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An investigation into minimizing urban heat island (UHI) effects: A UK perspective

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Abstract

Cities are major sources of Green House Gas (GHG) emissions and the effects of mass urbanization upon the environment have now become clear. Great opportunities exist within cities for tackling climate change. Urban Heat Island (UHI) effect is a phenomenon where significant temperature difference between inner micro-climates of a city and their neighboring micro-climates can be perceived. Mitigation of UHI effects can positively contribute to alleviate detriments of climate change. This research project aims to investigate effective and resilient UHI mitigation strategies and to provide guidance for their application in future. A review of literature indicates that UHI is a growing problem in the UK and that mitigation of such effects would enhance sustainable development at urban scale. The lack of guidance for designers and planners looking into mitigating the UHI effect is also identified. Utilizing ENVI-met simulations and through Urban Futures Assessment Method (UFAM), this research identifies and tests resilient and effective UHI mitigation strategies. Results show that building form, orientation and layout are among the most effective UHI mitigation strategies. Trees, shrubs and grass (TSG), and use of high albedo materials (HAM) in external building surfaces are also indicated as effective measures whose success is dependent on building form. All assessed mitigation strategies (TSG, HAM, UIWB) are shown to have a similar level of resilience which could be improved if properly future-proofed against subsequent changes. Accordingly some practical suggestions are provided to help improve the resilience of tested UHI mitigation strategies.

Selection and peer-review under responsibility of KES International

Keywords: Mitigating Strategies; Sustainable Cities; Urban Heat Island Effect; Urban Resilience; Urban Sustainability

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1. Introduction

The demographics of human habitat are changing towards urbanisation. Over 50% of the planet's population currently live in cities [1, 2]. The current release of Green House Gas (GHG) emissions (predominantly from cities) and increasing risks of climate change as a result of human action will decapacitate cities to respond to future generations' needs due to their deteriorating conditions. Therefore ideas about how to effectively combine urbanization and sustainability are of critical and immediate importance [3]. Concurrently the effects of mass urbanisation upon the environment have also become clear with cities contributing to 60% – 85% of the world's energy consumption [3, 4]. This is not only due to the need for heating/cooling the spaces in which we live or the need for hot water but also because the cities are the main centres of fuel intensive industries while also being the social, political and economic centres of the world [2]. Furthermore research has stated that the cities have the ability to effectively respond to issues such as climate change at a local level because the co-benefits of climate change mitigation and adaption are largest in cities [5, 6, 7].

This study aims to investigate strategies for mitigation and reduction of an Urban Heat Island (UHI) – a microclimate effect which indicates significant differences in temperature between urban adjacent areas, or between a city and its suburban areas. UHI is used as a quantitative measure to gauge and promote urban sustainability. To do so, Urban Futures Assessment Method (UFAM) will be employed to assess the resilience of UHI mitigation strategies. Resilience in this paper refers to the extent to which these UHI mitigation strategies will be able to achieve their design purpose and sustain in the face of a changing future. ENVI-met – a prognostic three-dimensional microclimate model, designed to simulate the surface-plant-air interactions in urban environment based on the fundamental laws of fluid dynamics and thermodynamics – will be deployed as tool to simulate UHI effects in the selected case for this study, a planned development in borough of west Kensington in city of London. The research is expected to be used first and foremost as a methodology and subsequently as an exemplar frame of reference for planning and design interventions for architects, urban designers, urban planners and city authorities to help them make more sustainability-aware decisions.

2. Literature review

2.1. Sustainable city

It is within the cities that lay a great opportunity for combating the climate change. Cities have an indisputable role to play in driving to, and securing of a sustainable future for humankind [8, 9, 1, 10, 6, 11]. Described a response to environmental disturbance, how habitats and ecosystems can re-organise spontaneously after a disturbance, or as vulnerability of a system to irreversible change resilience of cities and the need for cities of the future to be resilient has also been identified [12, 13, 14, 1, 15, 16] with today's sustainable strategies requiring the capability to deliver their intended benefits whatever the future may hold [17]. A sustainable city can be defined as a multifaceted complex entity with numerous interconnected networks and cycles [10].

2.2. The urban heat island (UHI) effect

The UHI effect is a phenomenon in which a significant difference in temperature can be observed between a city and its surrounding rural areas, or between different parts of a city [18, 19, 20, 21]. The areas of maximum temperature can be found within the densest part of the urban area [19]. This is commonly illustrated in Fig 1.

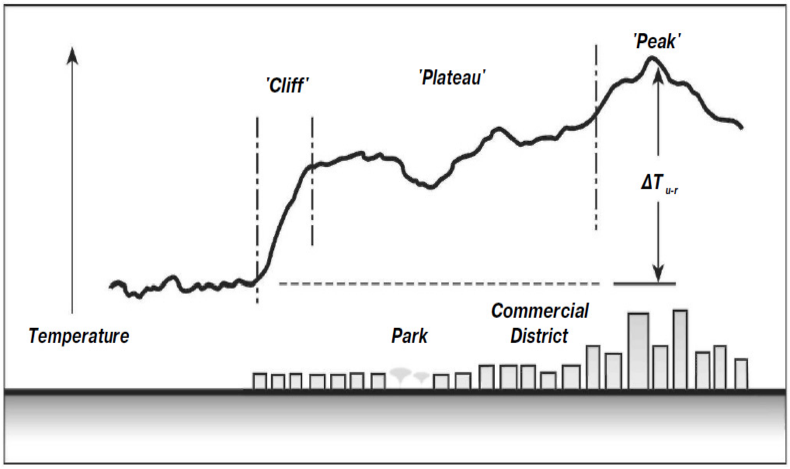

Fig. 1. UHI effects in city and its surrounding areas [19]

2.3. Causes and effects

The intense land coverage that is present within a city and vast amount of densely situated buildings with bulky thermal mass and heat retaining properties [20, 22], anthropogenic heat emissions, pollution and energy consumption within a city [4, 23], presence of urban street canyons resulting in lower rates of long-wave radiation loss during the night [23, 24], lack of green areas and presence of materials with reduced permeability [18, 24], presence of low-albedo materials in buildings [23], and reduced speed of wind caused by design and layout of the built environment [25] are known to be the most momentous causes of UHI.

Effects of UHI can be classified under two major categories: on people and on microclimates. However, the two are not mutually exclusive. The deterioration of physical well-being of a city's population [26, 27, 28], thermoregulatory system damage induced by heat stress in the form of heat syncope, cardiovascular stress, thermal exhaustion, heat stroke and cardiorespiratory diseases [27, 28, 29] are the ones with adversarial effects on inhabitants of a city which incur some secondary effects on microclimate by trying to improve the work/live/use conditions within individual buildings. On the other hand the microclimates of cities are affected as a result of increased air temperature within a city compared to rural areas [13, 19, 30], by formation of ground level ozone [27], alteration of local climates i.e. wind patterns, humidity changes, storms, floods, and change in local ecosystems [31, 32, 33] and lastly exacerbation of global warming by increased energy consumption for air-conditioning and increased heat emissions released into the local environment [22, 28, 34], each of which bears a secondary and in most cases a resonating drift on other effects involving the city's inhabitants.

2.4. Assessment Methodologies and Mitigation Strategies

Major assessment methods such as Building Research Establishment Environmental Assessment Methodology (BREEAM), Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and Building Environmental Assessment Method (BEAM) include criteria for mitigation of UHI effects. The largest number of UHI parameters is included in CASBEE, spreading across its three toolkits: CASBEE for Urban Development, CASBEE for Home (Detached House), CASBEE for New Construction. While BEAM does not cover UHI mitigation as extensively as CASBEE does, the criteria which it represents for UHI mitigation are very similar to CASBEE. Mitigation measures for UHI are not covered in LEED to the same extents as CASBEE but where they are, similarities to CASBEE and BEAM are evident. As a result, a general consensus in assessment parameters across all the methods can be summarised as: ventilation or passage of air, shading of buildings, presence of green areas or roofs, use of water and, external use of high albedo materials on buildings' surfaces. Taking a slightly different approach the Building Research Establishment (BRE) introduces BREEAM Communities which has assessment criteria to improve the urban microclimates. Although those criteria are not directly labelled as UHI mitigation measures, they can be associated with UHI effects since they aim to improve the health and well-being by offering the benefits of mitigation of UHI effects. These are capable of informing and, in the most optimistic scenarios, influencing the UHI mitigation strategies indirectly.

The inclusion of water retentive or porous materials in the design of the built environment, for example green roofs or porous paving has been pointed out in some previous research [13, 35, 36]. High albedo materials in building design [23, 29, 37], green spaces at city scale such as parks and open fields [13, 27, 29, 36], shading of urban areas by trees or man-made structures [37, 38, 39], presence of urban water bodies such as rivers and lakes within a city [27, 28, 29, 40], and harnessing natural wind [24, 29, 41] are other measures or strategies to mitigate UHI effects. Additional research has credited all types of vegetation as having a number of benefits for urban micro-climate such as, but not limited to mitigation of the UHI [19].

2.5. Implications for this research

Therefore, mitigation strategies which have been selected for evaluation within this research project are as follows:

- Vegetation in the form of trees, shrubs and grass (TSG).
- Presence of water in form of urban inland water bodies - excluding rivers and waterways (UIWB).
- Use of materials with high albedo rating (HAM).

Further to what was found in the literature in support of the selected strategies, there are also empirical reasons for this selection. Firstly they are among the most commonly design solutions used by urban planners, architects and landscape architects. Secondly they are favoured by the general public. And finally they seem to be the most affordable strategies not only at design stage but at implementation, operation and maintenance stages which make them appear on top of priority list of actions for local authorities.

3. Research methodology

Initially a critical literature review was carried out to investigate the concept of UHI where it was identified as a major contributor to the sustainability agenda at urban scale. The existing literature was also utilised to investigate causes, effects and mitigation strategies. Furthermore, current efforts made by sustainable assessment methods to mitigate UHI across the globe were also reviewed, compared and analysed. Subsequently three UHI mitigation strategies were selected for further assessment. A combination of qualitative and quantitative methods was selected as this would yield uniform basis throughout the intended outcomes while providing multiple avenues of discussion. The first assessment methodology selected was the Urban Futures Assessment Method (UFAM) which assesses the resilience of the selected mitigation strategies. The UFAM is a 5-stage assessment methodology (Fig 2) which assesses the ability of today's sustainable strategies to deliver their intended benefits in the future. The success of a sustainable strategy is dependent on its level of performance in four possible future scenarios set for the year 2050. At the next stage a selected sampling method was adopted to find appropriate participants for interviews to further investigate the UFAM

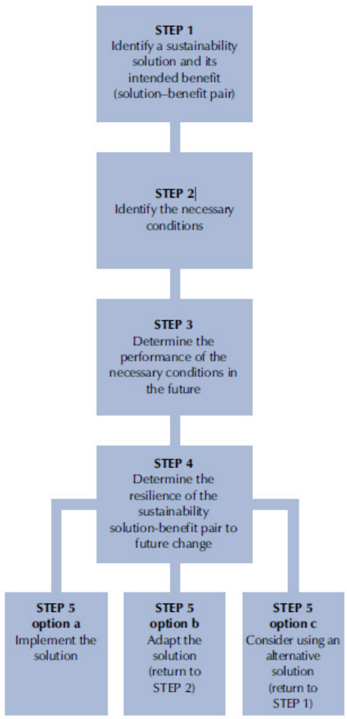

Fig.2. UF Step Process [17]

from an expert's point of view. The interviewees consist of the Urban Futures team, urban designers/planners who work in London and project team for Earl's Court and West Kensington Opportunity Area developments where Seagrave site, the witness test case for the selection of suitable methodologies, was located. The initial list included 50 recipients, which was narrowed down, in two different stages using purposeful sampling techniques, to 7 in order to have representation from all the expert groups included yet to avoid excessive data. Part of the proposed guidelines will be based upon numerical data demonstrating the efficacy of each UHI mitigation strategy. The efficacy of each UHI mitigation strategy will be determined based upon simulations conducted by ENVI-met simulation software. Results from UFAM and ENVI-met assessment were then used to provide guidelines for urban planners aiming at mitigation of UHI effects. This has been achieved through triangulation of outcomes interpreted and drawn-out of the literature review, interviews and the simulations. Furthermore, ideas which developed in post data analysis stages were also used to inform conclusions.

4. Study results

Vegetation was awarded a resilience rating out of 6.25 out of 10 and is therefore a reasonable choice when aiming for resilient UHI mitigation strategy. This local context also directly influenced the parameters inputted into ENVI-met software prior to simulation. The types of TSG inputted into the ENVI-met simulations had to align with that present in the surrounding area to the Seagrave car park and this significantly increased usefulness of outcomes. These included trees of 5-10m in height with dense crowns and dense hedges with a maximum height of 1.5m to abide by local police guidelines to maintain lines of sight. ENVI-met simulation results showed that TSG is the most effective mitigation strategy from those assessed (Fig 3). Presence of water scored a resilience rating of 6.67 out of 10. Therefore the local council/developers should also make this a priority for resilience to increase. With regard to ENVI-met simulations UIWB maintains a similar atmospheric temperature to the benchmark data (Fig 3).

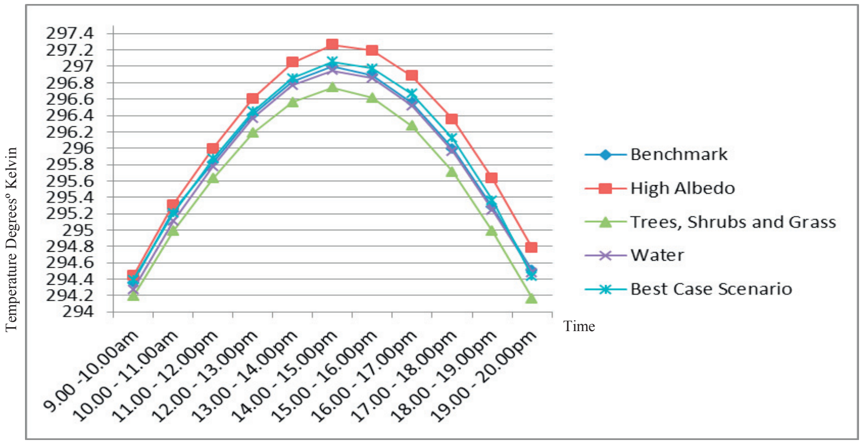

Fig.3. Comparison of three UHI mitigation strategies with the benchmark and the best case scenario

Use of HAM was heavily prescribed as an effective UHI mitigation strategy however the results show that it maintains considerably higher temperatures over all other simulations (Fig 4). Within these simulations only the buildings have a high albedo rating, therefore additional heat will have been reflected onto concrete pavement between buildings which would have caused an increase in temperature. As shown in Fig 4 in the two lower white circles, one area's (left circle) temperature is between 296.91º K (23.76º C) and 297.48º K (24.33º C) and the other area's (right circle) temperature is between 297.63º K (24.48º C) and above 297.91º K (24.76º C) which is within the highest temperature bracket. The urban canyon in each area has similar dimensions. The difference in temperature combined with similar dimensions of the urban canyon suggests that if HAM are combined with the stated urban canyon dimensions and are located away from the most southerly face of the site then micro-climate temperatures will be much lower. The highest temperatures across all simulations are those present in the top right region of the simulation. The layout of the buildings in this area reduces the amount of wind movement around the buildings' contour lines (Fig 4) and further increases the temperature. Additional results from ENVI-met simulations are related to distribution of surface temperatures across the site. The hottest surface areas of the site are in the areas of asphalt (tarmac) surfaces and these temperatures rise above 315.32º K (42.17º C), the hottest temperatures found anywhere on the site. This suggests that if road materials/colours are changed, they can help reduce the UHI effect.

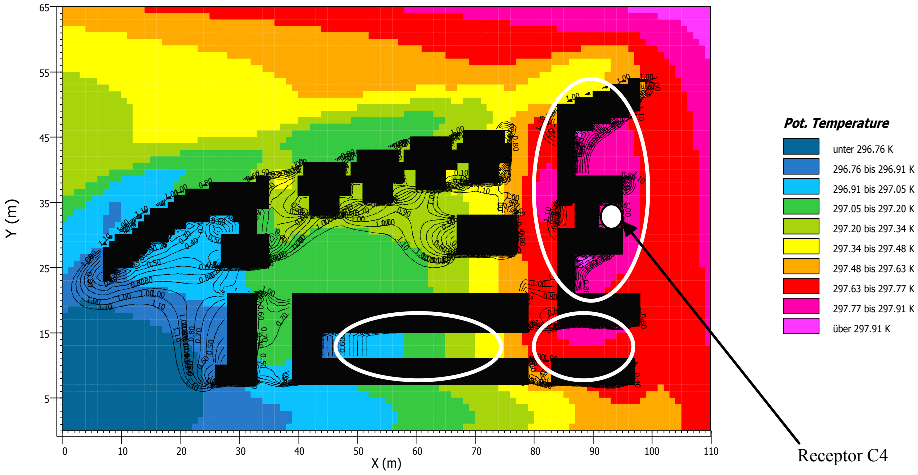

Fig.4. Average heat distribution across Seagrave site – HAM

5. Discussion of findings

5.1. Vegetation – Trees, Shrubs and Grass

The key issue preventing vegetation from gaining a higher rating is its vulnerability to removal as a result of land use change and issues related to maintenance. Therefore the local council and developers should make this a priority if resilience is to be increased. Significantly the UFAM method identified the local context within this area of London as very strong. Such that it overrides planning policy and that the local council is unwilling to construct anything which does not align with it. Therefore in terms of sustainable development the local context can have both a positive and negative effect. This outcome aligns with and further proves previous research stating that vegetation is effective for mitigating the UHI effect [19]. Research also indicates that parks and green spaces help to mitigate the heat island effect and reduce energy consumption for cooling buildings in the summer, while also maintaining changes of temperature induced by building materials [42]. Therefore there are multiple benefits related to inclusion of TSG within a development and is therefore highly recommended as an UHI mitigation strategy.

5.2. Presence of Urban Inland Bodies of Water (excluding waterways and rivers)

The key issue preventing water from gaining a higher resilience rating is also its vulnerability to removal as a result of land use change and issues related to maintenance. The results suggest that presence of water does not mitigate the UHI which contradicts with a wealth of literature suggesting otherwise [27, 28, 29, 40]. Although one major reason for such discrepancy can be the difference between the climate conditions of the cases studied in the literature and the selected case for this study, it is still a valid argument that ENVI-met's capability to effectively measure cooling effect of UIWB has been brought into disrepute with further testing required to quantify cooling effects of water within the Seagrave development.

5.3. High Albedo Materials

One potential reason for ineffectiveness of HAM compared with what was found in literature can be the site layout which may allow for multiple reflections of light and heat throughout urban canyons which is further amplified by the presence of HAM. These facts suggest that the use of HAM materials in a development can have both positive and negative effects on the microclimate between buildings and that the other factors need to be addressed for HAM to be an effective UHI mitigation strategy. Furthermore the results show that the position and layout of the buildings are an important factor to consider when aiming at mitigating the UHI effect and that for HAM to be effective, the site layout, the building form and layout must be designed accordingly. Additional research has stated that retro-reflective materials can be used to reflect solar radiation away from the urban canyons if both urban paving and the building envelope have a high albedo rating [43].

5.4. Further discussion

If the layout of buildings had been designed such as to harness natural wind patterns [24, 29, 41] this would have resulted in reduced temperatures. Furthermore it has been stated that wind velocity has a significant impact upon cooling and ventilation effects within a city [44]. Therefore an improved building layout determines how successful HAM is as a UHI mitigation strategy while also providing the opportunity to harness natural wind patterns which can further reduce UHI effect. Moreover it has also been stated that urban grids and structures have a significant impact upon thermal behaviour of built up areas [45]. It has been stated that the distribution of buildings and urban structures within a city affect the formation and intensity of UHI since this distribution determines the absorption of solar radiation and the formation of air flows and that optimisation of urban design/planning in relation to energy consumption of buildings allows savings of up to 30% [42].

Furthermore, overheating issues related to tarmac surfaces can be further exasperated if the buildings adjacent to them have a high albedo rating and therefore there is a potential increase of sunlight being reflected onto the road, as is the case for the HAM simulation for this research project. This implies that, as previously stated, the building form must be designed properly for HAM to be an effective UHI mitigation strategy. Therefore the replacement of tarmac with a material which does not retain heat would reduce the UHI effect in an area [46]. One such example is brickwork found in Lyric Square in the Hammersmith and Fulham region. The light coloured stones have a higher albedo rating than the black tarmac surface. As identified by UFAM, the local context and influence of the area is very strong and although the brickwork does not align with that of local roads, Lyric Square is still in the same borough of London. Therefore it is envisaged that this type of brick may be a suitable replacement for tarmac in an attempt to reduce UHI effect. However it is important to note that Lyric Square is used as a market square and is not a residential area. This reduces the chance of it being accepted within the local context. Therefore the local context can indirectly affect the temperature within the microclimates and how effective UHI mitigation strategies within that area can be. This indicates that a change in local context can indirectly be a UHI mitigation strategy but this can only occur once a change in the mindset of the local residents has happened. Additionally for sustainable solutions to be implemented, such as those assessed in this research project, legislations are essential. A political party is only ever in such a position to pass legislation of this type once it has been voted into office and if local governments' legislations do not align with views of the people then they will not be voted into power. This can create a self-contradictory dilemma and suggests that change needs to take place best in a bottom up approach; a change in mindset and views of people which will then enable political party to be voted in who will implement sustainable solutions by introducing the corresponding legislations. An additional benefit of implementation of brickwork of the type presently in Lyric Square is that it would create the impression of a pedestrianized area. The benefits of pedestrianized areas include increased perception of safety due to reduced speed limits for cars; this would have an especially positive impact upon families living in the Seagrave development with children. Another would be that all people in the development would be more likely to spend time outside and interact with each other with this positively affecting the social aspect of sustainability [19].

6. Conclusion

A methodology to test the resilience of the most commonly used UHI mitigation strategies in city of London, UK, was presented with assistance of simulation results using a prognostic three-dimensional microclimate model simulation online application. It was shown how this can be applied, how the results can be presented and compared to the benchmark studies found through the literature review of this study. This methodology along with the interpretation of results and detailed discussion of findings can be used by different design professionals and local authorities to make the best decisions in choosing UHI mitigating strategies and practically help them maximise the effectiveness of the chosen strategies. It is imperative that proper measures are taken to contextualise and calibrate simulation parameters, the context specifics as well as the results, findings and discussions of this study within any new setting – both macro-climate, micro-climate and building spatial layout – to ensure that the most reliable simulation results are achieved in order to be able to make the most informed decisions about the courses of action and to suggest the most effective interventions.

The building form, layout and design has become a recurring topic within this paper; first with regard to varying temperatures of seemingly similar spots in the site, secondly as a result of effects caused by the use of HAM on building envelopes, thirdly the HAM effects multiplied by the surface solar radiance effects, and surface temperature of open spaces (mostly hard surfaces), and finally during the new post best case scenario simulation. This combination of factors and the fact that success of other strategies is heavily dependent upon the building form and layout suggests that the latter two are very important and effective factors and perhaps the most significant UHI mitigation strategies of all. This indicates that other strategies' success pivots on appropriateness and effectiveness of the chosen form and designed layout. This fact aligns with and further proves that the most effective means to provide mitigation of the UHI is through the buildings themselves. This denotes that if the UHI mitigation strategies are to be most successful, the provision of them should start early on when a new project is at conception stages. This will help, with assistance of simulation and analysis of UHI effects proposed within this study, to select the most sustainability-aware building form and site layout so that not only the two, themselves, contribute to mitigation of UHI effects but they also help the others succeed and achieve the best possible results. Suffice to say that, in an urban setting, any isolated UHI effects mitigation study of layout and massing within a specific site will be most likely prone to fail if the microclimate effects of immediate site topographies – both natural topographies, in form of land topography, greenery, water bodies, etc. and manmade topographies, including buildings, infrastructures, etc. – are underestimated or ignored.

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