Built Environment Challenges Due to Climate Change

Zofia Zięba¹, Jolanta Dąbrowska¹, Marian Marschalko², Jorge Pinto³, Maria Mrówczyńska⁴, Agnieszka Leśniak⁵, Aleksandar Petrovski⁶, Jan K Kazak¹

¹Wrocław University of Environmental and Life Sciences, C. K. Norwida 25, 50-375 Wrocław, Poland
²VSB - Technical University of Ostrava, 17. listopadu 15, 708 00 Ostrava-Poruba, Czech Republic
³University of Trás-os-Montes and Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal
⁴University of Zielona Góra, Licealna 9, 65-417 Zielona Góra, Poland
⁵Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland
⁶Ss Cyril and Methodius University, Goce Delcev 9, 1000 Skopje, N. Macedonia

zofia.zieba@upwr.edu.pl

Abstract. Climate change has become one of the most significant problems of recent years. It results in a higher incidence of extreme events, such as strong winds, heavy precipitation, floods and droughts. Their consequences have a negative impact not only on the environment, but also on the engineering structures and the safety of the population. In this article, the relationship between the built environment and the effects of climate change is characterised in order to propose systemic changes to improve the adaptation of cities to climate change. Weather- and climate-related hazards for the built environment are analysed, and the possibilities to reduce the risk and mitigate the effect of construction disasters, should they occur. Moreover, a case study conducted in Central Europe has been presented. Based on quantitative data from the Central Office of Building Control in Poland from 2006-2018, the occurrence of construction disasters, their causes and consequences were examined. It was found that the main cause of disasters occurring in Poland during this period were random events (73%), which consisted in particular of extreme weather events such as strong wind or strong wind with accompanying heavy precipitation causing floods and landslides. The highest number of construction disasters (1113) was recorded in 2008, and as many as 95.6% were caused by random events. The conclusion indicates the need to prepare the built environment for climate change and to develop appropriate solutions to reduce the risk of climate-related hazards and to mitigate their effects. Based on the conducted analyses, a conceptual framework of improved climate-resilient built environment management was proposed.

1. Introduction
Socio-environmental systems are under significant pressures due to climate change in different forms worldwide. The impact of climate change, among others, is associated with Loss and Damage (L&D) in human and natural systems. The L&D discourse was started over 30 years ago and it was officially introduced to the international climate policy by the Warsaw Mechanism on Loss and Damages in 2013, and implemented to the Paris Agreement in 2015. Economic and non-economic L&D caused
by sudden- and slow-onset extreme events are a wicked problem afflicting many researchers and stakeholders throughout the world [1]. The international goal to mitigate climate change, defined in the Paris Agreement, is to undertake actions leading to limit global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C [2]. These benchmarks are strictly related to the results of research in the domain of environmental studies, which prove that natural hazards will be significantly more severe with temperature rise at the level of 2°C than 1.5°C in the context of available freshwater [3–5], temperature and related health risk [6,7]. Climate change has also a direct impact on the built environment (BE) covering both urban and rural areas which creates human habitats. Assuming low carbon emissions, around 190 million people currently occupy global land below projected high tide level rise for 2100. With the assumption of high carbon emissions, research shows that in 2100 this number will increase up to 630 million people living on land below projected annual flood levels, and up to 340 million for mid-century, versus roughly 250 million people at present. Moreover, it is estimated that one billion people occupy land less than 10 m above current high tide lines, including 230 million people below 1 m [8]. These numbers prove a strong relationship between built environment and climate change, while many other natural phenomena influence human settlements as well.

Following the classification of Andrić et al. [9], climate change and the BE nexus is divided into four main categories. According to this concept, the first category is building structure which is affected by several factors i.e. floods, landslides, storms and snow loads. The second element is building constructions influenced by fastening systems and water supply. Thirdly, building materials impacted by frost resistance, UV resistance and insulation properties. The final element is the indoor climate affected by humidity and temperature.

The above classification shows how broad this issue is, which results in high complexity of the assessment of climate change on the built environment. Therefore, the state of knowledge is still missing more detailed national and local analyses of environmental risks and their variability over recent years. Due to different geographical as well as socio-economic conditions the impact of climate change on BE can differ, which does not allow to assume one universal value describing the effects of natural disasters on human safety and security. This is the reason why there is a need to investigate the relation between the number of these events with the number of injured and killed people. Answering this question may allow further considerations on mechanisms of built environment disasters to indicate possible fields of improvements of future urban design. This study is an attempt to investigate BE in the relation with disasters caused by climate change.

2. Data and methods
First, we have reviewed relevant scientific literature, focusing on the interaction between the built environment and climate change. For the studied issue, we have identified problems, challenges and knowledge gaps. We then discussed disaster risk reduction for the BE as well as adaptation and mitigation strategies. The second part of the article is a Central European case study. Our research covers the quantitative analysis of statistical data describing construction disasters in Poland, as well as a review of reports and publications presenting the causes and consequences of selected failures. The analysis was based on data from 2006-2018. The quantitative data come from databases of the Central Office of Building Control in Poland - COBC (Główny Urząd Nadzoru Budowlanego – GUNB).

3. Results
3.1. Built environment challenges due to climate change – worldwide review
Buildings, bridges, roads, levees, dams and reservoirs, water and wastewater systems and other infrastructure should be designed and used taking into account changing climate conditions.
Nowadays, we are dealing with a rise in extreme weather and climate events. Building environment is more and more often affected by natural disasters, whose frequency, range and intensity are increased by climate change. In many areas new phenomena are occurring, for which the built, but also the natural environment is not prepared. For many years, specialists from many disciplines – meteorologist, geologists, environmental scientists, geoinformatists, computer scientists and others – have been working on natural hazard forecasting. Unfortunately, even high frequency and high resolution data from remote and wireless sensors and the possibilities offered by convergence of artificial intelligence (AI) and geographic information systems (GIS) do not allow us to accurately predict the time, place and severity of natural disasters [10–14].

Factors related to climate change are, apart from design and construction faults, foundation failures, extraordinary loads caused by non-climatic factors and negligence in maintenance, among the most common causes of buildings and engineering structures disasters[15–19]. Depending on regions and climate zones, the following weather- or climate-related hazards can be identified in detail: droughts, extreme temperatures, river and coastal floods, rainstorms, snowstorms, icestorms, thunderstorms and lightnings, windstorms including hurricanes, cyclones, tornadoes and whirlwinds, sandstorms, landslides, avalanches, sea level rise, fires and bush fires, overturning of trees. Scientists have also proven that climate changes increase the risk of earthquakes, tsunamis, and volcanic eruptions [9,17–23]. Moreover, climate change influences the energy efficiency of buildings and indoor climate. This increases the cost of living, but also poses a threat to people’s health, and reduces the productivity of workers, pupils and students [9,24,25]. Increased negative impacts are the basis for change in building codes and appliance standards, as well as for the creation of new, resistant construction materials. Infrastructure is affected by increased loads, extreme temperatures, heavy rainfalls, and in watercourses, reservoirs and hydrotechnical constructions we are dealing with extreme flows. Many authors insist that risk reduction options should be implemented into formal and informal construction decision making processes [26–29]. Disaster risk reduction (DRR), as well as the climate change adaptation and mitigation for the built environment, is becoming an important issue for civil engineering, real estate management, urban planning and designing [9,27,30].

The problems of a construction sector that increase hazard risks – e.g. building in hazard-prone locations, construction in one area exacerbates risks in neighbouring areas, building designs or construction methods that do not account for known risks, lack of risk reducing infrastructure – are still unresolved in many locations [31]. The following problems and needs have been identified in disaster risk reduction and building resilient cities [32]: ensuring the participation by all stakeholders, lack of DRR competencies among construction professionals (a dialogue with professional institutions is required, as DRR should be an element of professional competency), lack of aligned and coordinated approaches (strategic approaches are needed to encompass reconstruction planning, emergency planning, mitigation planning, and resilience planning), DRR is too often managed by wrong types of professionals, the existing urban development system is not capable of fostering DRR strategies, lack of available hazard information, especially information that is accessible in the public domain, lack of mechanisms to encourage DRR.

3.2. Central European case study
The analysis of data of the Central Office of Building Control in Poland concerning construction disasters (2006-2018) shows that their main causes are random events – the most common being strong wind or strong wind with accompanying heavy precipitation and lightnings (table 1, figure 1). The largest number of disasters concerned residential buildings, outbuildings or livestock buildings opened for use, in which no construction works were carried out. The affected buildings were mainly masonry or timber in use for over 10 years. Building elements subject to disasters were in most cases vertical construction elements, roofs and ceilings [33].
Table 1. Statistics on construction disasters in Poland (2006-2018) based on reference [30]

| Year | No. of disasters | Random events | Percent of random events | Injured | Dead |
|------|------------------|---------------|--------------------------|--------|------|
| 2006 | 385              | 234           | 60.8                     | 173    | 88   |
| 2007 | 520              | 447           | 86.0                     | 90     | 26   |
| 2008 | 1113             | 1064          | 95.6                     | 76     | 14   |
| 2009 | 269              | 199           | 74.0                     | 76     | 39   |
| 2010 | 731              | 478           | 65.4                     | 70     | 12   |
| 2011 | 648              | 230           | 35.5                     | 68     | 25   |
| 2012 | 426              | 345           | 81.0                     | 63     | 17   |
| 2013 | 258              | 113           | 43.8                     | 65     | 21   |
| 2014 | 242              | 209           | 86.4                     | 62     | 14   |
| 2015 | 305              | 242           | 79.3                     | 77     | 18   |
| 2016 | 367              | 313           | 85.3                     | 40     | 14   |
| 2017 | 627              | 536           | 85.5                     | 109    | 30   |
| 2018 | 249              | 177           | 71.1                     | 81     | 24   |

Figure 1. Construction disasters induced by weather- or climate-related hazards in Poland (2006-2018) based on reference [30]

The greatest construction disaster in Poland was the collapse of the exhibition hall at the Katowice International Fair in Chorzów, which took place on 28 January 2006. Sixty-five people died, and over 140 were injured. The General Inspector of Building Control in Poland appointed a special committee to establish the causes and circumstances of the disaster. The direct cause was considered to have been the loss of bearing capacity of the main truss girders with the simultaneous loss of bearing capacity of the columns in their upper part. Design and execution errors and improper use of the facility under excessive snow load were found. It was found that the snow load on large roof slopes exceeded that indicated by building code on average by 34%. On the other hand, in the central part, which collapsed during the catastrophe, the actual snow load was 63% higher than indicated in building code [34,35].
The committee investigated the disaster and made several recommendations, including the need to revise the snow load standard and the need to design large roofs with appropriate slopes (the slope of the roof should not be less than 5%) [35].

In the years 2007-2008, there were numerous disasters caused by a strong wind. Only in 2007, 401 of them were recorded, out of which in January 59 disasters caused by strong wind took place in the Łódź Province, in May, during a violent windstorm, a circus tent in the Lublin Province collapsed (more than 50 people were injured), and in July whirlwinds caused 263 disasters in Częstochowa County and 20 in the Świętokrzyskie Province.

In 2008 the number of disasters caused by strong winds reached a record number of 1000, of which as many as 542 disasters occurred in the Łódź Province. Therefore, the General Inspector of Building Control in Poland considered it advisable to take action to accelerate the Eurocode 1 package because it has about 40% higher calculation parameters than the PN-77/B-02011 Loads in static calculations. Wind loads standard in force at that time [33,36].

Two years later, in 2010, as a result of heavy precipitation, a number of disasters connected with floods and landslides were recorded. Due to the floods, 35 hydrotechnical structures were destroyed (the most in the Świętokrzyskie and Małopolskie provinces) [33,37]. However, the most severe damage was caused by the disaster of the earth dam on the Witka River in Niedów on 7th August 2010. As a result of the excessive inflow of water to the reservoir, a flood wave with a volume significantly exceeding its capacity was created, which broke the dam, causing serious damage of buildings and infrastructure in the settlements between Bogatynia and Zgorzelec and in Zgorzelec itself. The Niedów Reservoir was established at the turn of the 1950s and 1960s. The height of the reservoir’s dam was 12 m and its capacity at normal pool level NPL=210.00 m above sea level was 5.6 million m³, while the reservoir area was 183 ha [38]. The post-disaster research and analysis of the facility’s documentation showed that it was in good technical condition. Nevertheless, it was recognised that the regulations and guidelines for the design of hydro-technical structures in force in the 1950s and 1960s may not ensure safety because of the low class (importance/substantiality), the lack of overflows without maintenance, but also because of the extreme hydrological phenomena in recent years [39]. Between May and June 2010, intensive, prolonged rainfall contributed to numerous landslides. The largest disaster related to this occurred on 4th June 2010 in the village of Kłodne in the Małopolskie Province, where soil sliding with the speed of 1 m·h⁻¹ on the area of ca. 100 ha destroyed several dozen buildings [40].

In 2017, 536 construction disasters were recorded, and as the main cause heavy precipitation, strong winds, landslides and lightnings were indicated [33].

Random events are the main cause of construction disasters, human errors at the design and execution stage contribute to disasters in a much lesser degree. Climate change and global warming cause strong winds, floods, heavy precipitation and floods to occur with increasing intensity. They are a direct destructive factor, but also cause landslides and overturning trees. Some fires are caused by lightnings, high temperatures and drought. Climate change is also influencing the change in load standards, the structural elements are subject to greater forces, extreme temperatures, strong winds, whirlwinds, floods and landslides.

The magnitude of the impact of destructive climatic factors on the built environment structures is much greater than that considered in COBC reports. In 2010, 53 disasters caused by flooding were reported, a figure that is significantly underestimated, as only cases of violent and unintentional damage are entered in the register of building disasters, and in the vast majority of cases, flooded objects gradually degrade and are damaged, which results in demolition. COBC reports contain
information on the causes that induced the construction disaster – most often weather – or climate-related hazards. Often, after months of research and investigations, it turns out that there were also other causes – e.g. design and construction errors. There are large discrepancies between the information in COBC reports and scientific articles and the information from investigations. So the question arises whether a disaster induced by natural phenomena would have occurred if there had been no human errors?

Taking into account the current problems, data and knowledge gaps, constraints and opportunities, as well as solutions included in our paper, we propose an approach to create climate-resilient built environment (figure 2).

Figure 2. Conceptual framework of improved climate-resilient built environment management

4. Conclusions
Detailed research combining spatial and statistical modelling of land use [41,42] with other environmental drivers allow calculating the level of risk of some natural events like sea level rise [22,43], floods [44–46], stormwaters [47,48], avalanches [49,50], droughts [51,52], windstorms [23,27,53,54], heatwaves [55] landslides [27,56] and fires [21,57] which could constitute very important information for optimization tools [58,59] to select suitable and safe locations for the future human settlements to ensure low risk of natural hazards of the built environment. New design tools (i.e. PIEVC Protocol) are also created for planning and designing climate-resilient infrastructure [60]. However, besides technical solutions, to implement sustainable urbanization approach, there is a need for cooperation of many stakeholders across local municipalities [32,61]. In order to reduce the human impact on environmental systems, our BE management systems should consider reorganization resulting in lowering the environmental footprint of our cities and regions [62] which could allow minimizing the possible future negative impact of natural hazards caused by climate change. It is necessary to create standards for building and response systems. Multi-stakeholder approaches are needed on a local, national and global scale. The local scale is the most significant, as each region has its own unique characteristics and is affected by different natural disasters. It is crucial to understand the disaster risk, to strengthen the disaster risk management, building resilience, reconstruction and modernization of the structure according to the Building Back Better (BBB) principle. BBB is a post-
disaster recovery that delivers structures and buildings with reduced vulnerability to the future disasters [32,63].

It should also be mentioned that the BE itself can be used to adapt cities to climate change. The built environment creates urban heat island (UHI) effect. UHI can be mitigated through spatial planning, including the use of urban green and blue infrastructure. Hydrotechnical facilities for water retention and flood protection, sustainable urban drainage systems, urban layout with wind corridors are all elements of resilient-oriented cities. Through proper planning and configuring BE disaster risk may be reduced and comfortable urban climate can be created [64–66].

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