Dynamics of Urban Warming: How Human-Environment Interaction Creates Urban Heat Islands?

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Abstract

Through the interaction of human-environment components, cities create a positive temperature difference over their surroundings, and in many cases that difference is growing. Understanding how and why cities create their own warming is of great importance to alleviate the infrastructure management and human-centered sustainability challenges that urban heat islands pose. This paper lays the groundwork for the development of an integrated model/ game to study urban warming as a result of neighborhood-scale and city-wide feedback processes. A two-layer system dynamics model composed of interlinked citywide and neighborhood sub-models is presented that includes the feedback processes among social, economic, and environmental processes that influence urban heat island dynamics, such as land use changes, building material choices, efficiency of cooling systems, or transportation-related heat generation. The model is integrated with a game to explore how neighborhood and city-level decision-making interact with urban warming. The game will be used to inform model development, explore the effects of interventions across time and space, and study decision-making processes under varying circumstances. Experiments with the game, based on the model, will improve the understanding of the role and importance of representing decision-making processes in simulated environments.

Keywords: *urban warming, urban heat islands, land use, gaming, stakeholder engagement*

Introduction

A large number of cities worldwide show a positive temperature difference over their surroundings. For metropolitan areas with populations above one million, this *urban heat island effect* can create a 1 to 3°C increase in annual mean temperatures (Oke 1997). Furthermore, in many cases that difference is increasing. From 1951 to 2000, 39 out of 50 large US metropolitan areas registered a warming trend averaging 0.29°C per decade (Stone 2007). Understanding how and why cities create their own warming is of great importance to ultimately alleviate challenges for infrastructure control and management as well as a wide range of human-centered sustainability issues.

Increased absorption of solar radiation, increased heat storage, heat from anthropogenic sources, decreased evapotranspiration, and reduced heat convection alter the energy balance in urban areas to create a positive temperature anomaly (Oke 1982). With urban warming, important feedback mechanisms unfold over the long term. Regional and national policy and economic drivers shape land use changes down to the neighborhood scale, which in turn impact energy balances in urban areas (Stone and Rodgers 2001, Sung 2013). Land use dynamics affect the urban heat island intensity through changes in surface albedo, surface imperviousness, urban geometry, moisture content, and thermal properties of a city, disrupting the energy balance at the city scale (Giridharan et al. 2004, Zhang et al. 2010, Synnefa et al. 2011, Ng et al. 2012, Shahidan et al. 2012, Perini and Magliocco 2014, Feyisa et al. 2014, Coseo and Larsen 2014). The linkage between land use decisions and urban climate occur at multiple scales. Building regulations affect the indoor and street canyon climate through the choice of building construction materials, arrangement and placement of buildings, parks, and roads. Regional and city planning strategies affect the intensity and spatial extent of urban heat islands through their impacts and size and location of commercial, industrial and recreational areas.

Climate-related variables affect population migration decisions (Cushing 1987). Increased temperatures can make some northern cities more livable, attracting immigration. This pressure would lead to an increase in the size of these cities and/or decrease their urban vegetation to make space for larger populations, both of which contribute to the urban heat island (Baker et al. 2002). Increased population pressure and attractiveness of a city increase anthropogenic heat sources, such as waste heat from automobiles, industries, and air conditioning use (Fan and Sailor 2005, Wen and Lian 2008, Coseo and Larsen 2014). If, at the same time, the city does not (or cannot) invest in public transportation infrastructures, travel-related heat generation increases even more. More intense and more frequent heat waves also strengthen urban heat island intensity (Zhou and Shepherd 2010, Li and Bou-Zeid 2013). Climate change and urban warming can influence each other. Extreme temperatures can cause cities to experience reduced abilities to invest in adaptation, and hence be caught in a downward spiral, for instance, if cities have to invest in other climate adaptation investments such as dams, levees, or electricity and transportation systems, this may prevent cities from investing in urban heat island mitigation options. Also, individual's choices of building materials, and efficiency of appliances, for example, can change, as people adapt to increased temperatures.

In short, the urban heat island phenomenon is the manifestation of complex environmental, economic, and social processes, and there is a growing challenge to understand, model, and ultimately influence through changes in behaviors, investments, and policy decisions. Integration of data from the physical and social sciences is needed alongside new computational and participatory approaches in order to meet growing infrastructure management and human-centered sustainability goals.

As a part of a project that aims to advance the socio-physical simulation of urban warming at the city-scale, accounting for neighborhood-level processes and utilizing a participatory computational approach that allows for the representation of diverse geographic settings and a rich set of potential intervention mechanisms, this paper presents a system dynamics approach for the urban warming problem. As described above, the urban warming problem is driven by the feedback mechanisms that lie in the heart of interconnections between natural, social, and economic systems in the city, which requires a feedback-driven systemic approach. System dynamics has a long tradition of modeling the interactions of socio-economic systems in the urban context. Forrester's Urban Dynamics (1969) was the first model to address the endogenous causes of urban growth and decline. Similar to the Urban Dynamics model, the interactions between housing, businesses and jobs are major drivers in the urban warming through its effect on urban growth and change in land use. However, the effect of urban growth on its overall climate is not recognized in Forrester's model. Indeed, as an example of the open-loop test of independence between system and environment, Forrester states: "weather may affect migration, but migration does not affect weather" (p.8).

One important criticism of Forrester's Urban Dynamics model is its boundary selection (Alfred 1995). Excluding the suburban areas is regarded as a weakness due to the observation that the dynamics of a city is also driven by its interaction with suburbs (Schroeder 1974). The interaction of the city core with its immediate suburbs is critical for our problem. In the short term, the population and business distribution between urban core and suburbs determine travel demand, which is an important factor of urban heat island magnitude via heat generated from vehicles. In the long run, the land use change through urbanization of suburban areas creates further impact on urban warming. Thus, we set a larger boundary to include the suburbs. Another major component of our model is its ability to capture spatial variability. The geographical distribution of different types of houses, businesses by sectors, population by their income level, and the distribution of parks, amenities and other factors which affect desirability have impact on the overall measures. The system dynamics literature on urban problems provides similar spatially-aware examples. Among these, Burdekin (1979) and Sanders & Sanders (2004) are notablefor bringing a spatial dimension into the Urban Dynamics model.

Various other system dynamics models provide insights into the problems that are related to the urban warming problem. Güneralp et al. (2012) present a two-layer model for understanding the dynamics of urbanization. This paper makes use of system dynamics to model region-level factors that interact with a simple logit-choice model that represent urbanization. The two-level representation scheme fits our problem as different mechanisms take place at local and macro levels, both of which are important for understanding the mechanisms creating urban warming. The government sector in the Sustainable City Model of Radzicki & Trees (1995) provides a way to represent how taxes are collected and redistributed. Land Use, Transportation and Air Quality (LUTAQ) Model of Dwyer and Stave (2005) relate two important components, travels and pollution, to land use. Both of these models provide useful structures that we make use of in our model.

The system dynamics model is embedded into a gaming environment to enable the exploration of how decision makers may intervene in the unfolding dynamics, and to provide evidence for the usefulness of including human-in-the-loop system optimization and model development. The game and model development go hand in hand.

Problem Definition

It is well documented that cities are warmer and heat faster than their surrounding rural counterparts (Fig. 1). The warming manifests itself over the course of multiple decades as a result of decreased vegetation cover, thermal, and reflective properties of urban materials, and the waste heat generated by human activities. With further acceleration in global temperatures, cities face amplified, adverse long-term consequences for health, energy demand, and water consumption. With these observations, we identify our time horizon as 50 years. As our focus is on these long-term trends in urban temperatures, we ignore any short-term fluctuations.

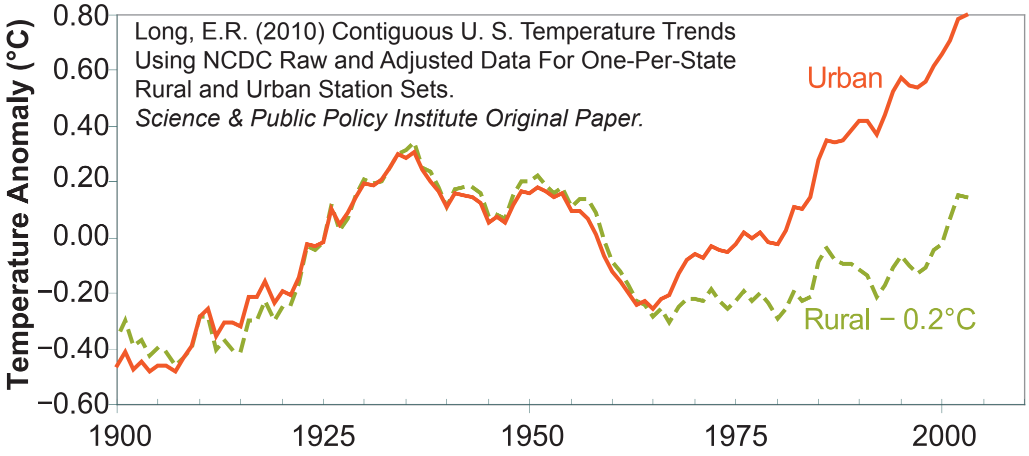


Figure 1. Reference behavior mode for the urban warming problem.

Our model takes the perspective of the state / metropolitan-area planning agency that has the capacity to enforce policies such as tax increases, restrictions on zoning, and investment in different transportation options. The model boundary is chosen to include all relevant mechanisms influencing metropolitan-area warming that connects processes at the macro-scale to neighborhood dynamics. Geographically, the model encompasses a metropolitan-area that might fall under jurisdictions of multiple municipalities.

Since system dynamics models focus on dynamic patterns rather than “events” or points in time, our aim is not to make a numerical point prediction of the urban heat island intensity at a specific year and neighborhood, but to understand the causes of long-term behavior patterns of urban heat islands (i.e., the acceleration of urban temperatures as depicted in Fig. 1), and to reveal intervention mechanisms that will improve this behavioral pattern.

Model Description

The structure of the model is generic in the sense that the same causal links will drive behaviors for different cities and at different times, although the magnitude of the causes and effects may differ. To test and refine our model, we will first parameterize it for the Metropolitan Boston area. The Boston metro area is already experiencing an average urban heat island of 0.7°C (based on daily temperatures from 2004–2013), which increases to 1.8°C for summer nights (Kenward et al. 2014). Over the past ten years (2004–2013), Boston also had 5 more days above 32°C each year than rural areas. Alder et al. (2010) point out that the likelihood of heat waves occurring in Boston with respect to the 1950–75 period more than doubled. However, urban warming has received little attention in Boston, even while preparing the city’s action plan for combating extreme heat conditions.

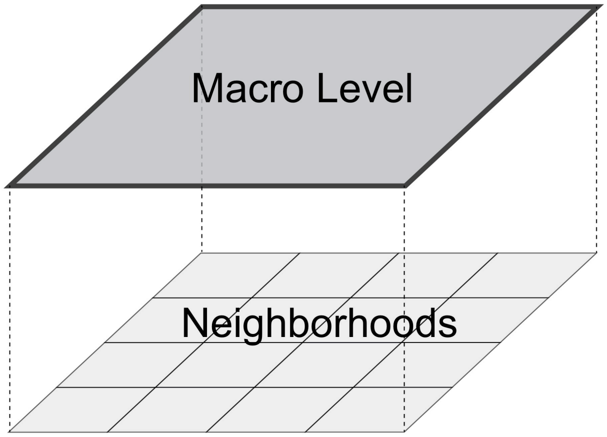


Figure 2. Hierarchical structure of the model.

The model is composed of two interconnected layers: a macro level that focus on metropolitan-area processes such as tax collections, investments and policies, and multiple neighborhoods that model the local processes (Fig. 2). Each neighborhood interacts with the macro level and with each other through providing labor, jobs, or businesses. Fig. 3 presents a simplified causal loop diagram of the model. The diagram is plotted assuming there are only two neighborhoods (A and B). The same connections are scalable to any number of neighborhoods. The variables at the neighborhood level are marked with indices, such as [A]. The diagram only includes variables in the neighborhood A, immediate connections to/from neighborhood B (marked as italic), and macro-level variables (marked as underlined).

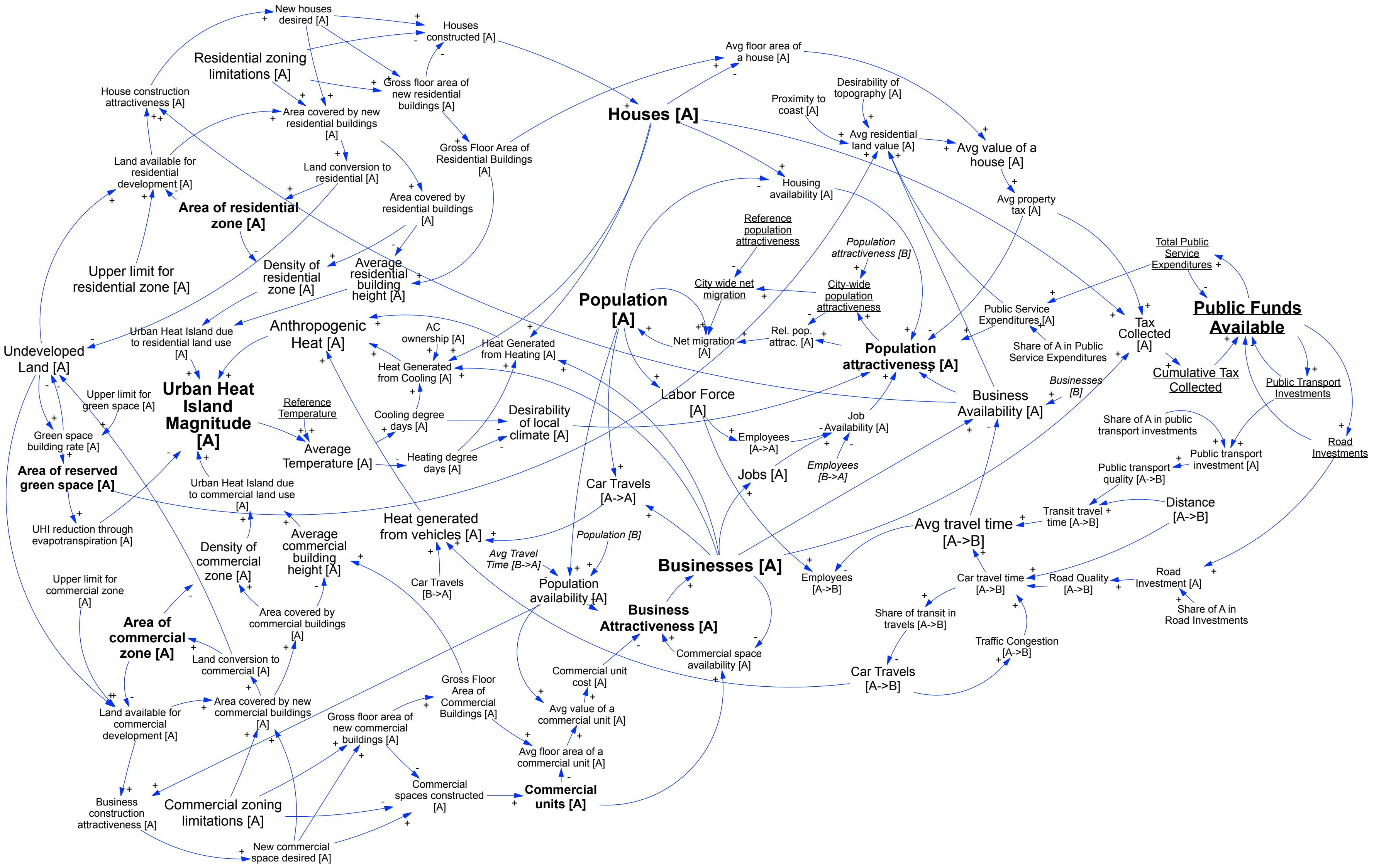


Figure 3. Simplified causal loop diagram of the model.

Neighborhood Level. Neighborhoods are subdivisions of the metropolitan area to reflect spatial variations. Following the classification scheme of Stewart and Oke (2012), we hypothesize that a neighborhood is composed of various local climate zones, such as compact high rise, open low rise, industrial or water, that vary by surface structure and surface cover (Fig. 4). This approach makes it easier to define urban heat island magnitude as a function of these well-defined categories. However, as we do not explicitly model the spatial composition within a neighborhood, using the relationship between properties of local climate zones and their impacts on urban heat island magnitude, we calculate the urban heat island magnitude as a function of surface structure (height and spacing of buildings), surface cover (pervious or impervious) and heat-generating anthropogenic activities (heating/cooling, transportation, and industrial production). Land use is tracked in seven categories; undeveloped, residential, commercial, industrial, roads, green space, and water. For residential, commercial, and industrial categories, we keep track of average height and density of buildings. The development in these categories is triggered by population or business demand, which is catalyzed by the attractiveness of the neighborhood, a measure of desirability calculated separately for different income levels of population and business sectors. Population is divided into three income levels; high, middle, and low. The same division applies to different kinds of jobs and housing units. For businesses, we make a distinction between retail stores, which serve the residents and hence contribute to the desirability of the neighborhood, and offices, which are assumed to only provide jobs.

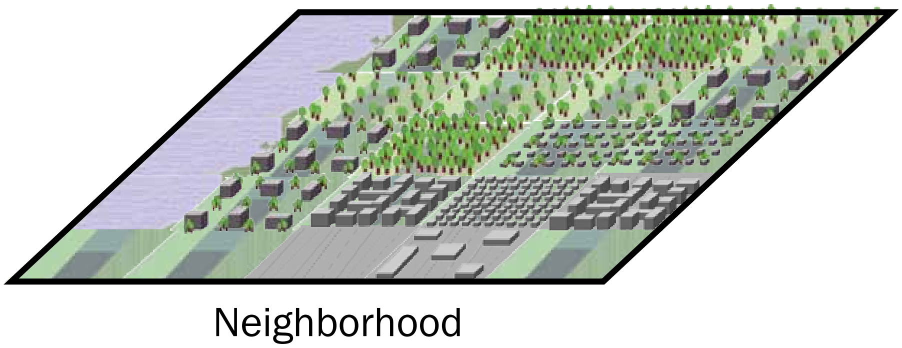


Figure 4. Neighborhood as a collection of local climate zones.

Macro Level. At the macro level, the model includes processes such as tax collection and distribution, transportation investments, calculation of travel durations between neighborhoods, intervention mechanisms such as zoning rules, energy efficiency measures, and tax rates. In this module, we also calculate how new and existing population, businesses and construction companies select neighborhoods to which to locate or in which to invest, depending on the relative attractiveness of each neighborhood. As shown in Fig. 3, the macro level and neighborhoods constantly interact through feedback.

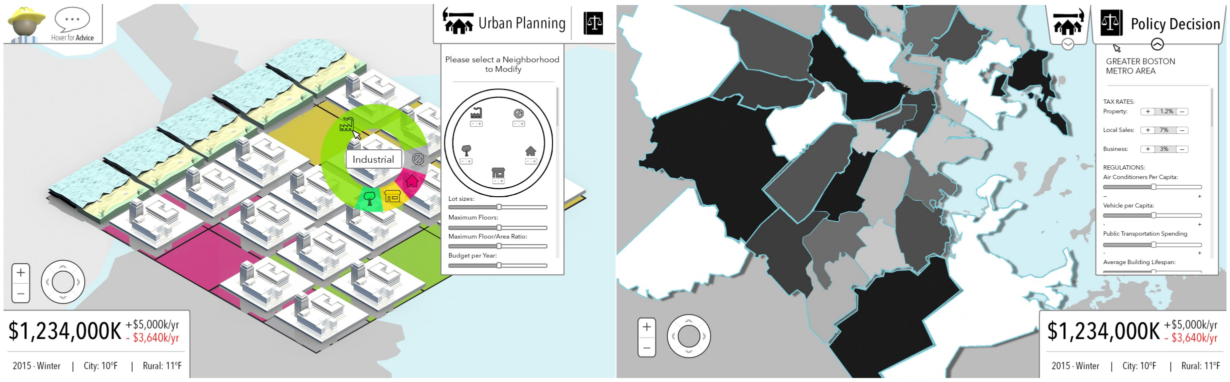
Validation and sensitivity analysis

Due to the behavior-oriented nature of system dynamics models, their validity is evaluated by their structural adequacy and their capability of generating valid patterns over time. There are two main facets of validation of system dynamics models: structure validity and behavior validity (Barlas 1989, Saysel and Barlas 2006). Structure validity is assuring that model structure is in agreement with the relations existing in real life (Qudrat-Ullah and Seong 2010). Behavior validity tests assess if the model and the real system produce similar output behavior patterns. We will improve the structure validity of our model by relying on established relationships set out in the literature, and using experts' opinion. Behavior validation of our model will be performed by comparing model simulation output with monthly urban heat island trends from 2000 to 2014. This also helps us to understand the different spatial and temporal patterns of urban heat islands.

Sensitivity analysis is a crucial step to evaluate the robustness of policies. Particular to model-based decision support tools that involve stakeholders, there are multiple sources of uncertainty (Walker et al. 2003). We will use a three-step sensitivity analysis. First, we will examine the effects of the values of model parameters, functional forms, and critical equations to identify the variables and connections to find out which model outputs are sensitive. Based on this analysis, we will explore the possibility of reducing the uncertainty in model outputs by improving the accuracy of our estimates for sensitive parameters. Next, we will prepare a number of scenarios that reflect uncertainties in variables related to the economy, technology, society, and climate. Finally, we will use these scenarios in gaming sessions to understand how policy actions vary under different scenarios. The following section gives types of policy actions on the neighborhood and macro level that we will analyze using an integrated game that we develop as a front-end to the system dynamics model.

Game Development

Games have the specific affordance to model socio-physical systems (Mayer 2009). They offer an opportunity for "reality checks" by representing physical systems (e.g., infrastructures, environment), while also representing social systems (e.g., stakeholders) to varying degrees through the inclusion of players. Our model is integrated with an interactive simulation game. The purpose of our game is to help us (a) identify missing system elements through player feedback and provide face validation of model outcomes; (b) explore how effects of interventions manifest themselves across space and time; and (c) study how decision makers behave under different circumstances and what rationale they provide. In the game, players take on the role of a policy maker and make decisions on the neighborhood and macro level over a period from the year 2000 to 2050. On the neighborhood level, players can (re)designate areas by manipulating an abstracted representation of a neighborhood (left screenshot in Fig. 5). The model determines to what extent such urban planning decisions are implemented. On the macro level, players can make decisions that affect all neighborhoods such as taxes and regulations and decide on specific interventions such as implementing green roofs, incentivizing albedo change or bringing travel restrictions (right screenshot in Fig. 5).



TAX RATES:
Property: 1.2%
Local Sales: 7%
Business: 3%

Figure 5. Two screenshots of the current urban heat island game. The first screen shot (left) shows the neighborhood level and the second (right) shows the macro level.

The game is developed with the Unity game engine and integrates the system dynamics model with Google Maps (see Fig. 5). This means that any urban area in the world can be visualized through this game. In theory, once a new city is chosen, databases are called to identify the neighborhoods and provide initial values for the various variables. Specific adjustments are made to play the game according to different social system conditions.

Discussion and Future Work

This paper presents an integrated system dynamics model / game approach to address the problem of increasing urban temperatures as a result of human activities in urban areas. The major aim of this study is to understand how and why human-environment interaction in the cities creates urban warming. The model will provide valuable insights towards this objective. Another objective is to discover high-leverage policies that can mitigate the adverse effects of urban warming. We will integrate the game with the model to identify and test these policies. From the onset we keep our vision in mind of a participatory approach and develop the model and game such that they are flexible and modular to allow for community development to happen. In terms of development, we limit ourselves to the creation of modding (modifying the games) tools and explore their uses in local contexts. The tools enable modelers and stakeholders to (1) change values of variables; (2) add or remove variables; (3) modify relationships between variables; (4) pick a city; (5) choose databases for initial parameterization, and (6) select a scenario. We aim to build a platform where a community of users can experience and explore scenarios and build model variations and additions. In this development, we apply the lessons learned from modding communities. A debugging tool will be provided to help users in fixing any errors. Requirements are that non-technical experts should be able to make these modifications, which requires extensive usability testing (Isbister and Shaffer 2008). Easy import and export of data into standard modeling and statistical tools (e.g., STELLA, Powersim, or MATLAB) will be provided to create option for expert users to work in their preferred environments. A discussion and library tool will be integrated to enable users to make suggestions for further explorations and to play/edit scenarios created by others, respectively.

At a minimum game development will inform model development. However, we hypothesize that it is important to consider decision making more fully, and that a participatory computational approach using gaming can give us a more comprehensive insights into what scenarios will unfold in the future by considering the effect of interventions and decision making behavior. There are different degrees on how a social system can be included in games. A single decision maker is less reflective of reality than representing a situation where multiple decision makers are present. Although more opinions and perspectives can slow down the decision making process and lead to conflicts (De Bruijn et al. 2010), we argue that through modeling and gaming tools such as used here, closer to optimal decision making will be a result due to the reality check and shared visualizations that these tools offer. Therefore, our main hypothesis is: increased grounding of the modeled decision making process in reality results in improved effectiveness in decision making in a simulated environment. With effectiveness we refer to the performance on the three pillars of sustainability: economic, social, and environmental.

We will gather a mix of qualitative and quantitative data to understand the decision-making process. Other than the dependent measures on effectiveness, we will collect behavioral telemetry data from the game, the conversations players may have had, the annotations they made, and their decision rationale. Alongside a chat system, the game comes with an annotation tool where players can at any time provide comments at a particular instance of play. At specific occasions players are further asked by a Non-Player-Character (NPC) to provide a rationale for their actions. The annotation and rationale serve as an alternative and written form of the think-aloud protocol (Nielsen 1993). Appropriate statistical and qualitative analyses will be performed to analyze the results (i.e., ANOVAs and open coding).

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