Toward a Decision Support System for Mitigating Urban Heat: Optimizing Economic and Environmental Goals in Urban Planning

Masterarbeit

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1 Introduction

1.1 Motivation

In December 2019, worldwide news is filled with reports from Australia. For weeks devastating bush fires have been destroying the country, and summer has just begun. On December 17, 2019, Australia set a national record for the average temperature of 40.9 °C (ntv (2019)). The impact of increasing global warming is exacerbated by urban heat islands (UHI). With the continuous rise of large cities, urban planners and politicians are increasingly concerned with the phenomenon of the UHI effect, which can be defined as urban areas, which, according to Gunawardena et al. (2017) and Li et al. (2019), experience significantly higher temperatures than the surrounding rural areas. Following the NASA (2008), land temperatures in densely built-up urban centers can be up to 10 °C higher than those of the surrounding forest landscapes.
While megacities with more than 10 million inhabitants are expected to double in population over the next ten years based on Desouza (2014), cities will typically have limited budgets and resources following Barham und Daim (2018). This development puts pressure on urban planners and policymakers to make cities more sustainable and liveable while meeting budget and time constraints.
However, as Ho et al. (2016) states, the UHI effect is strongest in densely built-up areas. Since both population density and the density of building development are particularly high in densely populated and built-up areas, these characteristics prove to be important indicators for the occurrence of the UHI effect.
Figure 1 summarizes, on the one hand, that urban populations will continue to increase (a) and, on the other hand, that the UHI effect is highest in urban centers and lowest in rural areas (b).

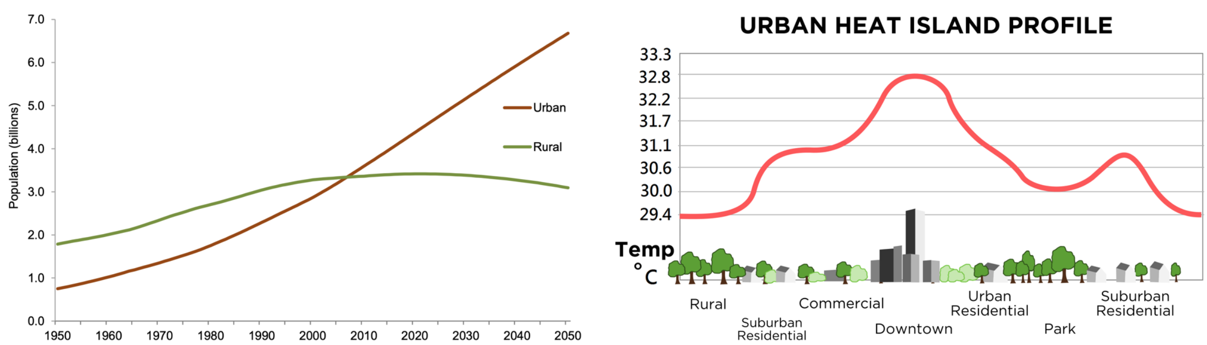

Figure 1 **(a)** Urban and rural populations of the world, 1950-2050 (Nations (2019)) and **(b)** Urban Heat Island Profile by Pariona (2019)

Due to the critical significance of buildings for the emergence of the UHI effect, this thesis focuses on built-up surfaces as the primary influencing factor. According to AECOM (2012), an increase in UHI intensity has negative consequences regarding the health of the inhabitants, their productivity, transport operation and infrastructure, energy demand as well as vegetation with trees and plants. As the latest news from Australia shows, temperature heating is becoming increasingly problematic and dangerous for cities, regions and countries. Countermeasures have to be established as soon as possible in order to mitigate the temperature rise, especially within big cities where most of the people live and where the temperature rise is most pronounced. Therefore, it is essential to consider the UHI effect in urban planning to reduce energy demand, heat-related illness, respiratory problems and death (Caldwell, 2017).

1.2 Objective

This section deals with the motivation regarding the UHI problem and describes how this thesis aims to contribute to the reduction of UHI intensity in urban planning. In order to identify a research gap within the UHI literature, a structured literature review was conducted. A variety of tools were identified within the literature that can perform microclimatic simulations of the UHI effect. However, no tool has been identified that links the economic interests of urban planning with the ecological effects of planning decisions. This thesis aims to develop a new type of tool in the form of a decision support system (DSS), which optimizes an area for the urban planner target group regarding an optimal balance between economic and ecological factors.

Thus, the DSS mainly contains an optimization model which assigns a selection of building and vegetation options to the corresponding location. A morphological analysis is carried out for the development of the tool in order to identify primary influencing factors from the literature and subsequently integrate them into the model.

Also, the relationship between the two objectives in terms of economic aspects, on the one hand, and ecological interventions, on the other hand, will be considered within the framework of a sensitivity analysis. The tool is intended to provide the first concept of a solution that will help urban planners to make optimal decisions with limited budgets and resources when designing and optimizing urban districts.

The optimization model is developed in two different variants since the following course of the thesis shows that the optimal balance is a trade-off relationship, as the economic interests can only be maximized by accepting a maximum UHI effect. Accordingly, the first model variant will contain a maximization of the revenue while maintaining a maximum limit for the UHI intensity. Revenue can be defined as the amount in monetary units that city planners receive in cooperation with the policymakers when selling land

to investors who invest in buildings in the respective areas afterward.
The second model variant is designed to minimize the UHI effect while maintaining a minimum revenue limit. As mentioned in the course of this thesis, both model variants are relevant for optimization due to different individual interests of the decision-makers. The user should be able to choose between both model variants within the framework of a holistic DSS, which consists of input, the model and a visualization of the results as well as a corresponding user interface. The research question of this thesis based on the objectives is formulated as follows:

How can urban planners maximize revenue while limiting urban heat island intensity?

This defined research question is frequently referred to in this thesis and provides a form of guideline. At the end of this thesis, the research question will be revisited, and an answer to it will be given as a result.

1.3 Structure

The structure of this thesis is based on a design science-oriented research methodology (DSRM) by Peffers et al. (2007). Following this structure, each chapter can be assigned to a specific stage. Each chapter begins with a classification of the contents and characteristics of the respective phase following the design science-oriented research. A classification of the structure is shown in Figure 2.

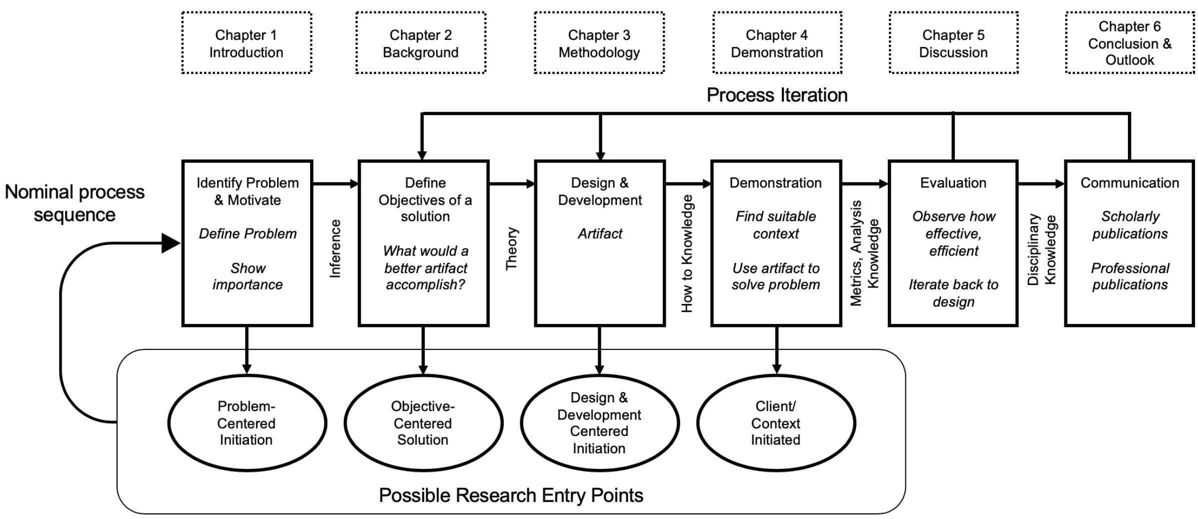

Figure 2 Classification of the structure into the design science-oriented methodology by Peffers et al. (2007)

After the explanation of the underlying UHI problem as well as the motivation of the DSS development as a solution approach in Chapter 1, the systematic literature search is presented in Chapter 2. First, the overall concept used for the literature analysis is described and subsequently, the results are presented. Following the identification of the research gap in Chapter 2, Chapter 3 presents the creation of the DSS in the context of the design and development stage. First, the morphological analysis for the identification of primary influencing factors is described followed by the development of the DSS in all its components.

In Chapter 4, the developed DSS is demonstrated in the context of an applicability check for Brisbane (Australia). It becomes apparent that the tool already provides realistic results for the decision support of the city planners in this early version. The results of the demonstration are subsequently evaluated and discussed in Chapter 5. Based on the limitations of the DSS and this thesis in Section 5.3, Chapter 6 provides an outlook for the further research process as well as a conclusion.

6 Conclusions and Outlook

In this section, the collected findings and results of this thesis are summarized once again in a compact form and then linked to an outlook for the implementation of further research projects for the development of the DSS. Furthermore, this section builds on the design science-oriented research process. It includes the communication in the form of the presentation of the tool to the respective target groups as well as possibilities and intended publications of the concept on a scholarly and professional level.

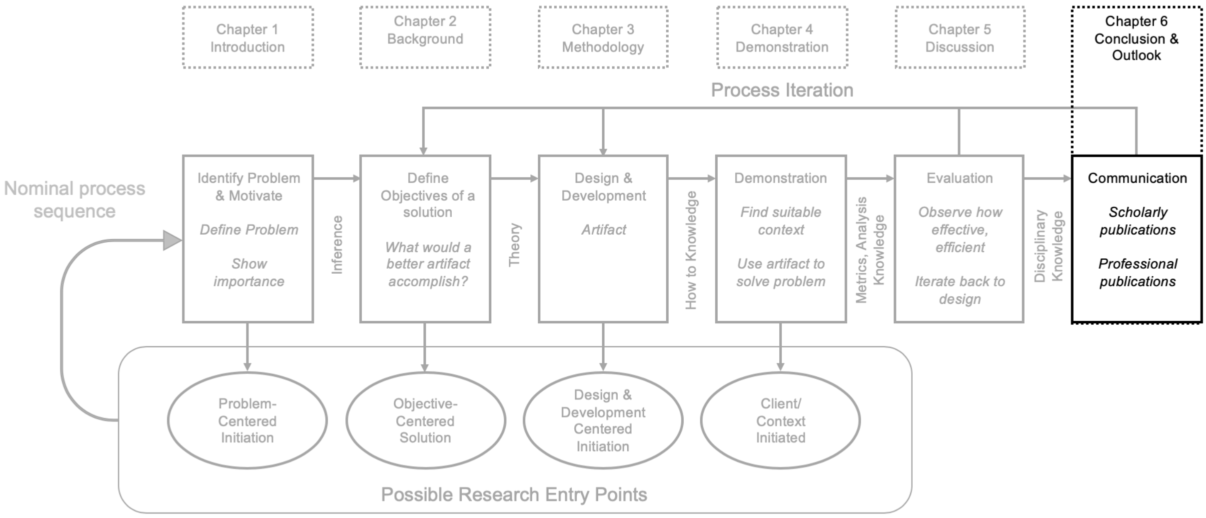

Figure 33 Classification of Chapter 6 into the design science-oriented structure of the DSRM Process model by Peffers et al. (2007)

The thesis deals with the research question of how the urban planner target group can maximize revenue in the future while limiting the UHI intensity. To this end, a structured literature analysis was first conducted to identify a corresponding research gap.
This makes it necessary to link a large number of environmental analyses of the emergence and reduction of the UHI effect with the economic interests of government representatives and urban planners, as they sell the land to investors, who subsequently ensure that the areas are built on accordingly.
The research gap results in the requirement for the development of a holistic DSS with an optimization model at its core, which optimizes the corresponding urban areas with respect to the highest possible revenue while maintaining an optimal building-vegetation balance.
The tool aims to provide appropriate decision support for the planning process before the sale, as existing tools such as ENVI-met can simulate the microclimatic conditions of the environment in detail, but do not link these findings to economic interests. The objective of the tools must, therefore, be to show urban planners, based on quantitative

values, that it is necessary to integrate appropriate countermeasures of the UHI effect, such as the integration of vegetation zones in the relevant districts.
Within the design science-oriented research process, according to which this thesis is structured, an optimization model in two variants was developed, which on the one hand maximizes the revenue while keeping a UHI maximum limit and on the other hand minimizes the UHI intensity while keeping a minimum limit for the revenue. The creation of both variants is due to the fact that the objectives of the city planners can be individually different.
During the demonstration, the developed DSS was subjected to an applicability check for the Brisbane site in Australia. Using realistic input data for the Northshore district, appropriate results could already be achieved in this early model version. Within the implementation, a sensitivity analysis could also be carried out, which again clarified the trade-off relationship between the two different objectives within the optimization and the research question.
Consequently, it is only possible to achieve maximum revenue for the sale of land if a maximum UHI intensity for the respective area is accepted. This is the result of a maximum built-up area for the highest possible revenue in case the whole area is sold to investors for development and the vegetation is completely neglected.
In order to map the financial consequences of an increase in UHI intensity within a discounted cash flow model in the future, further research projects based on this thesis are required. Within the communication of the design science-oriented research process, the concept of the model has already been presented to local government officials in the Brisbane area. The feedback from this presentation proved to be extremely helpful and was taken into account in further iterations of the research process in the design and development of both model variants.
Moreover, the optimization model was successfully submitted to the SIGGreen workshop and presented there in December 2019. The feedback received there was again incorporated into further iterations for the improvement of the optimization model.
A full workshop paper is planned for the near future, which will build on this thesis and the presentation of the SIGGreen workshop in Munich. Furthermore, the corresponding research question with the identified research gap offers sufficient perspectives for the development of an article based on these initial concepts, which can be submitted to the International Conference of Information Systems (ICIS).
Besides, the basic topic and the further development of the concept of this master thesis offers the possibility to continue research in a subsequent Ph.D. program. In this context, a more detailed literature search could be carried out first in order to define the research gap even more precisely. Also, the morphological analysis can be performed

again and to a significantly increased extent in order to provide further factors for a more realistic representation of the UHI effect. It may also be possible in the future to link existing tools such as ENVI-met with the optimization model and thus be able to deliver even more realistic results for the decision support.

An optimization model which offers a comprehensive discounted cash flow calculation in the future, including a variety of economic factors such as site-specific land prices, electricity costs for energy demand and air conditioning, as well as a variety of possible alternatives for building and vegetation types, and which can also perform microclimatic simulations with a level of detail similar to ENVI-met, would probably be the ideal solution for filling the identified research gap and answering the research question posed, which can therefore only be answered partially and with a first concept of the early model versions at the end of this thesis.

This concludes the conclusion of this master's thesis, and it can be stated that there is an extremely high demand for research in the corresponding field with regard to a holistic solution of economic and ecological interests in the overall problem of an increasing UHI intensity to create a cost-benefit analysis of actions which should motivate urban planers to mitigate the UHI effect to create the most possible sustainable cities in future.