Analytical framework for the analysis of co-benefits, conflicts and trade-offs of urban heat mitigation strategies

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Abstract. Many cities are undergoing urban heat challenges because of heat waves and urban heat islands (UHIs). During urban planning and design, properly adding cooling interventions, namely urban heat mitigation strategies, into cities and communities are essential to address urban heat challenges. However, cities are required to provide a variety of functions (e.g., buildings, transportation, park) and meet the requirements convenience, safety, health, comfort and wellbeing. Such functions and requirements result in some co-benefits, conflicts and trade-offs, promoting and constraining the application of urban heat mitigation strategies. However, the possible co-benefits, conflicts and trade-offs have not been well documented, where the improper use of cooling strategies may lead to unintended consequences. Therefore, it is essential to understand the co-benefits, conflicts and trade-offs of different cooling interventions. In particular, this study aims to develop an analytical framework for the analysis of the co-benefits, conflicts and trade-offs of different mitigation techniques. Mitigation techniques considered includes four clusters such as green infrastructure, blue infrastructure, white/grey infrastructure and urban design. The scope of urban functions and requirements, related to urban lives and urban operation, in ten aspects including economy, policy, ecology, environment, technology, space, urban beauty, practicality, culture, and transportation. The analytical framework was further applied to analyze the co-benefits, conflicts and trade-offs of cooling strategies in ten aspects of urban functions. Furthermore, it was used in environmental functions (e.g. local temperature regulation, stormwater regulation, waste treatment, air quality regulation, pollination, and recreation & aesthetic appreciation) and space functions (e.g. activity venue/entertainment venue, neighborhood vitality, resident satisfaction, space utilization and city identity), respectively. The results reveal that green infrastructure can provide the most aspects of benefits in ten aspects, and also in environmental and space aspect. Green infrastructure was followed by blue infrastructure, urban design and then white/grey infrastructure. Overall, the analytical framework offers a new perspective of the feasibility analysis of urban heat mitigation strategy and provides a reference for urban planners and designers to select proper urban heat mitigation techniques, with possible additional benefits of addressing other urban challenges.
1. **Introduction**

The world is urbanizing, during which period pervious surfaces are replaced by impervious surfaces, urban density and building height are increasing and ventilation is decreasing. Such modification patterns are associated with solar heat absorption and storage, latent heat reduction and anthropogenic heat release increase, and thereby the accumulation of excess heat within cities. As a result, cities are generally warmer than their surrounding rural/suburban areas, which has been well recognized as the phenomenon of urban heat islands (UHIs). Moreover, along with climate change, cities are increasingly attacked by heatwave, the phenomena of extreme hot days lasting for several days, in both frequency and severity. UHIs, heatwaves and even their synergistic effects are primary drivers to urban heat challenges.

Urban heat challenges many aspects. First, urban temperature increase threatens human thermal comfort and exerts stronger thermal stresses (Haddad et al., 2020), leading to the increase in morbidity (e.g. respiratory, digestive and cardiovascular diseases) and mortality. The most famous case is the heatwave striking European continent in August, 2020, causing the deaths of about 70,000 people. In 2020, England reported that more than 2500 people lost their lives due to extreme heat. Second, urban heat challenges lead to social inequity because of the vulnerabilities of the elder, children, pregnant women, patients and many other economically-disadvantaged groups. For instance, the England case indicated that 90% of the deaths were among people aged above 65. Third, urban heat challenges can further lead to the increase in electricity and water use, because of the use of air-conditioning cooling, water cooling and irrigation for adaptation (Santamouris, 2015). Moreover, existing studies reported that the peak electrical load increases by 0.45% to 4.6% for each degree of temperature increase - this is equivalent to an increase of about 21 ± 10.4 W of excess consumption per person per degree of increase (Santamouris et al., 2015).

Addressing urban heat challenges is therefore a very critical problem and it is imperative as urban heat challenges are projected to be aggravated in the future along with climate change and urbanization. A holistic system of urban heat prevention, mitigation and adaptation strategies have been proposed with the expected collaboration of many professionals, including climatologists, medical staff, urban planners, designers and policy makers. The urban heat mitigation strategies consist of green infrastructure, blue infrastructure, reflective and permeable materials, and urban design for shades and ventilation. Such mitigation strategies are mainly developed and applied for cooling purposes and their cooling performance can be enhanced through the optimization of materials, typologies, species and so on. Nevertheless, the only consideration of cooling purpose may introduce some unexpected impacts on many other aspects such as health condition, environmental quality and water demand. For instance, whilst the use of highly reflective materials can help reduce surface and air temperature, the application of them on the road may lead to human thermal comfort reduction and road glare. The use of permeable materials can reduce urban temperatures through water evaporation, while this increases the reliance on water. Therefore, it is essential to understand unexpected consequences and then avoid them in creating sustainable, resilient, safe, comfortable and livable cities and communities.

The unexpected consequences can be understood in aspects of co-benefits, conflicts and tradeoffs. The co-benefits refer to the strategies which can get extra benefits from the process of its application (Sharifi, 2021). For example, green space helps address the urban heat, while it also provides outdoor venues to enable citizens to communicate and exercise, improving living quality in both physical and psychological aspects. Therefore, the green space application generates more than two aspects’ benefits. Regarding conflicts or tradeoffs, one measure implemented may affect or damage the interests of another. For instance, fountains can cool surroundings through evaporation, while it increases investments to maintain. Many studies have measured co-benefits, conflicts and tradeoffs to balance cooling strategy application. However, these studies mostly focus on specific consequences or practicality of individual strategies. For instance, Susca et al. (2011) pointed out that in New York the

**Keywords:** Urban heat, Co-benefits, Trade-off
average temperature difference of 2°C in the most vegetated areas compared with the least. Meanwhile, there is not a systematic classification for the analysis of the co-benefits, conflicts and tradeoffs of cooling strategies. This reduces or even restrains urban planners and designers to effectively identify suitable cooling strategies for implementation.

To overcome this gap, therefore, this study aims to present a systematic analysis of the co-benefits, conflicts and tradeoffs of cooling strategies (e.g. green and blue infrastructure, innovative materials) in various aspects. To achieve this, this conference paper presents an analytical framework with the integration of ten aspects of urban functions. Upon this, the co-benefits, conflicts and tradeoffs of all potential mitigation strategies are identified and counted to generate a primary guidance for implementation. This study is meaningful to better understand cooling strategies and provide a new idea of information sorting for decision makers, simplifying initial selection of cooling strategies. It should be noted that it is just a preliminary framework, and in-depth work will be conducted to investigate co-benefits, conflicts and tradeoffs of cooling strategies to develop a sound framework supporting selection process of mitigation strategies across planning, design, construction, operation and maintenance. More following-up results will be added to the current framework.

2. Analytical framework for the analysis of co-benefits, conflicts and trade-offs of urban heat mitigation strategies

2.1. Aspects in urban area of picking

This study aims to analyze all possible co-benefits, conflicts and tradeoffs when selecting mitigation strategies. Therefore, it is essential to integrate all possible impacts of mitigation strategies relevant to as many stakeholders as possible including policy makers, urban planners and designers, suppliers, engineers, the public and so on. For instance, cities are artificially modified so that people are increasingly concerning environment and ecology. Under climate change, the global environmental issues such as biodiversity loss are considered (Valente de Macedo et al., 2021). Urbanization leads to environmental deterioration so that climate, pollution, and biodiversity should be urgently concerned (Lepczyk et al., 2017). Moreover, the application of such strategies are affected by space, social, ecology and economy functions (Hansen et al., 2019). In particular, space is the issue that urban designers should pay more attention to. Urban beauty, technology, and practicality are all issues that designers have to consider. Vitruvius in ancient Rome proposed three elements of design: firmitas, utilitas and venustas. For decision-making, economic and political benefits which brought about the problem of social equal by the implementation of cooling strategies are worthy of considering (Bush and Doyon, 2019). Finally, city residents, who are the largest part of the city, are likely to consider cultural and transportation aspects which are more relevant to life. After the consideration of urban function classification, ten aspects of analysis are generated. Figure 1 presents the ten aspects of urban functions including economy, policy, ecology, environment, technology, space, urban beauty, practicality, culture, and transportation.

2.2. Classifications of urban heat mitigation strategies

Heat mitigation strategies are classified into four categories: green infrastructure, blue infrastructure, white/grey infrastructure, and urban design. Green infrastructure includes trees, shrubs, and grass on the ground, rooftops, or facades can lower temperature and by providing shade, thermal insulation, and evapotranspiration cooling. In particular, green infrastructure mainly consists of green open spaces, shade trees, green roofs, and vertical greening system (Norton et al., 2015). Trees can provide shading and generate evaporative cooling impacts, providing people with cooler places. Apart from cooling benefits, green open spaces can help address biodiversity problems, and the restoration of biodiversity also has a positive effect on human health (Carrus et al., 2015). White/grey infrastructure can increase urban albedo or permeability for cooling. Cooling materials have low thermal conductivity, low heat capacity, high solar reflectance, or a high level of evaporation or permeability. Grey/white measures picked up in this study include cool surfaces, high albedo paving/high emissivity paving, retro-reflective materials and water-permeable/porous material (Akbari et al., 2016).
Figure 1. Classification of urban functions in economy, policy, ecology, environment, technology, space, urban beauty, practicality, culture, and transportation.

Blue infrastructure is related to water, which delays and buffers maximum temperatures due to its high specific heat. The evaporation process of water requires a lot of energy which comes from the surrounding air and water during the evaporation process. Through this process, the temperature of the surrounding air and water can be reduced. Besides, the low reflectivity of water can reduce the solar albedo around the water body and avoid heating (Fletcher et al., 2013). Evaporative cooling, pools and ponds, sprinklers, fountains, and evaporative towers are considered in this paper (Santamouris et al., 2017). Urban design, from urban planning and design to urban construction and renewal, mainly affects urban heat through urban form and relevant ventilation and shade. Compact development can increase urban vitality, increase land utilization, and share resources (Xia et al., 2020), while it may aggravate urban heat challenges. Solar radiation is the main source of heat storage in materials, so that casting shadows on surfaces is an effective way to reduce heat accumulation. Blocking solar radiation reduces the surface and average radiant temperatures of the canopy. Whilst shading does not necessarily reduce the air temperature, it significantly reduces near-surface radiant temperature. The improvement of outdoor thermal comfort leads to an increase in outdoor activity attendance, leading to in community-neighborhood relation improvement, economy growth and health improvement. Overall, strategies considered are relevant to solar radiation and urban ventilation such as shading device, sky view factor (SVF), building design and urban density.

2.3. Cooling effect of the mentioned mitigation strategies
Due to the different climatic, demographic, and social characteristics between of each region, the same strategy may lead to different results when applied in different regions. In this article, the criteria for selecting the effects of each specific cooling strategies to evaluate are:

1. Frontrunner cities of climate actions
2. Typical cities in some climate

The final eight typical climate cities selected for analysis of co-benefits, trade-offs and conflicts are: Bangkok (tropical monsoon climate), Chicago (temperate continental climate), Washington (temperate continental climate), Durban (tropical savanna climate), Mexico City (tropical savanna climate), Paris (temperate maritime climate), Vancouver (temperate maritime climate), Seoul (temperate monsoon climate). The reason for choosing these in the same climate region is that cities in the same climate region will have different results due to the implementation of different cooling strategies, which can provide some enlightening into the urban heat treatment response.

As for the selection of information on the effects of the corresponding cooling strategies, we collected the relevant information based on the following criteria:

1. Data given by official agencies
2. Feedback from the public

Moreover, when analyzing the co-benefits, conflicts, and tradeoffs, it is essential to consider urban scale as urban functions and the impact of cooling strategies vary with urban scale. Cooling strategies are primarily incorporated into cities at the community and neighborhood scale that is the basic unit of cities and a microcosm of the macro society. Therefore, co-benefits, conflicts, and tradeoffs are expected to be analyzed at the community level. The composition of urban functions is complex and requirements can be interrelated so that it is impossible to uncover and quantify the internal linkages. Therefore, when analyzing the co-benefits, conflicts, and tradeoffs, the potential linkages are currently not analyzed. Instead, once the cooling strategies can generate a certain impact, rather than little impact or weak pertinence, on a specific aspect of urban functions, the impact will be counted. Nevertheless, the study will be further updated for more information updates or new considerations in the future.

3. Results and Discussions

3.1. Co-benefits, conflicts and tradeoffs of cooling strategies in ten aspects of urban functions

Figure 2 presents the co-benefits, conflicts, and tradeoffs of cooling strategies in ten aspects of urban functions, where the row presents ten aspects of urban lives and processes, and column presents heat mitigation strategies. Green color represents that the strategy generates a positive effect, namely co-benefits. For instance, green space can reduce urban temperature and provide people with outdoor activity venues, while requires more land for construction, meaning sacrificing a part of economic development. Besides, green space should be irrigated to achieve expected cooling effects, requiring funds to maintain, namely tradeoffs which is denoted by pink color to show the strategy that has a contradiction. What’s more, grey means neutral, showing these measures have insufficient information. Therefore, their impact cannot be confirmed, or the application of these strategies have little impact in this aspect, and their promoting/contradictory effects can be ignored. For instance, the relationship between urban green space and culture aspects has not been well revealed.

Figure 2. Co-benefits, conflicts, and tradeoffs of cooling strategies in ten aspects of urban functions.
Overall, blue and green infrastructure measures received the highest scores, meaning the application of these strategies can bring the most benefits in ten aspects of urban functions. Scores of white/grey infrastructure and urban design came to lower, which might be because of insufficient information about their effects. Nevertheless, these measures are very targeted for ambient temperature reduction and the cost is low, so that they are options in many areas that urgently need to alleviate urban heat challenges.

3.2. Co-benefits, conflicts and tradeoffs of cooling strategies in Environmental function

Since each category of urban function consists of many more elements, it is essential to further analyze the co-benefits, conflicts and tradeoffs of cooling strategies in sub-functions. This section presents the co-benefits, conflicts and tradeoffs of cooling strategies in environmental aspect, with the consideration of local temperature regulation, stormwater regulation, waste treatment, air quality regulation, pollination, and recreation & aesthetic appreciation (Figure 3). Green color further indicates the positive impacts, pink color indicates negative impacts, and grey color indicates the measure does not meet or not promote environmental functions (Figure 3). For instance, reflective material still is chosen as an example, it has no effect on pollution control and air quality, so that it is marked as grey color in the table.

![Figure 3. Co-benefits, conflicts and tradeoffs of cooling strategies in Environmental function](image)

Green infrastructure had the highest score in environmental aspect, followed by blue infrastructure. Moreover, the lowest score was found in the improvement of urban density in urban design measures. The following explanation indicates the generation of such results. Green roofs can regulate the temperature, and they can regulate rainwater and air quality. Green roofs can also effectively reduce building energy consumption, improve air quality, support water management, improve sound insulation and ecological protection related benefits (Berardi et al., 2014). Street trees were found to reduce canopy
air temperature, where the increase in canopy cover increase from the 10% to 25%, can lead to an average daytime cooling benefit of up to 2.0 °C in local residential areas (Middel et al., 2015). Street trees can also provide shade and beautify the image of the city.

3.3. Co-benefits, conflicts and tradeoffs of cooling strategies in space function

Space is one of the most important issues for urban planners and designers. Whether the space created by these strategies is suitable is the key to design. First, space utilization is the most important indicator, as urban design vigorously promotes compact development in theory. In particular, shared resources can greatly reduce carbon emissions. The second is the question of whether the designed space can be used properly, so that space utilization and space comfort are assessment indicators, determining the neighborhood vitality and resident satisfaction. A place to accommodate residents’ leisure life should be considered in urban design. Moreover, each block should have its own unique characteristics. Designers should use the application of strategies to shape the identity of the area. Therefore, five indicators including activity venue/entertainment venue, neighborhood vitality (space utilization), resident satisfaction (space comfort), space utilization and shaping of city identity were used to assess the co-benefits, conflicts and tradeoffs of cooling strategies in space function (Figure 4).

![Figure 4. Co-benefits, conflicts and tradeoffs of cooling strategies in space function.](image)

Green infrastructure is the best choice for providing a variety of functions in outdoor spaces. It was followed by the blue infrastructure, urban design measures and then white/grey infrastructure. The construction of green infrastructure is often associated with parks, leisure seats under street trees, and sport equipment. They provide places where people can spend their leisure time. The livable
neighborhoods will always attract people from other neighborhoods to come to hang out, whether local residents or tourists. Local streets are the best choice for tourists to experience local identity.

3.4. Interconversion in different contexts

Both Chicago and Washington have a temperate continental climate, a type of climate that is mild and humid throughout the year, with distinctive features: no harsh winters, no hot summers, and a relatively even distribution of precipitation throughout the year. The climate is characterized by warm winters and cool summers, small annual temperature differences, year-round rainy seasons, more winter rains, smaller temperature differences, and even precipitation distribution. Since there is sufficient rainfall throughout the year, it is often important to consider the rainwater management system when applying the strategy. The tropical steppe climate has an average annual temperature of about 25°C, with high temperatures throughout the year and a distinct dry and wet season. Precipitation is concentrated in drought with little rainfall and a distinctly longer dry season. Tropical monsoon climate characteristics region keep high temperature all year round, the average annual temperature is above 22°C, the coldest month is generally above 16°C in the winter half of the year. Temperate monsoon climate annual average temperature is not less than 0°C, high temperature and rain in summer, cold and dry in winter, four distinct seasons.

![Figure 5](image)

**Figure 5.** Performance of different cities of the urban heat mitigation strategies.

Cities in the same climate zone have different coping strategies, and a low score in the framework of this theory can be transformed from a contradiction to a common benefit. For example, in Durban and Mexico City, where the dry and rainy seasons are evident, the spatial demand for rainwater management systems is not as high, and the design, operation and management costs even outweigh the benefits of rainwater harvesting, so the absence of this item does not represent a generalization of the conflicting benefits.

This suggests that contextual differences lead to co-benefits and conflicting interconversions, and by the same token it can be concluded that differences in the same response in different climatic zones can lead to conversion benefits. This deepening will be continued in subsequent studies.

4. Conclusions

Co-benefits, conflicts and tradeoffs are important for the selection of cooling strategies in order to ensure the application of a specific mitigation strategy can gain more benefits and avoid some unexpected consequences. However, there is limited understanding of the co-benefits, conflicts and tradeoffs of existing cooling strategies, constraining the implementation of cooling strategies. This paper developed an analytical framework by analyzing the co-benefits, conflicts and tradeoffs of four categories of mitigation strategies including green infrastructure, blue infrastructure, white/grey infrastructure and urban design. The co-benefits, conflicts and tradeoffs were first concerned in ten urban functions including economy, policy, ecology, environment, technology, space, urban beauty, practicality, culture, and transportation. Afterwards, an in-depth analysis was conducted in both environmental and space
aspects. Results showed that green infrastructure was the best one with the most aspects of benefits, followed by the blue infrastructure, urban design and then the white/grey infrastructure. The results suggest that development of green and blue infrastructure should be prioritized if more aspects of benefits are expected.

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