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Modern methods of counteracting urban heat islands

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Abstract: This article presents a complete compendium of knowledge in the field of urban heat island mitigation. The article presents both conventional methods and artificial intelligence algorithms to counteract urban heat islands. The study presents a systematisation of the causes and effects of urban heat islands in the context of climate change, urbanisation and the impact of human activity. Strategies for mitigating the effects of urban heat islands in the short term and in the long term have also been presented. Moreover, the article presents the advantages, disadvantages and limitations of artificial intelligence algorithms and techniques. The types and limitations of each group of algorithms are presented in the context of their application for urban data and resources management. A new aspect of the article is a holistic perspective of the problem of counteracting urban heat islands, taking into account the genesis of their generation and the limitations of conventional and artificial intelligence methods.

Keywords: urban heat islands, artificial intelligence, machine learning, architecture and urban planning

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Introduction

It has been observed that urbanisation alters local climate systems, resulting in regional warming, the urban heat island effect, extreme weather and deterioration of air quality (Luo & Chen, 2019). Extent of the urban heat island (UHI) phenomenon depends primarily on the size of the city, its urban structure, types of service zones and industry, as well as the number of inhabitants, the activities they undertake and the amount of energy consumed (Molina-Gomez et al., 2022; Santamouris, 2015).

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Cities are typically 2-3° warmer than the surrounding environment (Gokul et al., 2023). The predictions of developments in urbanisation and the associated effects of climate change reveal an upward trend in the number and size of cities. The findings of climate projection simulations running until 2050 suggest that urbanisation will lead to a warming of 1.9° on a regional scale (in China) (Chen & Frauenfeld, 2015).

As discussed in papers (Cheval et al., 2024), the problem of heat islands and heat waves should be examined in a broader context as a factor affecting, at the same time, thermal/energy, social and environmental/ecological aspects.

1. Urban heat islands – causes

Population growth is a key driver of urbanisation (Pearson, 2016). Urbanisation, in its turn, contributes to the physical development of urban areas and the formation of mega-cities, leading to the concentration of large numbers of people in small areas. Chapman et al. (2019) examines the impact of urban development and climate change on UHIs and heat stress in the city. It is noted that considering the combined effects of urban development and climate change is crucial to understanding how temperatures in urban areas will change in the future.

The modification of the spatial structure of cities should rely on tools that contribute to reducing the impacts of extreme weather (Chapman et al., 2019). The degree of change in the intensity of UHIs and their spatial extent depend on the way a city is built or rebuilt and on the materials used in the construction of city structural elements. There are two important features of cities that affect UHIs: urban canyons and the sky view factor (Lee & Levermore, 2019). A fixture of the urban structure, street canyons are characterised by tall buildings located on either side of long, narrow streets typical of most central districts. With their U-shaped design, they contribute significantly to UHIs by blocking air circulation and accumulating heat. One example of a cityscape with elevated nighttime temperatures associated with UHIs is New York (Shaker et al., 2019), as shown in Figure 1.

a) b) c)

Fig. 1. A view of an urban agglomeration: a) a view of an urban canyon towards the east, b) a view of an urban canyon towards the west, c) cityscape panorama (*photos by Paweł Pyzik*)

The lack of vegetation reduces heat loss through evapotranspiration, which is field evaporation (Shishegar, 2014). Majhi & Rath (2022) outlines urbanisation-induced land cover changes and their impact on land surface temperature (LST) as well as the role of vegetation in mitigating the effects of LST and UHIs. The study results show a significant increase in the LST of the area under consideration, following the expansion of the built-up area and reduction in vegetation.

The expansion of impervious surfaces (IS), such as paved areas, has been shown to significantly contribute to an increased land surface temperature (LST) (Wang et al., 2018). The transformation of permeable surfaces into impervious surfaces significantly modifies the local energy balance in urban areas (Vujovic et al., 2021). Areas with a high percentage of impervious surfaces tend to accelerate the increase in LST much faster than areas with a low percentage of impervious surfaces (Wang et al., 2018).

1.1. Urban heat islands – consequences

The impact of urban heat islands on human comfort and health is a well-studied phenomenon with significant implications. UHIs have been found to have significant impacts on human health, including physical health, mental health and overall health (Arifwidodo & Chandrasiri, 2020). The impact of UHIs on energy consumption varies according to local microclimate and urban area characteristics (Ren et al., 2023). Tian et al. (2021) has demonstrated that UHIs in urban areas dominated by air-conditioning can increase cooling energy consumption by about 10 % - 16 %. Li et al. (2024) asserts that UHIs could result in an average increase in cooling energy consumption of 19.0 % and an average decrease in heating energy consumption of 18.7 %. UHIs concentrate hazardous gaseous emissions from industry, energy and transport, leading to air pollution that can fall with rain, contributing to water pollution (Satrovic et al., 2024).

1.2. Artificial intelligence in urban planning

Artificial intelligence (AI) and artificial intelligence of things (AIoT) algorithms and techniques have been implemented on a large scale since around 2010. In addition to being able to use and manage huge databases, these tools have the capacity to learn and solve complex problems on their own. Given an exponential proliferation of areas where artificial intelligence is applied in our daily life, a similar trend is emerging in architecture, construction and urban planning. The functioning of cities and their parts allow for the constant provision of large data sets regarding, for example, sunlight, temperature and air condition, the continuous processing and use of which is a challenge due to their scale.

A wide range of areas of application and processing of datasets in the design of urban extensions and retrofits involving artificial intelligence algorithms is presented in (Allam & Dhunny, 2019). Allam & Dhunny (2019) identifies the risks of storing such large data sets, which may be used in an unethical manner. In turn, a significant increase in the ability to make decisions and provide data is possible thanks to the integration of the internet of things and machine learning.

Another area where artificial intelligence is applied in the operation of cities is social management algorithms, as described in Herath & Mittal (2022). When employed to manage energy, water and heat resources, these algorithms provide a useful tool to optimise the time-varying demand of urban areas for the aforementioned resources, minimising the time gaps associated with potential shortages of these resources in cities.

The most effective methods of counteracting UHI include interdisciplinary strategies (Tehrani et al., 2024), which combine more effective management of resources, such as energy, water and optimization of their use through the use of artificial intelligence techniques. This type of solution (Kwok et al., 2022) may allow for simultaneous short-term and long-term reductions in the peak temperatures of the urban structure. Examples of the applications of artificial intelligence algorithms in solving these urban heat island problems demonstrate their most important possibilities. They also show the great potential of their use in managing urban resources and counteracting crises.

2. Methods

The study employs an analytical method to systemise the current body of knowledge regarding the application of artificial intelligence in solving the problem of urban heat islands and environmentally friendly urban design. The multi-faced analysis considers today's solutions to the problem of urban heat islands in terms of modern artificial intelligence methods and techniques, urban planning and conventional architectural solutions. The analysis was undertaken based on two aspects. The first concerned the juxtaposition and comparison of conventional solutions to counteract urban heat islands, while the second concerned the analysis of the potential and limitations of using AI and AIoT algorithms in counteracting UHI.

3. Results

The multidimensional variability of urban shape has a significant impact on urban climate variability. Urban morphology can be defined using the urban canopy model (UCM), which defines the layout and materials of urban fabric elements and their geometry. The UCM is used to simulate the exchange of heat, momentum and moisture in the urban canopy. In the context of urban design/retrofit, it enables year-round simulations and evaluation of multiple design alternatives in terms of their impact on urban heat islands, outdoor thermal comfort and/or energy demand of buildings (Afshari, 2023).

Essential to this context is the sky visibility coefficient. The sky view factor, or the ratio of the visible sky area of a specific map point to the urban canopy (SVF), is another factor used to parameterise urban morphology (Middel et al., 2018).

Manipulating urban form based on the SVF suggests that UHI can be mitigated. One example of manipulating urban form to achieve a specific SVF is controlling the length of a street canyon, as shown in Figure 2. The SVF shows the potential to optimise urban form modelling with a view to making appropriate design decisions concerning UHIs (Ningrum, 2018). Characterised by a low sky view factor, urban canyons contribute to local overheating due to solar radiation on building surfaces (Morini et al., 2017).

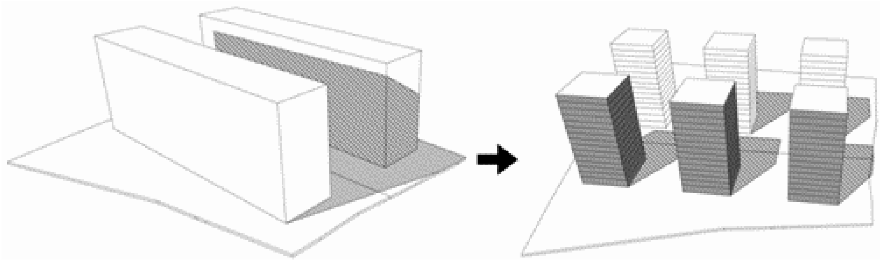

Fig. 2. Manipulation of urban form in terms of street canyons
(*visualization by S.T. Architekci studio*)

A review of literature shows how architects and urban planners can mitigate the urban heat island effect in street canyons. There is a strong relationship between the orientation of a street canyon relative to the ambient wind direction and its aspect ratio. In narrow canyons, the wind speed almost disappears at the bottom of a canyon. In wider canyons, air exchange is slightly more efficient. Where a street lies perpendicular to the prevailing wind direction, ambient air is carried along the walls to the bottom of a canyon, improving its microclimate (Takebayashi & Moriyama, 2012).

In addition, Leal et al. (2024) describes a method for simulating the maximum intensity of an urban heat island based on city geometry using H/W parameters (where W is the width of a road, and H is the height of a building). Leal et al. (2024) indicates that the daily net solar gain is larger for roads where W/H is greater than about 1.5, and the differences between north-south roads are smaller than among east-west roads. Green and blue infrastructure, including trees, green roofs and fountains, has been shown to reduce daytime surface temperatures and thermal amplitudes of surrounding areas, thus mitigating the UHI effect. The results suggest that in addition to larger GBI (e.g. parks, rivers), smaller structures can significantly reduce the UHI effect. As shown in Khan et al. (2021), close proximity to large water bodies such as seas, oceans or lakes is a vital factor in reducing the negative effects of heat islands.

Elevated air temperatures in cities are closely related to the thermal properties of building façades. Materials such as concrete and brick absorb and release heat, thus increasing UHI intensity. Orman et al. (2024) examines the thermal performance of various façade types based on their properties: heat absorption (brick wall), heat utilisation (green walls and submerged aluminium composite panels), reflection (reflective coating), insulation (expanded polystyrene) and shading or covering (aluminium composite panel and cement board). Increasing the reflectance of building façades from 0.1 to 0.4 reduces the air temperature near a façade by 0.6 °C and the façade temperature by 10 °C, leading to a reduction in the building's energy consumption of approximately 32 %. An increase in the albedo of a façade will result in an increase in the average radiant temperature in the city, exerting a negative impact on the urban thermal environment (Morini et al., 2018).

An urban canyon absorbs more energy than a flat, open surface due to the multiple reflections of sunlight. The use of more reflective pavements and façade materials determines the return of more energy to the atmosphere (Tahooni & Kakroodi, 2019). In this context, it is important to consider the insolation time of buildings.

3.1. Artificial intelligence algorithms and models

Artificial intelligence models are interpreted as devices/tools that can perceive the surrounding reality and take action with predefined purposes in mind. In this sense, the operation of such algorithms resembles that of human beings. Depending on their capabilities and characteristics, one may identify different models of artificial intelligence: Natural Computing (NC) and Machine Learning (ML) (Fazel et al., 2024). These algorithms are capable of learning based on information from outside. Based on cognitive ability, a distinction is made between Natural Language Processing (NLP) algorithms, referenced in Gao & Yang (2024), and Computer Vision (CV) and Fuzzy Logic (FL) (Musiał et al., 2023). Another group comprises of Evolutionary Computing (EC) algorithms, which are used for solving multi-faceted problems, optimising data and solving complex tasks (Li et al., 2024). With their wide range of applicability, the aforementioned algorithms can be combined into larger agglomerations, e.g. in the context of urban climate change. In such a case, the ML model, fed by CV, FL and NLP results, allows for improved solutions based on empirical data, additionaly interpreted in real time. Let us take, for instance, NLP algorithms. By analysing human speech in different languages about urban space and its microclimate conditions, they can generate responses in the form of increased sprinkling or ventilation of an urban interior.

In addition, a contemporary branch of the application of artificial intelligence algorithms is Artificial Intelligence of Things (AIoT). This tool is particularly useful in the fields of ecology, recycling and sustainable architecture and urbanism. It relies on sensors of everyday appliances and urban infrastructure to collect and process data, and elicit the right response from the device. Artificial intelligence algorithms of things, according to the article (Zhang et al., 2024) include such solutions as: Linear Regression (LR), Artificial Neural Network (ANN), Decision Trees (DT) and Support Vector Machine (SVM), Deep Neural Networks (DNNs), Random Forests (RF), Genetic Algorithm (GA), Convolutional Neural Networks (CNNs), Batch-Normalization (BN) and Adaptive Neuro-Fuzzy Inference System (ANFIS). The uses of the aforementioned techniques are extensive. For instance, CNN and DNN algorithms, along with ML, are applied to mimic how people achieve certainty in making a decision. DT and ANN algorithms, in their turn, are biologically inspired by the structure and functioning of the human brain. As for

DL algorithms, they are based on three neural network elements an input layer, an output layer and a hidden layer. In this respect, they are similar to simpler statistical techniques used in planning experiments, as described in Zhang et al. (2024). As suggested in Dhanush et al. (2023), artificial intelligence algorithms can be divided as shown in Figure 3.

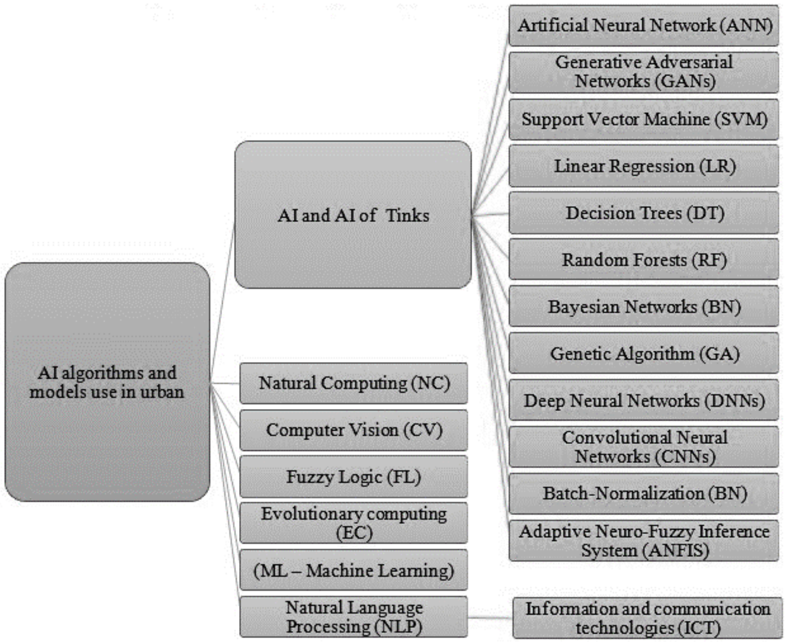

Fig. 3. Graphic diagram of AI and AIoT algorithms used in construction and urban planning (*own research*)

An important issue related to the use of AI and AIoT algorithms in construction and architecture is the aspect of security. For this reason, additional protections against cyberattacks are required. Moreover, the high energy consumption of devices and systems that use AI will influence the optimization of costs in urban resource management systems. As demonstrated in the work of Dhanush et al. (2023), the total energy demand required to power AI-driven systems may reach up to 20 % of the total energy demand in the future.

Conclusions

The conclusions of the present study provide information for the application and limitations in the use of AI techniques. In addition, the complexity underlying the cause-and-effect interaction of urban heat islands in the context of using AI and AIoT models is addressed.

Climate change is causing longer, more intense and more frequent heat waves. This phenomenon is largely intensified by factors associated with uncontrolled urbanisation. An increase in the amount of anthropogenic heat release generated by human activities leads to higher temperatures.

Among the artificial intelligence algorithms known today, the ones that are in general used to solve urban heat island problems are ML, FL and Big data. They deal with complex tasks on the basis of small and large data sets. They make it possible to control traffic and urban and energy infrastructure elements on the basis of historical and real-time data. The main limitation is the real-time processing of huge data sets.

Artificial intelligence algorithms are a tool that can be vulnerable to hacker attacks. For this reason, multi-layered protection structures have been developed to achieve a high level of protection. At the same time, an important factor is the attack detection time, which should be less than 14-15 ms for more than 90% of threats.

The stabilisation of the thermal conditions of the urban interior is a function of many factors, such as climate change, space use, resources, water, solar energy, level of industrialisation, air quality, etc. In the short term, the effects of urban heat islands can be countered by conventional measures such as reflective street paving, the implementation of green infrastructure such as green roofs and shaded streets, as well as the use of selected AI algorithms such as ML or VC, GA. On the other hand, long-term solutions to the problem require the synergic application of Big data, ML, FL, CV algorithms and the implementation of standardised policies to counter urban heat islands. Only a holistic approach can ensure the long-term reduction of the urban heat island phenomenon.

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