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Review

Review and Comparative Study of Decision Support Tools for the Mitigation of Urban Heat Stress

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Abstract: Over the last few decades, Urban Heat Stress (UHS) has become a crucial concern of scientists and policy-makers. Many projects have been implemented to mitigate Urban Heat Island (UHI) effects using nature-based solutions. However, decision-making and selecting an adequate framework are difficult because of complex interactions between natural, social, economic and built environments. This paper contributes to the UHI issue by: (i) identifying the most important key factors of a Decision Support Tool (DST) used for urban heat mitigation, (ii) presenting multi-criteria methods applied to urban heat resilience, (iii) reviewing existing spatial and non-spatial DSTs, (iv) and analyzing, classifying and ranking DSTs. It aims to help decision-makers through an overview of the pros and cons of existing DSTs and indicate which tool is providing maximum support for choosing and planning heat resilience measures from the designing phase to the heat mitigation phase. This review shows that Multi-Criteria Decision Analysis (MCDA) can be used for any pilot site and the criteria can be adapted to the given location accordingly. It also highlights that GIS-based spatial tools have an effective decision support system (DSS) because they offer a quick assessment of interventions and predict long-term effects of urban heat. Through a comparative study using specific chosen criteria, we conclude that the DSS tool is well suited and fulfils many prerequisites to support new policies and interventions to mitigate UHS.

Keywords: decision support tools; multi-criteria decision-making; heat stress; urban heat island

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1. Introduction

Urbanization and an exponential increase in population have brought the concept of Urban Heat Island (UHI) and heat stress into the limelight. The world has seen adverse effects, particularly a rise in air temperature, a higher mortality rate, and changes in weather patterns [1]. Most studies have focused on the UHI in densely populated capital cities and there is insufficient literature available for smaller cities [2].

Different authors explained that UHI has severe effects on the most vulnerable populations, especially during the summer season. This phenomenon indeed highly raises the consumption of cooling energy as well as the corresponding peak electricity demand of cities. Therefore, the UHI can be linked with a significant increase in urban pollutant concentrations and is concerned with the city's carbon footprint as well as ground-level ozone. Urban Heat Stress (UHS) severely affects health, comfort, and increases mortality problems [3]. In current times, urban planners and policy-makers are keen to address issues such as increased urban heat due to climate change triggered by human activities.

Europe, Australia and North America are the major continents among those working to mitigate UHS in different ways, for example, by increasing urban forestry or by using green and blue interventions. On the other hand, Asia has also worked on thermal comfort but their focal point is grey and blue infrastructure. Accommodating heat stress measures in urban areas is not the easiest task as it encounters issues such as water scarcity, high cost and unsuitable environments for green infrastructure.

It is the responsibility of the decision-makers to evaluate multiple possible solutions to resolve the issues by considering specific criteria. Urban planners are still perplexed due to the severity of changes that have taken place in different zones.

Sometimes, alternative decisions are to be taken in order to combat the complex situation by considering some criteria [4]. It is observed in previous studies that every location has unique characteristics and parameters and the decision-makers have concerns about criteria such as cost, efficiency, and materials. For every location change, the mitigation measure should be modified. To solve these issues, a proper decision support system (DSS) is required to help decision-makers.

A DSS is an information system that requires judgment, determination, and a sequence of actions. It assists the mid-and high-level management of an organization by analyzing huge volumes of unstructured data and information. It is either human-powered, automated or a combination of both and it can be used in any domain due to its versatility.

There are many studies related to climate vulnerabilities—some have used economic or mechanistic modeling [5–7] and other researchers have used outranking approaches that later have been criticized due to axiomatic violations [8,9]. The number of characteristics required for the evaluation of UHS management similarly challenges is not constant. There is a need for a tool that allows one to work in consideration of all parameters simultaneously and helps to identify negative trends of urban heat and eventually allow better adaptation measures.

This paper presents a comprehensive review of DSTs in the essence of UHI, climate change adaptation, and heat stress. In Section 2, the methodology of the paper is discussed, Multi-Criteria Decision Analysis (MCDA) approaches are reviewed in Section 3, and DSTs (toolkits and spatial tools) are discussed in Section 4 of the research paper. All tools are critically analyzed by 15 important criteria in Section 5 and, finally, the conclusion is presented in Section 6.

2. Materials and Methods

2.1. Review Strategy

In this review article, we have used a qualitative and exploratory approach. Peer-reviewed research papers were gathered from Google Scholar. The research papers were selected by using keywords such as multi-criteria decision, UHI mitigation, heat resilience and UHS DST. Tools that are developed for urban heat resilience under the banner of different projects were searched by using the same keywords. The survey is presented in two tables. In the first table, we reviewed 9 academic studies in which different MCDA approaches were applied for developing DSTs for UHS mitigation. In the second table, we performed a review on different DSTs which deal with the UHI, climate change risks, extreme heat events, heat resilience adaptation and mitigation measures.

2.2. Inclusion and Exclusion Criteria

In this paper, we analyze 12 DSTs with the principle aspects to analyze the support of the decision-making tool, such as: (i) experts' assistance in the development of a support system; (ii) social culture factors, for example, number of population and their age, their activities, health data and the local environment; (iii) adaptive capacity of the tool which allows the indication of the suspect areas, informs where intervention is needed and when to schedule outdoor activities; (iv) good integration with other domains, which is correlated to a rise in UHS, can make the tool more advanced and gives a possibility to use the tool universally; (v) input requirements from the user, which means the decision results depend on the input data; (vi) indicator showing the vulnerability, heat events and effectiveness of the intervention; (vii) political and administrative support for developing the tool; (viii) vegetation, which is a basic and natural intervention that helps to reduce heat stress; (ix) graphical interface and heat stress visualization by mapping; (x) spatial coverage, which helps to indicate the suspect areas in a city on a GIS map; (xi) cost assessment of the measure; (xii) quick assessment of the intervention's effectiveness in real-time; (xiii) user-friendliness, which shows how easy and difficult it is to use the tool; (xiv) uncertainty risk analysis, which gives trustworthy results; and (xv) plus points, which are when the tool provides a long-term effect of heat stress or considers other interventions apart from vegetation. These selected criteria were obtained after going through the literature and serve as a methodology, as shown in Figure 1.

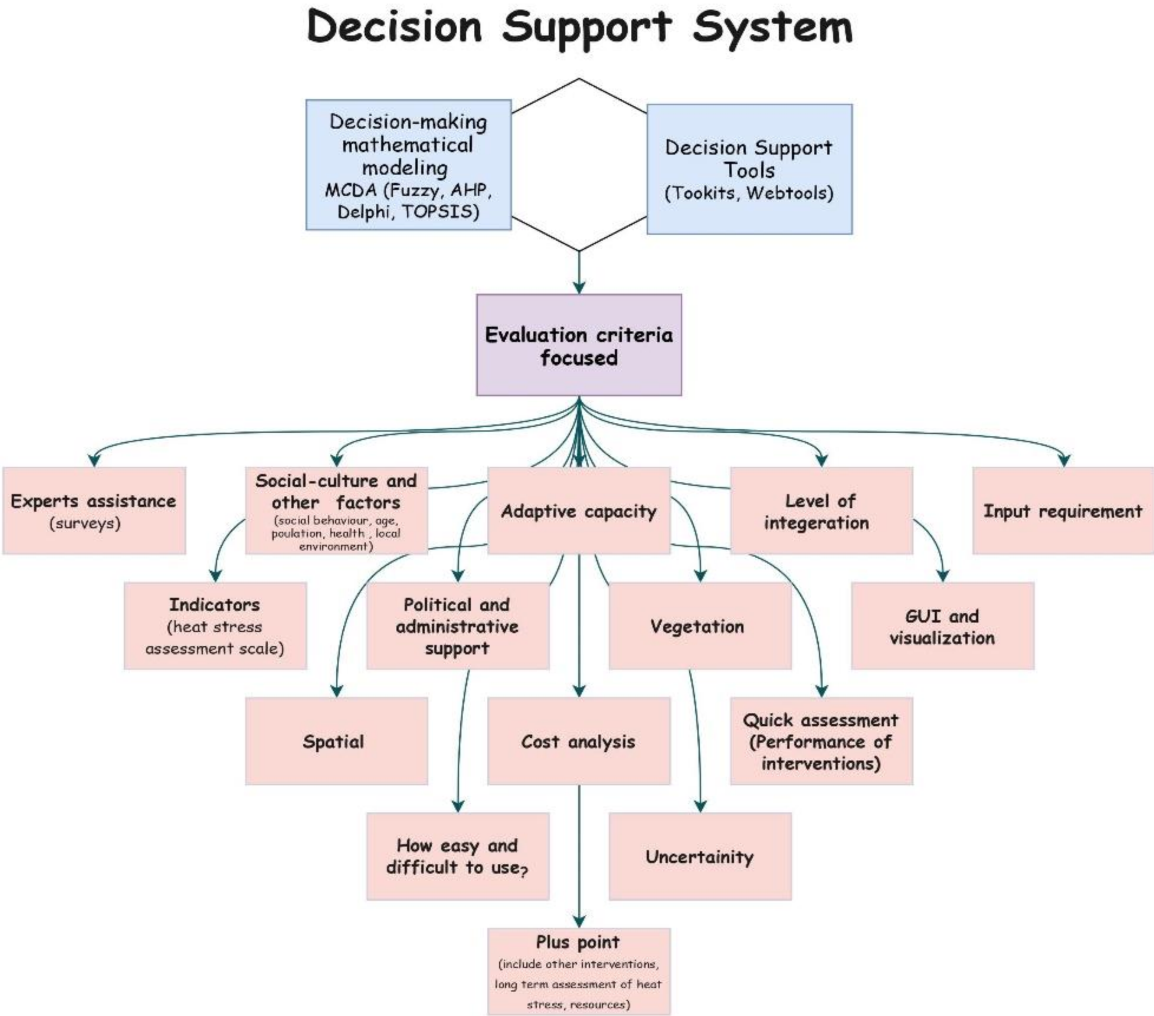

Figure 1. Methodology of the review paper.

3. Multi-Criteria Decision Analysis

Decision-making tools are valuable in tackling issues with numerous actors, criteria and objectives. Generally, MCDA is based on five components, which are: goals, decision-makers' preferences, alternatives, criteria and results, respectively. In light of many alternatives, differences can be catered between Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM), but both offer comparative characteristics. MODM is reasonable for the assessment of consistent options when there is a need to predefine constraints in the form of choice vectors. A set of target functions is optimized considering the limitations while decreasing the performance of at least one goal. In MADM, inherent characteristics are covered by prompting the thought of fewer options, and evaluation becomes difficult as prioritizing turns out to be more difficult. The result is obtained by comparing different alternatives concerning each criterion [10–12]. Different multi-criteria techniques are applied in the field of UHI mitigation, thermal comfort improvement, and the selection of the heat stress index. MCDA models are developed according to the researcher's point of view concerning demand and goal. It can be a direct or indirect methodology. In a direct approach, the task of priorities or weights is performed as a result of contributions from a questionnaire. In an indirect approach, all the potential criteria are separated into components and assigned weights as per past comparable issues, and the judgment of decision-makers is based on experience. MCDA is consistently complex because of the involvement of stakeholders and factors which are technical, institutional, legislative, social and financial. The overall strategy of the MCDA technique is presented in Figure 2. A survey has been conducted on the use of different MCDA techniques for UHI and UHS mitigation.

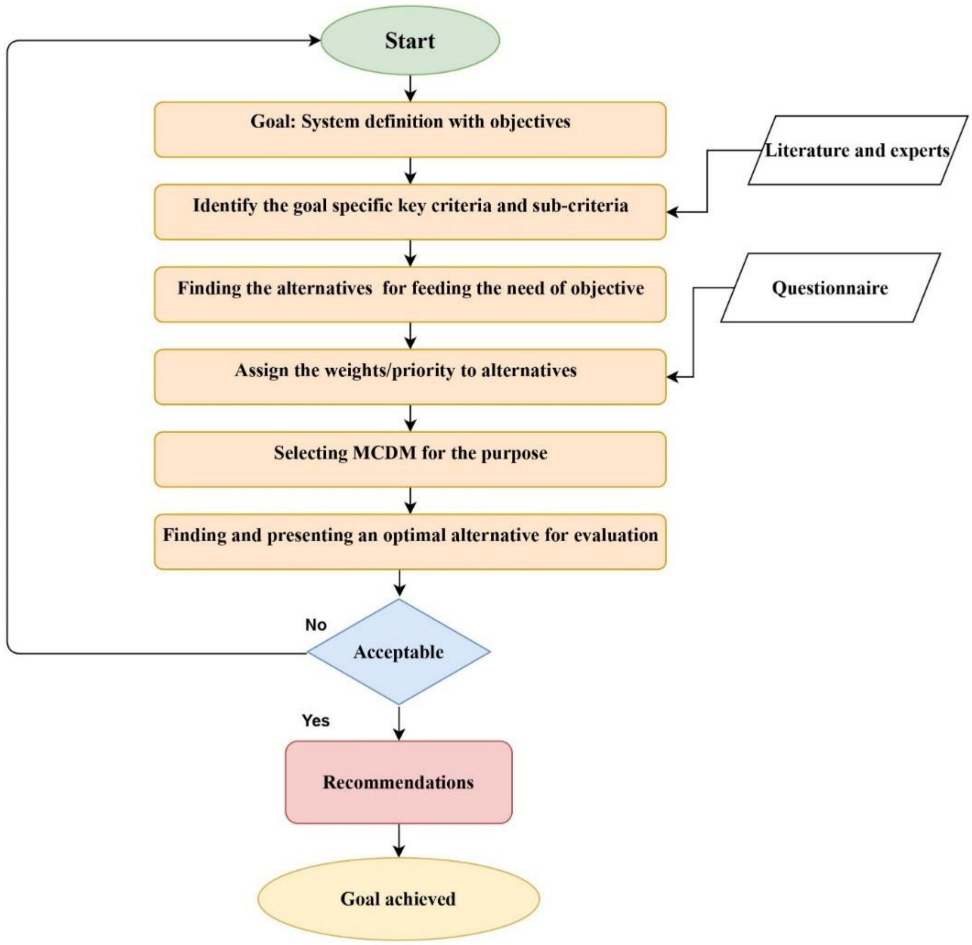

Figure 2. A general procedure of multi-criteria decision methods.

The following methods were applied for UHS [3,13–20] and are briefly discussed with their limitations in Table 1.

- Analytical Hierarchy Process (SWOT);
- Multi-criteria outranking approach (MCDA and IBVA);
- Enhanced Fuzzy Delphi Method (EFDM);
- Fuzzy decision-making trial and evaluation laboratory (FDEMATEL);
- Multi-criteria method by linear regression;
- The technique for order of preference by similarity to ideal solution (TOPSIS);
- Spatial Multi-Criteria Evaluation (SMCE);
- Fuzzy Analytic Hierarchy Process;
- Fuzzy TOPSIS.

Table 1. Review of academic research on multi-criteria DST approaches for urban heat mitigation.

Aim of the Study	Method	Step	Limitation	Reference
Green roof adaptation in Thailand to mitigate UHI. The relevant factors were identified in qualitative content analysis, structured alongside two dimensions (internal/external and positive/negative factors), and quantitatively assessed.	Analytical hierarchy process based on expert judgments, strength, weakness, opportunities, threats (SWOT) analysis.	1. Identification of initial factors (literature), investigation of contextual factors (semi-structured experts' interviews). 2. Strength, weakness, opportunities, threats analysis (7 internal and 7 external factors). 3. Analytical hierarchy process (AHP), experts' (academics, architects, landscape planners, and others) judgments and formulation of strategies.	A limited number of factors considered and lengthy pairwise comparisons.	Tachaya Sangkakool [13]
Assess the heat stress relative vulnerability of 15 local government areas in metropolitan Sydney.	Multi-criteria outranking approach (build analogy between multi-criteria decision analysis and indicator-based vulnerability assessment (IBVA)). Electric III ranking process.	Stage 1: Concordance and discordance matrices. $c_i(a,b) = \begin{cases} 0 \text{ if } I_{ib} - I_{ia} \geq p_i \\ \frac{p_i-(I_{ib}-I_{ia})}{p_i-q_i} \text{ if } q_i < I_{ib} - I_{ia} < p_i \\ 1 \text{ if } I_{ib} - I_{ia} \leq q_i \end{cases}$ Stage 2: Outranking matrix. $C(a,b) = \frac{1}{\sum_{m}^{i=1} w_i} \sum_{i=1}^{m} w_i c_i(a,b)$ $S(a,b) = \begin{cases} c(a,b) \text{ if } d_i(a,b) \leq c(a,b) \forall i = 1, m \\ c(a,b) \prod_{i \in I_v(a,b)} \frac{[1-d_i(a,b)]}{[1-c(a,b)]} \text{ otherwise} \\ \text{where } I_v(a,b) \text{ is the set of indicators for which } d_i(a,b) > c(a,b) \end{cases}$ Stage 3: Distillation and ranking procedures. $T(a,b) = \begin{cases} 1 & \text{if } S(a,b) \geq \lambda - g(\lambda) \\ 0 & \text{otherwise} \end{cases}$ $Q(a) = \sum_{k=1}^{m} T(a,k) - \sum_{k=1}^{m} T(k,a)$	Nonlinearities might not be incorporated in the outranking aggregation process.	Abbas El-Zein [14]

Table 1. *Cont.*

Aim of the Study	Method	Step	Limitation	Reference
Investigate the inner-dependencies between the benefits, opportunities, cost, risks for proper adoption of green roof installation.	The enhanced fuzzy Delphi method (EFDM) and fuzzy decision-making trial and evaluation laboratory (FDEMATEL) approaches.	Step 1: Select the panel of experts. Step 2: Design and distribute the questionnaire. Membership function is: $\mu_{\widetilde{A}}(x) = \begin{cases} (x-l)/(m-l) & ,l \leq x \leq m \\ (u-x)/(u-m) & ,m \leq x \leq u \\ 0 & ,\text{ otherwise} \end{cases}$ Step 3: Develop initial direct relation fuzzy matrix. $\widetilde{A}^{(s)} = \begin{bmatrix} 0 & \widetilde{a}_{12}^{(s)} & \cdots & \widetilde{a}_{1n}^{(s)} \\ \widetilde{a}_{21}^{(s)} & 0 & \cdots & \widetilde{a}_{2n}^{(s)} \\ \vdots & \vdots & \vdots & \vdots \\ \widetilde{a}_{n1}^{(s)} & \widetilde{a}_{n2}^{(s)} & \cdots & 0 \end{bmatrix} s = 1, 2, \ldots m$ Step 4: Normalize the initial direct relation fuzzy matrix. $\widetilde{\mathrm{E}}^{(s)} = \begin{bmatrix} \widetilde{\mathrm{e}}_{11}^{(s)} & \widetilde{\mathrm{e}}_{12}^{(s)} & \cdots & \widetilde{\mathrm{e}}_{1n}^{(s)} \\ \widetilde{\mathrm{e}}_{21}^{(s)} & \widetilde{\mathrm{e}}_{22}^{(s)} & \cdots & \widetilde{\mathrm{e}}_{2n}^{(s)} \\ \vdots & \vdots & \vdots & \vdots \\ \widetilde{\mathrm{e}}_{n1}^{(s)} & \widetilde{\mathrm{e}}_{n1}^{(s)} & \cdots & \widetilde{\mathrm{e}}_{nn}^{(s)} \end{bmatrix} s = 1, 2, \ldots m$ Step 5: Develop the total direct and indirect relation fuzzy matrix. $\widetilde{\mathrm{O}} = \widetilde{\mathrm{E}} \times (I - \widetilde{\mathrm{E}})^{-1}$ Step 6: Defuzzify the entries in the fuzzy total relation matrix. $o_{ij} = \left(l_{ij} + 4m_{ij} + u_{ij}\right)/6$ Step 7: Produce causal diagrams, values for D + R and D − R were calculated by the following equations: $O = \left(o_{ij}\right)_{n \times n}, i, j = 1, 2, \ldots, n$ $D = \left(\sum_{j=1}^{n} o_{ij}\right)_{n \times 1} = (t_i)_{n \times 1}$ $R = \left(\sum_{j=1}^{n} o_{ij}\right)_{1 \times n} = \left(t_j\right)_{1 \times n}$	Absence of significant relationships among environmental and economic opportunities.	Sanaz Tabatabaee [15]

Table 1. *Cont.*

Aim of the Study	Method	Step	Limitation	Reference
Identifying and assessing the critical criteria affecting decision-making for green roof type selection in Kuala Lumpur	An enhanced fuzzy Delphi method (EFDM) was developed for criteria identification. EFDM consists of two rounds: firstly, knowledge acquisition through a semi-structured interview, and secondly, criteria prioritization using a Likert scale questionnaire.	• First round: discuss the potential of criteria; • Second round; 1. Design the questionnaire and send it to the experts, 2. Organize experts' opinions collected from the questionnaire into an estimate, and create the Triangular Fuzzy Numbers (TFNs), 3. Select the criteria affecting decision making. **Fuzzy Delphi Method:** 1. Sets of pairwise comparisons according to the direction of influence of the relationship between the criteria/sub-criteria were generated. The comparison scale for pairwise comparison is 0, 1, 2, 3, and 4, which denote no influence, low influence, medium influence, and high influence, respectively. 2. The direct-relation matrix was generated, which is the average of pairwise comparison matrixes that have been generated in step 1 by 28 experts. An $n \times n$ matrix A, in which Aij is the degree to which criterion i affects criterion j.	If the expert decides to change an answer or decides to add any new information, the first round should be repeated, and the process will be time-consuming.	Amir Mahdiyar [16]
The study aims to map the UHI of a mid-size city (Rennes, France) and define the relevant land-use factors. The UHI was measured by 22 weather stations in different contexts: urban, suburban, and peri-urban.	Multi-criteria linear regression method used to build a model of the UHI.	1. The first step of the process was to build a regression model by selecting explanatory variables; 2. The second step of the process was to execute the selected regression during the first step; 3. The regression coefficients were applied to the associated raster.	Limited variables considered, do not provide reasoning and spatial method.	X. Foissard [17]

Table 1. *Cont.*

Aim of the Study	Method	Step	Limitation	Reference
Examines major local climate zones (LCZs), with greater coverage area, in the city of Nagpur, India by selecting critical LCZ and mitigation strategies such as greening, cool roof, and cool pavement using ENVI met tool. The study is conducted in three phases. The first stage deals with air temperature and UHI investigation. The second stage covers the issue of identifying criticality using multi-criteria decision making (MCDM) technique. The third stage examines the selection of mitigation strategies, simulation environment, and mitigation priorities.	The technique for order of preference by similarity to the ideal solution (TOPSIS).	1. Construct decision matrix (X) and assign weightage to the criteria. $X = \left(x_{ij}\right)$ $w = [w_1, w_2, \ldots, w_n]$ Considering $\sum_{j=1}^{n} wj = 1$ 2. Calculate normalized decision matrix N. $N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$ for $i = 1, \ldots, m; j = 1, \ldots, n$ 3. Calculate weighted normalized decision matrix v. $v_{ij} = w_j N_{ij}$ for $i = 1, \ldots, \mathrm{m}; \mathrm{j} = 1, \ldots, \mathrm{n}$ 4. Determine the positive ideal (A^+) and negative ideal (A^-) solutions. $A^+ = (v_1^+, v_2^+, \ldots, v_n^+) = \left(\left(max v_{ij} \mid j \in I\right), \left(min v_{ij} \mid j \in J\right)\right)$ $A^- = (v_1^-, v_2^-, \ldots, v_n^-) = \left(\left(min v_{ij} \mid j \in I\right), \left(max v_{ij} \mid j \in J\right)\right)$ 5. Calculate the separation measures from the positive ideal solution (di^+) and the negative ideal solution (di^-) $d_i^+ = \left(\sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^p},\right)^{1/p} \quad i = 1, 2, \ldots, m$ $d_i^- = \left(\sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^p},\right)^{1/p} \quad i = 1, 2, \ldots, m$ 6. Calculate the relative closeness to the positive ideal solution (Performance Score) and rank the preference order or select the alternative closest to 1. $R_i = \frac{d^-}{d_i^- + d_i^+}$ where $0 \leq R_i \leq 1, i = 1, 2, \ldots, m$	Quantitative analysis of urban geometric factors, street orientation, and thermal comfort and socio-economic condition assessments remain a limitation in this study.	Rajashree Kotharkar [18]
Spatial Multi-Criteria Analysis for Urban Sustainable Built-Up Area Based on UHI in Serang City.	Spatial Multi-Criteria Evaluation (SMCE) (utilizes software ILWIS (Integrated Land and Water Information System) 3.3 developed by ITC Netherlands).	UHI distribution, geometric correction, data processing, then simulations on SMCE model.	Does not consider the environmental factors (detailed challenges of UHI).	Putra Muhamad Iqbal Januadi [19]

Table 1. *Cont.*

Aim of the Study	Method	Step	Limitation	Reference
An exhaustive study proposing a new index aimed at quantifying the hazard of the absolute maximum UHI intensity in urban districts during the summer season by taking all the parameters influencing the phenomenon into account. In addition, for the first time, the influence of each parameter has been quantified.	Results are achieved by exploiting three synergistically related techniques: analytic hierarchy processes to analyze the parameters involved in the UHI phenomenon; a state-of-the-art technique to acquire a large set of data; and an optimization procedure involving a Jackknife resampling approach to calibrate the index by exploiting the effective UHI intensity measured in a total of 41 urban districts and 35 European cities.	1. The AHP step 1 consists of the Structure of the Problem to determine an index useful to quantify potential UHII in the urban district. 2. The AHP step 2 is used to individually analyze each aspect of the defined UHII problem in order to weigh the parameters involved. 3. The summary of priority is obtained by multiplying each criteria weight by the intensity range weight and adding the results.	Based on literature quantitative analysis.	Sangiorgio [3]
Weighting Criteria and Prioritizing of Heat Stress Indices in Surface Mining.	The viewpoints of occupational health experts and the qualitative Delphi methods were used to extract the most important criteria. Then, the weights of 11 selected criteria were determined by the Fuzzy Analytic Hierarchy Process. Finally, the fuzzy TOPSIS technique was applied for choosing the most suitable heat stress index.	1. The formation of implementing team and monitoring the Delphi process; 2. Selecting the experts and participants; 3. Adjusting the questionnaire for the first round; 4. Editing the questionnaire grammatically (deductive and removing ambiguities); 5. Sending the questionnaire to experts; 6. Analyzing the obtained responses in the first round; 7. Preparing the second-round questionnaire considering the required revisions; 8. Sending the second questionnaire to the same experts; 9. Analyzing the results of the second questionnaire; 10. Determining the relative weights of each criterion using the fuzzy AHP; 11. Choosing a heat stress index among the existing ones in the study using the fuzzy TOPSIS method.	WBGT overestimates the heat stress.	Asghari [20]

4. Decision Support Tools

From an environmental perspective, decision-making involves multiple complex steps for various stakeholders with different objectives and priorities. Most concerned people tend to attempt heuristic or intuitive approaches in order to simplify the problem to make it manageable. By following this approach, stakeholders lose important information and may discard the contradictory facts and factors of uncertainty and risks. In other words, it is not suitable for making thoughtful choices that can focus on all the important points of the process [21]. Therefore, a proper strategic decision-making tool is helpful to assess the decision-makers to bring about the process strategically and manage the multitude of ideas properly [22,23]. Additionally, during the process of decision-making, practitioners are supposed to take the elements of biodiversity, social innovation, governance, and urban management into consideration within a socio-ecological framework [24,25].

These tools are defined as an approach involving any techniques, models, frameworks (one project's framework can be seen in Figure 3), or methodologies that strategically manage and support the decision-making [26]. Moreover, decision-making tools help to evaluate and monitor the co-benefits systematically [27] and processes for connecting, reflecting and investigating, exploring, and modeling while suggesting proper solutions [28].

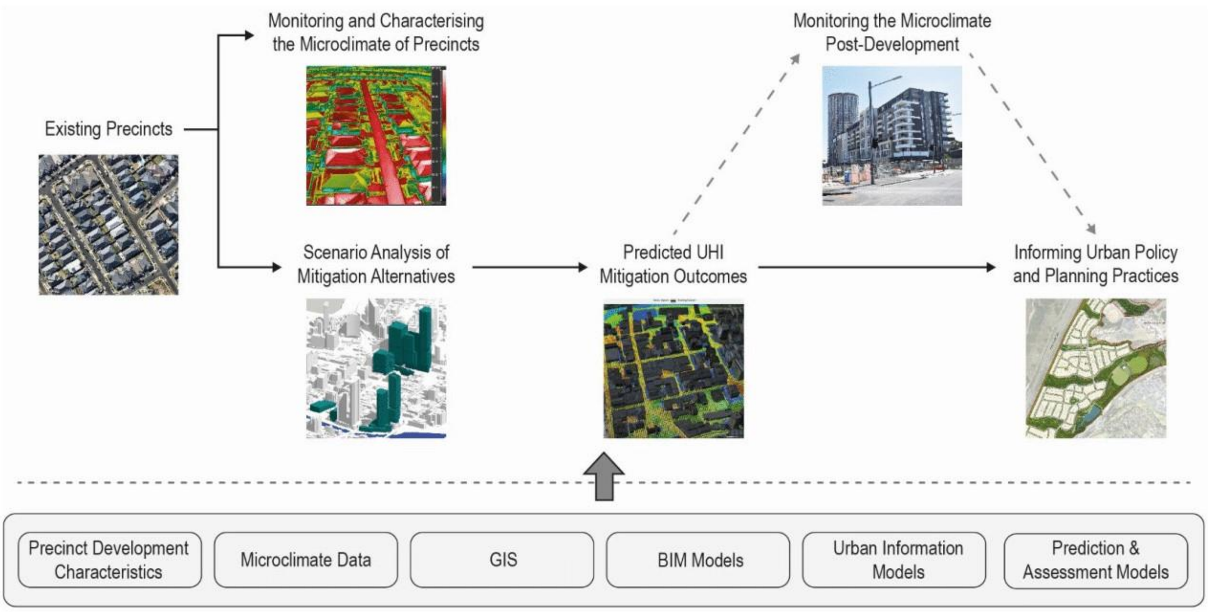

Figure 3. Framework of RP2023; Microclimate and Urban Heat Island Mitigation Decision-Support Tool [29].

One such example of these tools is the Adaptation Planning Support Tool (APST), which is specifically designed to focus on the impacts due to climate change. This toolbox has been proven to be useful for policy-makers and has been applied practically in many cities [30].

The Mitigation Impact Screening Tool (MIST) is another decision software-based tool developed by the US Environmental Protection Agency (EPA) for an assessment of the impacts of UHI mitigation strategies' (mainly albedo and vegetation) increase on the reduction in urban air temperatures, ozone, and energy consumption for over 200 US cities [31]. The tool is currently unavailable as it was disabled by the EPA due to the update of the methodology and data inputs. Nevertheless, some authors have analyzed how it functioned, as it attempted to provide a practical and customized assessment for UHI reduction.

Furthermore, there are various nature-based solutions and their implementation can offer multiple benefits, for example, Stadtklimalotse, Wiki, REGKLAM, SUPER (Sustainable Urban Planning for Ecosystem Services and Resilience), and many more [32,33].

Table 2 represents the review of tools designed for policy-makers and urban planners to use during the process of decision-making for urban heat, climate change, heat vulnerability, health heat events, etc.

Table 2. Review of DSTs.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
Stadtklimalotse (Urban climate pilot)	Developed for urban planners and policymakers from small and medium-sized towns and cities who need quick and easy access to information.	Energy, health, tourism, water, infrastructure, transportation, green spaces, air quality, agriculture, forestry, heat stress.	Practice guides of 78 adaptation measures are available for resisting heat events, and among all only 3 are about green spaces in open public and private spaces, 330 links to legislative texts, and 61 examples for planning and implementation of heat stress measures.	German	Online toolkit. • Search ability of the entire database with a simple search mask. • Does not attempt to make direct recommendations for action. Developed and published in 2013.	-	Green spaces	Bundesinstituts für Bau-, Stadt- und Raumforschung (BBSR)—under different projects. (Germany)	[34]
WBGT decision support tool	High school athletes adjust practice schedules based on heat threat through the week	Heat stress	• Input data WBGT are temperature, dew point temperature, wind speed, relative humidity, pressure. • Forecasting data from National Digital Forecast Database (NDFD). • Past 24 h: Real-Time Meso-scale Analysis (RTMA). • WBGT estimations are compared to measurements taken from Kestrels at 2 sites and an ExtechHT30 at 1 site.	English	Online tool • Publicly accessible tool assesses hourly WBGT which helps to avoid heat stress exposure by making informed decisions about when to schedule outdoor activities. • Provides guidelines for actions to take for WBGT risk categories. • Spatial coverage is for North Carolina.	WBGT	-	Collaboration between the State Climate Office of North Carolina, the SE Regional Climate Center, and the Carolinas Integrated Sciences and Assessments	[35]

Table 2. *Cont.*

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
California Heat Assessment Tool (CHAT)	Target practitioners group includes local government such as urban planners, policy makers, public health associations and agencies.	Long-term public health impacts of extreme heat.	Meteorological dataset (minimum temperature (Tmin), maximum temperature (Tmax), minimum vapor pressure deficit (vpdmin), and maximum vapor pressure deficit (vpdmax)) for the years 1984–2013 were obtained from the PRISM Climate Group, and data were extracted at a daily time-step and at a resolution of 4 km. Analyzed historical medical and meteorological data and set a threshold for prediction mapping of heat health events (HHEs). Heat vulnerability data, solutions, publications are available.	English	Decision support user-friendly web tool. • Generates projected heat health event maps changing between 2011 and 2099. Helps to identify existing areas of need over 63 unique, health-informed heat thresholds tailored to California's diverse tapestry of climates and demographics. • Spatial coverage limited to California.	Projected heat events, heat vulnerability, social vulnerability (% of outdoor workers, poverty, no health safety diploma, no vehicle access), health events (rate of asthma and cardiovascular diseases) environment ($PM_{2.5}$ concentration, ozone exceedance, UHI delta, % of tree canopy).	-	Four twenty-seven conducted UNA (California heat tool project)	[36,37]
Right place—right tree	For city officials as well as residents who are interested in expanding or maintaining Boston's urban forest.	Informs decision-making for planting new trees for UHI mitigation.	• Provides full fact sheets that indicate the tree's potential for heat reduction. • Provides resources that can be consulted for maintenance of selected tree, includes links for contacting Boston's tree maintenance teams, up-to-date information about pests, and tips for maintenance from the government website.	English	Decision-making online tool for Boston only. • Highlights priority regions for canopy expansion indicating Boston-specific Heat Vulnerability Index (HVI), and summer daytime land surface temperature. • Provides information in census tract, city, state, and federal owned properties, Boston housing and redevelopment authorities, and public land which may influence decision making.	Summer morning land surface temperature, and heat vulnerability index.	Trees (33 species)	Supported by the BU URBAN Program, funded by a National Science Foundation Research Traineeship (NRT) grant to Boston University (DGE 1735087).	[38,39]

Table 2. *Cont.*

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
Nature-based solution selection tool	Urban planners, municipalities	Challenges city is facing:Heat waves, biodiversity, flooding, public health and wellbeing, water quality, urban renewal, air quality and green space provision.	• Provides challenges and nature-based solutions catalog and gives recommendations for solutions of challenges with respect to users' input. • Priority factors are evaluated through multiple criteria decision-making methods.	English	• Decision support Excel toolkit. • Provides decision interventions considering political and executive support, suitable internal regulation policy, staff time and motivation, advanced community management skills, alignment of internal departments and disciplines, culture of innovation and risk tolerance.	-	18 green interventions and cool pavements	A toolkit developed under the project of URBAN Green Up funded by the European Union's Horizon 2020 program. Eight cities were involved in this project, including 3 European cities: Valladolid (Spain), Liverpool (UK), and Izmir (Turkey).	[40]
Adapting to the urban heat	Local government	Urban heat mitigation	Potential energy savings maps and thermal images of locations with and without interventions are presented to indicate benefits.	English	DST in a detailed document. • Explains how and when local government can adopt each method considering several criteria, including effectiveness at reducing heat, improving public health, saving money, and providing environmental co-benefits, and governance criteria including administrative and legal considerations.	Benefits and co-benefits analysis.	Cool roofs, green roofs, cool pavements, and urban forestry.	Published by Georgetown climate center—A leading resource for state and federal policy (America).	[41]

Table 2. *Cont.*

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
Urban adaptation support tool	Decision-makers, urban practitioners and municipalities	Climate change; heat waves, flooding, water scarcity, ice and snow, drought.	Step by step provides: links of Climate-ADAPT case studies of concrete examples from multiple European cities, guidance and tools relevant to local adaptation action, publications, reports and other Climate-ADAPT database resources, relevant EU-funded projects, Covenant of Mayors for Climate and Energy resources.	English	This tool is based on the adaptation policy cycle, assists cities with making climate strategy and offers valuable support in detailed guidelines and database through adaptation plans	-	Green spaces	Published and updated under European project	[42]
Microclimate and Urban Heat Island Mitigation Decision-Support Tool	Government municipalities, urban planners, and urban policymakers	Thermal comfort and vulnerability, UHI due to climate change	Fact sheets and publications and case studies are available.	English	• This spatial web tool for Sydney aims to integrate scientific models, performs and assesses evidence-based UHI mitigation strategies.	UTCI	Vegetation, shading, water bodies, building coatings	Tool developed under the project named RP2023 was carried out by UNSW Sydney and Swinburne University in collaboration with government and industry partners.	[43]
Climate Resilient city toolbox	Urban planners, landscape architects	Heat stress, pluvial water safety, pluvial floods, and drought.	• Handbook for adaptation measures, description of adaptation key performance indicators, water balance model, and multi-criteria score tables of the selection tool in terms of suitability are available.	Dutch	• Spatial web tool offers 18 adaptation measures for reducing heat stress and estimating the intervention's cost. • Various plan alternatives (scenarios) can be quickly drawn up, compared with each other, and with previously set adaptation goals by this tool.	PET °C	10 green and 7 blue interventions in different ways and 1 albedo.	The tool is developed by the cooperation of the following Dutch (Netherlands) partners: Deltares enabling delta life, Wageningen University and Research, Atelier Groen Blauw, TNO, Bosch Slabbers, Tauw and Hogeschool van Amsterdam.	[44,45]

Table 2. *Cont.*

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
Extreme Heat Map tool	Urban planners, local government, community	Climate vulnerability assessment	Tool based on: • Land Surface Temperature layer is derived from data from Landsat 8 Thermal Infrared Sensor (TIRS) imagery taken during a heatwave in July of 2016. • Other data include the 2016 Generalized Land Use and the 2015 Twin Cities Metropolitan Area 1m Urban Tree Canopy Classification.	English	• Spatial web tool for Minneapolis indicates land surface temperature on GIS map, assesses the effectiveness of tree shades. • Allows users to determine what land cover classes may contribute to mitigate the extreme heat.	Land surface temperature.	Tree shades (Coniferous and Deciduous tree canopy and shrub wetlands).	Developed under Metropolitan Council local planning assistance (Minneapolis)	[46]
Groen Tool	City planners, planters, builders, designers, analysts, maintainers, etc.	Heat stress, air quality, water management, biodiversity, sound, CO_2 absorption, and recreation and proximity.	• Policy documents, practice booklet, literature and case studies, and plans are available on the website.	Dutch	• Spatial Web tool for Antwerp. • Calculate the adaptation measures' impact for the selected area. • Effectiveness maps of green adaptive measures for all themes, i.e., heat stress, air quality, etc., with sub themes (e.g., air quality (PM_{10} $PM_{2.5}$, NO_2 and elemental carbon)) and indicates the high, medium and low risk areas.	UH impact °C, average radiation temperature °C	Different green measures and their combinations.	The city commissioned VITO and Ghent University to develop this tool. (Belgium)	[47]

Table 2. *Cont.*

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
Decision Support System (DSS)	Urban planners, decision-makers and users who are interested in mitigating urban heat.	UHI mitigation	• Pilot (Bologna/Modena, Venice/Padua, Wien, Stuttgart, Lodz/Warsaw, Ljubljana, Budapest and Prague) simulations based on the data collected within the UHI project. • Provides user-defined report in an Html page which comprises three primary components: a climate change assessment of the selected area, a set of normative data applicable to the selected area and skills, a bunch of potential mitigation strategies.	English	• A free and user-friendly spatial database management tool but not open-source. • Allows users to choose mitigation actions at building and urban scale and analyze the feasibility of the selected measures on an interactive map of central Europe. • Provides economic assessment of chosen measures through online calculator. • A set of maps shows change in the average annual mean temperature in every decade, changes in annual near-surface temperature during 2021–2050 and 2071–2100 and heat wave frequency during 1961–1990 and 2071–2100.	Change in annual mean temperature and surface temperature, heatwave frequency.	• Cool roofs, green roofs, green facades, cool pavements, planting trees within the urban canyon and parks.	Tool developed by UHI. The project was implemented through the Central Europe Programme co-financed by the European Regional Development Fund.	[48,49]

5. Results and Discussion

Multi-criteria mathematical models [3,12–19] are a valuable, theoretical, qualitative, and quantitative way of decision making and also a first step towards developing a DST. These models are supported by expert assistance which considers the socio-cultural factors and local environment. They cover the criteria which can be assessed statistically, e.g., cost analysis and political and administrative support.

The AHP is a qualitative approach and depends on the judgments of the people who are involved in the task, but lengthy pairwise comparisons might lead to inconsistency. Multi-criteria outranking is also controversial, and questions were raised about outranking procedures, nonlinearities' incorporation, and aggregation processes. Similarly, in FDEMATEL, no significant relationships could be found for some criteria. Another issue is that the questionnaire can have a low response rate, be time demanding, and have a low probability of filtering out specific opinions.

Most of the time, this is a trial and error process.

Decision-making for urban heat mitigation involves multiple and complex steps that vary on different stakeholders with various adaptation measures and needs. Plus, during the process of decision-making, practitioners should take into consideration the criteria of biodiversity, social innovation, governance, and metropolitan management within a socio-ecological framework.

Some North American, European and Australian DSTs are critically analyzed concerning all the criteria which were considered in this review paper. The results are summarized and classified in Table 3. For future development, recommendations of approaches learnt from the surveyed tools are highlighted by a color-coding scale shown in Table 4.

The DSS [49] was developed in the framework of the European project "Development and application of mitigation and adaptation strategies for counteracting the global phenomenon UHI". This tool is user-friendly and covers many aspects which are needed to support urban planners.

It is known that every testing (pilot) site is different depending on several factors such as climate, population, group of persons, building infrastructure, availability of existing interventions and number of heat events. The development of a DST depends on the scale of the project. Objectives and limited spatial coverage are always a drawback because all decision results are based on different pilot sites' data and tools are based on those characteristics.

Table 3. DSTs with respect to each criterion.

Evaluation Criteria/ Tools	Stadtklimalotse [34]	WBGT Decision Support Tool [35]	CHAT [37]	Right Place—Right Tree [38]	NBS Selection Tool [40]	Adapting to the Urban Heat [41]	Urban Adaptation Support Tool [42]	Microclimate and Urban Heat Island Mitigation Decision-Support Tool [43]	Climate Resilient City Toolbox [44]	Extreme Heat Map Tool [46]	Groen Tool [47]	Decision Support System (DSS) [49]
Expert assistance	+	+	+	+	+	+	+	+	+	−	+	+
Social culture and other factors	−	−	+	+	+	−	−	−	+	−	-	+
Adaptive capacity	−	+	+	+	+	−	−	+	+	−	+	+
Good integration	−	−	+	+	−	−	−	+	+	−	+	+
Input requirements	−	−	−	−	+	−	−	+	+	−	+	+
Political and administrative support	+	+	+	+	+	+	+	−	−	+	+	more or less
Quick assessment of interventions	−	−	−	+	+	−	−	+	+	+	+	+
GUI and visualization	−	+	+	+	−	−	−	+	+	+	+	+
Vegetation	+	−	−	+	+	+	+	+	+	+	+	+
Other interventions	−	−	−	−	+	+	+	+	+	−	−	+
Cost analysis	−	−	−	−	−	−	−	−	+	−	−	+
Spatial	−	+	+	+	−	−	−	+	+	+	+	+
Heat stress indicator	−	+	+	+	−	−	−	+	+	+	+	+
User-friendly	+	+	+	+	+	−	−	+	+	+	+	+
Uncertainty assessment	−	−	+	+	+	−	−	−	+	−	−	+
Recommendation priority												

Table 4. Color code scale.

Color Codes	Explanation
	Covers all criteria (Highly recommendable)
	Covers 14/15 criteria (Highly recommendable)
	Covers 12/15 criteria (Strongly recommendable)
	Covers 11/15 criteria (Strongly recommendable)
	Covers 10/15 criteria (Recommendable)
	Covers 7/15 criteria (Slightly not recommendable)
	Covers 4/15 criteria (Not recommendable)

6. Conclusions

Decision-making is a difficult task that has to go through different phases such as identifying reliable and efficient measures, assessing the challenges to investigate the case studies, and building a systematic framework for decision support. The MCDA approach is a valuable and very important initial step to develop a DST to deal with UHS. Toolkits in the form of handbooks are neither spatial nor interactive. Web-based tools are mostly interactive and can provide an assessment of green, blue and grey interventions on heat impact in real-time and help decision-makers to take actions on the heat vulnerability of the suspected area. In these tools, economic and environmental assessment can be performed quite easily through a graphical interface; however, the results always depend on input data which are often difficult to obtain.

In this review and comparative study, we conclude that despite many existing publications and reported tools, there is still room for improvement, which can be achieved by a holistic approach dealing with subjective and objective aspects of heat stress, combining various inputs from sensors as well as from experts and residents' feedback, and using different techniques such as MCDA, GIS, urban planning and, in the end, artificial intelligence tools to correlate these aspects with each other to develop a reliable DSS for the mitigation of heat stress.

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