presenza di fumi e fiamme lungo percorsi e spazi di movimento, secondo un'ottica di minimizzazione del tempo di esodo [18]. In un sisma, invece, gli utenti devono essere guidati attraverso i percorsi con il minor livello di rischio, legato essenzialmente alla vulnerabilità delle strutture e agli effetti su essi indotti dall'evento [25].

Le tre principali soluzioni di gestione del processo di evacuazione nell'ambiente costruito indoor e outdoor, e la relativa assistenza agli evacuanti, riscontrate in letteratura e nella pratica applicativa sono: passive, più diffuse e normate [26],[27]; attive/interattive [14],[16],[28],[29]; cognitive [14],[18],[30],[31]. Figura 1 confronta le caratteristiche



SOLUTIONS	MAIN MONITORED CONDITIONS	MAIN FEATURES
Passive (tradizional)	in-situ monitoring of the environmental conditions to detect the presence of an emergency driver (e.g.: for fire, detection of flames or smokes) and to alert the occupants towards evacuating (in the previous example: Detection and Fire Alarm Systems by the so called "Impianti Rivelazione e Allarme Incendio – IRAI")	• easy to be implemented also in existing scenarios; • low impact and low cost solutions • the emergency plan and the escape paths do not vary with the environmental conditions • very simple monitoring of human presence by detecting individuals' motion (e.g. by video surveillance systems) • "statically"-provided information to occupants, addressed by "collective" signage systems (placed in the Built Environment and visible at the same time to all the occupants placed nearby) • procedures of emergency teams (generally pre-determined) neglecting factors of effective organization of the crowd in emergency [25] • deterministic approach on environmental factors and crowding assessment, evolution and monitoring • limited cooperation between implemented monitoring systems (mainly connected to alarm purposes)
Active (interactive)	based on environmental data (also with management tools like BIM tools) [29] or position / movement of the occupants [28]	• complexity / cost / implementation impact • capable of monitoring the specific considered emergency conditions • "interactive" management based on collected real data, by dynamically guiding evacuees through coordinated databases and advanced algorithms [14] • limited integration of forecast models and algorithms (generally applied to current conditions) • normally used only for indoor scenarios, with application to outdoor scenarios only to research purposes [16] • interaction with people through collective [32] or individual (on personal devices and related apps) signage systems, which change displayed information (i.e. direction to take) basing on the result of the algorithm
Cognitive (innovative)	effective combination of environmental and behavioral data towards a real Intelligent Evacuation Guidance System-IEGS [14]	• complexity / cost / implementation impact • interpretation of high-level data (natural language, movement) • optimization of assistance through forecasting scenarios of disaster conditions • optimization of resources by including management actions (integrated supervision with the emergency manager's interactions); • warning and directional (like for active systems) alerts and suggestions to users through collective and individual devices, to address safety actions to be taken (by including specific messages to individual devices); • integration with "smart" building components placed in the built environment

Figure 1. Characterization of passive, intelligent and cognitive solutions for users' support in emergency and evacuation conditions.

This work starts from Figure 1 overview to propose a definition of CBE solutions for users' support in SUODs, according to a unifying framework which includes a user-centered approach and takes advantage of related holistic performance indicators (Key Performance Indicators-KPIs) [13]. The SUODs considered in this work are fire in an indoor scenario and an earthquake in an outdoor scenario, in order to describe the CBE principles with respect to the peculiarities of the disaster itself, as well as of the Built Enviroment. Finally, the CBE effectiveness is tested by focusing on evacuees' safety performance, and by developing sensoring (monitoring), processing and actuation (interaction with users) elements which can be integrated in building components.

3. PHASES AND METHODS

The work is divided into three phases. In the first one (Section 3.1), the CBE architecture is proposed in relation to the emergency application, by organizing the general requirements of their components (sensors, heuristic algorithms, actuators). In the second one (section 3.2), the metrics for evaluating the effectiveness of the CBE on the evacuative process (Key

principali dei tre sistemi. In particolare, i sistemi passivi diventano particolarmente inefficaci in ambienti altamente affollati (es.: edifici pubblici, manifestazioni all'aperto, grandi eventi), in cui le logiche di organizzazione spontanea dei gruppi e di conoscenza degli spazi e delle procedure da parte degli utenti portano ad uno scostamento significativo tra condizioni di esodo attese ed effettive [25].

Questo lavoro sfrutta il quadro di soluzioni al fine proporre una definizione dell'architettura di sistemi CBE per assistere le persone negli SUODs, secondo un framework unificante, che includa anche logiche di tipo user-centered producendo pertanto indicatori di performance (Key Performance Indicators-KPIs) di tipo olistico [13]. Gli SUODs coinvolti riguardano incendio in indoor e sisma in outdoor, in ambienti rilevanti, al fine di declinare i principi CBE rispetto alla peculiarità del disastro stesso. L'efficacia dei sistemi CBE è infine testata rispetto alla prestazione di sicurezza per gli evacuanti, sviluppando pertanto elementi di monitoraggio, elaborazione e attuazione, all'interno di componenti edili integrati allo spazio architettonico.

3. FASI E METODI

Il lavoro si articola in tre fasi. Nella prima (Sezione 3.1) si affronta la

Performance Indicators-KPIs) are defined, and implemented in the systems control algorithms. Finally, in the third one, the CBE is applied to relevant case studies: fire evacuation of a historic building with high crowding (university), focusing on the users' behavior detection, by performing the effectiveness analysis by evacuation drills (Section 3.3); post-earthquake evacuation of a part of a coastal tourist urban center, by integrating the buildings damage prediction, and by using simulation with advanced calculation models to evaluate the CBE effectiveness (Section 3.4).

3.1. CBE REQUIREMENTS AND OVERALL ARCHITECTURE

CBE must to detect the input data from the Built Environment, to heuristically process them and consequently to make changes to the status of the connected components (i.e. to support the evacuation process). The IoT technologies [10] allow interoperability criteria between the CBE modules and devices. Additionally, they should be appropriately located and widespread in the controlled area: the devices, therefore, create an interconnected network in which each of them is able to communicate, exchange data (between them and with the central processing core) and hold a degree of elaborative autonomy (albeit limited).

Figure 2 organizes the three main functional elements related to this system logic, by indicating, in a non-exhaustive way, their substructure in terms of methods and devices. The *sensor nodes* are responsible for monitoring the basic variables linked to buildings and occupants, in order to measure magnitudes on evacuees' flows, presence of missing / trapped individuals, danger conditions and usability of the spaces and the paths. To guarantee an overall adequate performance to the entire built space, a *central processing core* is identified: it firstly applies the control algorithms, combines the data from the *sensor nodes* to obtain information on the process, and then produces alerts and communications about escape routes to the occupants. The analysis process is dynamic as the emergency evolves over space and time, and integrates forecasting scenarios through advanced logics and integrated environment/evacuation process. Finally, the *actuation nodes* direct the evacuees along the best escape routes, by producing a dynamic evacuation plan, and contemporary make aware of the safety managers about the Built Environment, the occupants' and the disaster scenario conditions. *Actuation nodes* features, sizes and applications can depend on the considered scenario. Finally, the same building component can perform more functions locally in terms of: monitoring and implementation; processing core (e.g.: control of local evacuees' flows) operation; local storage of environment monitored

definizione dell'architettura del CBE per l'emergenza, organizzando le caratteristiche generali dei componenti (sensori, algoritmi euristici, attuatori). Nella seconda (sezione 3.2) si definiscono le metriche di valutazione dell'efficacia dei componenti edili cognitivi sul processo evacuativo (Key Performance Indicators-KPIs), implementati anche negli algoritmi di controllo dei sistemi. Nella terza, infine, i componenti edili cognitivi sono applicati a casi di studio rilevanti: evacuazione antincendio di un edificio storico ad elevato affollamento (polo universitario), focalizzando l'attività sulla componente di rilevamento del comportamento, tramite prove reali (Sezione 3.3); evacuazione post-sisma di una porzione di centro urbano turistico costiero, integrando un sistema di previsione del danno per gli edifici ed outdoor, tramite simulazione con modelli di calcolo avanzati (Sezione 3.4).

3.1. ARCHITETTURA DEL CBE PER L'EMERGENZA

Il CBE deve essere di rilevare i dati di input, elaborarli euristicamente ed operare di conseguenza cambiamenti allo stato dei componenti connessi. Le tecnologie IoT [10] permettono criteri di interoperabilità tra gli elementi costituenti, che devono essere adeguatamente collocati e diffusi nell'area da controllare: i devices creano quindi una rete interconnessa in cui ciascuno è in grado di comunicare, scambiare dati (tra loro e con il nucleo elaborativo) e detenere un grado di autonomia elaborativa (seppur limitata).

Figura 2 organizza i tre elementi funzionali principali correlati a questa logica di sistema, indicando, in maniera non esaustiva, la sottostruttura in termini di metodi e dispositivi. I nodi sensoriali sono effettivamente responsabili del monitoraggio delle variabili di base legate a costruito e occupanti, al fine di misurare grandezze su flussi di persone, presenza di dispersi/intrappolati, pericolosità e fruibilità dello spazio. Nel garantire una prestazione complessiva adeguata all'intero spazio costruito, viene identificato un unico nucleo elaborativo, che applica gli algoritmi di controllo, combinando i dati dai nodi sensoriali per ricavare informazioni sul processo e quindi produrre indicazioni su allerte e vie di esodo da comunicare agli occupanti. Il processo di analisi è dinamico all'evolversi dell'emergenza ed integra scenari previsionali tramite logiche avanzate e integrate ambiente/processo evacuativo. Infine, i nodi attuativi indirizzano gli evacuanti lungo le vie di fuga elaborate, in un piano di evacuazione dinamico che aggionra in tempo reale anche i gestori dello spazio. I dispositivi di attuazione variano impiego, dimensionamento ed applicazione in funzione dello spazio costruito considerato. Lo stesso componente può svolgere localmente più funzioni in termini data, in a IoT distribution approach. By this way, it can allow addressing local conditions even in the case of interrupted interconnection, and it can also accelerate the calculation process.

The three elements are sequentially connected at emergency start (by automatic/manual detection). The cyclic iteration is characterized by a clock time that depends on emergency features and/or to evacuation guidance logics (e.g.: for fire, some seconds, to control the people's movement in a significant route section), so as to guarantee the response CBE in dynamic terms. The cycle ends when the safety conditions are restored.

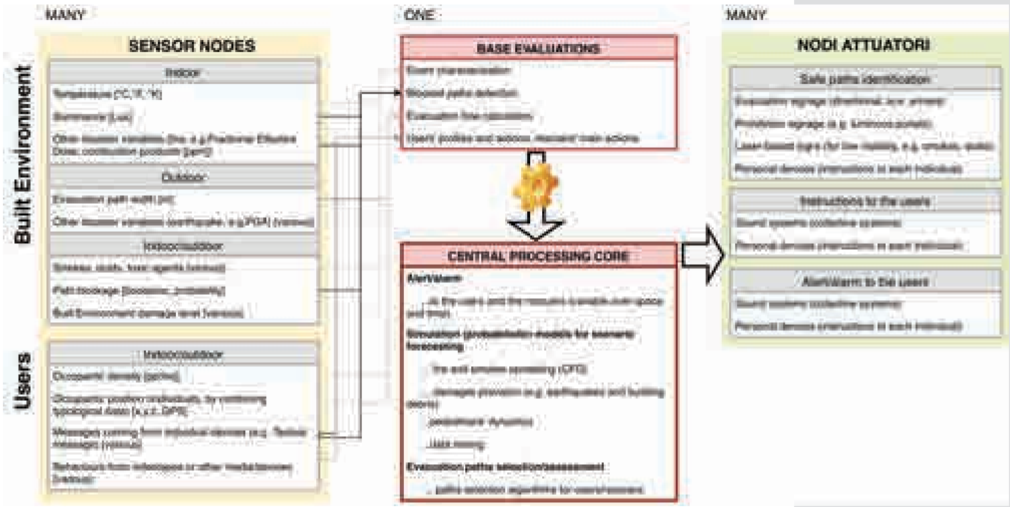


Figure 2. CBE scheme (many-one-many) by pointing out the composing parts. For each part, the diagram shows the main methods/devices to be used, the related application scenarios and the measured quantities (from a not exhaustive point of view).

3.2. KEY PERFORMANCE INDICATORS

Starting from the definition of the paths graph, which is organized by sections (e.g. by using links between two decision points), the KPIs are used by the *central processing* core to retrieve the safest ones through routing algorithms (e.g.: shortest path, minimum cost path) [16,18,28,30]. Figure 3 proposes the overview on the basic variables, adopted in this study, by defining them for fire and earthquake.

Such variables are combined to select the best evacuation path minimizing the associated cost. Furthermore, KPIs can assess the effectiveness of the CBE on respect of the user's safety level, since they combine environmental and behavioral data (individual and collective behaviors, related variables) in a unique framework. The effectiveness differences between the evacuation processes without and with CBE can be evaluated by calculating the KPIs variations, in absolute or percentage terms. A comprehensive discussion of fire and earthquake cases (both KPIs and comparison terms) is proposed in

di monitoraggio e attuazione, ed integrare anche l'elaborazione (es.: controllo dei flussi locali), ed effettuare storage locale dei dati del sistema, in una logica distribuita IoT, per permettere di affrontare condizioni locali anche in caso di interconnessione interrotta, ed accelerare il processo di calcolo.

I tre elementi sono sequenzialmente connessi dal momento in cui il CBE rivela l'insorgere dell'emergenza (automaticamente o manualmente). L'iterazione ciclica ha tempo di clock legato ai caratteri dell'emergenza o alle utilità del sistema (es.: per incendio, alcuni secondo, al fine di controllare il movimento delle persone in un tratto significativo di percorso), così da garantire la risposta dinamica del CBE. Il ciclo termina al rientro dell'emergenza stessa.

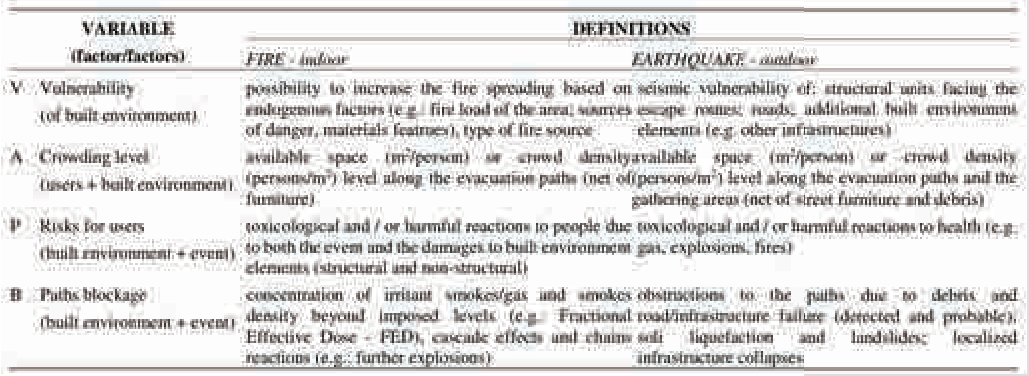
3.2. KEY PERFORMANCE INDICATORS

A partire dalla definizione della struttura dei percorsi, organizzati per tratti (es. tra due punti di decisione), I KPIs sono usati dal nucleo elaborativo per reperire quelli sicuri tramite algoritmi di instradamento (es.: shortest path, minimum cost path) [16],[18],[28],[30]. Figura 3 propone le variabili base, nella loro definizione per incendio e sisma, adottate in questo studio.

Esse sono combinate per selezionare il percorso ottimale per gli evacuanti, minimizzandone il costo associato. Inoltre, i KPIs possono valutare l'efficacia del CBE sul livello di sicurezza degli utenti, poiché combinano dati ambientali e di processo (comportamentali individuali e collettivi, variabili correlate) in un unico quadro. La differenza di efficacia nei processi di esodo senza e con CBE sono valutabili come variazione dei KPIs, in termini assoluti o percentuali.

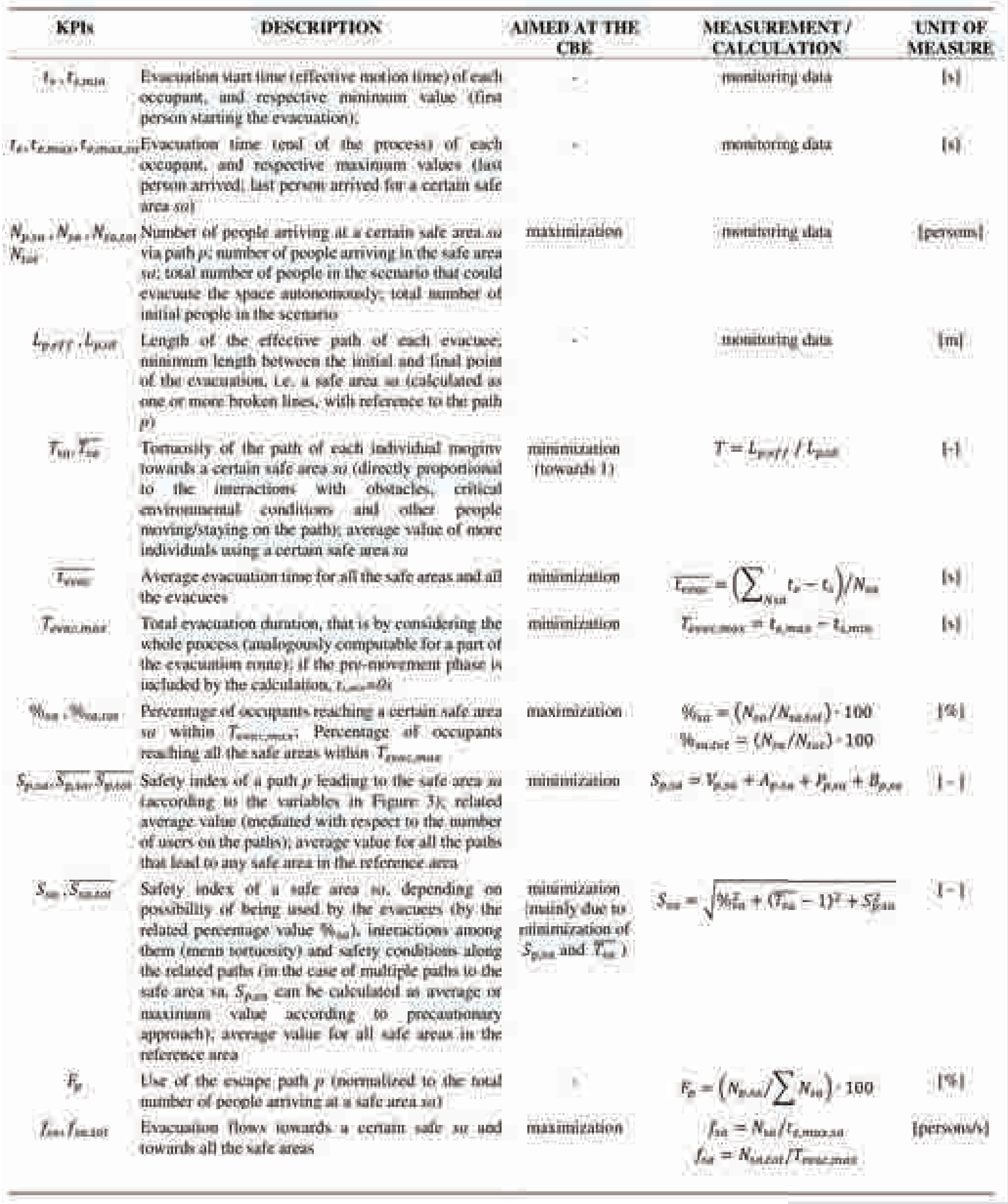
[14,25]. The complete list of KPIs used in this study is shown in Figure 4, which is based on standard definitions for both indoor/outdoor conditions.

Una trattazione esaustiva per i casi incendio e sisma è proposta in [14],[25]. L'elenco completo



	VARIABLE (factor/factors)	DEFINITIONS	
		FIRE - indoor	*EARTHQUAKE - outdoor*
V	Vulnerability (of built environment)	possibility to increase the fire spreading based on endogenous factors (e.g. fire load of the area; sources of danger, materials features), type of fire source	seismic vulnerability of: structural units facing the escape routes; roads, additional built environment elements (e.g. other infrastructures)
A	Crowding level (users + built environment)	available space (m²/person) or crowd density (persons/m²) level along the evacuation paths (net of furniture)	available space (m²/person) or crowd density (persons/m²) level along the evacuation paths and the gathering areas (net of street furniture and debris)
P	Risks for users (built environment + event)	toxicological and / or harmful reactions to people due to both the event and the damages to built environment elements (structural and non-structural)	toxicological and / or harmful reactions to health (e.g. gas, explosions, fires)
B	Paths blockage (built environment + event)	concentration of irritant smokes/gas and smokes density beyond imposed levels (e.g. Fractional Effective Dose - FED), cascade effects and chains reactions (e.g.: further explosions)	obstructions to the paths due to debris and road/infrastructure failure (detected and probable), soil liquefaction and landslides; localized infrastructure collapses

Figure 3. Key Performance Indicators (KPIs) basic variables (i.e. for the routing algorithms).



KPIs	DESCRIPTION	AIMED AT THE CBE	MEASUREMENT / CALCULATION	UNIT OF MEASURE
t_s, $t_{s,min}$	Evacuation start time (effective motion time) of each occupant, and respective minimum value (first person starting the evacuation);	-	monitoring data	[s]
t_e, $t_{e,max}$, $t_{e,max,sa}$	Evacuation time (end of the process) of each occupant, and respective maximum values (last person arrived; last person arrived for a certain safe area *sa*)	-	monitoring data	[s]
$N_{p,sa}$, N_{sa}, $N_{sa,tot}$, N_{tot}	Number of people arriving at a certain safe area *sa* via path *p*; number of people arriving in the safe area *sa*; total number of people in the scenario that could evacuate the space autonomously; total number of initial people in the scenario	maximization	monitoring data	[persons]
$L_{p,eff}$, $L_{p,sa}$	Length of the effective path of each evacuee; minimum length between the initial and final point of the evacuation, i.e. a safe area *sa* (calculated as one or more broken lines, with reference to the path *p*)	-	monitoring data	[m]
T_{sa}, $\overline{T_{sa}}$	Tortuosity of the path of each individual moving towards a certain safe area *sa* (directly proportional to the interactions with obstacles, critical environmental conditions and other people moving/staying on the path); average value of more individuals using a certain safe area *sa*	minimization (towards 1)	$T = L_{p,eff} / L_{p,sa}$	[-]
$\overline{t_{evac}}$	Average evacuation time for all the safe areas and all the evacuees	minimization	$\overline{t_{evac}} = \left(\sum_{Nsa} t_e - t_s\right)/N_{sa}$	[s]
$T_{evac,max}$	Total evacuation duration, that is by considering the whole process (analogously computable for a part of the evacuation route); if the pre-movement phase is included by the calculation, $t_{s,min}=0$)	minimization	$T_{evac,max} = t_{e,max} - t_{s,min}$	[s]
$\%_{sa}$, $\%_{sa,tot}$	Percentage of occupants reaching a certain safe area *sa* within $T_{evac,max}$; Percentage of occupants reaching all the safe areas within $T_{evac,max}$	maximization	$\%_{sa} = (N_{sa}/N_{sa,tot}) \cdot 100$ $\%_{sa,tot} = (N_{sa}/N_{tot}) \cdot 100$	[%]
$S_{p,sa}$, $\overline{S_{p,sa}}$, $\overline{S_{p,tot}}$	Safety index of a path *p* leading to the safe area *sa* (according to the variables in Figure 3); related average value (mediated with respect to the number of users on the paths); average value for all the paths that lead to any safe area in the reference area	minimization	$S_{p,sa} = V_{p,sa} + A_{p,sa} + P_{p,sa} + B_{p,sa}$	[-]
S_{sa}, $\overline{S_{sa,tot}}$	Safety index of a safe area *sa*, depending on possibility of being used by the evacuees (by the related percentage value $\%_{sa}$), interactions among them (mean tortuosity) and safety conditions along the related paths (in the case of multiple paths to the safe area *sa*, $S_{p,sa}$ can be calculated as average or maximum value according to precautionary approach); average value for all safe areas in the reference area	minimization (mainly due to minimization of $S_{p,sa}$ and $\overline{T_{sa}}$)	$S_{sa} = \sqrt{\%_{sa}^2 + (\overline{T_{sa}} - 1)^2 + S_{p,sa}^2}$	[-]
F_p	Use of the escape path *p* (normalized to the total number of people arriving at a safe area *sa*)	-	$F_p = \left(N_{p,sa}/\sum N_{sa}\right) \cdot 100$	[%]
f_{sa}, $f_{sa,tot}$	Evacuation flows towards a certain safe *sa* and towards all the safe areas	maximization	$f_{sa} = N_{sa}/t_{e,max,sa}$ $f_{sa} = N_{sa,tot}/T_{evac,max}$	[persons/s]

Figure 4. Key Performance Indicators (KPIs) overview: for each KPI proposed and adopted by this work, the description, the use in the CBE structure (i.e. algorithm solving) and the related calculation and unit of measure are offered.

3.3. INDOOR APPLICATION: FIRE

The application case study is a part of the faculty of Economics at the Polytechnic University of Marche (ex-barrack “Villarey”) - Ancona. This historic building mainly accommodates teaching classrooms. Figure 5 shows the layout of the Built Environment involved in the drill. The evacuation of the classroom of Figure 5-B (placed on the first floor) was considered. Taking advantage of the symmetrical layout, a unique drill was conducted [14]. The classroom was divided into two parts by signaling tape: each part and the respective escape routes are associated to the use of passive evacuation assistance systems (left) [26] and CBE (right). In the drill, 56 individuals (aged 19 to 24, average age 20) entered from the main route (US revenue and UD in Figure 5-B). Then, moving towards staircases SS and SD, they finally entered the classroom and randomly seated in the related classroom part. Participants were only familiar with this entrance route, and they were not informed of the evacuation plan (shown by the green arrows in Figure 5) and of other spaces. To allow monitoring through *sensor nodes*, each individual was equipped with an RFID TAG (recognition and positioning). Sensor nodes were placed at the start of the paths section (doors; intersections between vertical and horizontal paths). The drill was organized in this way: 1) during the lesson, a fire alarm was given; 2) the occupants got up and evacuated the space being supported by the evacuation wayfinding system placed in their classroom part; 3) the evacuation ended when the last occupant exited the building.

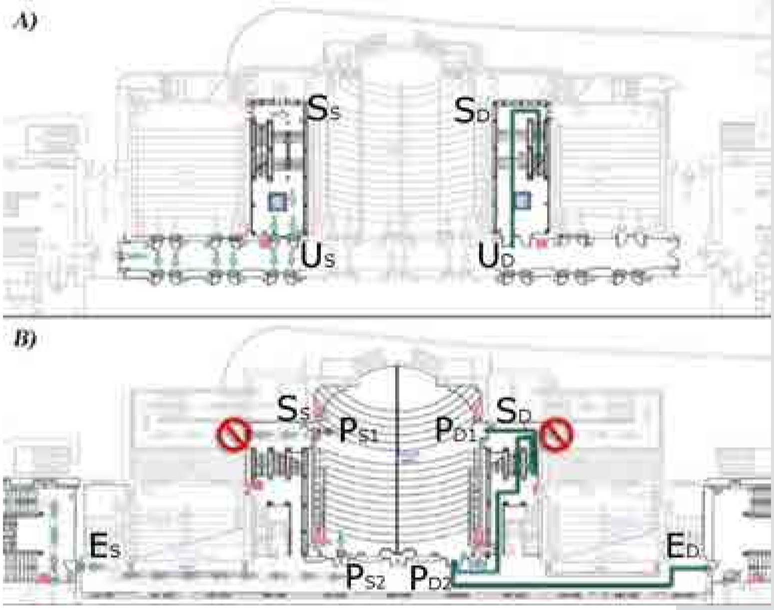


Figure 5. Layout of the application scenario for indoor fire evacuation: A) plan of the ground floor; B) plant of the first floor. The figure points out: the emergency exits (U_S and E_S; U_D and E_D); the evacuation routes for each considered half of the building (arrows according to the emergency plan for the left half, which involved passive solutions; continuous line for the right half, which involved CBE); the staircases (S_S and S_D); exit doors from the classroom.

dei KPIs usati nel presente studio, uniformati per le condizioni indoor/outdoor, è riportato in Figura 4.

3.3. APPLICAZIONE INDOOR: INCENDIO

Come scenario di applicazione è stata scelta una porzione della facoltà di Economica dell’Università Politecnica delle Marche (ex-caserma “Villarey”)-Ancona. L’edificio storico accoglie prevalentemente aule didattiche. Figura 5 mostra il layout della porzione di spazio coinvolta nei test. Si è considerato l’esodo di un’aula didattica di Figura 5-B (posta al primo piano). Sfruttando il layout simmetrico, si è condotta un’unica prova [14]. L’aula è stata divisa in due parti tramite nastro segnalatore, associando a ciascuna, e alle rispettive vie di fuga, l’uso di sistemi di assistenza nell’evacuazione passivi (sinistra) [26] e CBE (destra). Nella prova, 56 individui (dai 19 ai 24 anni, età media 20 anni) sono entrati dal percorso principale (entrate US e UD in Figura 5-B) principale, usando poi le scale SS e SD, e infine disponendosi in maniera casuale nelle due metà dell’aula. Essi avevano familiarità solo il percorso di ingresso, e non sono stati informati del piano di evacuazione (mostrato dalle frecce verdi di Figura 5). Per permettere il monitoraggio tramite nodi sensoriali, ogni individuo è stato dotato di TAG RFID di riconoscimento e posizionamento, monitorato ai varchi del percorso (porte; intersezioni tra percorsi verticali e orizzontali). Le modalità di prova sono state le seguenti: 1) durante la lezione, è stato dato un allarme sonoro; 2) gli occupanti si sono alzati e hanno evacuato lo spazio servendosi del

The evacuation paths, suggested by the CBE, were based on the optimization of $S_{p,sa}$ (compare to Figure 4) by considering al the possible related paths (green lines in Figure 5). In the drill, V_p, P_p and B_p were considered constant over the time and the space. A_p values were dynamically calculated according to the evacuees' position, for each path. The evacuation direction was interactively provided to the users by using luminous portals (path: open = green; closed = red) and directional arrows (see Figure 6), which were placed inside the classroom and along the rest of the paths. The analyzed KPIs focused on the building scale to evaluate the benefits of the CBE adoption on each element of the evacuation network. In particular, $S_{p,sa}$ and S_{sa} were not considered because of they depended only on A_p.

Figure 6. CBE application in the building: along the corridors, the evacuation path was addressed by LED stripes portals placed on the wall (left), to address usable paths (green lights) and prohibited paths (red lights); in the classroom, the evacuation direction was addressed by directional (LED) arrows, placed on the wall, straight to the floor level (right).

3.4. OUTDOOR APPLICATION: EARTHQUAKE

A part of the historical fishermen's village of Civitanova Marche (MC) was considered for the application to outdoor evacuation, by considering the occurrence of an earthquake with intensity VIII degree EMS98. The conditions of the case study are critical in terms of historical building vulnerability and presence of hosted population (a seaside tourist center). Figure 7 shows: the case study layout, by stressing the paths, which are organized according to a "cardo and decumanus" scheme, and have a width between 3m and 12m; the safe areas network; the position of the *actuation nodes* of the CBE, which can be integrated into urban furnitures and other existing structure, as shown in the example of Figure 8.

The CBE effectiveness evaluation was carried out thorugh post-earthquake evacuation simulation [32]. At the starting of the emergency, the considered individuals were randomly placed in the red area highlighted in Figure 7. The area was considered to maximize the length of paths towards the safe areas.

supporto del sistema a loro afferente; 3) l'evacuazione è terminata quando l'ultimo occupante è uscito dalla struttura.

Il CBE, in particolare, ha fornito il percorso migliore tramite calcolo di $S_{p,sa}$ per tutti i percorsi (linee verdi in Figura 5), considerando V_p, P_p e B_p costanti e uguali nel tempo e nello spazio, e usando dinamicamente i valori di posizione delle persone per il calcolo di A_p. La direzione è stata fornita in maniera interattiva tramite frecce portali luminosi (percorso: aperto=verde; chiuso=rosso) e frecce direzionali (vedi Figura 6) sia all'interno dell'aula che lungo il resto del percorso. Data la scala di singolo edificio, i KPIs analizzati si focalizzano sui benefici del CBE su ogni elemento del network d'emergenza, trascurando i dati relativi a $S_{p,sa}$ e S_{sa} data la sola variabilità di A_p.

3.4. APPLICAZIONE OUTDOOR: SISMA

Una porzione storica del borgo marinaro di Civitanova Marche (MC) è stata considerata per l'applicazione al caso di evacuazioni outdoor, in seguito ad emergenza sismica di intensità VIII grado EMS98. Le condizioni del caso di studio sono critiche in termini di vulnerabilità dell'edificato storico, come pure di presenza di popolazione ospitata, essendo il caso di studio un centro turistico balneare. Figura 7 mostra: il layout del caso di studio, con i percorsi orientati secondo cardo e decumano, e con ampiezza compresa tra 3m e 12m; il sistema di zone sicure; la posizione dei nodi attuatori, mostrati esemplificativamente in Figura 8, che possono essere integrati in arredi urbani e le strutture già presenti.

La valutazione di efficacia è svolta tramite simulatore di evacuazione post-sisma [33]. Gli utenti considerati sono stati fatti partire da posizioni casuali nella zona in rosso evidenziata in Figura 7, al

The simulation had a maximum time of 600s. The case study is described in more detail in [25]. According to the urban scale application, the analyzed KPIs focus on CBE benefits for the entire area, neglecting to assess punctual data related to each part of the evacuation paths network.

fine di massimizzare la lunghezza dei percorsi alle zone sicure. La simulazione ha tempo massimo di 600s. Il caso di studio è descritto più approfonditamente in [25]. Data la scala urbana, i KPIs analizzati si focalizzano sui benefici del

Figure 7. Application to post-earthquake evacuation case study: a part of the historical fishermen's village of Civitanova Marche - MC), by highlighting: evacuation paths layout (source: openstreetmaps, last access: 6/5/2019); safe areas positioning (gathering point signs); position of the actuation nodes of the CBE (green circles); initial positioning area of the considered persons (red area).

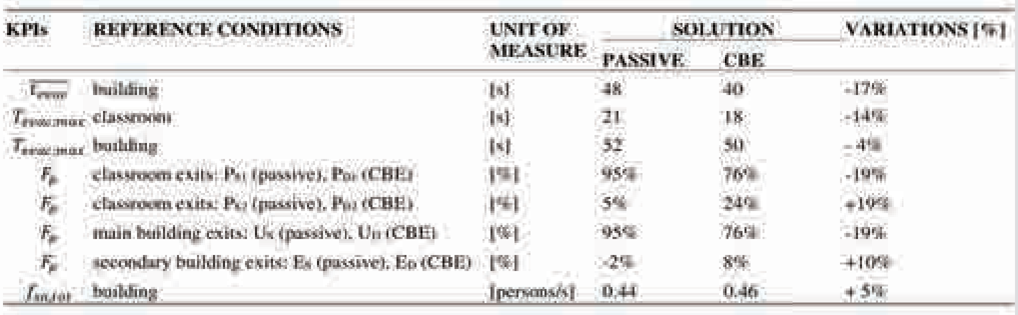
Figure 8. A street view to provide an example of the actuation nodes application in the acse study (in stret funritures, by means of poles or other signs, including street lights).

4. RESULTS

The adoption of CBE for emergencies in the considered cases allowed increasing the safety performance for users, in terms of overall and partial evacuation process.

4.1. INDOOR APPLICATION: FIRE

As shown by Figure 9, CBE was able to better distribute the evacuees through the paths, by also addressing them towards the secondary ones (including exit doors from the classroom) and by avoiding critical overcrowding conditions (see F_p values in Figure 9). This result was significant especially inside the classroom, where the relative T_{evac} time was reduced by 14% because of the reduction of crowding conditions at the most used door (P_{D1}). In the following, no person was heading towards ES, while 8% of the occupants moved towards ED: $\overline{t_{evac}}$ for CBE decreased by 17%, given the limited length of this path. The limited reduction of $T_{evac,max}$ while using CBE in respect to the passive solution (-4%) was related instead to the exit times from US and UD. However, this result produced a slight increase in $f_{sa,tot}$. It is worthing to note that the percentage value of F_p for ES is negative: 2% of people preferred to abandon the passive wayfinding signs in order to move towards the exit signaled by the CBE, as a proof of the occupants' trust in the CBE also in relation to unknown routes that are reported as usable.



KPIs	REFERENCE CONDITIONS	UNIT OF MEASURE	SOLUTION		VARIATIONS [%]
			PASSIVE	CBE	
$\overline{t_{evac}}$	building	[s]	48	40	-17%
$T_{evac,max}$	classroom	[s]	21	18	-14%
$T_{evac,max}$	building	[s]	52	50	- 4%
F_p	classroom exits: P_{D1} (passive), P_{D1} (CBE)	[%]	95%	76%	-19%
F_p	classroom exits: P_{D2} (passive), P_{D2} (CBE)	[%]	5%	24%	+19%
F_p	main building exits: U_S (passive), U_D (CBE)	[%]	95%	76%	-19%
F_p	secondary building exits: E_S (passive), E_D (CBE)	[%]	-2%	8%	+10%
$f_{sa,tot}$	building	[persons/s]	0.44	0.46	+ 5%

Figure 9. Results for the indoor fire evacuation: KPIs comparisons by considering the use of passive and CBE solutions.

4.2. OUTDOOR APPLICATION: EARTHQUAKE

Figure 10 shows how the use of CBE increased the number of people who successfully completed the evacuation process by reaching a safe area (+ 14%) within the $T_{evac,max}$, whose values were conditioned by the 600s simulation time limit.

The average escape time was greater while using the CBE (+35%) essentially

CBE per l'intera area in esame, trascurando i dati puntuali relativi ai singoli componenti del network d'emergenza.

4. RISULTATI

L'adozione di CBE per l'emergenza nei casi proposti dallo studio permette un incremento delle prestazioni di sicurezza per gli utenti, in termini di processo complessivo e di porzioni di ambiente costruito.

4.1. APPLICAZIONE INDOOR: INCENDIO

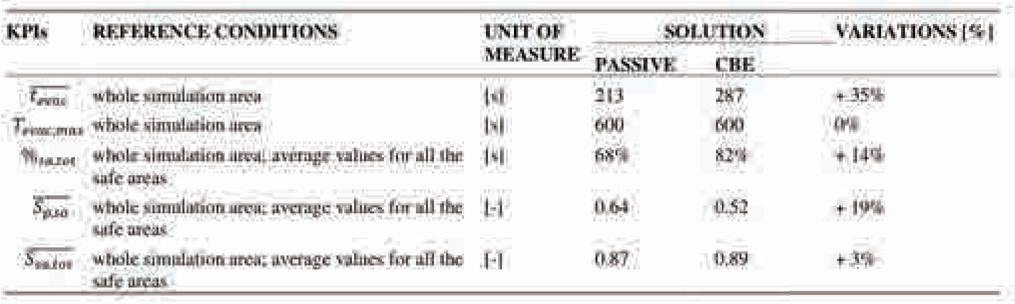
Come mostrato in Figura 9, il sistema riesce a distribuire meglio gli evacuanti attraverso i percorsi, indicando anche quelli secondari (comprese le porte di uscita dall'aula) ed evitando che si creino condizioni critiche per l'affollamento (si vedano i valori di F_p in Figura 9). Questo è particolarmente significativo all'interno dell'aula, con tempo T_{evac} relativo per la sola uscita dall'aula che si riduce del 14%, grazie alla riduzione dell'ingorgo nella porta maggiormente usata (P_{D1}). In seguito all'uscita, mentre nessuna persona si dirige verso ES, l'8% degli occupanti si muove verso ED: (t_{evac}) decresce del 17%, data la limitata lunghezza di tale percorso. Le variazioni non significative di $T_{evac,max}$ nei due sistemi solo legate invece ai tempi di uscita da US e UD. La riduzione del 4% di $T_{evac,max}$ comporta, tuttavia, un lieve aumento di $f_{sa,tot}$. È interessante notare che il valore di F_p per ES risulta negativo: il 2% delle persone ha preferito infatti abbandonare il sistema passivo per muoversi verso l'uscita segnalata dal CBE, a riprova della fiducia nel sistema anche relativamente a percorsi sconosciuti ma segnalati come utilizzabili.

4.2. APPLICAZIONE OUTDOOR: SISMA

Figura 10 mostra come l'impiego di CBE incrementi il numero di persone che concludono con successo l'evacuazione (+14%) entro $T_{evac,max}$, il cui valore è condizionato dal limite temporale di simulazione di 600s.

Il tempo di esodo medio risulta maggiore (+35%), proprio perché because this greater number of people coming from the more distant scenario areas and arriving to a safe area. Likewise, the average risk along the paths $\overline{S}_{p,tot}$ was reduced (-19%) thanks to the use of optimum path algorithms based on $S_{p,sa}$. The combination of these conditions means that $\overline{S}_{sa,tot}$ increases, but in a non-significant way: therefore, CBE application produced a negligible increase in the safe areas safety.

un maggior numero di persone provenienti dalle aree più distanti dello scenario arriva in una zona sicura. Parimenti, il rischio medio lungo i percorsi $S_{p,tot}$ risulta ridotto (-19%) grazie all'utilizzo di algoritmi di optimum path basati su $S_{p,sa}$. La combinazione di tali condizioni fa si che $S_{sa,tot}$ aumenti, ma in maniera non significativa: pertanto, a condizioni migliorate di esodo corrisponde un aggravio trascurabile alla sicurezza delle zone di raccolta.



KPIs	REFERENCE CONDITIONS	UNIT OF MEASURE	SOLUTION		VARIATIONS [%]
			PASSIVE	CBE	
$\overline{t_{evac}}$	whole simulation area	[s]	213	287	+35%
$T_{evac;max}$	whole simulation area	[s]	600	600	0%
$\%_{sa,tot}$	whole simulation area; average values for all the safe areas	[s]	68%	82%	+ 14%
$\overline{S_{p,sa}}$	whole simulation area; average values for all the safe areas	[-]	0.64	0.52	+ 19%
$\overline{S_{sa,tot}}$	whole simulation area; average values for all the safe areas	[-]	0.87	0.89	+ 3%

Figure 10. Results for the outdoor earthquake evacuation:
KPIs comparisons by considering the use of passive and CBE solutions.

5. CONCLUSIONS AND REMARKS

The design of indoor and outdoor Built Environment according to Cognitive criteria allows controlling environmental and behavioral conditions so as to improve the performance of the Built Environment itself, by taking advantages of the possibility to influence users' choices and behaviors. This study applies this standpoint to emergency safety issues. The Cognitive Built Environment (CBE) architecture is defined from an ontological point of view, to create the bases for the implementation of "unified" cognitive solutions from systemic (sensor, processing and actuation nodes) and process (through the definition of evaluation indices, that are the Key Performance Indicators) points of view. The capabilities of the approach are shown through the applications in relevant contexts (indoor fire evacuation; post-earthquake evacuation in urban areas), in order to verify how cognitive building components can optimize the individuals' safety by understanding the critical boundary conditions referred to the architectural spaces, the movement of people, the effects induced by the disaster occurrence.

The results show an increase in the number of people who can autonomously reach a safe area, thanks to the orderly and controlled management of the evacuation flows and to the limitation of possible critical issues in man-man and man-environment interactions. This study represents a preliminary application and testing, but results encourage future applications of the proposed principles and systems in the Built Environment. Main applications

5. CONCLUSIONI

Lo sviluppo dello spazio architettonico interno ed esterno secondo criteri basati sul Cognitive Built Environment CBE permette di poter controllare le condizioni ambientali e di comportamento per migliorare le prestazioni del costruito stesso, sfruttando in particolare la possibilità di influenzare scelte e comportamenti degli utenti. Il presente studio applica queste logiche alle problematiche di sicurezza in emergenza. L'architettura del CBE è definita da un punto di vista ontologico, per creare il fondamento alla implementazione di soluzioni cognitive unificate dal punto di vista sistemico (nodi sensoriali, di elaborazione e di attuazione) e di processo (tramite la definizione di indici per l'analisi del processo, Key Performance Indicators). Le potenzialità dell'approccio sono mostrate tramite applicazioni a contesti rilevanti (evacuazione incendio indoor; evacuazione post-sisma in ambito urbano), che verificano come componenti edili cognitivi possano ottimizzare la sicurezza delle persone comprendendo quali sono le condizioni critiche al contorno (costruito, movimento delle persone, effetti indotti dal disastro).

I risultati, infatti, rilevano un aumento nel numero di persone che raggiungono autonomamente una zona sicura, grazie alla gestione ordinata e controllata dei flussi di esodo e alla limitazione di possibili criticità nell'interazione uomo-uomo e uomo-ambiente. Lo studio, ovviamente, offre solo applicazioni e verifiche preliminari che, tuttavia, incoraggiano future applicazioni dei principi e dei sistemi proposti. Principali applicazioni al tema della sicurezza potranno riguardare to the theme of safety may concern different configurations of built space layout (indoor spaces; single parts of the urban fabric like squares or streets, also in case of significant crowding conditions; urban scale), as well as the development of different levels of Built Environment and users' monitoring, as well as of interactions with the suers (collective solutions, individual devices, coordination with management actions). Moreover, the design criteria can be extended to other fields of application in Building Operation, for the optimization, for example, of comfort, consumption, maintenance, users' flows in ordinary conditions.

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diverse configurazioni di layout costruito (spazi interni, singole piazze o strade anche in caso di affollamento rilevante, scala urbana), come pure lo sviluppo di diversi livelli di monitoraggio del costruito e della folla, e di interazione con le persone (dispositivi collettivi, individuali, coordinamento con azioni di management). Inoltre, i criteri di progettazione potranno essere estesi ad altri campi di applicazione nella Building Operation, per l'ottimizzazione, ad esempio, di comfort, consumi, manutenzione delle strutture, flussi delle persone in condizioni ordinarie.

6. RINGRAZIAMENTI

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