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Merging heat stress hazard and crowding features to frame risk scenarios within the urban built environment

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Abstract. Risk assessment for SLow Onset Disasters (SLODs) in the built environment combine the hazard features, and its effects on the built environment itself, with users' exposure and vulnerability, including behavioral issues. Although different methods exist for identifying the main SLODs drivers and their trend over time and space, limited information is found to set up significant risk scenarios by effectively merging hazard and crowding' features. Hence, this research is aimed at testing a methodology to create relevant risk scenarios for a single SLOD type, in the urban built environment. The work focuses on heat stress because of its growing incidence trend in urban areas. The methodology is applied to a neighborhood portion in Milan, Italy, which is a significant urban scenario for the considered SLOD. Through the application of quick and remote data collection methodologies, preliminary risk levels are traced over the daytime merging hazard and exposure, thus enabling a quick methodology application by practitioners. Results organize extreme and recurring risk scenarios considering relevant users' types and behavioral patterns in respect to both the neighborhood space use and the heat stress arousal. Such scenarios can contribute to the definition of input conditions for simulation-based risk assessment.

Keywords: Slow onset disaster, climate change, heat stress, users' behavior, emergency scenario.

1 Introduction

Climate change evidence has been found since the 1950s, mainly attributed to anthropogenic activities [1]. This phenomenon has affected the level of wellbeing and safety for the users of the Built Environment (BE). In fact, most of SLow-Onset Disasters (SLODs) are recognized effects of climate change. Although SLODs are characterized by a slow unfolding[1], their destruction capacity and impact on society are large, especially on urban BEs, characterized by physical vulnerabilities, large population density and current space intended uses [2].

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[1] https://www.preventionweb.net/news/view/53004 (last access: 22/04/2021)

In such contexts, heat waves events are a recurrent and a critical evidence (human health wise) of increasing temperature SLODs within the BE. Especially, given their gradually rising frequency and intensity [3–5], and their correlation with hospital admissions for heat strokes [6]. Temperatures, and complementary environmental conditions, can produce severe perceived temperature in people, especially those who are prevalently outdoor, and those less capable of tolerating heat (i.e. elders and children) [6–8]. To recognize and quantify the degree of such hazard, heat stress perception categories have been allocated to outdoor thermal comfort metrics.

Increasing temperatures SLOD, is characterized by people repeatedly and/or continuously exposed to unfavorable thermal conditions that progressively deteriorate health. These conditions mainly arise on summer, although mid-seasons also witness such distressing events. Moreover, BE characteristics can boost the hazard intensity, according to the BE physical vulnerability. Such vulnerability is associated with the phenomenon of the Urban Heat Island (UHI). Higher urban air temperatures are the resulting positive thermal balance of urban BE associated to their inherent anthropogenic heat release and their tendency towards: (1) excess storage of solar radiation, (2) lack of green spaces and heat sinks, (3) non-circulation of air in urban canyons and (4) low emitted infrared radiation to the atmosphere [2].

In addition, the increasing temperature SLOD risk should be determined by the combined effect of hazard and physical vulnerability factors, together with the number (exposure) and type of users (social vulnerability) hosted in urban BE. The latter can vary depending on [8–13]: (1) the users' behavioral dynamics (e.g. movement and presence patterns over time and space), mainly referred to the number of people who present and exposed to the hazard; (2) the users' features and preference determining individual vulnerability (e.g. age, health and body characteristics), linked to the groups of people who are more fragile to the studied hazard.

2 Literature review

The environmental conditions and perceived heat stress, can vary across the urban BE (e.g. micro-climates). Such distribution, can be modelled throughout the use of computer-aided simulation tools [14], but the human dimension is normally excluded when analyzing this type of hazards [15]. Thus, input data of temporal and zonal occupation should be provided, as a result of the interaction between the BE and its users, to perform granular simulation-based methodologies for risk-assessment [16] and risk-mitigation (mainly, BE modifications that relieve UHI [17]).

To simulate human behavior when exposed to certain environmental conditions, models have been created using such as urban stressors [9]. Yet, their application remains extremely complex, specially when determining an specific starting input scenario configuration and the computational time [18, 19]). Overlooking the issue of efficient hardware [20], the configuration of relevant scenarios remains an open problem. Remote sensing strategies and online tools surge as good alternatives to obtain environmental conditions, BE elements dimension, use and users' habits (according to the space function), that allows creation of time-dependent weather, crowding levels and behavioral patterns. Nevertheless, methodologies are needed to detect extreme and recurring risk conditions in the BE that can increase the applicability and ease of risk assessment strategies, focusing on critical and/or most probable distressing conditions to which BE users could be potentially exposed.

In this perspective, this work is aimed at developing and testing a methodological procedure to narrow down relevant scenarios of recurrent and intense heat stress risk of a delineated area to enable and ease further BE risk assessment through simulation-based approaches. The methodology is set for a urban BE portion (i.e. a part of a neighborhood) evaluating the frequency of heat stress hazard for BE users (considering both the environmental features and the BE physical vulnerability), and their exposure. Data on hazard and exposure are collected through remote analysis techniques, and they are organized over a daily trend. Then, the most severe and recurrent scenario conditions are identified according to a comparison-based approach.

3 Methodology

The proposed methodology defines single-hazard SLOD plus exposure conditions needed as input scenarios for human behavior modelling in a representative BE. The methodology is organized in 2 main steps. First, hazard (Section 3.2) and exposure data (Section 3.3) are collected according to a time-dependent approach. Then, data are compared to retrieve extreme (i.e. most severe) and recurring (i.e. frequency) combined conditions (Section 3.4), by additionally assigning main users' behavioral patterns according to the specific site characteristics.

3.1 The case study built environment

The case study is located in northern Italy. A region that has been labelled on the EM-DAT [4] as a "extreme temperature affected country" and the European Environment Agency (EEA)[2] has reported a 0.3-0.35 °C average annual temperature increase trend for the same area. From which, Milan (Italy) is a representative location to study heat-stress risk within densely populated cities [21]. Moreover, the district of Città Studi was identified as a region with likely high exposure (high population density) and physically vulnerable based on their Land Use Land Cover. It has a low greenery area coverage (15.4 %), fairly high built surface area (29.4%) and volume coverage.

This city portion hosts an average concentration of susceptible population (adults >65 and toddlers <5 years-old represent 22.3%). Which can be attributed to the hosted home cares (2) and educational institutes (20). Finally, this area has reliable open weather data sources for studying its fluctuations (Milano - via Juvara). However, only a narrower representative portion of the identified district (20108 m^2) was studied (see Fig. 1), because: (1) this portion hosts a significant number of residents; (2) it has different urban BE units (e.g. piazza, piazzale and urban canyon) with busy roads [3]; (4) it holds potential crowding points (e.g. schools, nearby university, theatre, religious building), a nearby water body and embed greenery.

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[2] https://www.eea.europa.eu/data-and-maps/figures/trends-in-annual-temperature-across-1 (last access: 04/11/2020)

Fig. 1. Case study area from municipality's GIS tools (https://geoportale.comune.milano.it/sit/, last access: 04/11/2020; left side) and Google Maps view (right side).

3.2 Collecting and processing hazard data

Hazard detection necessitates a well-equipped sensor network and a reference standard for comparing the estimates of heat stress. Data was processed as follows:

1. Identify available weather stations' location and datatypes collected for selecting the most appropriate data sources to estimate hourly outdoor heat stress.
2. Collect sufficient data (e.g. 5 year records) to be processed. For each hour, compute heat stress and establish if moderate heat stress level hazard is existent (TRUE = 1) or not (FALSE = 0), based on a reference standard.
3. Organize hourly Boolean data and average them by time (e.g. 08:00).
4. Plot average values to delineate the daily profile of the mean frequency heat stress hazard arousal for each hour of the day.

3.3 Collecting and processing exposure data

Given the heat stress nature, most exposed users are those who repeatedly attend the BE, such as residents, frequent visitors, and/or workers. Buildings intended use was retrieved through available GIS tools (i.e. online open ArcGIS API) and combining Google Maps and Google Street View (goo.gl/maps/LtPrx2ABaFwmK2GX9, last access: 22/04/2021). The building covered area and number of floors was extracted with GIS tools, and/or determined with "Map Area Calculator" tools (calcmaps.com, last access: 26/04/2021) and Google Street View visualization where data was missing. Adopting a conservative approach, the gross building total area was calculated by multiplying covered area and number of floors, and grouped by building type.

Then, the building users' by type was calculated by multiplying its gross area by an established occupancy load density (persons/m^2). For every case, the load factors were allocated from values suggested for an ordinary European context [22, 23] as follows: (1) for residential building, 28.3 m^2/person; (2) for commercial buildings, 17 m^2/person; (3) for restaurants and bars, 6.1 m^2/person; (4) for educational, religious and homecare buildings, 5.4 m^2/person; (5) for the theatre, 2 m^2/person. Point 1 was associated to *residents* in terms of users' category, while points 2 to 5 were related to the *visitors'* category. Furthermore, *pedestrians* were assumed to occupy sidewalks and open spaces at a 10 m^2/person.

To introduce social vulnerability, residents were divided in four BE user types given their age: toddlers (0 to 4 years); young people, i.e. students (5 to 24 years); adults (25 to 65 years); elderly (over 65 years). The residents percentage for each users' type is derived from census databases (https://www.comune.milano.it/aree-tematiche/dati-statistici, last access: 26/04/2021). School and homecare occupants were divided into students or elders and workers (0.8-0.2 and 0.4-0.6 respectively). Visitors were only considered as adults. The following assumptions were provided for the occupation dynamics over daytime, by identifying the different main users' types and their statistically constructed occupancy profiles [22]: (1) toddlers and elderly were always considered present over time; (2) young people were considered at home from 0:00 to 7:00 and from 14:00 to 24:00, following school activities; (3) adults were considered at home from 0:00 to 7:00 and from 19:00 to 24:00, according to standard working time in Italy. The visitors' presence (only adults) was set depending on the specific opening time of the building, retrieved from Google Maps statistics. Finally, pedestrians were considered constant from 7:00 to 1:00, from superimposing commercials buildings opening time.

3.4 Retrieving extreme and recurring conditions

Hazard and users' exposure data are organized over time, considering a standard working day because of its frequency over the year. Relevant scenarios are then evaluated by pointing out the daytime in which hazard and exposure high values coincide. Then, recurring environmental conditions are estimated by calculating the modal values, to outline the most severe risk and probable-hazard scenario to test BE and user's interaction under increasing temperatures SLOD risk.

4 Results

4.1 Frequent intense heat stress hazard encountered

Weather data was extracted from 2015 to 2019 from the regional environmental monitoring agency ARPA Lombardy[3]. In specific, from a station <1 km distant from the center of the case study.

However, Mean Radiant Temperature could not be computed with available data. Thus, heat stress was allocated using RiskT [24] (employing only air temperature, solar radiation, wind speed and relative humidity), assuming that BE users will not be exposed to direct solar radiation neither high air velocity. RiskT weighting factors were set as:

- $t_{db\text{-}air}$ = 0.4 for temperatures above 26 °C, or $t_{\mathrm{db\text{-}air}}$ = -0.4 if below 18 °C;
- I_{tot} = 0.3 for irradiation over 300 W/m^2;

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[3] https://www.arpalombardia.it/ (last access: 04/11/2020

- $RH = 0.15$ for values below 30% or above 70%; and
- $V_a = 0.15$ for values below 2 m/s.

RiskT was screened for 44124 hours to determine the existence of heat stress if RiskT > 0.5. During this period, $t_{db\text{-}air}$ peaks were registered above 38°C, while I_{tot} reached 952 W/m^2 as a maximum registered value. Also, more than 5000 hours were reported having a hazardous heat stress condition (i.e. 5364), which represents approximately 12% of the collected data.

Then, the discrete 0 (FALSE) and 1 (TRUE) values of presence of hazardous heat stress were grouped and averaged by each of the 24 hours/day to establish the mean frequency in which they arise. These showed hazard frequency arousal peaks between 10:00 and 18:00, with the maximum between 15:00 and 16:00 hours (see Fig. 3).

4.2 People exposure trends

Table 1 resumes the results concerning the users' exposure by quantifying the maximum number of exposed people for each building intended use and the related building features. Excluding the time-related trends in the use of the BE, residential buildings represent ~25% of the potentially exposed population. Considering residents only, 22.3% (233) of them would fall within the toddlers and elders category, while 60.3% (182) would be adults, this being considered workers, and 17.4% (628) would be young people, considered students. Schools involve the ~36% of the exposed users, but their occupation is focused on morning hours. Finally, commercial activities, the church and the homecare center are less relevant in terms of crowding, but they are critical attractors for the BE users' movement in outdoor areas [16].

Table 1. BE users' maximum occupancy for each building type, including their gross area.

Building intended use	Gross area [m^2]	Maximum users' number [persons]
Homecare center	1860	345
School	8120	1504
Theatre	1124	562
Church	603	112
Residential	29513	1043
Commerce (stores + bars)	1871 + 680	111 + 112
Pedestrian area	3828	383

Starting from the occupancy per building type, Fig. 2 summarizes the BE occupation number over time depending on the users' categories, for a typical working day, because of its statistical frequency over the year. Results show how the impact of *visitors'* number (i.e. students) leads to the peak values in users' exposure during the morning time.

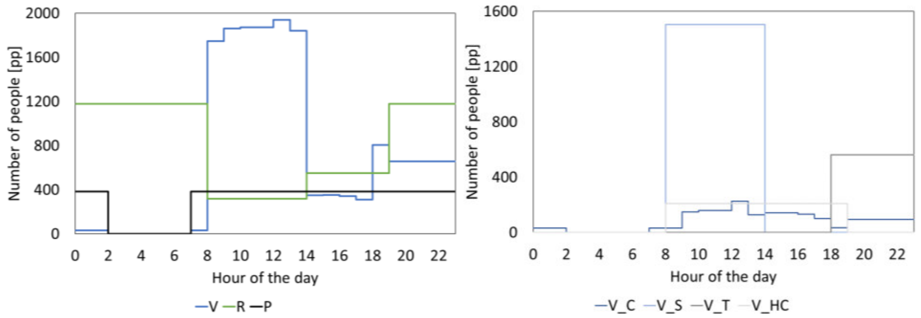

Fig. 2. Daily occupation trend by aggregated BE user categories, on the left, considering Visitors (V), Residents (R) and Pedestrians (P); and, diversified visitors (commercial buildings (V_C), schools (V_S), theaters (V_T) and Homecare (V_HC)) on the right.

Before coupling hazard and exposure, the complexity of the problem was reduced by grouping BE users only on main demographic groups. Fig. 3 presents a direct comparison between the frequency probability of hazards and a nominal occupancy profile differentiated by working-age (workers), studying-age (students), and elders and toddlers (Elders & toddlers). The hazard-related frequency in Fig. 3 is expressed in terms of RiskT, while the exposure-related values have been normalized by the maximum number of people present. As reported in Fig. 2, Fig. 3 highlights a high exposure during the morning time because of the concentration of students' present.

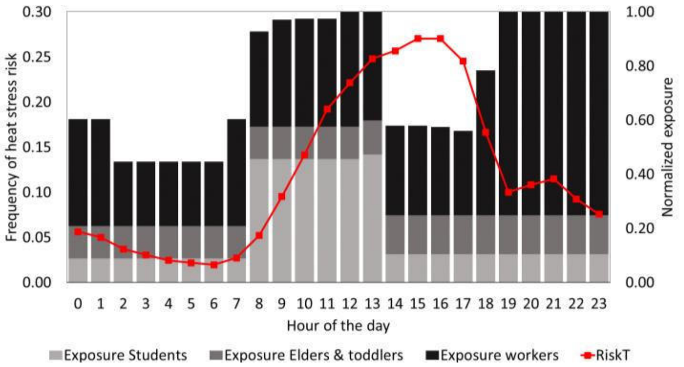

Fig. 3. Daily hazard and exposure trend of the case study BE, by demographic group type.

4.3 Significant scenarios for simulating users' behavior

Scenarios were selected aiming for both frequent and severe conditions, using RiskT arousal probability and level of exposure. Thus, assessing Fig. 3, the following were recognized as useful input for future work on granular analysis of SLOD risk (RiskT > 0.20): in the late morning (12:00 and 13:00), when studying and working-age visitors are more exposed; and, in the mid afternoon (15:00 and 16:00) when the presence of working-age visitors prevail. Hence, for those hours, the mode of the rounded integer values of the environmental parameters were found for the 5-year period (Table 2).

Table 2. Scenario configuration for simulation approaches under high heat stress conditions. Exposure divided in working age (E_W), studying-age (E_S) and elders and toddlers (E_E&T).

Hour	$\overline{\text{RiskT}}$	E_W [pp]	E_S [pp]	E_E&T [pp]	$t_{db\text{-}air}$ [°C]	RH [%]	V_a [m/s]	I_{tot} [W/m^2]
12	0.22	1119	1203	318	28	38	2	745
13	0.25	1021	1203	318	28	40	2	760
15	0.27	735	233	318	30	36	2	628
16	0-27	724	233	318	30	34	2	574

These scenarios have similar conditions, air temperatures approximately at 28 or 30 °C, relative humidity between 35 and 40%, wind velocity at 10 m from the ground around 2 m/s, and un-obstructed solar irradiation between 574 and 760 W/m2 (approximately, twice the 300 W/m2 threshold limit for heat risk). Although the environmental conditions are similar, the time of the day plays an important role, as the position of the sun would redefine the direct sola radiation distribution and intensity.

Therefore, an extreme and recurrent risk scenario would be the one at 13:00, because of the combine peak between exposure and hazard frequency of arousal (i.e. see RiskT). Meanwhile, the conditions retrieved between 15:00 and 16:00 can be considered as the most recurring risk scenario because of the significant number of exposed people and the peak of RiskT >0.5 frequency of arousal (see Fig. 3).

5 Discussion

To consider users' behavior outdoor on permanence, displacement speed and paths traversed (which determine the real affections, and are driven by heat stress) requires input scenarios to ease its realization. Therefore, a methodology that systematically obtains such settings, as those presented for hours 12:00,13:00, 15:00 and 16:00, could be of great interest. Also, the presented methodology has great value as it does not require complex computation techniques, neither lengthy machine time, it uses freely available data sources, and can be easily managed by non-expert practitioners.

Having the scenario baseline, it is possible to obtain granular distribution of heat stress within the BE; to later introduce user behavior models to adapt their walking speed to minimize stimulation, or to find refuge [9, 16]. Such models, could adopt as well, agent based modeling approaches that combine the different group of users' preferences (e.g. elders), with the daily users' routines while moving in the BE spaces [25]. By doing so, outdoor behavioral patterns are expected to show attraction to trees, and/or shaded areas. This aspect is crucial above all in the use of squares and forecourts, while it can affect the volumes of pedestrian traffic in urban canyons.

However, the present work did not consider how the opening and closing time of some activities affect traffic levels, thus released anthropogenic heat (i.e. motor vehicles). Utilized weather datasets were limited, motivating gross assumptions generating higher variance of the allocated risk (i.e. employing RiskT instead of UTCI). Moreover, full or no occupancy rates were inserted in the occupancy profile, thus possibly overestimating exposure, and generating a possible shift in the timeframes selected.

6 Conclusion

A relevant case study in Milan, Italy has been studied with a rapid methodology for identifying significant scenarios for future studies on risk conditions of increasing temperature SLOD. The methodology focuses on the interaction between exposure and hazard factors, identifying extreme and recurring risk scenarios in the BE.

Identifying relevant scenarios related to main drivers of users' behaviors in the built environment (in this case, heat), can facilitate further BE analyses aimed at adopting simulation-based risk assessment techniques (e.g. seismic evacuation). Another area, area size or type of SLOD can be rapidly assessed by researchers with the same methodology, such as the concentration and distribution of air pollution.

These methodology is foreseen to help provide information to planners and citizens for making the BE more secure and resilient throughout testing of targeted mitigation strategies on BE users' exposure and/or environmental hazard.

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