Visualization Methods for Sustainable Planning

Vom Fachbereich Informatik der Technischen Universität Kaiserslautern
zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften (Dr.-Ing.)
genehmigte Dissertation
von

Dipl.-Ing. Sebastian Petsch

Datum der wissenschaftlichen Aussprache: 16. Dezember 2011

Dekan:	Prof. Dr. Arnd Poetzsch-Heffter
Vorsitzender des Prüfungsausschusses:	Prof. Dr. Arnd Poetzsch-Heffter
1. Berichterstatter:	Prof. Dr. Hans Hagen
2. Berichterstatter:	Prof. Dr. Achim Ebert
3. Berichtertatter:	Prof. Dr. Subhrajit Guhathakurta

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Abstract

In urban planning, both measuring and communicating sustainability are among the most recent concerns. Therefore, the primary emphasis of this thesis concerns establishing metrics and visualization techniques in order to deal with indicators of sustainability.

First, this thesis provides a novel approach for measuring and monitoring two indicators of sustainability - urban sprawl and carbon footprints – at the urban neighborhood scale. By designating different sectors of relevant carbon emissions as well as different household categories, this thesis provides detailed information about carbon emissions in order to estimate impacts of daily consumption decisions and travel behavior by household type. Regarding urban sprawl, a novel gridcell-based indicator model is established, based on different dimensions of urban sprawl.

Second, this thesis presents a three-step-based visualization method, addressing predefined requirements for geovisualizations and visualizing those indicator results, introduced above. This surface-visualization combines advantages from both common GIS representation and three-dimensional representation techniques within the field of urban planning, and is assisted by a web-based graphical user interface which allows for accessing the results by the public.

In addition, by focusing on local neighborhoods, this thesis provides an alternative approach in measuring and visualizing both indicators by utilizing a Neighborhood Relation Diagram (NRD), based on weighted Voronoi diagrams. Thus, the user is able to a) utilize original census data, b) compare direct impacts of indicator results on the neighboring cells, and c) compare both indicators of sustainability visually.

Acknowledgements

I would like to take the opportunity to thank all the people who have supported me during the work on this dissertation. First of all I would like to thank Prof. Dr. Hans Hagen for giving me the chance to be a part of the IRTG 1131. I deeply appreciate his advices and valuable suggestions in work and non work related matters, which guided me through the last four years and helped me completing this dissertation. Furthermore I would like to thank my co-advisor Prof. Dr. Subhrajit Guhathakurta for his guidance, ideas and advices which were essential for completing this thesis.

I would like to thank all my colleagues in the "Computer Graphics and HCI" group and the IRTG for fruitful discussion and intellectual exchanges, especially Prof. Dr. Achim Ebert, Daniel Engel, Florian Höpel, Daniel Burkhart, Kerstin Müller and Luc Heischbourg. Special thanks go to Mady Gruys, Inga Scheler and Roger Daneker who were always available when I needed them for managing all the organizational things in the background.

I would like to thank my colleague and friend Peter-Scott Olech for the last four years where we shared an office. Furthermore I would like to thank Ariane and Björn for great hospitality and wonderful times during my visits at the Arizona State University. Special thanks to my friends Tanja and Uli for proof-reading parts of my thesis.

I would also like to take the opportunity to thank my girlfriend Sara for her love and support and for enduring my varying moods, especially in the weeks before the final submission.

Last - but certainly not least – I would like to thank my parents for their love, support and patience during my whole education time. Without their ongoing encouragement and confidence, this dissertation would not have been possible.

CONTENTS

Chapter 1

Introduction

1.1 Motivation

In the era of globalization and climate change the term sustainability is among the most pressing international concerns. Since sustainability is automatically connected to questions about future developments, sophisticated simulation models are utilized in order to provide information about future impacts on urban environments based on alternative scenarios. Those output datasets, for example the amount, attributes or spatial distribution of future households within a predefined study area, provide an overview of future development and are supposed to support planners for sustainable decision-making. But by conceptualizing those sustainable future developments urban planners still have to face the need for an adequate interpretation of those large and unstructured output datasets. Establishing well-defined metrics for indicators of sustainability becomes an essential part of this process.

Another challenge planners are dealing with is the question how to communicate resulting findings, ideas and conceptions to non-experts and the public in general in an adequate manner. Given the multidimensional and multidisciplinary aspects of sustainability, the conceptual and visualization tools planners have typically employed are often limited in terms of intuitiveness, suitability or visibility. The portfolio of visualization tools in urban planning is most commonly reduced to two-dimensional representations within geographical information systems (GIS). Despite of the doubtless potential of GIS, those systems are strongly limited in terms of user-interaction and adaption. Furthermore they do not account on awaking demands for three-dimensional visualization techniques.

This interdisciplinary thesis demonstrates how high bandwidth of visualization methods in computer science, especially the techniques developed in the fields of scientific and information visualization, can account on the demand for intuitive and comprehensive representation of planning problems related to indicators of sustainability. The advances in computer technology provide a unique opportunity to use digital visualization techniques to represent indicators of sustainability especially in public communication and participation programs.

This thesis focuses on two indicators of sustainability - carbon footprints and urban sprawl - in a predefined study area. Since those phenomena have been addressed by various scholars at the level of metropolitan areas, the demand of facing those phenomena at the urban neighborhood scale automatically arises. Those neighborhood-based metrics could not only illustrate a more detailed insight in order to assist future policy decisions but also will allow individuals and families to make judicious decisions and make them carefully consider the impacts of their behavior on the environment.

By providing both novel metrics for indicators of sustainability as well as adequate and intuitive visualization methods, this dissertation accounts for the challenges mentioned above and therefore represents an interdisciplinary approach in associating demands in the field of urban planning with techniques provided by computer science. All presented results were obtained as part of the research as a member of both the *Digital Phoenix Group* at the Arizona State University, AZ, USA and the *IRTG 1131* at the University of Kaiserslautern, Germany.

1.2 Thesis Structure and Contribution

Following the challenges and demands in section motivation introduced above the remainder of this dissertation can be divided into two categories of research topics: (1) *indicators of sustainability* and (2) *visualization*. Chapter 2 starts with introducing and defining the chosen indicators of sustainability – carbon footprints and urban sprawl - and also gives an overview about significant related work. Each of those indicators is covered by an individual chapter of this thesis. The second research topic *visualization* is introduced and defined in Chapter 3. Requirements for an adequate visualization are established and subsequent visualization techniques and methods for are introduced. For the reader's convenience each chapter of indicators of sustainability includes a respective section of visualization. Likewise, each of those chapters ends with its own conclusion section.

Chapter 4 deals with the indicator carbon footprints. The chapter starts by introducing the study area Maricopa County (Section 4.1), the data estimation using UrbanSim (Section 4.2) and the different scenarios used in this thesis (Section 4.3). Subsequent carbon emissions are calculated for individual households and consequently for the whole study area, concerning future years and different scenarios (Section 4.5). In Section 4.6 a new visualization techniques is introduced, based on Coons Patches, accounting for predefined requirements and well-suited for visualizing gridcell based indicators of sustainability. In particular, the scientific contributions provided by this chapter are:

Chapter 5 deals with the indicator urban sprawl. Based on an existing method (Galster et al. 2001), different dimensions (indicators) of urban sprawl are defined and applied for the study area (Section 5.1). In Section 5.2 those dimensions are adjusted into the gridcell-based approach and finally urban sprawl indices are presented for Maricopa County. Similar to Chapter 4, the visualization method based on Coons Patches is utilized to present results for urban sprawl visually in Section 5.4.

In contrast to previous chapters, Chapter 6 focuses on the visualization technique itself while the application on indicators of sustainability follows in two case studies in Section 6.3. After defining application demands for local comparison of non-spatial information in partial spatial data in Section 6.1, Section 6.2 starts by describing a novel and generic solution - a Neighborhood Relation Diagram. This technique is based on the geometric computation of Voronoi diagrams according to a weighted neighborhood metric. The shape of spatial regions within this diagram is characterized by a directed and constrained deformation according to the non-spatial relations to neighboring regions. The benefits of this approach are testified by two case studies in Section 6.3 as well as by utilizing this approach in order to compare different indicators of sustainability in Section 6.4.

By summarizing the described work, Chapter 7 concludes this dissertation and furthermore points out possible directions for future work, especially focusing on other application areas such as software engineering.

1.3 Contribution

In particular, the scientific contributions provided by this thesis can be structured and stated as follows:

- *Visualizing Carbon Footprints*
    - Modeling carbon footprints for individual households, based on three dimensions of emission contributors and dependent on different household attributes.
    - Successful application of those household emission number on Maricopa County households, based on linear regression and utilizing output data of UrbanSim for future years and different scenarios of land use development.
    - Introduction of a new visualization method for illustrating gridcell-based indicators of sustainability, combining advantages from color coding and three-dimensional representations.

  - Introduction of a graphical user interface (GUI) which enables the user to access resulting numbers visually and in addition offers the possibility to compare carbon footprints for different years and scenarios.
- *Visualizing Urban Sprawl*
  - Adjusting an existing method for measuring urban sprawl to the gridcell-based approach introduced in this thesis.
  - Introducing a gridcell-based sprawl-index which consists of different indicators of urban sprawl.
  - Applying resulting sprawl indices to the three-dimensional visualization method, introduced in Section 4.6 in order to present urban sprawl in Maricopa County visually.
  - Extending the GUI, introduced in Section 4.6, to be able to compare both results of carbon footprints and urban sprawl.
- *Visualizing both indicators of sustainability, focusing on direct neighborhood relations*
  - Introduction of a novel visualization technique for the illustration of local relations between non-spatial parameters within a neighborhood of unstructured partially spatial data.
  - Therefore providing a suitable method for comparing different indicators of sustainability.

Chapter 2:

Indicators of Sustainability

Since the 1960s a central issue in the context of environmental planning has been its sustainability but it was not until the late 80s of the last century that the term sustainability was generally introduced as a political objective through the report "Our Common Future" by the UN World Commission on Environment and Development (WCED). The definition stated at this Brundtland Commission [Uno87] report is perhaps the most widely quoted definition of sustainability: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In 1992 those tasks were transformed into binding guidelines in the Rio Declaration on Environment and Development [Und11], separated by ecological, economical and social aspects. As an instrument the action program "Agenda 21" was developed, focusing on goals of sustainable development at the national scale. The resulting challenges for planners and decision makers which followed can be formulated in two principle questions:

- How can those goals are achieved?
- How can sustainability be measured?

To answer the first question one can refer to another definition of sustainability, stated by the European Foundation for the Improvement of Living and Working Conditions [Ell94]:

"Sustainable development is the achievement of continued economic and social development without detriment to the environment and natural resources. The quality of future human activity and development is increasingly seen as being dependent on maintaining this balance." Following this definition, the second question still remains: How can one measure the quality of future human activity and development? How can one measure the quality of life? This leads to a serious consideration if sustainability is measurable after all. Since the answer to those questions depends on one's particular vision of sustainability the goals have to be clearly identified in order to know if a target has been reached or not. Heinen [Hei94] noticed that "sustainability must be made operational in each specific context [...] and appropriate methods must be designed for its long-term measurement". The Bellagio Principles for sustainable development [HH97] followed and supported this theory:

- What is meant by sustainable development should be clearly defined (principle 1)
- Progress towards sustainable development should be based on the measurement of a limited number of indicators based on standardized measurement (principle 5)

Since working with indicator approaches have been successfully employed in several research fields, e.g. by biologists to gauge ecosystem health, the use of indicators have been seen as the core element in operationalizing sustainability [BM08]. The only question remaining would be: how many and which indicators are needed to measure sustainability?

2.1. Overview of indicators of sustainability

Searching for indicators of sustainability is a recurrent task in the planning community. Literature provides several approaches for deploying indicators of sustainability starting with the United Nations working list of indicators of sustainable development based on Agenda 21 in Rio 1992. Several other indicator frameworks have also been developed by Kuik and Verbruggen [KV91], Izac and

Swift [IS94], Harger and Meyer [HM96], Gilbert [Gil96], Bossel [Bos01], among others. One of the most recent approaches is the Environmental Sustainability Index (ESI), created by Yale and Colombia Universities, with the goal to express sustainability within one single number for each country [Sed11]. By using 22 different indicators which have equal weights the final ESI, calculated on national-state basis, is a set of numbers with a theoretical minimum of 0 (most unsustainable) and a theoretical maximum of 100 (most sustainable). Although those approaches seem to be transparent and understandable at a first glance, one must point out that those rankings, especially the choice of indicators, depend on personal opinions of only a specific kind of experts.

Another approach to estimate and measure sustainability is the ecological footprint developed by Wackernagel and Rees [WR96] with the goal to "[…] translate sustainability concerns into public action". The idea behind this approach is that every person, activity and region has an impact on the earth. After measuring this data, those impacts are converted into a biologically productive area which finally represents the ecological footprint. Van den Bergh and Verbruggen [vdBV99] refer to the lack of a clear objective, constraints and instruments in determining the ecological footprint of a place.

The purpose of this chapter is not to evaluate those different approaches but to give a short overview of different frameworks of indicators of sustainability. And regarding all of those approaches mentioned above the major critique and problem become clear: indicators of sustainability try to encapsulate complex and diverse processes in relatively few simple measures. Does it mean that any kind of approach in this direction has to be considered as incomplete or just wrong due to the complexity of sustainability concepts? Harrington [Har92] pointed out that in order to deal with complex problems "[…] scientists have to simplify to survive [...]".

This work will not address the question how much simplification is acceptable to keep indicators of sustainability meaningful. Instead, the following chapters concentrate on two indicators of sustainability - carbon footprints and indicators of urban sprawl - which have been addressed within the scope of the "Digital Phoenix Project" [GKP+09] at the Arizona State University, AZ, USA. By developing a multidimensional digital representation of the Phoenix metropolitan area in time and space, the goal of the project was to create a dynamic planning tool with an integrated visualization platform [Mid08]. Figure 2.1 illustrates both the architecture of "Digital Phoenix" and its integration of indicators of sustainability chosen in this work.

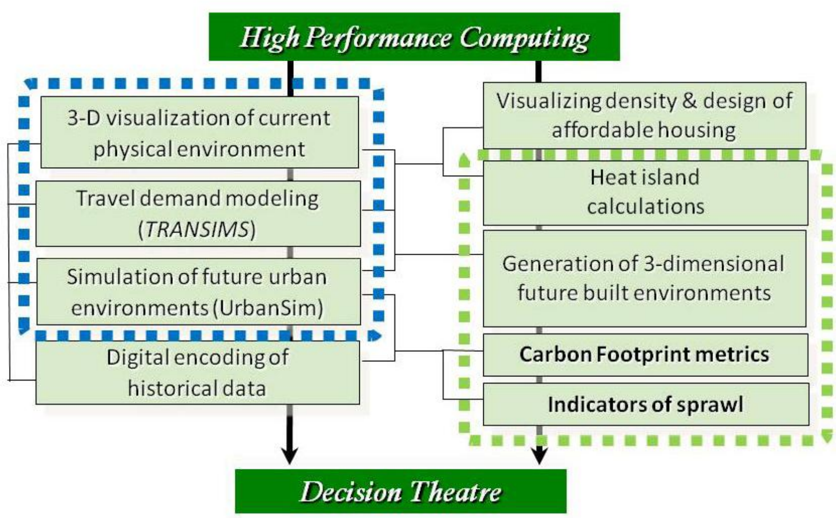


Figure 2.1: Digital Phoenix Project: Integration of indicators of sustainability, derived from [GKP+09, p.160]

2.2. Carbon footprints

The urgency of reversing climate change is among the most pressing international concerns and a key aspect of sustainability. Increasing concentration of greenhouse gases (GHG) in the atmosphere is expected to trigger significant changes in temperature and precipitation patterns. According to numerous scientific studies and the work of International Panel for Climate Change (IPCC), the changing climate will lead to unacceptable impacts on human health and livelihood in different parts of the globe. One of the major anthropogenic contributors to the changing climate is carbon dioxide (CO_2) emission from burning fossil fuels. In the United States, energy-related CO_2 emissions account for 82% of total GHG emissions [Use10b].

This study focuses on carbon dioxide, which is the most noteworthy of the greenhouse gases. For the sake of completeness one has to refer to the Kyoto Protocol[1], which lists Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6) as other GHG gases. The European Commission specifies "carbon footprint" as a complete life-cycle assessment of goods and services with the analysis limited to emissions that have an effect on climate change [Eur07]. But there are different opinions about what carbon footprints should include besides CO_2 such as other greenhouse gases mentioned above, e.g., methane. The consensus found in the literature suggests that CO_2 is the most significant contributor and has more direct connections to human actions [WM07]. This study defines carbon footprint as the sum total of CO_2 from household consumption behavior, household energy use, and household travel behavior.

2.2.1. Overview carbon footprints

The term "carbon footprint" describes the total amount of CO_2 emitted into the atmosphere by individuals and organizations, mostly through the use of fossil fuels

[1] The Kyoto Protocol, as an international agreement linked to the United Nations Framework Convention on Climate Change, was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005 [Unf11].

[PGH+10] [Cat10]. According to Carbon Trust [Cat10] one can distinguish between two main types of carbon footprint:

- Organizational carbon footprint, which includes emissions from all the activities across the organization, including buildings' energy use, industrial processes and company vehicles.
- Product carbon footprint which includes emissions over the whole life of a product or service, from the extraction of raw materials and manufacturing right through to its use and final reuse, recycling, or disposal.

The definitions above refer to organizations; but they can also be adopted for individual households. The next section of this chapter illustrates how carbon footprints can be estimated from different dimensions of household carbon emissions. This study defines carbon footprint as the sum total of emissions from household consumption behavior, household energy use, and household travel behavior.

While carbon footprints at local, regional, national, and global scales have been estimated in numerous studies, few have used bottom-up emission calculations starting with individual households. The principal idea behind this method is to capture the "demand side" of carbon emissions by assigning all emissions resulting from household consumption to the specific household rather than to the region or the industry where this emission is generated. For example, when a household obtains a television set, all emissions generated during the life cycle of the product (cradle to grave) will be assigned to that household regardless of the fact that the television might have been manufactured in South Korea, transported to New York, and bought online from a Seattle-based retailer. The same household will also assume the emissions generated during disposal of the set. In other words, almost all industrial and service related emissions are assigned to households in proportion to their consumption patterns.

2.2.2. Dimensions of a total household carbon footprint

This work concentrates on carbon footprints as an indicator of sustainability at the level of individual households. To complete the total portfolio of household CO_2, emissions from household energy use (electricity, natural gas, oil, etc.) and from energy required for household travel should be added to emissions from consumption behavior. Indeed about 40 percent of total household carbon emissions are associated with household (operational) energy use and household travel [Use10b]. Figure 2.2 shows the three dimensions of a total carbon footprint.

Of those three sources of household emissions, transportation is quite distinct since urban forms and design of neighborhoods have an important role to play in household choices of travel modes and destinations [CR96] [Cer02]. Benfield et al. [BRC99] and Newman and Kenworthy [NK99] both point out that if population or household density doubles towards compact areas, the automobile usage drop about 40%. Therefore far-reaching transformation of energy use will require both household decisions and policy choices about urban form and transportation accessibility [Bar10] [ClQR+07].

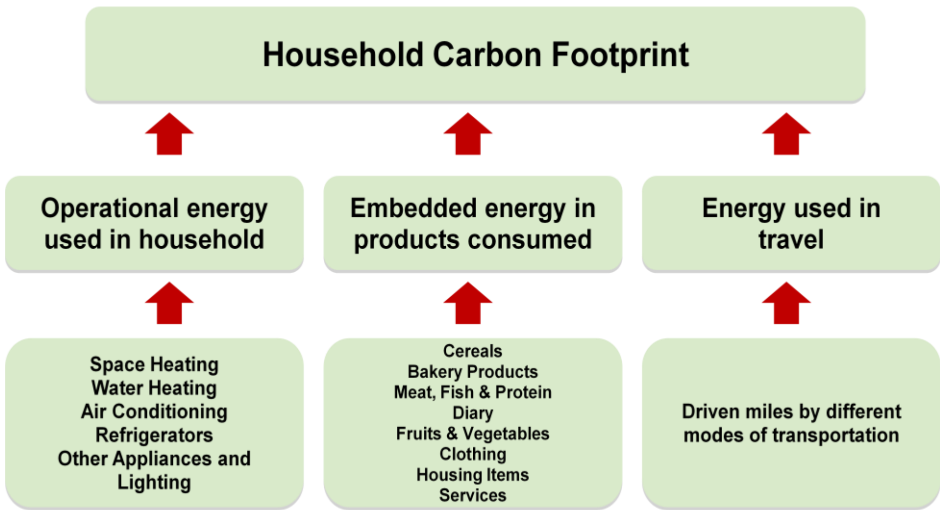


Figure 2.2: Components of a total Carbon Footprint at the level of individual households

2.2.3. Related work carbon footprints

As mentioned above, defining the term "carbon footprint" is difficult as it is conceptualized differently in different research fields [WTC+08] [PGH+10] [Cat10] and requires a clear statement of underlying assumptions and methodological approaches [Pet10] [WM07]. It can be defined as "a measure of the amount of carbon dioxide released into the atmosphere by a single endeavor or by a company, household, or individual through day-to-day activities over a given period" [Onl11].

There is a growing body of work on measuring and monitoring carbon footprints. This literature is organized under three related topics:

- studies of carbon footprints at metropolitan scale,
- prior studies using consumption based emissions estimates, and
- studies discussing carbon impacts of travel and land use patterns.

Carbon emissions in metropolitan areas have been addressed in several studies during the last decade (e.g., Hankey and Marshall [HM10]; Brown and Logan [BL08]; Sovacool and Brown [SB09]). Most of the studies on metropolitan carbon footprints accounted for transportation and building (mostly residential) energy as the primary sources of carbon emissions. A comparative profile of carbon emissions in 100 U.S. metropolitan areas was provided by Brown, Southworth, and Sarzynski [BSS08]. Another comparative study by Sovacool and Brown [SB09] reported on the carbon footprints of 12 global metro areas based on a survey of published reports. A somewhat similar comparative exercise was undertaken by Glaeser and Kahn [GK08]. They quantified the carbon dioxide emissions associated with new construction in different locations across the United States, including emissions from driving, public transit, home heating, and household electricity usage. By comparing results from cities in different states they pointed out that California has the lowest emissions areas while the highest emissions areas can be found in Texas and Oklahoma.

The Vulcan project [GSA$^+$08] [GMT$^+$09], housed in Purdue University and funded by National Aeronautical and Space Administration (NASA) and the U.S. Department of Energy (DOE) offers another approach for estimating carbon emissions at a high spatial (10 km) and temporal (hourly) resolution. The objective of this project is to recreate the complete carbon profile for the continental U.S. by using a series of close to real time inputs from point, area, and mobile sources at the spatial and temporal resolution noted above. Parshall et al. [PGH$^+$10] evaluated the ability of the Vulcan Project to measure energy consumption in urban areas and addressed the methodological challenges of this type of analytical exercise. They suggested that county-based definition of urban areas would be preferable to other common definitions since counties are the smallest political unit for which energy data are collected.

Studies of consumption-based methods for estimating carbon footprints have broadly followed two approaches: 1) the application of input-output transactions table and sectoral energy flows to determine energy intensities of household consumption baskets (e.g., Jöst [Joe99]; Hertwich and Peters [HP09]; Parauchi [Pac04]; Moll et al. [MNK$^+$05], Holden and Norland [HN05]; Lenzen et al. [LWC$^+$06]; Norman, MacLean, and Kennedy [NMK06]); and 2) deriving direct energy requirements of household consumables typically to provide public information about carbon emissions through web-based calculators. Shammin et al. [SHHW10] describe a consumption-based approach for estimating carbon emissions from a basket of goods in the Consumer Expenditure Diary Survey (CES) but focuses more on energy intensities of sprawled versus compact urban environments. Weber [Web08] and Weber and Matthews [WM08] defined 13 broad consumption categories of household level carbon footprints, such as education, home energy, and private transport. While his work provides information about emission values of those consumption items for the average American household and points out their interrelationship with income and household sizes, it mainly focuses on global aspects and the importance and involvement of international trade. Jones [Jon05] also started with a similar consumption-based approach by estimating the greenhouse gas and conventional pollutants related to goods and services consumed by the typical U.S. household. He describes the sources of emissions in five different categories (Transportation, Housing, Food, Goods, and Services) of consumption based on the Consumer Expenditure Survey (CES) for the typical U.S household.

The purpose of Jones's work was to develop a framework for creating an online Consumer Footprint Calculator for understanding the impacts of spending decisions on the environment and economy. Other examples of popular carbon calculators include projects like Carbon Fund [Caf10], DOPPLR [Dop10] and Safe climate [Saf10]. Although they provide convenient tools for estimating and managing personal and household CO_2 emissions [PSCV08], most of the models behind them are limited in many aspects and lack common standards, which makes them inconsistent, and often contradictory [KG09].

There is also a large and growing literature on the relationship between land use and transportation (e.g., Ewing and Cervero [EC01], Anderson et al. [AKM96], Handy [Han96], Crane [Cra00] or Meyer [Mey10]), the relationship between built environment and travel behavior (Hankey and Marshall [HM10], Donoso et al. [DMZ06], or Rodier et al. [RJA02]), and their combined impacts on energy use and CO_2 emissions [Epa06]. In addition, estimates of transportation emissions, presented in Chapter 4.5.3, benefits from studies concerning vehicle emission standards [Elm10] as well as from prior research on emissions estimates of different modes of transportation [Bra07] [Gle06]. For example, Paravantis and

Georgakellos [PG07] developed aggregate car ownership and bus fleet models to forecast and compare fuel consumption and CO_2 emissions from passenger cars and buses. He concluded that the passenger automobile would emerge as the dominant CO_2 source in road passenger transport within the current decade. In estimating CO_2 emission from household transportation this work also considers emissions at every stage of a vehicle's lifetime including vehicle usage, fuel production, extraction of raw materials and manufacturing of component parts. Austin et al. [ARSL03] note that only 75% of emissions are caused by vehicle usage.

2.3. Urban Sprawl

In this section, a second indicator of sustainability is introduced, related to urban development and land use patterns. During the greater part of the last century, people have been realizing the "American Dream" by pursuing opportunities in the suburbs of a metropolitan area [RS04]. The term suburbanization is used to describe this process of movement of population from central areas of cities and towns to peripheral areas. Suburbanization is attributed to factors such as the density of cities, pollution by industry, high levels of traffic congestion and even poor governance. Among the important effects of suburbanization is the increase of urban sprawl.

2.3.1. Overview Urban Sprawl

The literature on urban sprawl is vast and often conflates causes, conditions and consequences. The lack of common accepted definitions, measurements [EPC03] [TA00] and, more importantly, good coordination among policies [BCB02], are considered to be the major impediments in combating urban sprawl. In order to identify urban sprawl within the scope of this work, Clawson [Cla62] provided an adequate definition: “[the] rapid spread of suburbs across the previously rural landscape, tendency to discontinuity [...]”. In other words urban sprawl could be defined as low density, leapfrog, commercial strip development and discontinuity [Ewi97] [GHRW+01] [Tsa05] and can directly be identified with urban growth [BBC03]. Urban sprawl is reported to be a significant contributor to traffic congestions [NW04], job-housing mismatches [Ewi97], racial and income segregation [Squ02], environmental degradation [Joh01], among other urban issues that have an influence on the quality of life and on the air quality of an urban area. Several studies around the globe already pointed out the strong correlation between urban form and air quality. The influence of urban heat islands [Oke87] on urban temperatures and the resulting regional ozone formations [RZZ95] are strongly connected with urban land use patterns. In fact, Stone [Sto08] documented that large metropolitan areas with high sprawl indices are dealing with a higher number of ozone exceedances than more spatially compact regions.

2.3.2. Related work urban sprawl

Since the term “sprawling” was first mentioned by Earl Draper in 1935 to describe unaesthetic and uneconomical urban developments in cities [Was02], the current literature on urban sprawl is vast and studies have been conducted for many urban regions across the globe [BXS99] [TA00] [BMRL01]. While these earlier studies have indicated that sprawl may be associated with social and environmental problems [Sto08], measuring and quantifying urban sprawl is a relatively young research field [Kah01] [EPK02]. Tsai [Tsa05], who is dealing with quantitative variables to characterize urban forms at the level of metropolises, developed four variables that can measure four dimensions of urban forms, namely the metropolitan size, the activity intensity, the degree to which the activities are evenly distributed as well as the extent to which the high-density sub-areas are clustered. This degree of clustering is an important part in distinguishing compactness from sprawl.

Ewing [Ewi97] defined sprawl as a compilation of different indicators. This includes poor accessibility and the lack of functional open space. Fulton et al. [FPNH01] has only focussed on density for a measurement of sprawl. Other studies like Jordan, Ross and Usowski [JRU98] also use density gradients and the distances from city centres to describe how far a population has moved towards a peripheral area. Lopez and Hynes [LH03] described the development of urban sprawl over the past decade in different metropolitan areas. They also pointed out that the density of population is the most important "data" to measure sprawl or to create a sprawl-index. Their calculated sprawl-indices for over 300 metropolitan areas use census data to construct a measure of residential sprawl. Worth noting is the fact that their calculation was only based on density and concentrations.

The approach adopted in Chapter 5 benefits from the work of Galster et al. [GHRW$^+$01], who developed a detailed mathematical approach for measuring sprawl. He defined eight dimensions of urban sprawl and ranked different metropolitan areas on each of these dimensions. He also aggregated them to calculate an overall sprawl score. In the aggregated score all of these dimensions had equal weights. His approach presents an excellent starting point for the upcoming calculation of the indicators of urban sprawl for Maricopa County in Chapter 5.

Chapter 3:

Visualization in environmental planning

Given the complexity and multidimensional aspects of both carbon footprint and urban sprawl phenomena, the conceptual and visualization tools planners have typically employed are often inadequate [WGBD02]. This work demonstrates how high bandwidth of visualization methods in computer science, especially the techniques developed in the field of information visualization, can be applied in planning problems related to carbon emissions and urban sprawl. The advances in computer technology provide a unique opportunity to use digital visualization techniques to represent planning issues especially in public communication and participation programs [Alk99] [AL05]. But in order to associate this work with the context of visualization three crucial preconditions have to be accomplished:

- How is the term visualization defined?
- What are goals for "good" visualization within the scope of environmental planning?
- What are adequate methods in order to represent data such as indicators of sustainability?

3.1. Definition "Visualization"

In general the term "visualization" can be defined as any kind of technique in order to present information e.g. through images, maps, drawings or diagrams. The field of computer science usually distinguishes between scientific visualization, information visualization and software visualization [Sch04] [Sch08] while in the context of urban and environmental planning visualization was traditionally linked to the domains of cartography or architecture [RIK+94] [Alk02]. In 1987 the term “geovisualization” was first mentioned in a NSF (National Science Foundation) report on visualization in scientific computing [MDB87], integrating knowledge and expertise from various related research fields. According to the 2001 research agenda of the International Cartographic Association (ICA) Commission on Visualization and Virtual Environments, geovisualization today is defined as follows: “Geovisualization integrates approaches from visualization in scientific computing (ViSC), cartography, image analysis, information visualization, exploratory data analysis (EDA), and geographic information systems (GIS) to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data” [MK01]. Therefore visualization has to be considered as an effective way to transform complex data, analysis and attribute relationships into a transparent human understanding. “Data visualization will no longer be looked upon as simply an act of information presentation but rather as a bi-directional process that takes into account interaction with end-users” [RIK+94].

3.2. Goals for visualization in environmental planning

Following the definition in Section 3.1 and considering Ware [War04], who pointed out that data visualization in particular with its sheer quantity of information can be rapidly interpreted only if it is presented well, some essential goals for a “good” visualization can be enunciated. According to Mackinley [Mac86] and Schumann and Müller [SM00], a good visualization has to be

- expressive,
- efficient and
- suitable.

By applying those goals to this work, the following five visualization requirements were chosen to evaluate the different visualization techniques in Chapters 4, 5 and 6:

- Identification: visualization has to support understandable identification of problems, expectations and questions in context of the data
- (No) Information overload: visualization should be restricted to essential data which is needed for understanding.
- Suitability: visualization should address the knowledge and skills of the user group (different visualization methods for e.g. research experts and stakeholders with no background in this field)
- Completeness of presented data
- Navigation: geovisualization is dealing with geospatial data. In contrast to abstract data (data without any georeference, usually display in information visualization), distances and directions have an immediate relevance.

Considering a more human-centered approach, presented in Chapters 4 and 5, one must not neglect the usability aspect of visualization systems. The definition of usability by Gould and Lewis not only expresses requirements for the Graphical User Interface (GUI), but also can be applied to general requirements for a visualization technique in an interdisciplinary research field such as environmental planning. “Any application designed for people to use, should be easy to learn (and remember), useful, that is contain functions people really need in their work, and be easy and pleasant to use” [GL85].

3.3. Related work on visualization in environmental planning

There are few research fields which are more addicted to visualization than the field of urban and environmental planning. Depending on the application field the variety of possible tools ranges from drawings and sketches over physical models and maps to interactive GIS systems and computer simulations. Since it is not in the focus of this work to provide an overview of all visualization tools in environmental planning, the interested reader might be referred to the literature [Dan92] [Lan92] [Soe96] [Alk99] [Alk02] [Del00]. This work concentrates on selected tools and techniques which will be discussed in the following chapters. At this point it is important to make a clear distinction between the terms "tool" on the one hand and "method/technique on the other hand. The term "tool" is defined as an instrument used for visualization, while the term "method" or "techniques" describes a technique which is used for visualization. For instance, color-coding (detailed in Section 3.4 is a method for using the tool GIS (detailed below).

The advances in computer science during the last decades have included Geographic Information Systems (GIS) (example illustrated in Figure 3.1) which is now considered to be one of the standard tools in the field of environmental planning [RIK$^+$94].

As a system which was "designed to capture, store, manipulate, analyze, manage, and present all types of geographically referenced data" [Esr90], it combines technologies of cartography, databases and statistical analysis in order to support and improve decision making.

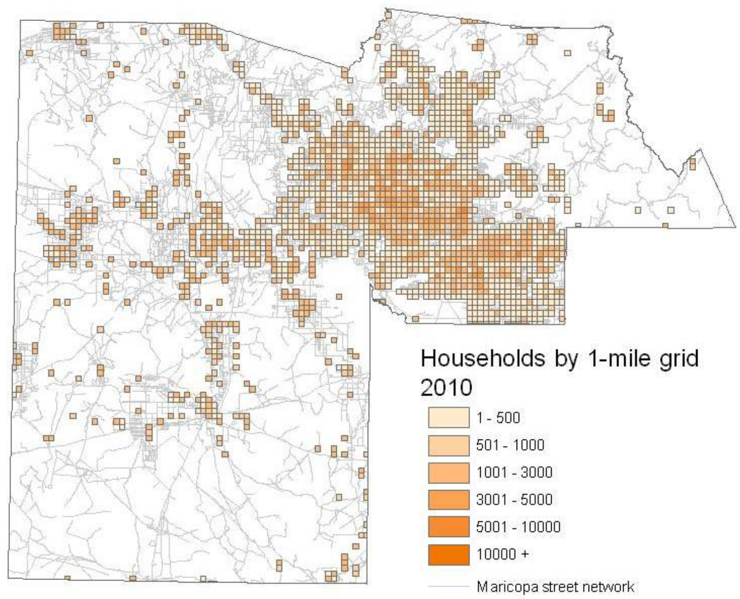


Figure 1.1: Example of GIS visualization: Household density in Maricopa County, AZ, USA, [Guh11]

But in the context of visualization there are some major drawbacks of those complex systems:

- GIS handle only two-dimensional data
- The capability in supporting user-interaction is missing
- Software packages such as ESRI's ArcGIS don't allow for integrating independent visualization techniques

The GIS visualization toolkit might be appropriate for depicting geospatial data such as street layouts or simulated data such as the density of households. But the question how abstract data can be visualized in a way that allows analyzing facilitates understanding and supports decision making remains unaddressed.

Those limitations of GIS-based visualization options call for a more sophisticated geovisualization technique. An excellent overview of state-of-the-art methods in geovisualization is provided by Keim et al. [KPS05], Nöllenburg [Noe07] or Kraak

[Kra06], such as CommonGIS [AAV03], GeoVISTA Studio [TG02] or the Mashup concept [Mid08].

A different but long established way to encode non-spatial information in spatial regions is to modify the size and shape of spatial regions based on their non-spatial parameter. Minard's map (Figure 3.2) of Napoleon's campaign into Russia (1812-1813) is a prominent example for this approach [Kra03].

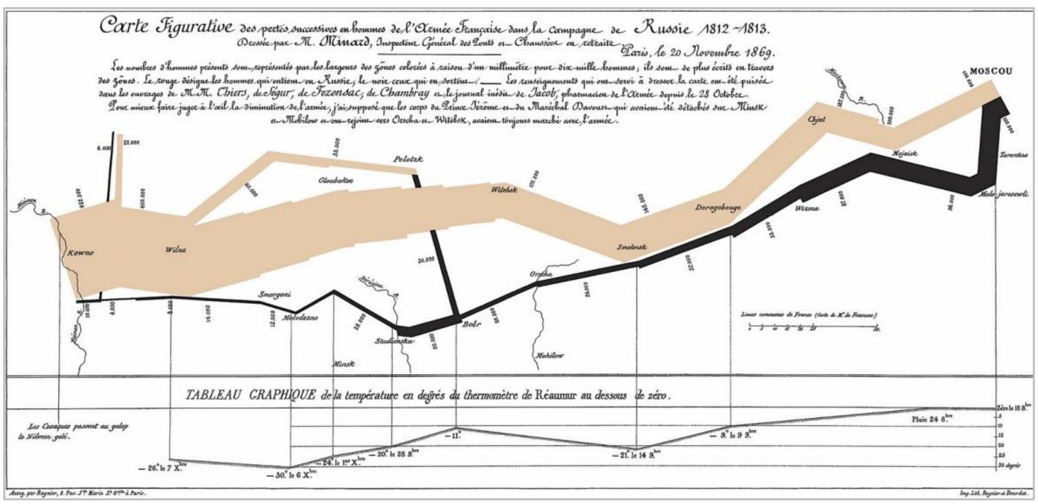


Figure 3.2: Minard's map of Napoleons campaign into Russia 1812-1813 [Tuf11]

Cartograms follow the same underlying principle. A continuous cartogram encodes a non-spatial parameter of a geospatial region by adapting the size of the region. Figure 3.3 illustrates this method by displaying the U.S. state population with the presidential election result of 2000.

An excellent introduction to cartograms is given by Tobler [Tob04], who covers 30 years of research in this area. Further details on the construction of continuous cartograms are also given by House and Kocmoud [HK98] or Keim et al. [KNP04]. Keim et al. [KNP04] also introduce different types of cartograms (e.g., rectangular) and discusses related problems that occur when distorting the spatial reference of the data.

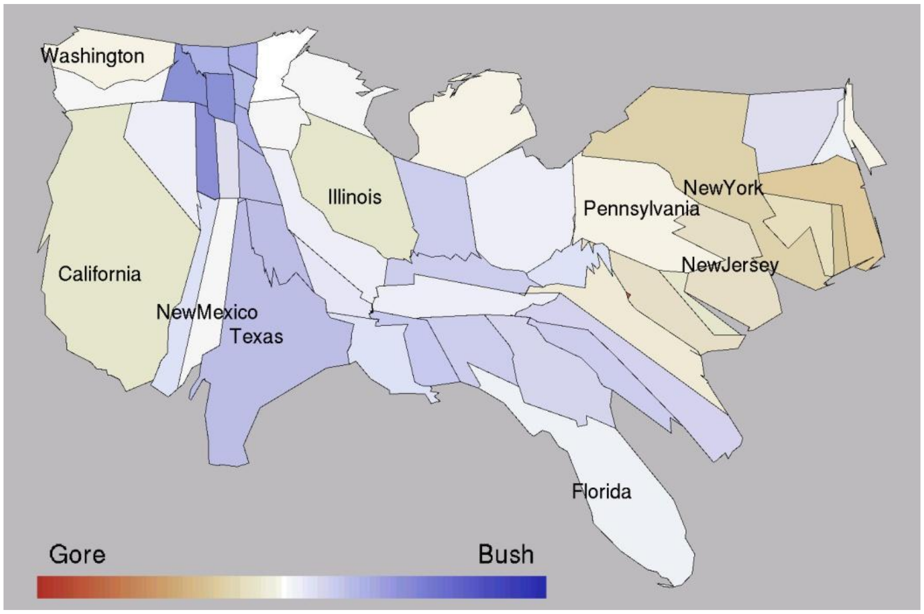


Figure 3.3: Example for cartogram visualization: U.S. state population and the presidential election result of 2000 [KNP04]

3.4. Visualization methods for representing indicators of sustainability:

This section provides visualization methods and techniques which are considered to be adequate in representing indicators of sustainability within the scope of this work. Literature on visualization of indicators of sustainability is few and far between. Carbon footprints are usually displayed within tables [GK08] [SHHW10] or two-dimensional (GIS) representation [GSA+08] [PGH+10a]. Also most of the indicators of sprawl available in the current literature rely on tables [GHRW+01] [Sto08] or two-dimensional maps [JGK08] [SRJ04] to present the results (Steinnocher, et al. [SGH+05] represents an exception in using rudimentary 3D representations to indicate sprawl). An interesting approach is provided by Quay and Hutamuwatr [QH09], who introduced hierarchical visualization methods such as Treemaps as an appropriate way to visualize indicators of sustainability.

In the following sections an overview of the methods used and adapted in this work is presented followed by a detailed discussion about their limitations and benefits in relation to other possible visualization methods. Specific references to the chosen applications (carbon footprints and urban sprawl) are provided in their respective Chapters 4 and 5.

3.4.1. Color Coding

Using color to illustrate information is a common approach. Almost all kinds of visualization techniques in different research fields are strongly connected to “color’s great dominion” [Tuf90]. In computer graphics one distinguishes between different color models such as RGB or HSV [BB06] according to the theory that all colors differentiated by a human eye can be affiliated to an additive mixture of three primary colors. For more information concerning human color perception the interested reader might consult studies such as Judd and Wyszecki [JW63], Pinker [Pin97] or the books on visualization by Edward Tufte [Tuf90] [Tuf97]. Another important aspect is the natural (or psychological) human association of certain colors to certain attributes. Colors red, orange, and yellow are associated with heat and their use let objects appear larger and closer. In contrast, colors blue and violet, associated with coldness or water, cause decreasing distance effects [BB06].

Within the scope of visualization the term color coding describes the technique to visualize spatial data attributes using different colors. For example a color map defines the mapping of one quantitative parameter to color. The non-spatial parameter in the data is displayed by colored spatial data. For example, city blocks may be displayed in conjunction with an underlying color to convey the respective population density. This allows for a quick and intuitive identification of values. Numerous studies deal with color coding and appropriate color maps to represent a single parameter. For instance, Ware [War04] gives a widespread introduction to the use of color in information visualization. In urban and environmental planning color coded visualizations are standard representations in multiple domains such heat island or noise mapping, illustrated in Figure 3.4. This visualization technique is also implemented in standard planning tools such as CAD or GIS.

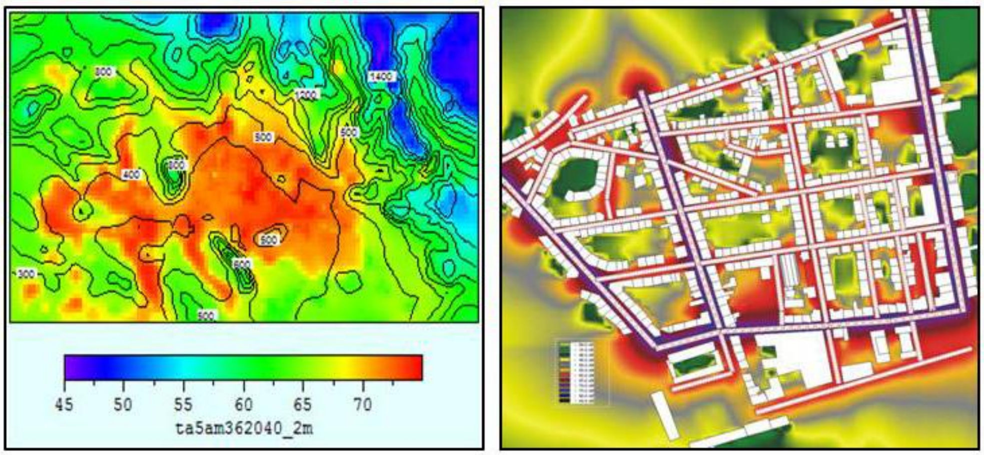


Figure 3.4: Heat island mapping in Phoenix, AZ, USA (left side, [GZLG10]) and noise mapping in Kaiserslautern, Germany (right side)

Other visualization techniques also investigate the mapping of more than one parameter to color schemes. MacEachren et al. [MGP+04] use a bivariate color scheme to achieve a mapping of two parameters. Shanbhag [Sha05] propose an interesting combination of multi-attribute, temporal, and comparative visualization techniques. According to their findings, a mapping of multiple parameters may be achieved by displaying parameters in wedges, slices, and rings.

3.4.2. Coons Patches

Regardless of the advances in computer science a two-dimensional map is still one of the main representation method in the field of urban and environmental planning. Despite the advent of information systems and the increasing availability of three-dimensional data only a few modern planning approaches utilize real three-dimensional data [KB98] and three-dimensional visualization. In computer sciences, more precisely in the computer graphics environment, surfaces are designed within many applications such as design of cars, airplanes or modeling robots [HS87]. In the context of this work, a surface can be defined as the three-dimensional representation of a two-dimensional data representation with the advantage to illustrate additional information within the third dimension.

Literature on computer graphics provides multiple techniques for designing surfaces [BFK84] [Hag86] [Far94] [Hag96] such as Bézier curves, B-Splines or NURBS. The surfaces, presented in this work in Chapters 4 and 5, are built by tessellating the faces of height-fields using linear Coons Patches. In contrast to other techniques mentioned above Coons Patches reproduces piecewise linear curves and there is no artificial smoothing. Therefore quantitative data can be precisely displayed in relation to underlying geographical information.

Since there is a demand for three-dimensional representations in environmental planning, especially in the context of GIS [RIK+94] [KB98] [DH00], Coons Patches have never been used within this research field. Coons Patches, named after Steven Coons, was originally a concept used primarily in the automobile industry (Steven Coons worked as an adviser for Ford in Detroit). This modelling tool was used for the calculation of surfaces for automobiles and is also a standard tool for rapid prototyping [Wri01] due to its ability to integrate all possible curve types.

The principle function of Coons Patches is described as follows: During the design process of a new car, initially a static model of wood or clay is constructed. Next, this model is digitalized with the help of CAD packages. This process generates single digital points. Across these points one can create curves (in the majority of cases they are interpolated splines). Finally a surface is generated by this network of curves [Far94].

The method is depicted in Figure 3.5: A patch is defined by its four corner points A, B, C, D. A point P with parameter (u,v), 0 <= u,v <=1 on the patch can be computed by:

$$P = (1-u)*(1-v)*A + u*(1-v)*B + u*v*C + (1-u)*v*D \quad (3.1)$$

The resulting height-field surface is C^0 continuous. To improve the appearance of the surface each vertex of the height-field obtains a normal, which is computed by averaging the normals of its incident faces. For example, one can identify for corner point A in Figure 3.5, a normal N_A. The normal of point P can now be calculated by:

$$N_P = (1-u)*(1-v)*N_A + u*(1-v)*N_B + u*v*N_C + (1-u)*v*N_D \quad (3.2)$$

With this approach one can maintain the appearance of a smooth surface even though the surface is only C^0 continuous. The continuity of a curve describes how two curve segments meet within a piecewise curve. There are four possible types of continuity. C^0 continuity implies that the endpoints of two curves meet and the curves have positional continuity only.

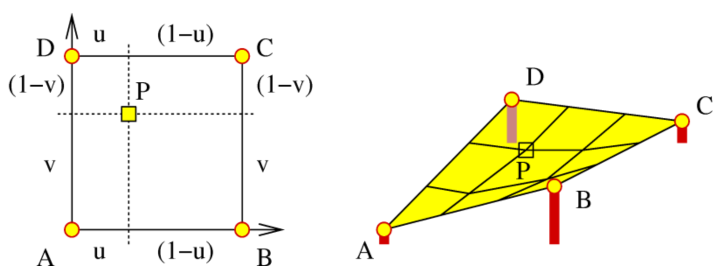


Figure 3.5: Interpolation per face and resulting surface (yellow)

Therefore, this method achieves a very good trade-off between the visualization's speed and quality. By cutting into the surface with planes, spanned by a particular direction and the normal vector, one gets the traditional 2D- piecewise linear curves.

3.4.3. Voronoi diagrams

Although not typically used in geovisualization, the application and output of Voronoi diagrams can be quite similar to those of cartograms, mentioned in Section 3.3. Voronoi diagrams subdivide space into partitions (Voronoi cells) for an equal number of spatial reference points (generators) such that each partition defines the region which is closer to its corresponding reference point. Several distance metrics may be used to define this distance interpretation. A weighting of the distance metric can be used to influence the subdivision by non-spatial parameters. This makes Voronoi diagrams flexibly adaptable to many application areas. Okabe [Oka00] and Aurenhammer [Aur91] give excellent introductions to the field.

In general Voronoi diagrams subdivide a region of R^n space in k partitions called Voronoi cells $Cell_{VD}(P_i)$ for k generator points $P_1,\ldots P_k$, also called sites, where

$$Cell_{VD} = \left\{x \in R^N \middle| d(x, P_i) \leq d\left(x, P_j\right), 1 \leq i, j \leq k\right\} \tag{3.3}$$

and $d(x, y)$ equals the distance between two points in space given by a distance metric [Oka00]. The Euclidean distance $\sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}$ is commonly used, but depending on the chosen application other metrics can be found. The resulting cells $Cell_{VD}(P_i)$ are convex polyhedra in R^n which enclose points that are considered by the distance metric to lie closer to the cell's generator point P_i, than to any other generator point. The points building the faces of the polyhedra, however, mark a region in space where the points have more than one closest generator point. These regions are commonly called bisectors [Oka00]. Points where three or more faces meet are defined as Voronoi vertices.

A Delaunay triangulation for a given set of points in R^2 is the dual graph to the planar Voronoi diagram, containing straight-line edges that connect two sites if, and only if, their respective Voronoi cells share a common edge as a bisector. One important property of the Delaunay triangulation is that the minimum angle within all triangles is maximized for the triangulation. It is also the supergraph of the minimum spanning tree and the relative neighborhood graph [Aur91]. Due to this duality, a planar Voronoi diagram's vertices lie at the circumcenter of the triangles in a Delaunay Triangulation. The Voronoi diagram is constructed by connecting each circumcenter of these triangles with the circumcenter of neighboring triangles, while the circumcenter of a triangle is the intersection point of the edges' half-perpendiculars.

Weighted Voronoi diagrams partition space according to weighted generator points. With given weights $w_1,..,w_k$ the resulting cells may be defined as

$$\mathrm{Cell}_{MWVD}(P_i) = \left\{ x \in R^n \,\middle|\, \frac{d(x,P_i)}{w_i} \leq \frac{d(x,P_j)}{w_j}, 1 \leq i,j \leq k \right\} \qquad (3.4)$$

Weights can also be applied additively by a metric such as $d(x,P_i) - w_i$. While the used distance metric and the application of weighting may differ in many diagrams, some aspects of this interpretation remain constant. The effects of weights are not constrained and reflect on unoriented cell growths in space. In the multiplicatively weighted case, this cell growth is in direct proportion to its weighting, while in the additively weighted case, weights can be seen as an offset for their growths. This can easily lead to overgrown and unconvex cells [Oka00]. A change of one weighting can change the resulting diagram dramatically, which might be difficult to handle in some cases where weights are applied freely to any points. Another important aspect of multiplicatively weighted Voronoi diagrams is that bisectors are not straight line segments but arcs, which may be considered unaesthetic in some applications.

In urban planning, Voronoi diagrams are especially interesting because of the domain's affinity to structured layouts. After all, a city layout is a subdivision of space that is computed by planners based on spatial and non-spatial information.

Several studies show that Voronoi diagrams can produce valuable insights in this application. For example, Huang et al. [HZG09] use a Voronoi model to investigate the spatial distribution of commercial services within city limits. Their work gives an example of how spatial partitioning diagrams can be utilized for proximity analysis of partially spatial data. Scheler and Hagen [SH09] use weighted Voronoi diagrams in urban planning by introducing a novel semantic distance metric. Multiple parameters containing user semantic interpretations of non-spatial properties are integrated into this metric to aid in decision making and collaboration.

Chapter 4:

Household Carbon footprints in Maricopa County, AZ

When focusing on household carbon footprints this study distinguishes, as mentioned in Chapter 2.2.2., between three different contributors of CO_2 emissions, namely energy (electricity), consumption behavior and transportation. Therefore it offers a novel approach for calculating and visualizing carbon footprints at the level of individual households aggregated by neighborhoods. The definitions of neighborhoods have been fluid in the literature and even when such definitions are accepted, neighborhood boundaries have been difficult to delineate objectively [EMK01] [SSW04]. The problem of defining a neighborhood has been acknowledged by many scholars but most ultimately resort to aggregating smaller levels of census enumeration districts into larger blocks according to some chosen criteria to form neighborhoods [HDRJ07] [KB03] [FMS08].

This chapter not only presents a new metric for estimating carbon footprint in an urban region at the scale of individual neighborhoods (Section 4.5) but also involves a new form of visualization (Section 4.6) that goes beyond the two-dimensional thematic maps and provides better representation of multidimensional spatial data. This study assumes an area defined by 1 mile by 1 mile grid to be a neighborhood. This gridded spatial extent of Maricopa County was available from a database used for running an urban simulation model called UrbanSim [Wad02]. Aligning the conceptualization of a neighborhood to the 1-mile square grids enabled future carbon footprint calculations from simulated future households that were derived from UrbanSim model outputs. In Section 4.2 a short introduction about UrbanSim is given which illustrates how this work benefits from its output data.

Given that the work on household carbon footprints is mostly concerned about the residential component of carbon emissions, it will not include another important aspect of carbon accounting, which are emissions from industry. However, a component of industrial emissions is included in our accounting strategy since we include the embedded energy and related emissions of all consumables households purchase for their necessary and lifestyle purposes. By shifting the focus from the spatial location of the source of carbon emissions (i.e., production centers) to the location of the source of consumption, this study acknowledges that carbon emissions are equally deleterious regardless of where it occurs and therefore the focus is more on the patterns of consumption rather than production strategies as being among the most significant issues related to carbon emissions.

The author has to admit that this approach, however, does not account for embedded energy related to building construction and carbon emissions from natural gas, water, and sewage disposal. But this strategy also provides a particularly useful and straightforward path to future projections of carbon emissions. This is accomplished with the assumption that technologies of production are static and consumer lifestyle choices remain the same over time (but vary by type of households). Although these are limiting assumptions, the projections provide the upper range of estimates for future emissions considering changes in energy mix and production technologies.

4.1. Study area Maricopa County

Maricopa County, located in the south-central part of Arizona, includes the largest portion of the Phoenix metropolitan (statistical) area and was home to about 3.82 million people in 2010 [Usc11]. Despite the vast urban distention the region is administratively divided into 30 cities, towns, or census designated places and 17 other unincorporated communities (see Figure 4.1).

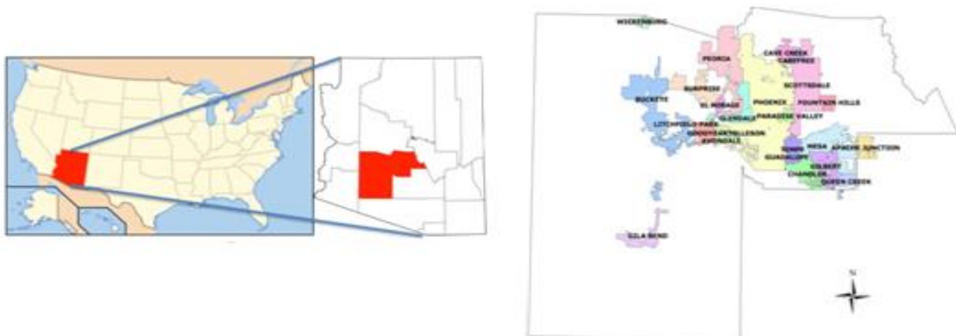


Figure 4.1: Location and Cities of Maricopa County (derived from [Wik11] and authors own sources)

The county is the fourth largest in the U.S. in population, which also makes it more populous than 24 of the 50 states in the Union. It was also the fastest growing county in U.S. from 1990 to 2000. The population build-up has sparked the growth of smaller cities in the county as well. A 2007 Forbes study ranked Buckeye, Surprise, and Goodyear as the 2nd, 3rd, and 4th fastest growing cities, respectively, in the nation [Woo07]. Several of the cities, such as Paradise Valley and Sun City, are relatively small enclaves; others such as Phoenix, Mesa, and Scottsdale are large conurbations. According to unofficial projections, Phoenix is currently the fifth largest metropolitan region in the United States having surpassed Philadelphia sometime in 2005 [Wik11]. Those unique features as well as the pace and character of their growth make Maricopa County an ideal candidate for the longitudinal study of carbon footprints and urban sprawl indicators.

4.2 Data estimation using UrbanSim

Since this work establishes metrics of indicators of sustainability demographic projection data from software-based simulation model called UrbanSim [Wad02] provides the necessary databases for further calculations. In the past planning models were often restricted in terms of interrelations between planning of land use, transportation, and environmental quality or in managing side effects of urban growth such as urban sprawl [Wad02]. UrbanSim was designed to respond to those requirements taking into account various data sources such as Census data[1]. The advantages of this simulation model, in contrast to other planning models and particular in regarding this study, can be stated as follows:

- UrbanSim is probably the only agent-based model[2] of urban growth.
- UrbanSim is an open source software package which is also well documented (easy to implement).
- UrbanSim provides demographic data at the household level which is considered as a crucial requirement within the scope of this work.

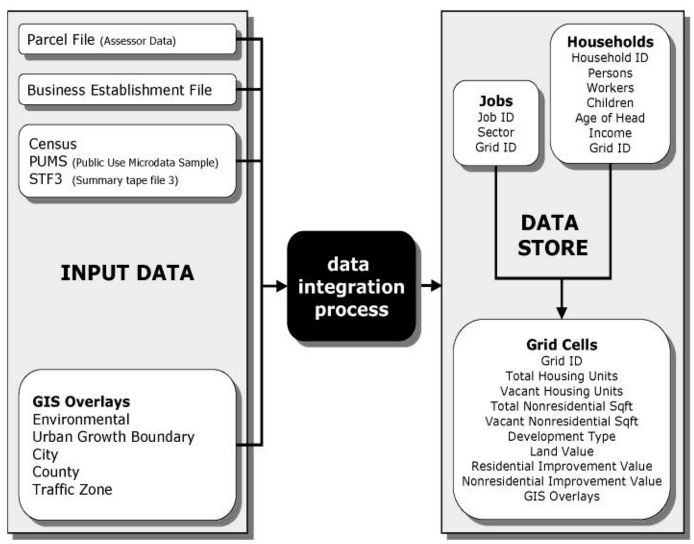


Figure 4.2: Process of data integration in UrbanSim [Mid08]

[1] Since the recent Census data (2010) was not available at the beginning of this research, the following studies are based on Census 2000.

[2] Agent-based modeling can be defined as a computational method which allows researchers to deal with models composed of rule-based agents who interact within a predefined environment. Those models are closely related to multi agent systems and cellular automata. Further information can be found in [GT00] or [BT04].

Further information about the evolution and detailed components of UrbanSim can be found in [BWF08] and [Wad02]. Figure 4.2 illustrates the process of data integration within the model.

Besides the job and grid cell table, the household table consists of demographic characteristics for each household in the metropolitan area which will be fundamental for upcoming work in Chapters 4 and 5. By setting the spatial resolution of the underlying grid cell structure to 1 mile x 1 mile, the output projection tables provide data on future households for each of those cells, including grid cell location and demographic characteristics. Within the scope of the Digital Phoenix Project [Guh11] as one of the first documented applications[3] which has integrated UrbanSim for future predictions of Maricopa County, the simulation was running for a predefined number of years (2000-2030) as well as for multiple scenarios. A detailed description of the scenarios, chosen in this study, is presented in the next Section 4.3.

4.3 Scenarios

In order to demonstrate the utility of both approaches (carbon footprints and urban sprawl indicators) results are calculated for two different development scenarios in Maricopa County. In this manner and in combination with predicted UrbanSim data this study is able to address following questions:

- How do Carbon Footprint and Urban Sprawl numbers develop over a medium-term future?
- How can different policy decisions have an influence on those numbers?
- What are advantages/drawbacks of those scenarios regarding sustainable development?

[3] The prototype application was Eugene-Springfield, Oregon, followed by other cities in the U.S. or in Europe.

In general scenario planning has been a well-established instrument in the field of urban planning for developing more resilient conservation policies, facing and visioning the uncontrollable and uncertain future. Therefore scenarios are considered as “informed speculations that emerge from an exercise in simulation modeling and participatory brainstorming” [Guh09 pp 38-39]. The literature on scenario-based planning is vast but the interested reader might be referred to scholars such as [Kha91] or [Guh02].

As mentioned above the simulated results for the next 30 years offer the possibility of visualizing trends regarding both indicators of sustainability over a medium-term future. The chosen scenarios assume different policy options for dealing with land held in Trust belonging to the State of Arizona.

Congress gifted about 8.4 million acres by granting two sections of each township to benefit common schools when Arizona became a territory and another two sections when Arizona became a state. Today, about 8.1 million acres still remains in the Trust, most of it is outside the boundaries of Maricopa County. The Land Department is the entity charged with the fiduciary responsibility to manage and safeguard the land trust in accordance with the Trust’s mission. The Department is charged with generating revenue for the Trust from this land by disposing appropriate parcels of state land through an auction process and also by the sale of natural products (such as sand, gravel, water and fuel wood), and from royalties from mineral materials. The proceeds are invested in stocks, bonds, and interest bearing securities. The income from such investments is then used to fund education related budget items in Arizona. The availability of large tracts of land around the urban area of Phoenix provides enormous leverage for the state of Arizona to direct future developments.

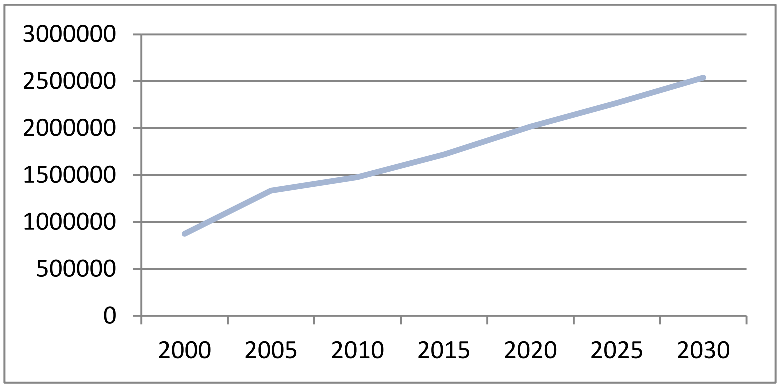


Figure 4.3: Total number of households for each year of predicted UrbanSim data

Since the scenarios chosen for this exercise show the difference in development patterns between allowing state lands to be auctioned as per current rules ("BAU" scenario) and the alternative of freezing all state owned lands in Maricopa county to 2005 levels ("Stateland" scenario), they do not differ regarding total number of predicted households. Figure 4.3 illustrates those total household numbers for the predefined timeframe.

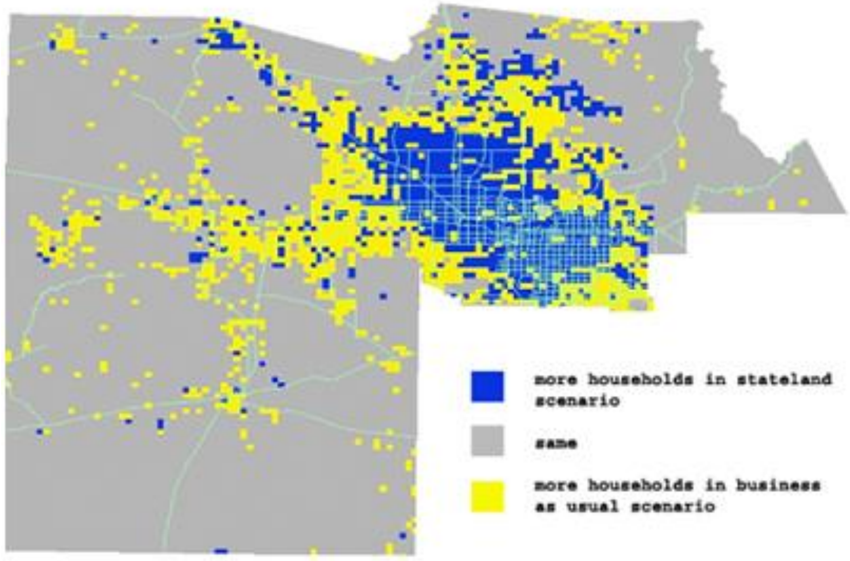


Figure 4.4: Household distribution for the scenarios "stateland" and "business as usual"

Regarding sprawl indices the scenario with no development on state lands shows a higher density of households in the urban core (Figure 4.4), especially around transportation corridors.

The “business as usual” scenario seems to provide more sprawling and leapfrog development. By considering multiple indicators of Urban Sprawl this work will refer to those characteristics in Chapter 5. Within the scope of CO_2 emissions, the carbon intensity of the two patterns of future growth in Arizona is also expected to be different due to vastly different transportation options as well as different types of development (single-family vs. multi-family).

4.4 “Back to the envelope” calculation

Before embarking on the household consumption-based neighborhood level approach to estimating carbon emissions, this chapter starts by calculating roughly what these emissions could be for the region using average values. By estimating the gross emissions from electricity and automobile travel a point of comparison with the later calculations based on household consumption is given. For this "back of the envelope" calculation this study utilizes the average carbon dioxide emissions for each kilowatt-hour of electricity consumed and the average emissions per year for a typical automobile. According to the Energy Information Administration, the average CO_2 emission for electricity generation in Arizona is about 1.05 lbs per kilowatt-hour [Use09]. Based on the U.S. Department of Energy, one can assume that the CO_2 emissions estimate for a typical car is 8.3 tons per year. These figures were applied to the average household in Maricopa County that consumes about 13000 kilowatt-hours of electricity per year and possesses two cars [PHM+09]. The results of this analysis show that the emissions for household electricity use are about one-third (ca. 3.98 million tons of CO_2) the emissions from automobiles used by these households (ca. 11.86 million tons of CO_2).

In addition, by accounting for household growth estimates (Figure 4.5), those CO_2 emissions in 2030 will be almost four times that of 2000 (ca. 11.58 million mt of CO_2 from household electricity and ca. 35.04 million mt of CO_2 from automobiles).

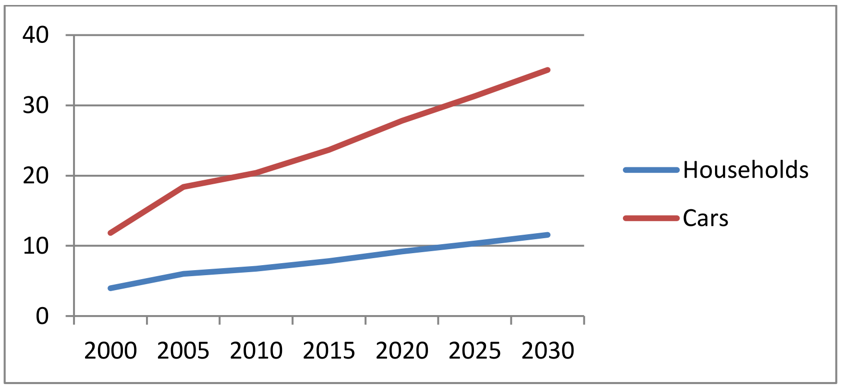


Figure 4.5: Total CO_2 emissions (tons) by different units per year

Figure 4.6 breaks down the total household emissions in Maricopa County by type of household. The figure highlights the fact that a Hummer (a General Motors manufactured automobile), which travels 15000 miles per year generates almost as much CO_2 as a large single family home in that time.

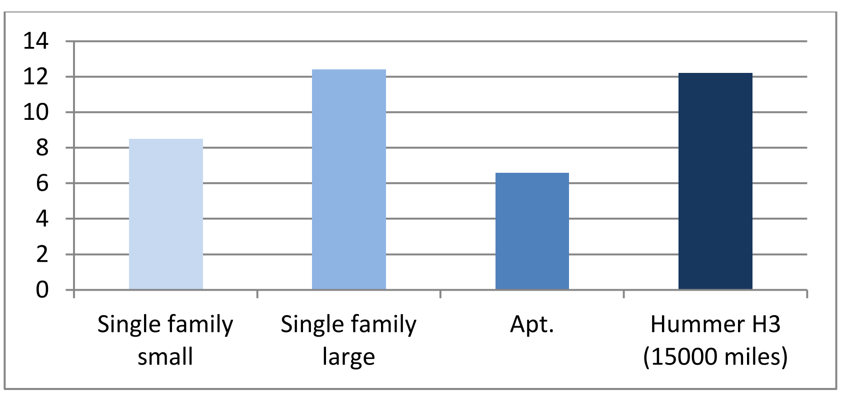


Figure 4.6: Emission numbers (tons) in a context (single unit)

4.5 Calculation of different dimensions

As illustrated in Figure 2.2, the definition of a household's carbon footprint consists of three dimensions. For each of those dimensions, energy and resulting carbon emissions are estimated by different types of households. The households are characterized by differences in income, race, and household size. Those three attributes were chosen because they offer the widest variation in household types and often are related to other attributes such as age of household head. UrbanSim provides this input data for the predefined timeframe as well as for each scenario. Table 4.1 presents the range of variation in each of the three household attributes noted above. Based on those attributes carbon emissions for the different dimensions of a total household carbon footprint are calculated in the upcoming sections of this chapter. Subsequent to separate approaches for each dimension the resulting numbers can be combined respectively their predefined household attributes.

Income class:	1: < $10000
	2: $10000 - $19999
	3: $20000 - $34999
	4: $35000 - $49999
	5: $50000 - $70000
	6: > $70000
Race:	White/non-Hispanic
	Hispanic
	African American
	Asian/Pacific Islander
	American Indian
	Other
Family size:	1 - 8

Table 4.1: Household attributes

In Section 4.5.4 detailed emission numbers are provided depending on different household categories.

4.5.1. Operational energy used in households

Regarding the first dimension "operational energy used in households" the 2005 Residential Energy Consumption Survey (RECS) is used to derive CO_2 emissions from operational energy used in households [Use10b]. This survey provides detailed information about household energy use (in Btu – British thermal unit) for different types of households. It includes:

- space heating,
- air conditioning,
- water heating,
- refrigerators,
- other appliances and lighting[4].

Given that different fuels vary in their carbon dioxide emission coefficients this work separates different forms of energy end uses to calculate the total amount of CO_2 emissions for operational energy use.

Fuel	**Emission Factor in kg CO_2 / MMBtu**
Natural Gas:	53.06
Electricity:	94.7
Propane:	63.1

Table 4.2: Fuel CO_2 Emission Coefficients

[4] It does not include primary electricity and wood. While site energy is reported to be energy directly consumed by end users, primary energy is defined as site energy plus energy consumed in production and delivery of energy products [Use10b].

The coefficients shown in Table 4.2 only include those fuels, which are mostly consumed in Maricopa County (based on the 2005 Housing Characteristics Tables for West Census Division Mountain [Use10b].[5] By breaking down the total household energy end use consumption into its different categories this work also takes advantage of 2005 Housing Characteristics Tables [Use10b], which provides information about the percentage of households using different kinds of fuels. Therefore one knows that 66% of households in Maricopa County use natural gas for space and water heating, while 26% use electricity and only 8% use propane. For air conditioning, refrigerators and other appliances, and lighting one can assume that 100% of all households use electricity.

Given this distribution in addition to the emission coefficients c_t in Table 4.2, the total annual emission numbers CO_2 for a certain household category (H_i) can finally be calculated as follows, considering that E is the energy end consumption and T = {natural gas, electricity, propane}:

$$CO_2(H_i) = \sum_{t \in T} E_t(H_i) * c_t \tag{4.1}$$

Therefore total results of carbon emissions in kg of CO_2 are illustrated in Figure 4.7 by different family sizes.

Those results support the hypothesis that the number of persons is mainly responsible for the amount of energy used within a household, especially by highlighting the gap between single households and family households. Since space heating and other appliances and lighting seem to be the main contributors for all types of households the biggest differences regarding different household sizes can be detected in water heating, air conditioning and other appliances and lighting.

[5] For other fuels such as fuel oil or kerosene, data was withheld either because the Relative Standard Error was greater than 50 percent or fewer than 10 households were sampled [Use10b].

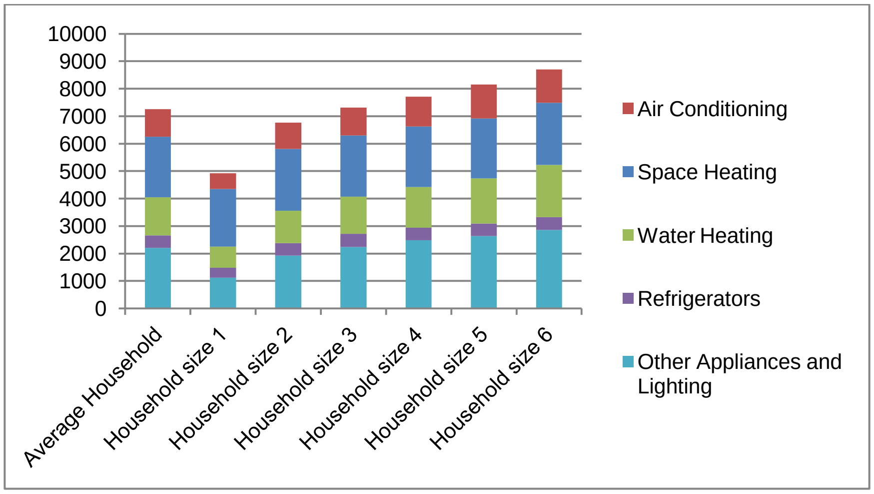


Figure 4.7: Emissions in kg of CO_2

A reasonable argument for constant refrigerator emission numbers could be the fact that the number of installed refrigerators within one housing unit is usually independent from the size of a family. In contrast, the constant emission numbers in space heating seem to be unreasonable due to the assumption that the size (space) of a housing unit is usually dependent on the household size (persons). Nevertheless since those numbers are derived from RECS, they provide a detailed distribution of operational household energy in Maricopa County.

4.5.2. Embedded energy in products consumed

Every product consumed by individuals and households requires some amount of energy to procure, manufacture, and dispose of. The type of energy expended during the life cycle of the product determines the amount of carbon emissions generated by its consumption.

However, the carbon emissions associated with a product can vary for several reasons. It can be manufactured using different primary energy sources, such as hydroelectric, natural gas, coal, etc., leading to different levels of carbon emissions.

Similarly, different modes of transportation with different energy requirements may have been utilized in various stages of a products life cycle. In addition, production and distribution efficiencies may vary greatly among facilities.

This study adopts the methodology used by the UC Berkeley's Renewable and Appropriate Energy Lab (REAL) and the Cool Climate Network [Coo11a] to determine the typical carbon intensity of household consumables like food, goods, and services. This methodology benefited from CO_2 emission factors derived from Economic Input-Output Life Cycle Assessment – EIO-LCA created by the Green Design Institute at Carnegie Mellon University EIO-LCA, [Eio10].

Food:	
Cereals and bakery products	741 $gCO_2/\$$
Meat, fish and protein	1452 $gCO_2/\$$
Dairy	1911 $gCO_2/\$$
Fruits and vegetables	1176 $gCO_2/\$$
Miscellaneous foods	467 $gCO_2/\$$
Others:	
Clothing	436 $gCO_2/\$$
Furnishings & Household items	459 $gCO_2/\$$
Services	178 $gCO_2/\$$

Table 4.3: Carbon intensities for different consumables

Besides the data on carbon content of household consumables, goods and services (Table 4.3), this approach relies on the Consumer Expenditure Diary Survey (CES) for the year 2006 [Usl08] to estimate the consumption patterns by different households by types noted in Table 4.1. For each household category the annual expenditure, in US Dollars, on specific consumption items and services is estimated.

In total the CES contains expenditure data for various items. Summarized in item groups one can generally distinguish between expenditures for food, housing, transportation, furnishing, clothing, health care, entertainment, personal insurance, cash contributors, and misc expenditures. Some groups are covered by the other dimensions within this work (transportation in “energy used in travel” or “entertainment” partially within electricity consumption in “operational energy”), other such as health care, personal insurance and cash contributors are considered as inappropriate in terms of determining carbon intensity. Therefore by accounting for food, furnishing, clothing and partially for housing in terms of household services this dimension covers almost all[6] allegeable expenditure items respecting CO_2 determination.

The CES data allows developing separate consumption baskets for the different types of households. This data, however, is based on the national sample since the smaller set of Maricopa County households in that sample does not provide enough information for all the household types which have been included in this analysis. In addition consumption patterns for goods and services of selected Maricopa County households by type are compared to similar households in the national sample. The differences were insignificant enough to enable using national consumption coefficients ($) for each of the consumption categories. Figures 4.8 - 4.10 illustrate the annual expenditure distribution and resulting CO_2 emissions for households by the attributes income, race and family size used in this study.

[6] Item group “misc expenditures” could not be defined in order to make an appropriate statement

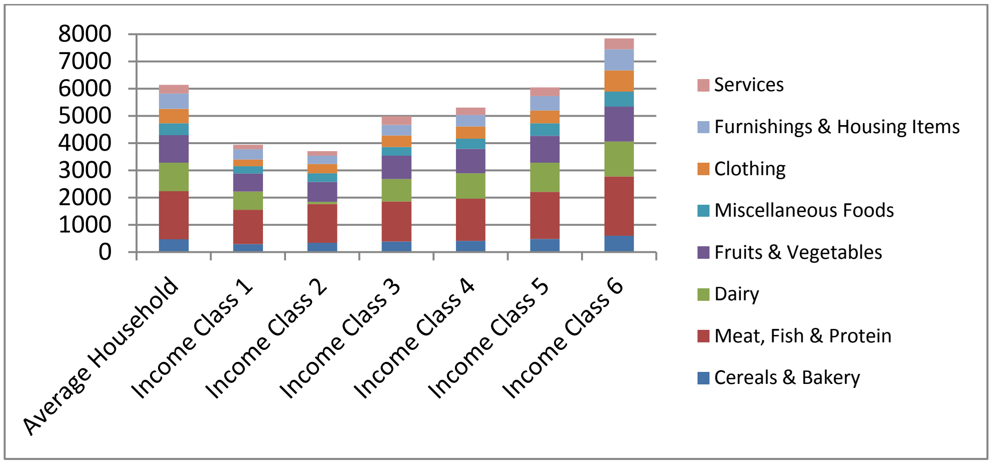


Figure 4.8: Annual expenditure emissions in kg of CO_2 by income classes

Distinguished by different income classes (Figure 4.8) one can generally point out that the higher the income level of households the higher are their expenditure emissions. Noteworthy is the gap between income classes 5 and 6 (1800 kg of CO_2) and therefore the fact that the average household emissions are located between those classes 5 and 6.

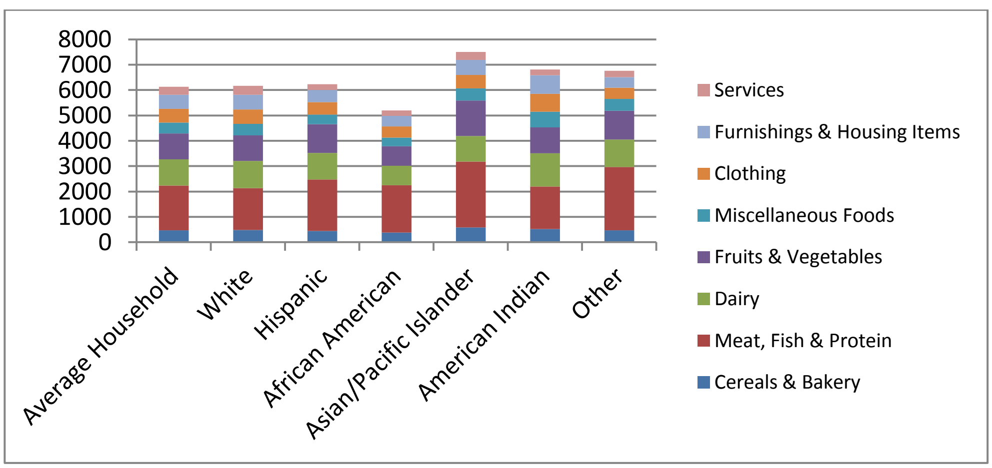


Figure 4.9: Annual expenditure emissions in kg of CO_2 by race

By breaking down the expenditure emission numbers by the ethnical background of households (Figure 4.9), the differences can be generally regarded as marginal.

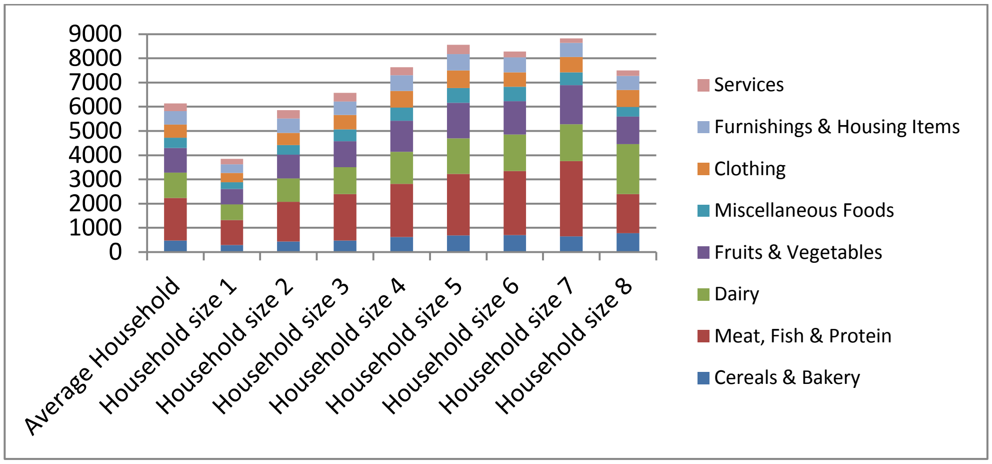


Figure 4.10: Annual expenditure emissions in kg of CO_2 by household size

The only product emissions which vary across the races are "meat, fish and protein" and "fruits and vegetable", especially in African American and Asian households. It can be also stated that those ethnical groups are considered as the lowest (African Americans) and the highest (Asian/Pacific Islander) contributors in terms of expenditure emissions. Focusing on expenditure emissions depending on household sizes (Figure 4.10) the emission numbers show pretty much the same pattern in variation like the emissions from operational energy, presented in Section 4.5.1. In conclusion, this approach illustrates the importance of income level as well as sizes of households in terms of expenditure emission distribution. In reverse, this study points out that the household attribute race can be regarded as a minor contributor in terms of expenditure emission variation.

4.5.3. Energy used in travel

The third dimension energy used for travel has been studied extensively, partly because of the availability of good data sources and the need for municipalities to monitor and plan for adequate levels of transportation services. Maricopa Association of Governments (MAG) is the county entity in this study area responsible for transportation planning. MAG undertakes periodic travel surveys for the region to assess travel demand by mode, link, origin destination choices, and by demographic characteristics of travelers. This study utilizes the Maricopa Regional Household Travel Survey, conducted by NuStats (under contract from MAG) from February through December 2001. The survey provides data from 4018 households in Maricopa County and includes the basic household characteristics which have been used to define household types within this whole approach.

The street network file "Arizona Roads 2000" (provided by MAG) is utilized to geocode the households in the survey and derive information about travel behavior by household type. The information extracted includes average miles traveled per week by household type, by mode and by trip purpose.

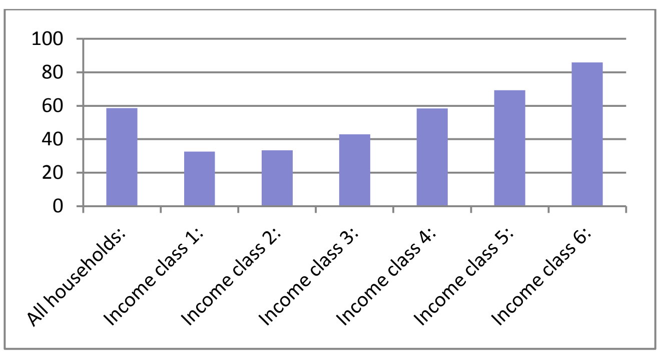


Figure 4.11: Miles per week by income class

The preliminary results suggest that household travel behavior varies by income, household size and by race / ethnicity. Household income seems to be a significant factor determining the amount of travel in miles per week. The average weekly travel of households earning over $70,000 in annual income in Maricopa County is more than twice that of households earning $35,000 or less (Figure 4.11).

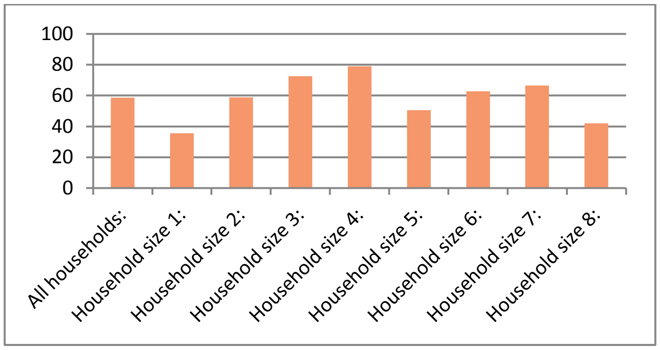


Figure 4.12: Miles per week by household size

The amount of weekly travel shows a bimodal distribution for variation in households by size (Figure 4.12).

Miles traveled per week increases for additional household members up to a total of 4 members. Larger households travel less than 3 or 4 member households, with 8 member households traveling only slightly more than single households.

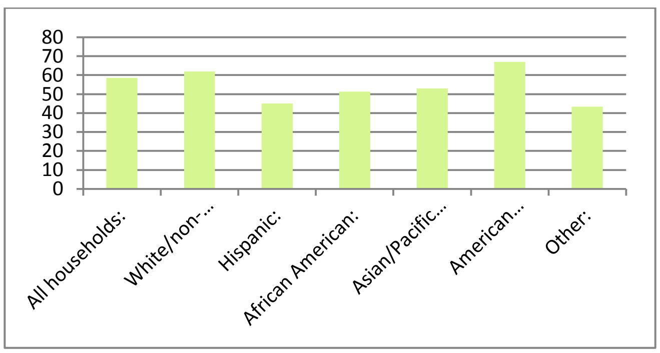


Figure 4.13: Miles per week by race

In terms of variation by race and ethnicity, the data show that Non-Hispanic White and Native American households drive more than all other groups (Figure 4.13). Translating vehicle miles traveled by mode to CO_2 emissions requires knowledge of emissions coefficients per unit distance traveled. As mentioned above, the travel survey provides information about mode choice for each household trip. These different modes of transportation included in the survey are car, bus, motorcycle, shuttle service, taxi, bicycle, and walking. Due to insufficient information for motorcycles and shuttle services for different household categories (fewer than 5 trips were sampled for single households), these two modes were removed from our analysis. In addition, we did not consider walking or bike trips since they do not produce carbon dioxide emissions. The modes included in our analysis are private automobiles, bus, and taxi. For each of these three modes [Bra07] provides information about grams of CO_2 per passenger mile (Table 4.4).

Cars/Taxis:	371g CO_2 /passenger mile
Buses:	299g CO_2 /passenger mile

Table 4.4: CO_2 coefficients modes of transportation

Overall carbon emissions would also include vehicle life cycle emissions. The distribution of vehicle life cycle emissions is provided by Austin et al. [ARSL03], who compared carbon intensities of the leading automobile companies by measuring the CO_2 emissions associated with their current sales and profits.

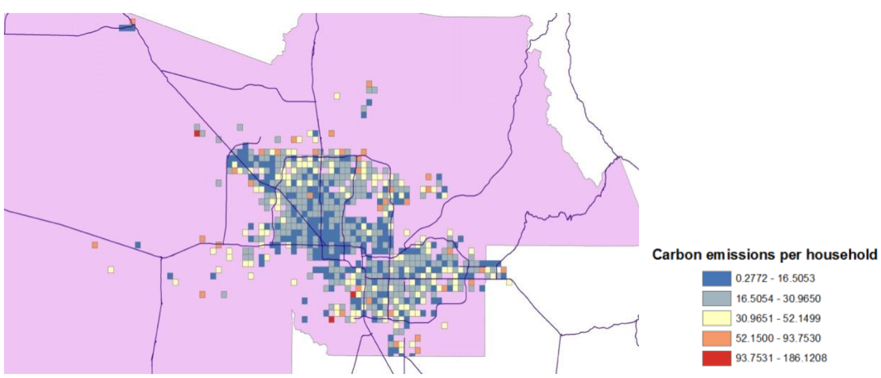


Figure 4.14: Carbon emissions per household in kg of CO_2

However, it is difficult to assign life-cycle emission for automobiles to households without knowing how long they have owned the vehicle and whether the vehicle was obtained new or had changed hands several times. Therefore, this study only focuses on emissions caused by operation of the vehicles.

The travel survey output data provide trip information for a period of 48 hours, therefore emission numbers, illustrated in Figure 4.14, show carbon emissions in kg of CO_2 per household for this 2-day period.

These emission figures have been derived from vehicle miles traveled (VMT) information available in the travel survey by mode of travel after assuming a typical emission factor for each mode of travel for each mile. It may be noted from Figure 4.14 that, besides household attributes, location and land use patterns also contribute to differences in carbon emissions in travel. Households with the highest emissions are typically located away from the central areas and are often areas with lower than average densities. This result corroborates previous findings by other researchers [ER08] [HM10].

4.5.4. Total carbon emissions for individual households

Finally emissions from all three dimensions are combined in order to present a total household carbon footprint by different type of households. In the previous steps separate emission numbers by each dimension for different types of household were calculated. Figure 4.15 presents the distribution of 34 chosen examples, measured in kg of CO_2.

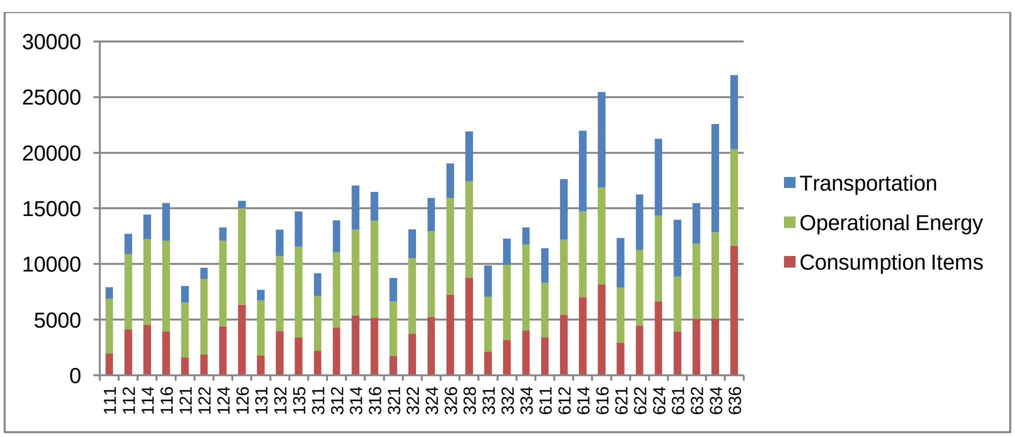


Figure 4.15: Distribution of CO_2 emissions in kg by type of household

Cat.	Cereals & Bakery	Meat Fish & Protein	Dairy	Fruits & Veg.	Service	Housing Items & Furnish.	Misc Food	Cloth	Space Heating	Air Con.	Water Heating	Refrigerator	Other Appl. & Lighting	Transp.	Totals
111	168	554	396	374	69	170	156	78	2.093	576	767	369	1.117	1.017	7.828
112	301	1.453	729	754	185	394	266	50	2.242	956	1.177	464	1.922	1.818	12.661
114	694	1.196	902	752	71	128	383	390	2.208	1.079	1.485	454	2.481	2.229	14.063
116	378	1.515	931	490	188	-	149	282	2.179	1.240	1.642	464	2.632	3.378	15.187
121	143	387	363	342	16	168	67	137	2.093	576	767	369	1.117	1.491	7.900
122	101	415	368	274	81	89	423	134	2.242	956	1.177	464	1.922	1.024	9.537
124	366	1.456	943	950	98	198	269	136	2.208	1.079	1.485	454	2.481	1.163	13.151
126	619	1.884	958	1.306	-	1.017	539	-	2.258	1.212	1.907	464	2.860	639	15.662
131	157	776	279	305	21	104	127	31	2.093	576	767	369	1.117	974	7.665
132	318	1.611	489	728	68	458	259	41	2.242	956	1.177	464	1.922	2.340	13.034
135	342	1.512	452	659	-	114	198	131	2.179	1.240	1.642	464	2.632	3.165	14.600
311	220	471	451	427	142	194	189	116	2.093	576	767	369	1.117	2.052	9.069
312	370	1.267	808	767	295	348	280	142	2.242	956	1.177	464	1.922	2.896	13.792
314	579	1.860	989	907	53	195	487	304	2.208	1.079	1.485	454	2.481	3.987	16.764
316	634	2.052	579	1.391	13	310	165	44	2.258	1.212	1.907	464	2.860	2.603	16.446
321	153	316	199	392	117	159	249	146	2.093	576	767	369	1.117	2.093	8.601
322	352	1.304	565	864	90	206	173	204	2.242	956	1.177	464	1.922	2.606	12.922
324	431	1.782	976	1.192	95	276	271	220	2.208	1.079	1.485	454	2.481	2.983	15.713
326	399	2.724	1.604	1.527	94	261	439	175	2.258	1.212	1.907	464	2.860	3.122	18.871
328	578	3.133	2.583	2.138	-	-	194	112	2.258	1.212	1.907	464	2.860	4.470	21.797
331	180	857	218	334	39	193	171	133	2.093	576	767	369	1.117	2.821	9.737
332	297	1.112	432	589	75	222	199	247	2.242	956	1.177	464	1.922	2.361	12.047
334	431	1.477	737	730	76	295	238	49	2.208	1.079	1.485	454	2.481	1.553	13.245
611	273	932	526	544	196	408	271	245	2.093	576	767	369	1.117	3.105	11.178
612	444	1.439	952	991	273	612	397	322	2.242	956	1.177	464	1.922	5.436	17.305
614	625	1.869	1.387	1.283	308	625	536	377	2.208	1.079	1.485	454	2.481	7.262	21.602
616	762	2.441	1.801	1.336	194	676	626	340	2.258	1.212	1.907	464	2.860	8.572	25.108
621	251	430	544	684	254	204	152	433	2.093	576	767	369	1.117	4.473	11.915
622	345	1.515	654	865	100	191	229	578	2.242	956	1.177	464	1.922	5.010	15.669
624	587	2.038	1.064	1.019	225	860	440	417	2.208	1.079	1.485	454	2.481	6.896	20.837
631	302	1.123	829	615	195	273	176	432	2.093	576	767	369	1.117	5.108	13.543
632	368	1.916	667	863	141	599	254	247	2.242	956	1.177	464	1.922	3.657	15.227
634	521	1.742	794	798	164	291	325	500	2.208	1.079	1.485	454	2.481	9.734	22.079
636	1.247	5.229	1.500	2.049	46	302	1.194	47	2.258	1.212	1.907	464	2.860	6.644	26.911

Table 4.5: Distribution of annual emissions in kg of CO_2 by household category

All those households are coded into categories (see Table 4.1) depicted by a three-digit code. The first digit denotes the income class, the second digit represents the race/ethnicity of the head of household and the last digit denotes the family size. By estimating the expenditure emissions on national scale the choice of household types was no longer limited to only 34 different types of household [PGH+10b] and therefore this study can provide total emission numbers for a large band width of different household types. In addition, as mentioned earlier in Section 4.5, Table 4.5 provides detailed distribution of those different emission dimensions for our 34 randomly chosen household categories. By analyzing those resulting values the early assumptions are proven right that primarily income and family size are responsible for carbon footprint variations. As expected single households with the lowest income class (111, 121 and 131) are the smallest emitters with annual carbon emissions of approximately 8 tons of CO_2. In contrast the biggest emitters, according to our approach, are large households with high income (636 = approximately 27 tons of CO_2 per year). To illustrate the relevance of income levels one can exemplarily point out to household category 116 with only 15 tons of annual emissions. The same situation can be found regarding household sizes (the gap between single households and households with at least 6 persons is nearly 9 tons of annual emissions, e.g. 111 and 116). A closer look at Table 4.6 illustrates those assumptions. While approaches like Drummond [Dru10], Aldy [Ald07] are referring to "per capita" emission numbers, this study applied this kind of approach to the average results for the household categories. The average per capita emission number is 5.48 metric tons per year for this approach, while e.g. Drummond is quoting 9.3 tons for sectors Residential and Transportation in 2007. The largest contributors for high emission households are space heating and transportation. Especially the results for the dimension transportation are notable because the only significant attribute seems to be household size.

Income	**Average Emission**	**Standard Deviation**
1	12.36	3.106313681
2	13.04	3.992242822
3	14.29	3.315794222
4	15.51	3.524821117
5	16.6	4.288699406
6	19.14	4.428554819
Race	**Average Emissions**	**Standart Deviation**
1	16.74	4.444231722
2	15.19	3.909003323
3	14.37	4.330633222
4	14.66	4.046183577
5	15.18	5.862911277
HH_Size	**Average Emission**	**Standard Deviation**
1	9.58	1.718470629
2	14.21	2.714012468
3	14.74	2.666768793
4	16.74	2.90445812
5	18.29	3.618095891
6	19.63	3.844990753
7	19.39	3.232806232
8	17.36	4.674073115

Table 4.6: Average emission numbers (tons) and Standard Deviations per household attribute

But as mentioned above the spatial location must also be considered as an important contributor to variations in carbon emissions.

4.5.6 Carbon Footprints in Maricopa County

In the previous sections a metric for carbon footprints at the level of individual households was introduced depending on particular household attributes. Since those results were derived from various survey data this section presents an application to illustrate predicted UrbanSim data on county level. Introduced in section 4.2, UrbanSim provided, within the scope of the Digital Phoenix Project, demographic characteristics for Maricopa County households for 30 years as well as for two scenarios (BAU and Stateland). By utilizing ArcGIS in order to intersect and summarize the resulting household emissions numbers (Section 4.5.5) within the grid cell boundary file of UrbanSim (1 mile x 1 mile), this approach is finally able to identify the location of each household within the study area.

A detailed description of those working steps is presented as follows:

1) According to previous calculation, total household Carbon Footprints depending on household attributes (income, race and size) are stored in a database (.dbf files).

2) UrbanSim provides data on household characteristics (among others necessary attributes income, race and size) within the household table files (.dbf files) as well as a predefined grid cell boundary file (.shp file).

3) Since the resulting emission numbers of “energy used in travel” are strongly dependent on household locations, linear regression (within SPSS) is used in order to apply those results to Maricopa County households.

   Detailed definitions and description of ordinary least squares regression models can be found in studies such as Stone and Brooks [SB90] or Hayashi [Hay00]. Significant variables within the travel survey output data within this work are presented in Table 4.7. As a result, total miles and therefore total carbon emission numbers for dimension “travel” for all UrbanSim household tables can be calculated.

	Regression coefficient B	β	Significance
(Constant)	2.951		0
Income level	0.112	0.19	0
Distance to city center[7]	0.014	0.083	0
Location Gilbert	0.262	0.033	0.059
Location Glendale	0.359	0.034	0.053
Location Goodyear	0.64	0.036	0.04
Rural location	0.124	0.044	0.013
Hispanic ethnicity	-0.156	-0.051	0.005
Other ethnicity	-0.451	-0.048	0.006

Table 4.7: Dependent Log of total miles

4) By using ArcGIS household carbon emissions for dimensions "operational energy used in households" and "embedded energy in products consumed "are assigned to their respective households in Maricopa County. As a result a new household attribute (sum of all three dimensions) is included in the original UrbanSim household table.

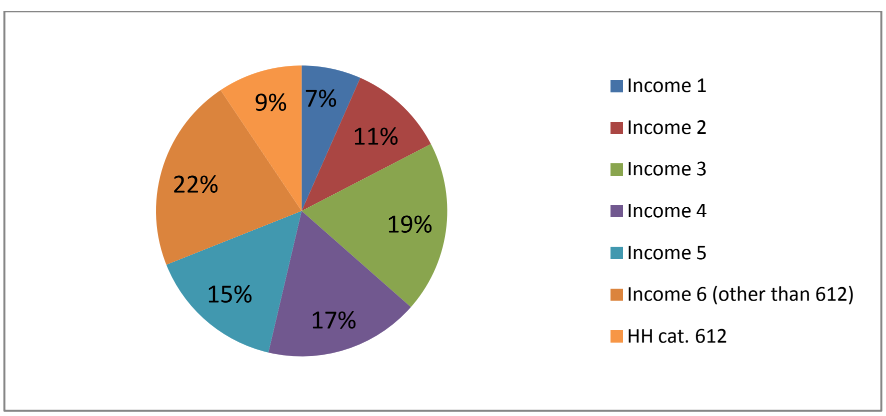


Figure 4.16: Distribution of households per income level in Maricopa County in 2010

[7] Downtown Phoenix was chosen to represent the center of Maricopa County.

Figure 4.16 shows the resulting distribution of households per income level for Maricopa County in 2010. One can detect household category 612 (income level 6, white, household size 2) as the most existing household (138956 households) within this specific year.

5) Finally all households within one grid cell are summarized and subsequent those summarized household data sets are joined with the grid cell shape file.

As a result this approach provides total Carbon Footprints depending on household categories by taking into account the spatial component as well. Figure 4.17 exemplarily illustrates the spatial distribution of total carbon emissions for Maricopa County in 2010. As expected the highest concentration (red) is located within the city areas or next to the highways, due to the high household density in those regions.

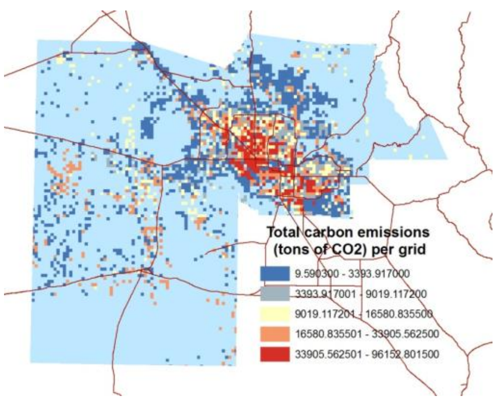


Figure 4.17: Total CO_2 (tons) per grid in 2010

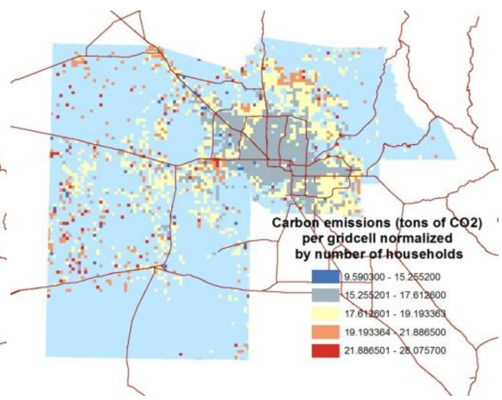


Figure 4.18: Average CO_2 (tons) per grid in 2010

By normalizing the total emission numbers by the amount of households per gridcell Figure 4.18 provides carbon emissions for Maricopa households detached from urban densities. In contrast to Figure 4.17 the biggest emitters are located outside the urban areas and not necessarily in close distances to highways.

While both illustrations represent the scenario "BAU" in the year 2010, it is interesting to compare those results to the second scenario "Stateland" in order to detect differences caused by policy decision. By applying the same procedure to the UrbanSim household table "Stateland 2010", Figures 4.19 and 4.20 present both total tons of CO_2 as well as average tons of CO_2 for the scenario "Stateland" in the year 2010. Those results show that the total emission numbers for the scenario "Stateland" does not differ significantly from those for "BAU".

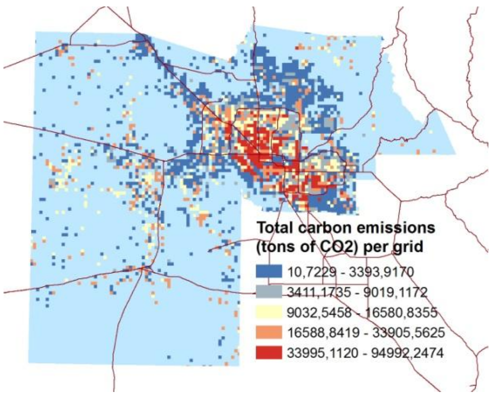


Figure 4.19: Total CO_2 (tons) in 2010 Stateland

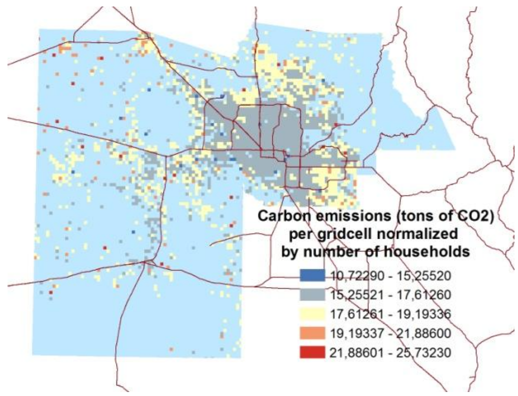


Figure 4.20: Average CO_2 (tons) in 2010 Stateland

Differences can be located in rural areas due to the fact that "Stateland" prohibits future development by freezing all state owned land which is mostly located in rural areas. In contrast to "BAU" there are fewer big emitters. Those who can be detected are also mostly located along highways. Therefore, location and concentration of carbon emissions can be controlled by restricting particular developable land and shifting the action space away from rural environments.

The correlation of distances to the city center and income levels which have been stated as one of the most significant household attributes (Section 4.5.3) is illustrated in Figure 4.21. While total carbon emissions for all income levels increase continuously concerning small distances to the city center, differences can be stated if those distances become larger. The higher the distances of household locations to the center of Maricopa County, the higher is the gap of carbon emissions between income levels of those households.

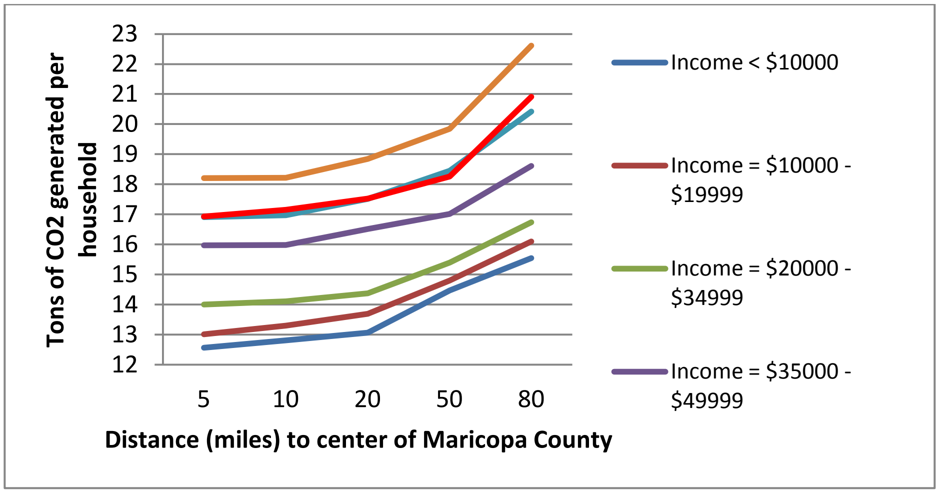


Figure 4.21: Carbon emissions per household dependent on the correlation between distances to the center of Maricopa County and income levels

Noteworthy is the fact that results of household category 612 (as mentioned above the typical household in Maricopa County) are ranked equally to income level 5.

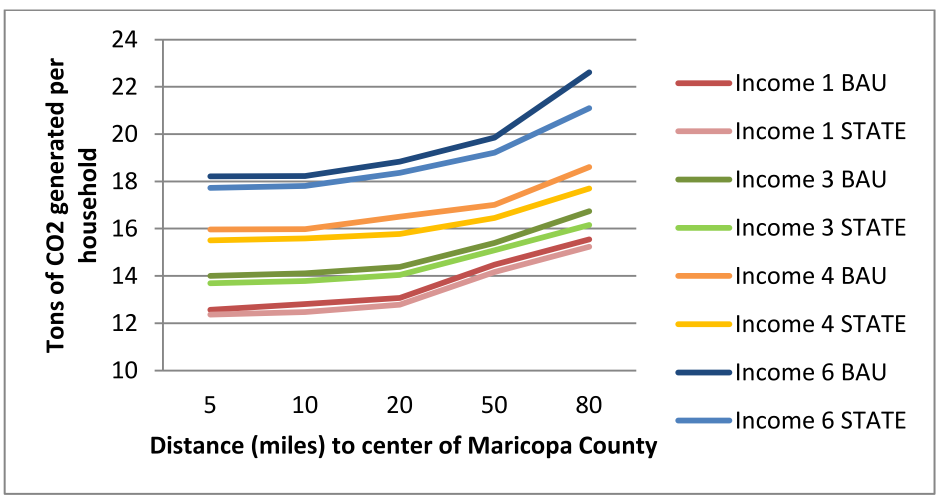


Figure 4.22: Carbon emissions per household dependent on the correlation between distances to the center of Maricopa County and income levels for both scenarios

That shows that all attribute have significant influence on carbon emissions. By comparing results for income level 2 and household category 612 it would imply that other ethnical backgrounds than “white” and different household sizes than “two” must have significantly higher emission numbers. By comparing those results for different scenarios in Figure 4.22 one can state that starting from a distance of ca. 50 miles from the city center the gap between emission numbers of both scenarios by income level increases significantly. Since the Digital Phoenix Project utilizes UrbanSim to provide predicted data for future years, this study is able to simulate future carbon emissions and offer the possibility of visualizing trends in consumption and travel behavior over a medium-term future. By illustrating those emission numbers in Figure 4.23, it becomes obvious that adequate policy decisions will be necessary in order to prevent those inevitable impacts on future Maricopa County.

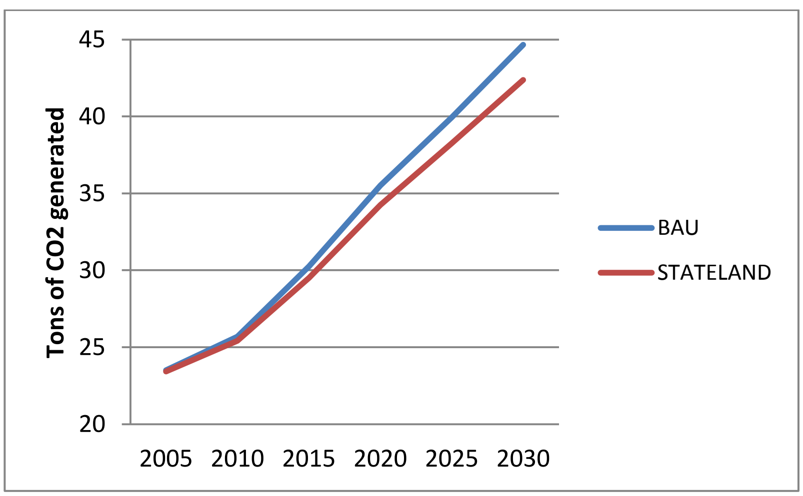


Figure 4.23: Total carbon emissions (both scenarios) for future years

Figure 4.23 presents total CO_2 numbers for Maricopa County from 2005 till 2030. As expected, emission numbers drastically increase in future years in both scenarios. However one can also detect significant differences between both scenarios. While being almost equal in 2005 (23.5 million tons in BAU to 23.4

million tons in Stateland) emission numbers in "Stateland" increase less heavily to the year 2030 (42.3 million tons in Stateland to 44.6 million tons in BAU). A reasonable argument is the fact that scenario "Stateland" is considered to be less sprawl. Household locations are much more concentrated and the distances to the predefined city center are far less in contrast to "BAU" households.

Since detected differences between scenarios are more convincing by considering the locations, Figures 4.24 and 4.25 show exemplarily visual results for both scenarios in 2030. In contrast to figures 25 and 26 those results immediately illustrate the increasing amount of carbon emissions in the year 2030.

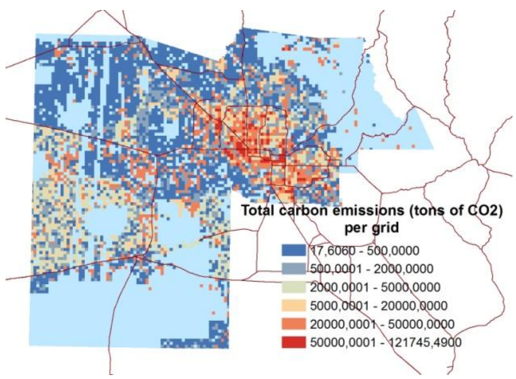


Figure 4.24: Total CO_2 (tons) in 2030 BAU

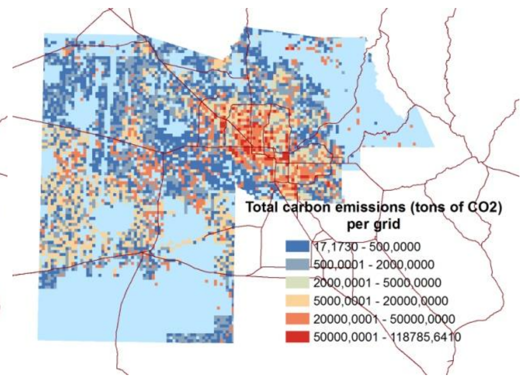


Figure 4.25: Total CO_2 (tons) in 2030 Stateland

Numbers in "Stateland 2030" can be considered as more concentrated, while the emission values in rural gridcells are significant higher in contrast to their respective "BAU" cells. The total portfolio of visual results considering all years and scenarios is provided in utilizing a Graphical User Interface (GUI) in Section 4.6 of this chapter.

4.5.7 Discussion of results

This chapter presents a model to calculate a total carbon footprint for individual households by distinguishing different emission contributors. By providing a high number of different types of households this model is unique and gives the user detailed information to estimate impacts of daily consumption decisions and travel behavior by household type and the resulting amount of CO_2 emissions. Compared to similar approaches in literature [SHHW10] [Web08] the results in this work confirm the generally accepted relevance of expenditure effects on greenhouse gas production and provide in addition detailed information of their emission distribution. Notwithstanding a comparison with other approaches would be limited due to different data limitations, calculation approaches and definitions of emission contributors one can point out that the annual CO_2 emissions of an average household, based on our data, amount to 15.3 metric tons of CO_2. While approaches like [Dru10] and [Ald07] are referring to "per capita" emission numbers, this study applied this kind of approach to the average results for our household categories.

Although focusing on the individual household scale those results agree with the basic statement of Glaeser and Kahn [GK08], who conclude that if one can hold population and income constant, the spatial distribution of the population is also an important determinant of greenhouse gas production. In fact this work shows that differences in household attributes such as income do lead to different carbon emission numbers as well as their spatial location.

A critical discussion of the described approach also includes statements about its limitations. First the number of households and therefore the amount of different household categories for a certain year are equal in both scenarios. While urbanism produces the same kinds of households for each year, scenario output data allocates them to different grid cells depending on their development and land use restriction. However the resulting carbon emissions of those households are also depending on their different locations. By comparing results of two different scenarios this work points out the correlation between emission distribution and policy decisions. A second issue is related to the input data for calculations of different dimensions. Since survey data is used to represent real households in Maricopa County, a potential point of critique could be the fact that all surveys are conducted in different years. The unavailability of more appropriate data has to be cited for that reason.

Nevertheless this approach can be considered as an important step towards informing people about the extent of carbon intensity of their consumption and travel behaviors as well as their lifestyles. Better information will allow individuals and families to make rational decisions and make them carefully consider the impacts of their consumption and travel behavior on the environment.

4.6 Visualizing Carbon Footprints in Maricopa County

Household carbon footprints calculated in previous sections are usually visualized within GIS in two-dimensional representations such as Figures 4.19 or 4.24. Referring to Chapter 3 this work also focuses on visualization techniques which are able to support insight extraction from data for future decision making. The aim is to transform data into information which people can understand immediately. Tufte [Tuf97] pointed out that "there are right ways and wrong ways to show data".

The use of color has been considered as a suitable technique in order to present data in various research fields. Defined as one visual variable [Ber67], color coding has become a standard visualization technique which was already a core element in previous GIS-illustrations within the scope of this work. But one of its major drawbacks becomes obvious by detecting outliers within the data, especially within geographical data. Furthermore, by referring to carbon emissions for predicted data in future years (e.g. CO_2 in 2030, illustrated in Figures 4.20 and 4.25), color coding has limitations in presenting large numbers of data which do not differ significantly. Differences such as between "BAU 2030" and "Stateland 2030" are hard to detect without adding another dimension.

Another possible technique to present geographical data is the use of three-dimensional surfaces. While this method seems to be a perfect fit for illustrating outliers, it would be difficult to see marginal differences within resulting numbers. Therefore, this section provides a new visualization method for carbon footprints and urban sprawl indicators (Chapter 5), which combines advantages from both color coding and three-dimensional representations by using Coons Patches. In addition, it is detached from commercial software systems such as GIS and therefore individual adaptable as well as reproducible.

4.6.1 Surface visualization of Carbon Footprints

The location co-ordinates of the grid cell centre points as well as the calculated indicator values represent the basis for this surface calculation. First a height-field composed of the centers of the grid cells and the selected values as their heights is generated. Based on this height-field, a surface with C^0 continuity can be constructed.

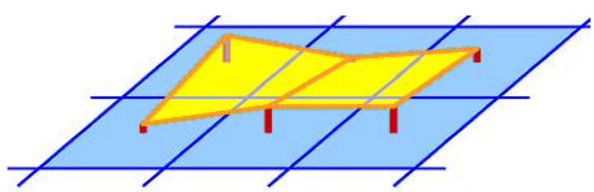


Figure 4.26: Regular grid (blue), dedicated height-field (red/orange) and resulting surface (yellow)

Figure 4.26 shows an example with a regular grid marked in blue, its height field in red/orange, and the resulting surface in yellow.

Following the fundamentals of this underlying structure, the actual visualization technique is distinguished into three modes:

1. Color coded surface in 2D
2. Three-dimensional representation of resulting numbers
3. Three-dimensional surface including color coding

As mentioned above a major purpose of this approach is to create a visualization tool which is detached from commercial GIS software packages. Since a two-dimensional color coded map is considered to be the standard representation method within GIS, the first step of this approach is to illustrate data on a two-dimensional surface by drawing z-values as zeros. Figure 4.27 shows exemplarily carbon emission numbers for Maricopa County in 2010 (BAU).

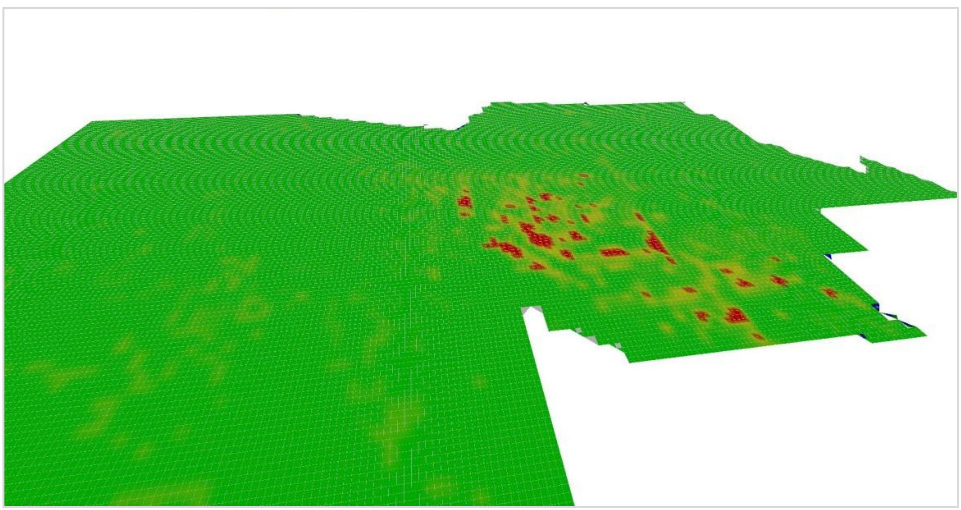


Figure 4.27: 2D surface of total carbon emissions for BAU 2010

The advantage in this approach is the wide range of possible surface settings. While the use of different color schemes is also standard in ArcGIS for drawing quantities, the major benefit of this approach is the ability to change the perspective. Although the resulting “surface” appears two-dimensional, the whole system works in the three-dimensional space. Therefore, any possible perspective can be illustrated. In addition, the classification of illustrated color levels can be customized. For reasons of simplicity Figure 4.28 is exemplarily confined to a limited color scheme.

As a second step a three-dimensional surface is constructed, based on total values of the application.

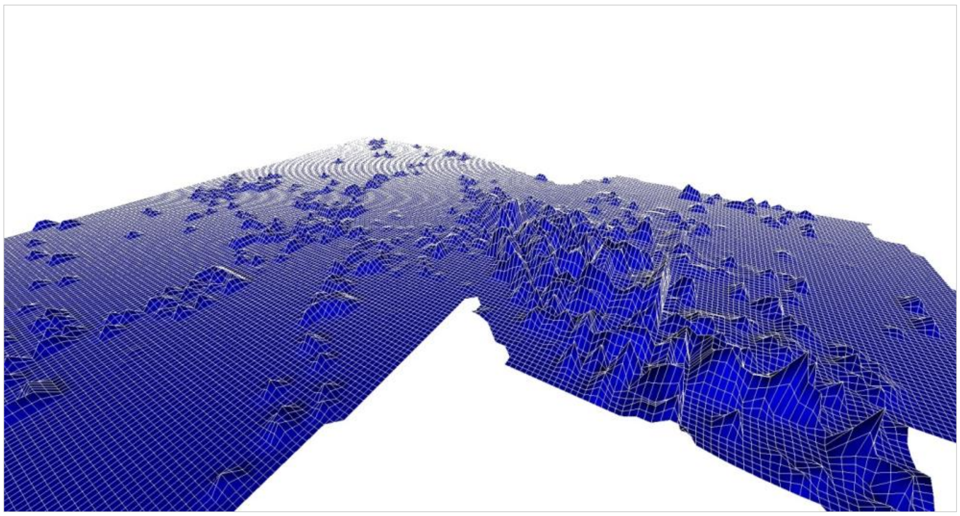


Figure 4.28: 3D surface of total carbon emissions for BAU 2010

Height fields have been chosen in order to show the magnitude of resulting data as well as taking into account the multi-dimensional nature of the data. Consequently, Figure 4.28 illustrates total carbon emissions for households in Maricopa County for scenario BAU in 2010. The high emission concentration in the center of the metropolitan area can be detected easily as well as the outliers within the rural areas. This second mode also offers the possibility to overlay result surfaces of different years or scenarios in order to detect differences in the third dimension (height = emission numbers). Figure 4.29 exemplarily presents total carbon emissions for both scenarios in 2020 using different layer and transparency.

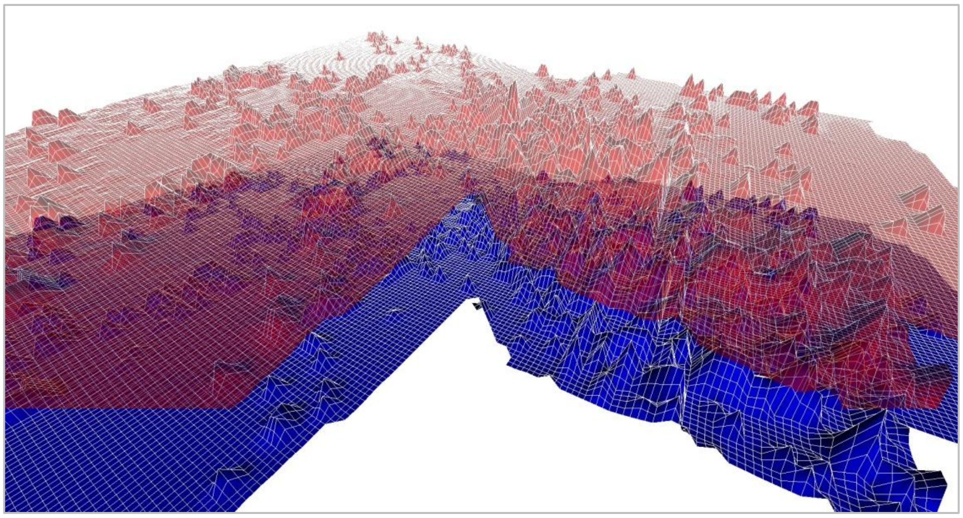


Figure 4.29: Transparent overlay of emissions for BAU 2020 (blue) and Stateland 2020 (red)

Since the use of overlays and transparency shows advantages in an interactive environment where the user is able to navigate through the three-dimensional space, a single screenshot such as Figure 4.29 is not able to highlight those benefits.

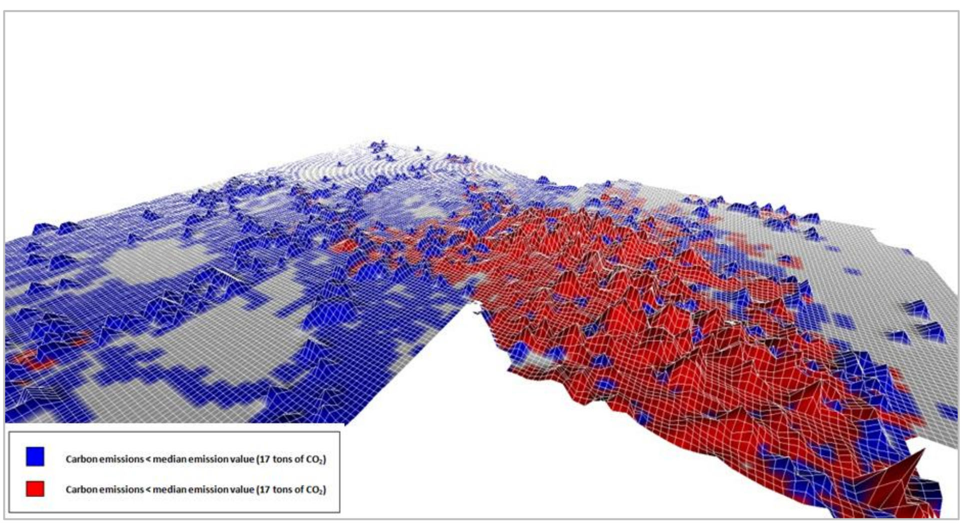


Figure 4.30: Differences between scenario emissions BAU and Stateland in 2020

Therefore a better way to illustrate two data sets is to show only the differences instead of total emission values, as shown in Figure 4.30. The grid cells are colored in blue, if the BAU emissions are higher than the Stateland emissions while they will be colored red, if it is the opposite situation. The height of each grid cell illustrates the amount of these differences. By regarding those results for the year 2020, the development of carbon emission numbers within the two scenarios as well as the benefits of this representation method becomes clearer. The sprawling development in scenario BAU proceeds continuously over the rural territory since almost the whole study area is dealing with increasing carbon emission numbers. Regarding the Stateland scenario, only urban emission numbers increase significantly.

By illustrating only differences this approach provides an adequate way to focus on developments of emission numbers over a defined mid-term future and consequences of different policy decisions.

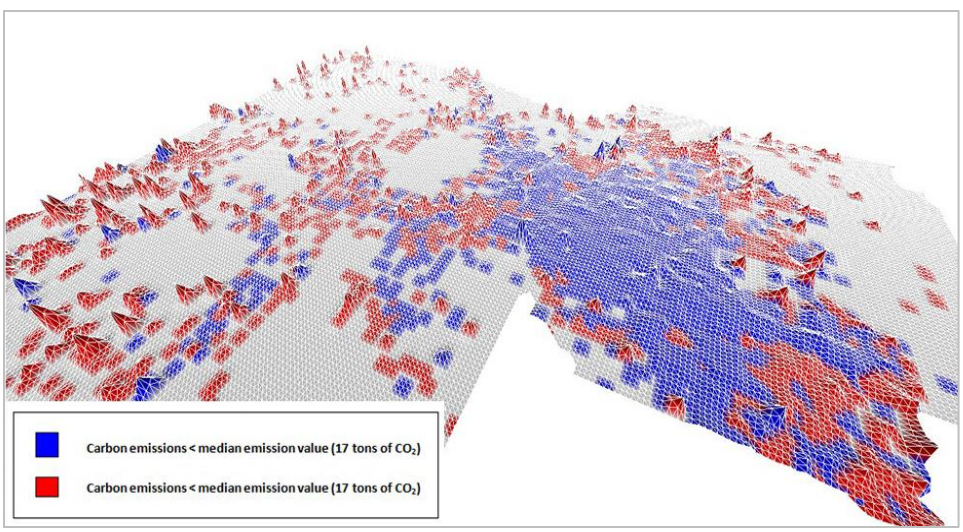


Figure 4.31: Differences in carbon emissions (BAU 2010) per grid from median

Since those numbers are representing total household carbon footprints this visualization techniques is also suitable to present average carbon emissions for Maricopa households detached from urban densities, illustrated above in Figure 4.18 (Section 4.5.6). Therefore, Figure 4.31 shows the differences in average household emissions per grid cell from the median household emission value (17 tons of CO_2) in Maricopa County in 2010.

Here the grid cells are colored in red, if the emissions are higher than the median while they will be colored blue, if it is the opposite situation. As already mentioned the biggest emitters are located outside the urban areas. But in contrast to Figure 4.18, those crucial emissions can be located much easier by using a three-dimensional representation instead of a two-dimensional color map.

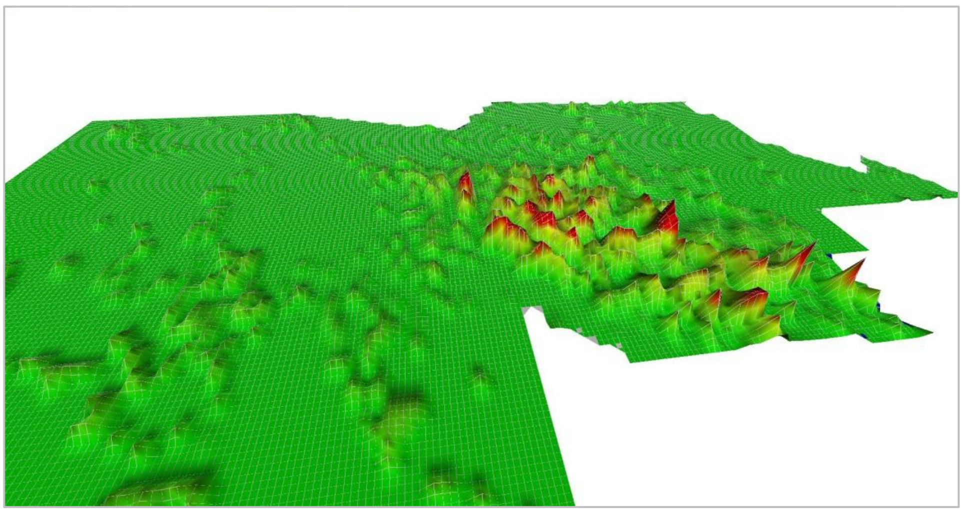


Figure 4.32: 3D surface of total carbon emissions for BAU 2010

So far this approach has provided a two-dimensional representation similar to standard GIS maps as well as three-dimensional surfaces depending on total carbon emission numbers. In a third step both techniques are combined to a three-dimensional color coded surface. Figure 4.32 illustrates total carbon emissions for BAU 2030.

As a result carbon emission, especially high peaks and/or outliers, can easily be located and classified within the study area. By referring to the predefined visualization goals in Chapter 3.2 this approach can be validated as follows[8]:

- Identification: In all three modes emission numbers can be identified in relation to their respective grid cell id, especially by switching between various perspectives. Limitations such as the absence of legends or reference numbers can be considered as neglectable. Since this approach is not detached to commercial software, additional information such as the highway network (see Figure 4.33) can easily be included by implementing into the source code.

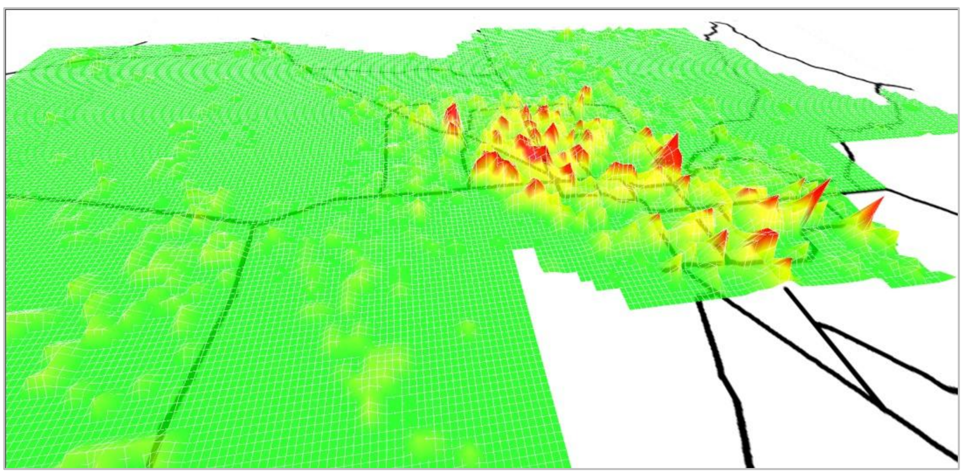


Figure 4.33 : 3D surface of BAU 2010 with underlying highway network of Maricopa County

- (No) Information overload: Illustrations are restricted to essential information concerning the application. Additional information such as an underlying geographical location map (see Figure 6.6 in Chapter 6) can be hided depending on purpose, application and target user group.

[8] The completeness of data is assumed to be an essential requirement in order to provide visualization within this approach

- Suitability: Similar to “Information overload” the amount and type of illustrated data can be customized in order to take account of the users’ knowledge as well as of the purpose of the visualization. Three-dimensional surfaces such as Figure 4.32 seem to be adequate in order to present the amount of emission numbers to the public. In contrast, decision makers and planners would need more detailed information for adjusting policy in terms of future land use development such as illustrated in Figures 4.31 or 4.33. By switching modes and customizing visible information this approach is able to account for all sorts of possible purposes.
- Navigation: In contrast to e.g. GIS representations, this approach allows for navigating (six degrees of freedom) within the three-dimensional space.

Accounting for those goals of visualization this approach represents an efficient way to visualize indicators of sustainability. However the author has to admit that in this version the approach is also limited in terms of data acquisition. Before being able to implement the data into this visualization “tool” a lot of data preparation has to be made, using GIS and database engines. Furthermore the whole approach is based on the predefined spatial resolution of the underlying grid cell structure. Therefore, it is only adaptable for study areas with similar basic structures.

However, by providing various modes to illustrate calculated results, it combines advantages from both color and surface representations and accounts for the demand of utilization of 3D in environmental planning, especially in the context of GIS [RIK+94] [KB98] [DH00].

4.6.2 GUI

In order to communicate resulting findings to the public and, in addition to provide a visualization tool which, users can access those visual representations online through a website. By implementing a graphical user interface (GUI) this thesis also takes account of usability aspects of visualizations, referring to Chapter 3.2. While not elaborating usability factors at this part of the thesis, the interested reader might be referred to scholars such as [SCM99], [Lau05] or [KKUW07].

The GUI provides several options for customizing the multidimensional indicator visualization (see Figure 4.34):

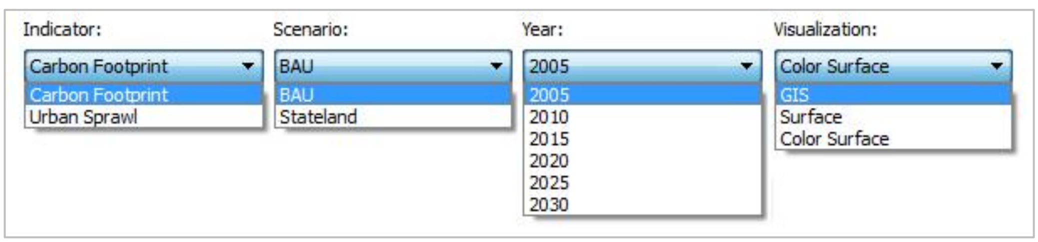


Figure 4.34: GUI attributes for customizing visual carbon footprint representations

The user can chose between the indicator of sustainability[9], the scenarios "BAU" and "Stateland" (Chapter 4.3), the year as well as the final visualization method, based on the three modes introduced in Chapter 4.6.1. Therefore, this tool provides an intuitive way for presenting carbon footprints for Maricopa County (see Figure 4.35).

It is easy to use, well-structured and focuses only on essential information, dependent on user's choices. In Chapter 5, dealing with the second indicator of sustainability "Urban Sprawl", this GUI will be extended in order to provide possibilities to compare and analyze both phenomena.

[9] Utilizing this GUI concerning the indicator Urban Sprawl will be discussed later in Chapter 5.4

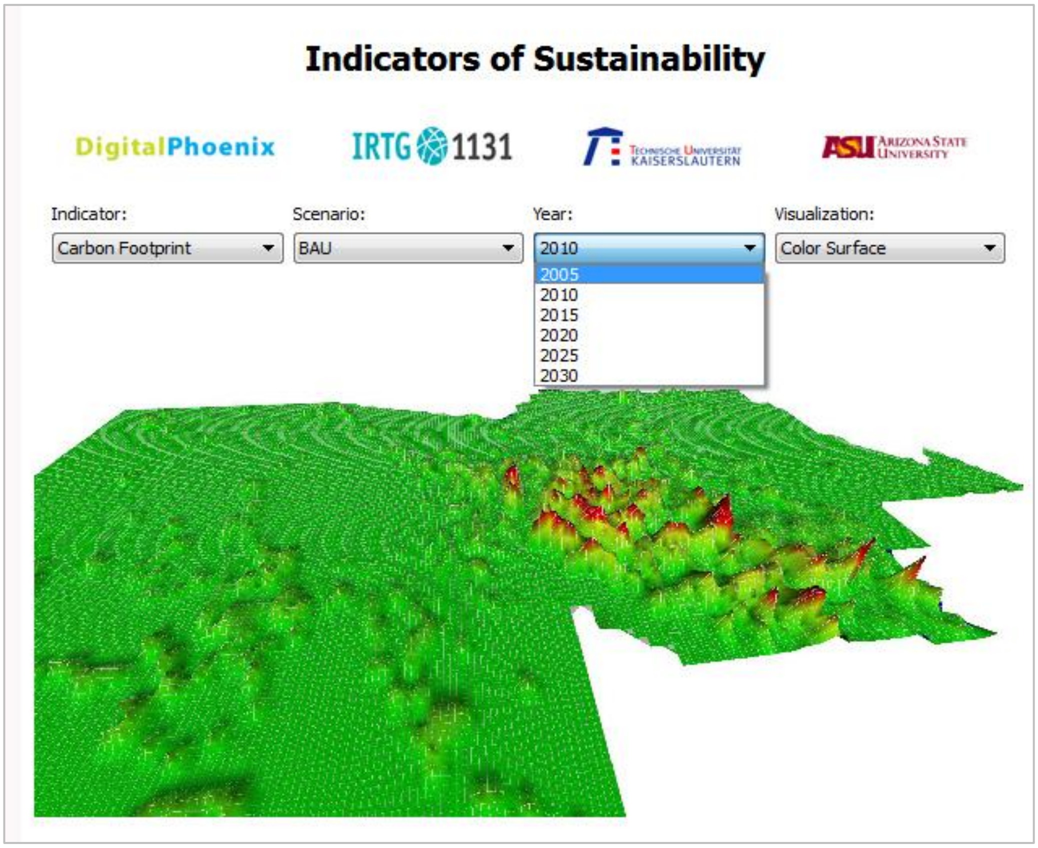


Figure 4.35: Web-based access to visual presentations of indicators of sustainability

Chapter 5:

Urban Sprawl in Maricopa County, AZ

Referring to Chapter 2.3 the phenomenon of urban sprawl is hard to define and it is even more difficult to measure adequate data in terms of specifying indicators to be able to validate sprawl within metropolitan areas. Scholars such as Chin [Chi02] or Couch and Karecha [CK02] define urban sprawl as one phase within the urban growth cycle:

1. growth in the core of the urban area;
2. suburbanization, with fastest growth just outside the core;
3. counter-urbanization, with population in the core and suburbs moving out to more rural areas;
4. re-urbanization, with an increase in population in the core of the urban area.

Urban sprawl could be classified as the third phase of this urban growth cycle [Chi02]. Dividing the process of urbanization into different phases might be useful in terms of defining urban sprawl, but on the other hand this approach has to be argued critically because sprawl might also be associated with any phase due to the fact that distinction between those phases is often overlapping and very blurred [CK02].

In contrast, another group of scholars distinguishes between different characteristics of urban sprawl in order to clarify this phenomenon - spatial patterns, root causes and main consequences [BLD+02]. Based on output data of UrbanSim and its predefined grid cell structure (see Chapter 4.2), this study mainly focuses on spatial pattern corresponding to scholars such as Ewing et al. [EPC03] and Galster et al. [GHRW+01]. By applying the results to future predictions of development as well as to policy driven scenarios (see Chapter 4.3), this study particularly accounts for root causes and main consequences in addition.

5.1 Indicators of Urban Sprawl

While developing a new model for calculating carbon footprints at the level of individual households in Chapter 4, this chapter takes advantage of an existing method [GHRW+01] to measure urban sprawl. To be able to understand sprawl, it is necessary to first determine the indicators of sprawl. The eight dimensions of Galster et al. [GHRW+01] are the basis for the upcoming indicator calculations. They define urban sprawl as "[…] a pattern of land use in an urban area that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, compactness, centrality, nuclearity, diversity, and proximity." As a result they combine numbers for each dimension to an overall sprawl index in order to rank 13 metropolitan areas in the U.S. according to their respective urban sprawl. In other words, for each study area a total number of each dimension is provided which than conclude in one total sprawl index number for the whole area.

In contrast to this approach, this study focuses on providing sprawl indices not only for the total area but for each grid cell. Galster et al. [GHRW+01] and other studies such as Ewing et al. [EPC03] are focusing on aggregate sprawl indices for metropolitan areas. Therefore, not all indicators allow transferring them to an urban neighborhood scale because they were originally built up for total metropolitan areas.

For that reason this study only accounts for dimensions density, continuity, diversity and centrality. However, by considering those four chosen dimensions as sufficient for establishing a sprawl index, this study finds consensus in scholars such as Fulton [FPNH01], Jordan, Ross and Usowski [JRU98] or Lopez and Hynes

[LH03], who point out that density and distances (in this case centrality) are the most important “data” in measuring urban sprawl.

The following definitions are adapted from the work of Galster et al. [GHRW+01] in order to create the common sprawl index:

1. Density (Figure 5.1) is defined as “[…] the average number of households per square mile of developable land in the total area”.

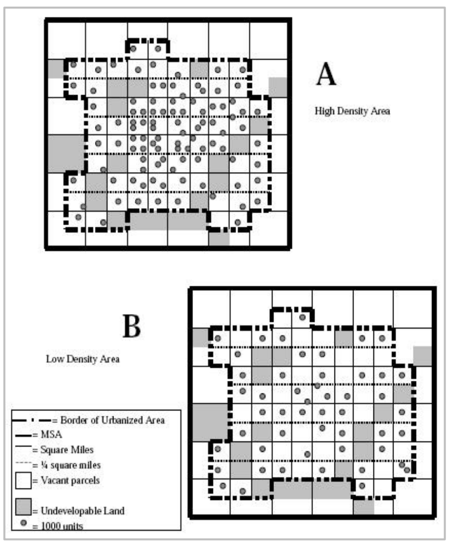


Figure 5.1: Density, [GHRW+01] p. 689

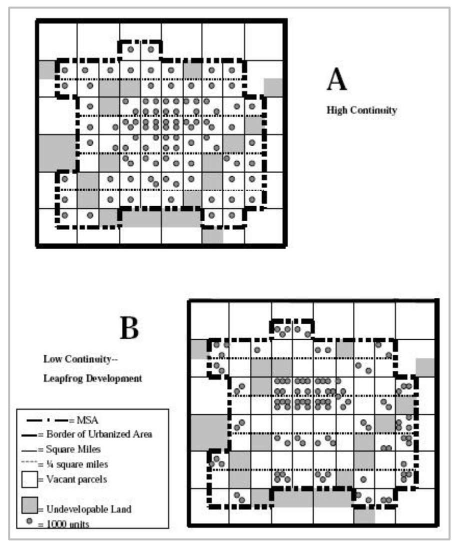


Figure 5.2: Continuity, [GHRW+01] p. 691

Density in this case means the number of residential units per grid cell. As mentioned above, density is the most widely used indicator of sprawl.

2. Continuity (Figure 5.2) can be defined as “[…] the degree to which developable land has been developed in an unbroken fashion throughout the total area.” In other words, leap-frog areas are considered to be more sprawl-like.
3. Diversity or mixed uses (Figure 5.3) is defined as “[…] the degree to which substantial numbers of two different land uses exist within the same area and this pattern is typical throughout the urbanized area.” Greater diversity values

of land uses within a given area are considered as the opposite of sprawl. The intuitive interpretation of this index is the average density of a particular land use (measured by number of households) in another land use's (measured by the number of employments) area.

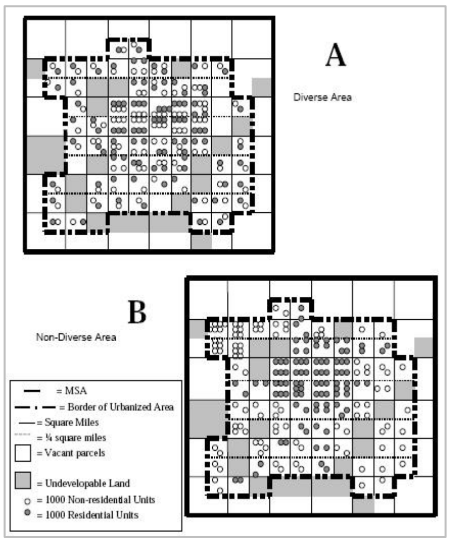


Figure 5.3: Diversity, [GHRW+01] p. 698

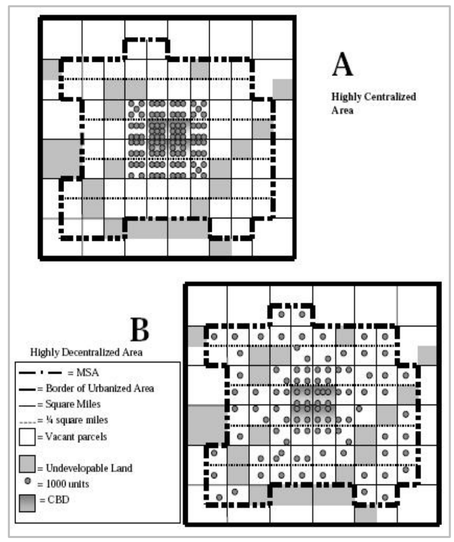


Figure 5.4: Centrality, [GHRW+01] p. 695

4. Centrality (Figure 5.4) is defined as "[…] the degree to which residential and/or nonresidential development is located close to the central business district of an urban area".

Except for centrality, all other indicators have the following attribute: a higher indicator value indicates a lower sprawl factor. Consequently, based on predicted data of UrbanSim (see Chapter 4.2), sprawl indicators are calculated for future years as well as for both scenarios (see Chapter 4.3). Given the input data

- total number of households T (i) per gridcell,
- total number of employments T (j) per gridcell,
- total developable area in Maricopa County (Au),

- single grid cell (m),
- distance between centroids of grid k and grid m (F [k,m]),

each dimension can be operationalized as follows [GHRW+01]:

- Density:

$$D(i)u = \frac{T(i)u}{Au} = \sum_{m=1}^{M}[T(i)m]/Au \tag{5.1}$$

[min = 1000 units per square mile (U.S. Bureau of the Census standard for urbanized areas); max = unlimited]

- Continuity:

$$CONT(i)u \sum_{m=1}^{M}[D(i)m > 39\ hh\ and\ 199\ empl. = 1; 0\ otherw]/M \tag{5.2}$$

- Diversity:

$$Div(j\ to\ i) = \sum_{m=1}^{M}(D(i)m * \left[\frac{D(j)m}{T(j)u}\right])/D(i)u \tag{5.3}$$

- Centrality:

$$CBDDIST = T(i)u(A^{\frac{1}{2}})/\sum_{m=1}^{M}F(k,m)T(i)m \tag{5.4}$$

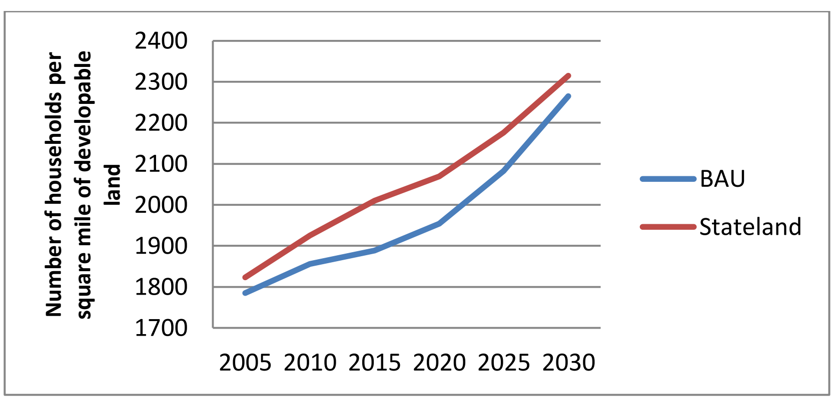


Figure 5.5: Indicator “density” in Maricopa County for scenarios BAU and Stateland

The results for predefined years for each scenario are provided in figures 5.5 – 5.8. As illustrated in Figure 5.5, densities of households per square mile of developable land significantly increase in both scenarios. A reasonable explanation of the decreasing differences in numbers after the year 2020 might be the fact that the output data of UrbanSim reaches the limit in terms of available land area in Maricopa County.

However, Figure 5.5 clearly demonstrates that in terms of household density the scenario “Stateland” has to be considered as lower sprawl. By focusing on the dimension “continuity” in Figure 5.6, this assumption becomes more obvious. Up to the year 2030 the percentage of gridcells with more than 39 households in addition with more than 199 employees increases significantly stronger in “Stateland” (about 15 %) in contrast to scenario “BAU” (about 9%).

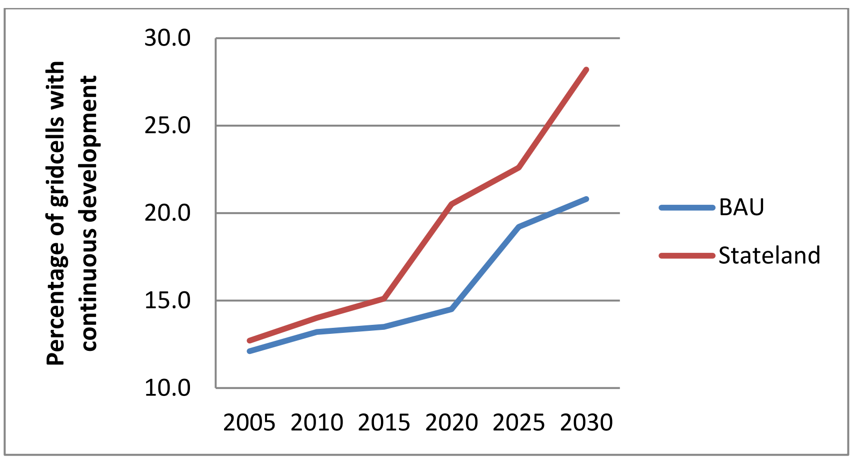


Figure 5.6: Indicator “continuity” in Maricopa County for scenarios BAU and Stateland

This situation is quite different in dimensions “diversity” (Figure 5.7) and “centrality” (Figure 5.8). Certainly the assumption of a lower sprawl in “Stateland” is generally certified by those dimensions (higher numbers in diversity and lower numbers in “centrality” for “Stateland”) but by looking at the trend of both lines, the differences are neither significant nor are they indicating any contrary development over time.

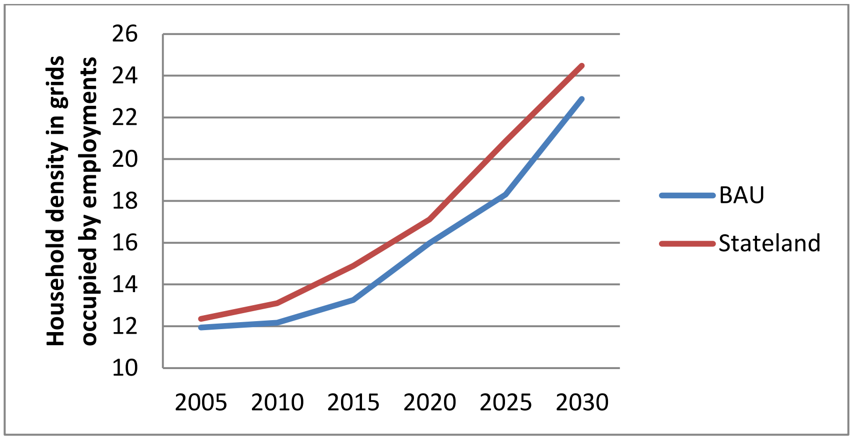


Figure 5.7: Indicator "diversity" in Maricopa County for scenarios BAU and Stateland

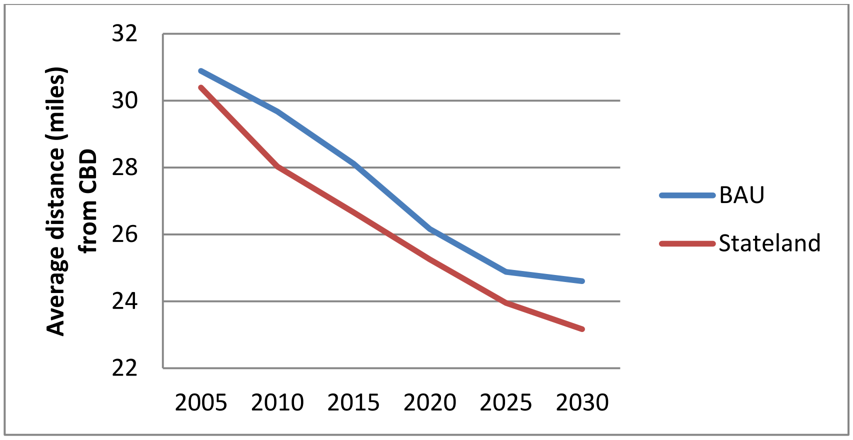


Figure 5.8: Indicator "centrality" in Maricopa County for scenarios BAU and Stateland

By utilizing this approach, which provides single numbers for the whole study area, those results for the four chosen indicators of urban sprawl clearly illustrate following findings regarding future years as well as scenarios "BAU" and "Stateland" for Maricopa County. Independent of any scenario, the predicted outcome of UrbanSim testifies a decreasing sprawl development for Maricopa County. This has to be considered very critical because it would mean that

Maricopa County in 2030 is confronted with far less sprawl than it was stated in 2005.

This allows for three conclusions:

a. In 2030 the study area is simply facing less urban sprawl.
b. The predicted data of UrbanSim is not adequate and sufficient enough to account for dealing with the phenomenon of urban sprawl.
c. Since the approach by Galster et al. [GHRW+01] was implemented in order to rank sprawl values of different metropolitan areas, it may not be suited for future development simulations.

Denying conclusion a) and b), a reasonable argument can be given considering conclusion c). The dimensions of Galster et al. [GHRW+01] are strongly connected to the density of household, stated above. But in those metrics the minimum number of household densities is stated as 1000 units per square mile. Gridcells with lower number of units are not taken into account. Thus, in contrast to Galster et al. [GHRW+01], this study provides sprawl indices not only in total but also for each single gridcell in order to break down urban sprawl to the neighborhood scale.

Nevertheless, by splitting up urban sprawl into different dimensions, it becomes obvious that the scenario “Stateland” indicates a huge improvement in fighting urban sprawl, since those results clearly illustrate lower sprawl number in comparison with scenario “BAU”. Furthermore, dealing with different dimensions becomes necessary because therefore the resulting combined sprawl-index does not rely on single dimensions which may be misleading in some cases (e.g. Figure 5.7 or 5.8).

5.2 Urban Sprawl in Maricopa County

Since this approach is limited to one number for each dimension for the whole study area, it is not possible to detect single locations with high or low sprawl values or even to visualize them geographically. As already mentioned, the purpose of Galster et al. (2001) was to rank different metropolitan areas by means of those single sprawl indices. But in order to validate urban sprawl within one of those metropolitan areas, further adjustments in those urban sprawl metrics become necessary.

Therefore, as one of the major contributions, this study focuses on sprawl indices on the neighborhood scale by defining:

- $Density(i)m = D(i)m$ (5.5)
  (household density per grid cell is already given as input data)

- $Continuity(m) = D(i)m > 39 \; and \; D(j)m > 199 = 1; 0 \; otherwise$ (5.6)
  [min = 0; max = 1]

- $Diversity(m) = D(i)m * [D(j)m/T(j)u]$ (5.7)
  [min = 0; max = max $D(i)m$ observed in any area occupied with j]

- $Centrality(m) = F[k,m]$ (5.8)
  (distances to the nearest CBD are already given as input data).

Finally, those gridcell-based results are combined to one total “sprawl index” for each grid cell. Since previous results represent total numbers for the calculated sprawl indicators, results for the gridcell-based approach are normalized in order to provide reasonable and comparable sprawl indices. One has to note that by summing up those single dimension numbers, all indicators become an equal weight[1]. Table 5.1 illustrates both basic attributes and normalized sprawl dimension indices for sample gridcells in 2010.

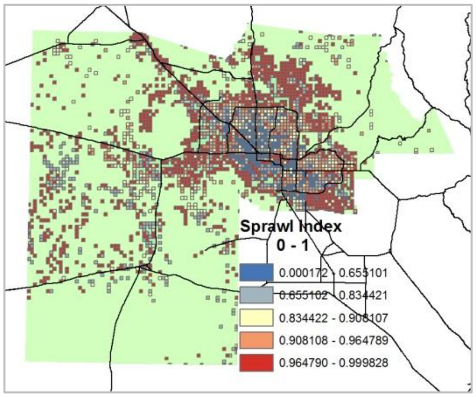
Grid ID	No. hh	No. employ.	Grid area in square miles	Distance to nearest CBD (miles)	Density Index	Diversity Index	Centrality Index	Continuity Index	Total Sprawl Index
6313	49	57	0.9996	0.66	0.887	0.506	0.03	0	0.355
6314	39	58	0.9996	0.19	0.992	0.396	0.01	0	0.349
6315	693	844	0.9996	0.42	0.993	0.483	0.02	1	0.624
6316	349	538	0.9996	1.02	0.881	0.382	0.04	1	0.577
6317	370	587	0.9996	1.63	0.940	0.371	0.07	1	0.595
6318	453	680	0.9996	2.50	0.936	0.392	0.11	1	0.609
6319	889	1118	0.9996	3.45	0.922	0.468	0.15	1	0.635
6320	3728	3515	0.9996	3.85	0.847	0.624	0.17	1	0.660
6321	1887	2030	0.9996	3.59	0.360	0.547	0.16	1	0.516
6322	3020	2470	0.9996	2.91	0.676	0.719	0.13	1	0.630
6323	3377	3059	0.9996	2.15	0.481	0.649	0.09	1	0.556
6324	1491	918	0.9996	1.15	0.420	0.955	0.05	1	0.606

Table 5.1: Sample grid cell attributes and resulting indices for both dimensions and total urban sprawl in Maricopa County, 2010 (indices have ranges from 0 = low sprawl to 1 = high sprawl)

Table 5.1 impressively shows the need for a multidimensional strategy in establishing an overall sprawl index. For example, gridcell *6314* shows high index number in density but low indices in the remaining dimensions. Alternatively, gridcell *6324* shows low indices in density and centrality but high numbers in diversity and continuity. Therefore, it appears necessary to account for multiple dimensions instead of reducing urban sprawl to only one aspect. Those findings are also highlighted by Figures 5.9 and 5.10, which illustrate and compare resulting

[1] Since literature does not provide comprehensive rankings on indicator rankings, statements about the different weightings of single dimensions are not subject of this study.

sprawl indices for Maricopa County for dimension density (Figure 5.9) and combined dimensions (Figure 5.10) in scenario "BAU" 2010.



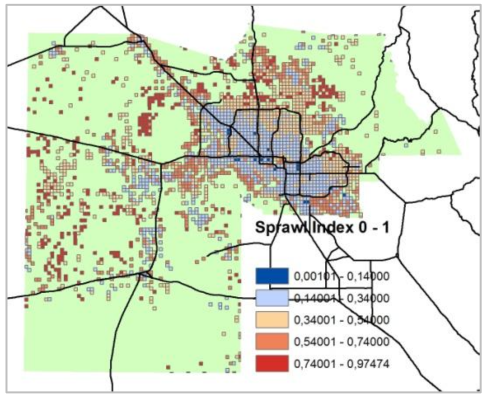


Figure 5.9: Density Index for Maricopa County in BAU 2010

Figure 5.10: Total Urban Sprawl Index for Maricopa County in BAU 2010

By focusing on household density, one can find that sprawling neighborhoods are located in the suburbs and along the highways, especially in the northern part of Phoenix metropolitan area. However, one also finds particular neighborhoods near the heart of the metropolitan region, especially south of I-10 to have high sprawl values. This calculation suggests that sprawling neighborhoods predominate in the suburbs but are not exclusive to them. By defining urban sprawl based on all dimensions (Figure 5.10), the distribution of sprawling neighborhoods changed significantly[2]. Thus, reducing urban sprawl to only one dimension has been indicated as inappropriate and could lead to wrong argumentations and effect future planning decisions.

As illustrated in Figure 5.11 and in comparison to Figure 5.10 scenario "Stateland" produces vastly fewer sprawl numbers in the suburbs. Therefore, restricting state owned land for future development has positive impacts in fighting urban sprawl in Maricopa County.

[2] Due to high household densities within BAU 2010 the classification in Figure 5.10 had to be changed in order to receive comparable results in sprawl indices.

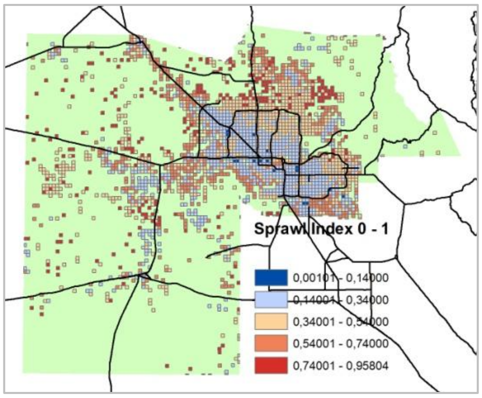


Figure 5.11: Total Urban Sprawl Index for Maricopa County in Stateland 2010

When working with different dimensions, it becomes interesting to interrelate them in order to detect possible dependencies. The correlation between household densities and distances to the next Central Business District (CBD), which both has been considered as the most important indicators of urban sprawl, is illustrated in Figure 5.12.

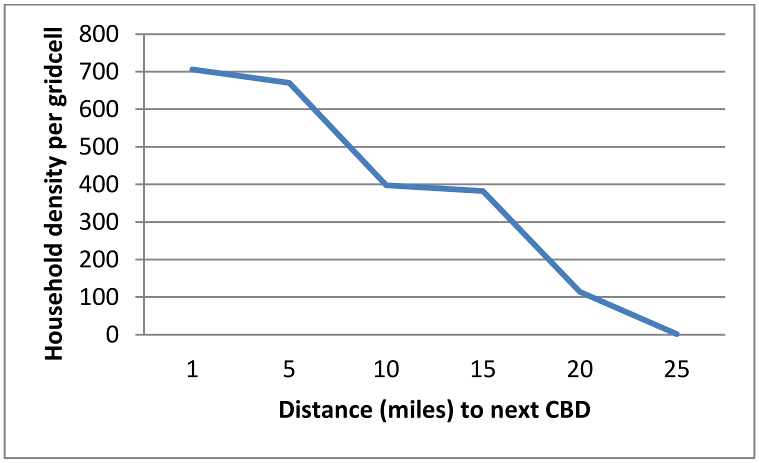


Figure 5.12: Correlation between household densities and distance to the next CBD in Maricopa County 2010

As expected, one can point out that the higher the distance from single gridcell from the next CBD is located, the lower is the household density within this particular gridcell.

Similar to the carbon footprint calculations in Chapter 4.5.6, predicted UrbanSim data is utilized to present future developments in urban sprawl for both scenarios. Figures 5.13 and 5.14 illustrate the combined urban sprawl index for the year 2030 and clarify the positive impact of policy decisions on future land use development.

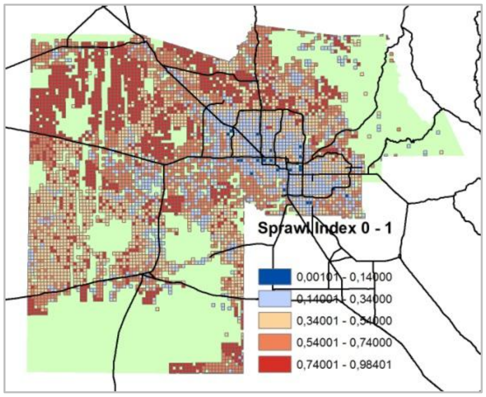


Figure 5.13: Total Urban Sprawl Index in BAU 2030

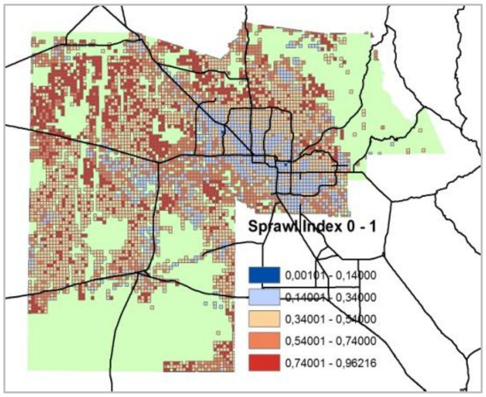


Figure 5.14: Total Urban Sprawl Index in Stateland 2030

5.3 Discussion of results

By introducing a sprawl index for each grid cell, this study takes into account the number of households and employments within each grid cell as well as cell size and distance to the nearest Central Business District (city centers). In contrast to studies like Ewing et al. [EPC03] or Galster et al. [GHRW$^+$01] sprawl indices are implemented at the neighborhood scale. Sprawl indices are established by combining single indicators density, continuity, diversity and centrality. This multi-dimensional approach admittedly benefits from Galster et al. [GHRW$^+$01] but further focuses on neighborhoods in contrast to total numbers for the whole study area. Therefore, it provides sprawl locations and, in addition of scenario modeling, future development in those locations. Furthermore, this method can easily be adapted to other study areas for comparing urban sprawl in different metropolitan areas.

5.4 Visualizing Urban Sprawl in Maricopa County

Introduced in Chapter 4.6.1, the three-dimensional visualization method using Coons Patches is utilized in order to illustrate resulting sprawl indices for Maricopa County. In the following, result surfaces for total urban sprawl indices are illustrated regarding both future years and different scenarios.

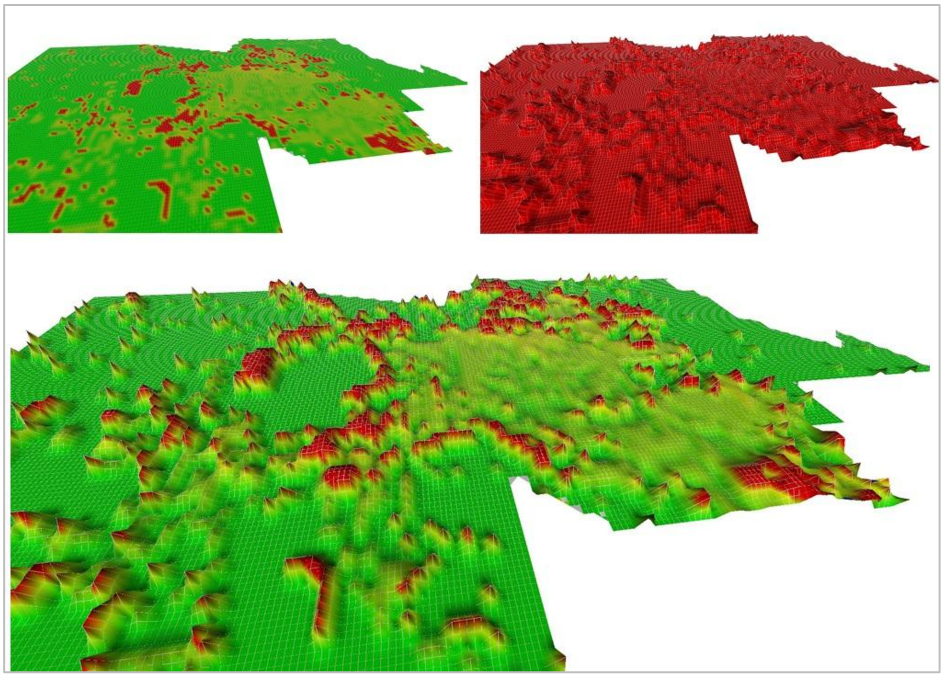


Figure 5.15: Three modes of visualization of Urban Sprawl Indices for scenario BAU in 2010

Figure 5.15 illustrates urban sprawl indices for scenario “BAU” in 2010. In contrast, Figure 5.16 presents those indices for scenario “Stateland”. By comparing both Figures, one can immediately point out differences related to gridcells. For the user’s convenience one can chose between different visualization methods. The total portfolio of visual urban sprawl results is provided online through a webpage similar to results for carbon footprints (see Chapter 4.6).

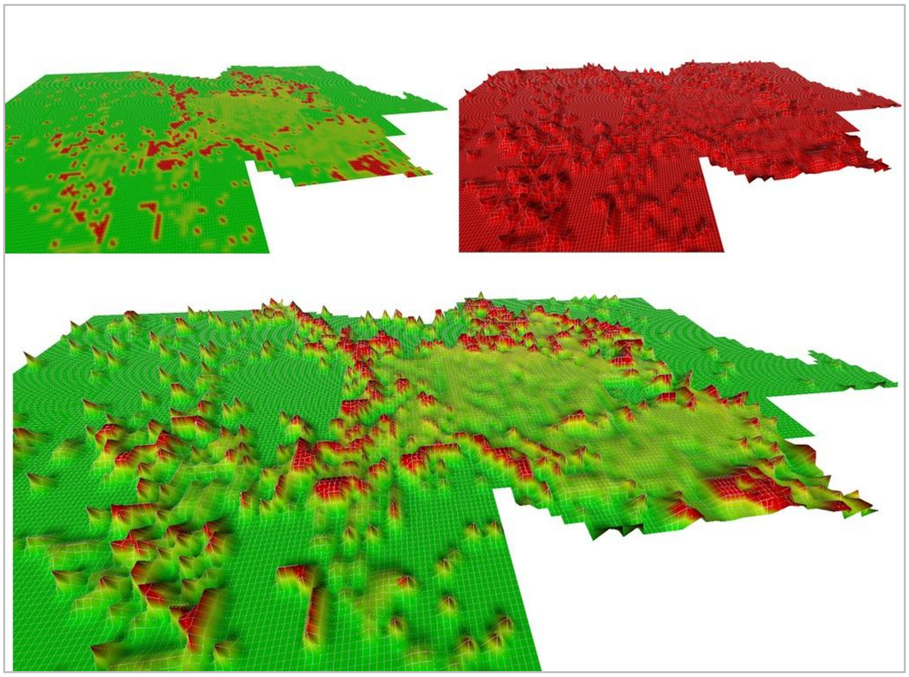


Figure 5.16: Three modes of visualization of Urban Sprawl Indices for scenario Stateland in 2010

As already stated in Chapter 4.6, this visualization method is an efficient way to present indicators of sustainability in combination with the benefits of various visualization techniques. An extended version of the GUI (see Chapter 4.6.2) now combines all indicators of sustainability and visualization techniques to provide an intuitive tool for illustrating the results of this thesis. Introduced in chapter 4.6.2, the GUI allows the user to customize the visual representation by choosing the parameters *indicators, scenarios, years* and *visualization method* (see Figure 4.34). By establishing a second indicator of sustainability in this chapter, the GUI has to be adjusted for allowing comparisons and further analyses. To accomplish those requirements, a second viewport is added into the GUI (see Figure 5.17), which allows for the same parameter assignment and therefore offers a wide-ranging possibility to compare indicator results and visualization methods with each other.

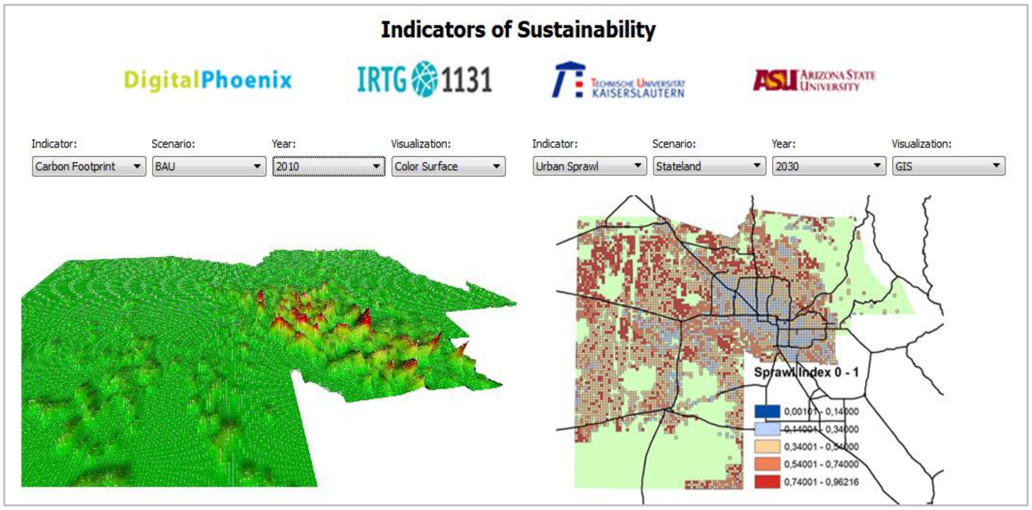


Figure 5.17: Extended GUI for comparison of different indicators of sustainability

Figure 5.17 clearly illustrates an intuitive way for comparing visual results of different indicators of sustainability. The next section will build on that in order to provide possibilities for indicator comparisons within one illustration.

5.5 Urban Sprawl vs. Carbon Footprints

The following section gets to the bottom of the possible correlation between urban sprawl and carbon footprints. Scholars such as Stone [Sto08] documented that large metropolitan areas with high sprawl indices are facing higher impacts on air quality than more spatially compact regions. But this can only be stated by looking at metropolitan areas as a whole. By downscaling the research to the neighborhood scale, this study can point out that higher emission numbers are located at dense areas while sprawl areas usually have less carbon emissions. Figure 5.18 shows that if focusing on total carbon emission numbers in particular grid cells, higher carbon emissions are located in less sprawl areas (see also Figure 5.10). On the other hand, if concentrating on single household numbers, results show that households with the highest emission numbers are located in sprawling areas within the suburbs.

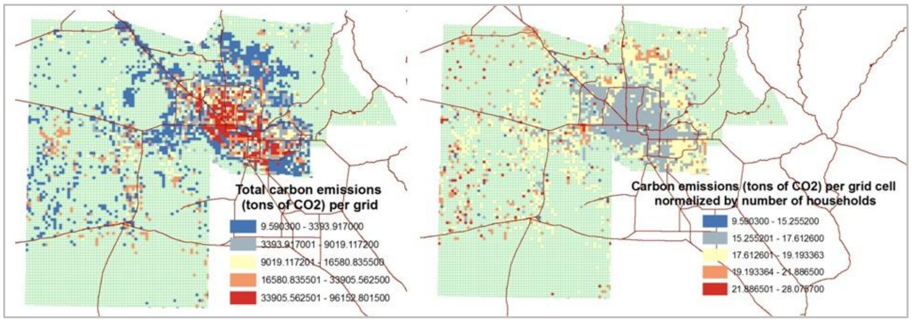


Figure 5.18: Comparison of total and single household carbon footprints in Maricopa County 2010

Since this way of comparison is dependent on considering multiple illustrations, a transparent overlay of both resulting surfaces presented in Chapter 4.6 is created (Figure 5.19).

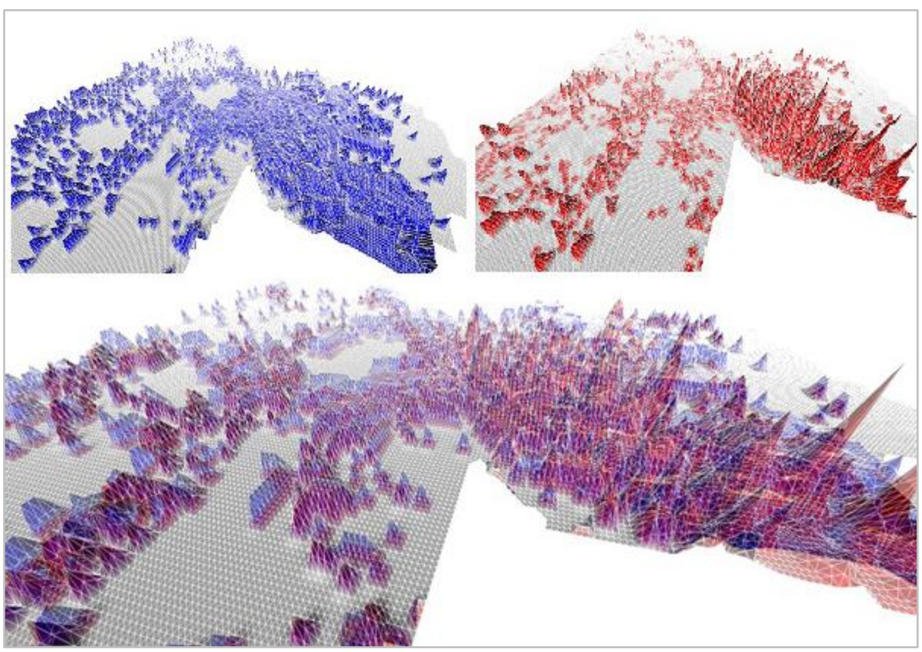


Figure 5.19: Transparent overlay (bottom) of Urban Sprawl Index surface (top left) and Carbon Footprint surface (top right) for Maricopa County in 2010

In order to analyze this relationship between urban sprawl and carbon emissions per household, this study takes advantage of statistical analysis. By correlating both sprawl indices and per capita carbon emissions per grid cell, a positive correlation is indicated (0.3369[3]). The proportion of the variance of sprawl to the variance of per capita carbon emissions (r-square) is 0.113, which can be interpreted that approximately 11 % of per capita CO_2 is directly related to urban sprawl. The positive slope (4.139) also indicates a positive relationship between both phenomena. Therefore, this study demonstrates statistically as well as visually a positive relationship between urban sprawl and carbon footprints.

The presented results agree with literature [Sto08] [SHHW10] and basic statements such as Glaeser and Kahn [GK08], who conclude that if one can hold population constant, the spatial distribution of the population is also an important determinant of greenhouse gas production.

But in terms of illustrating the relationship between urban sprawl and carbon footprints, this section indicates a major drawback. How can two different phenomena with totally different value scales be compared apart from using statistics or comparing different illustrations with each other? Using surface overlays as presented in Figure 5.19 could be one solution. But the author has to admit that this method has to be considered critically in terms of visibility. An answer to that question is given in Chapter 6.

[3] This correlation coefficient ranges from -1 (perfect negative relationship) to +1 (perfect positive relationship)

Chapter 6:

Neighborhood Relation Diagram (NRD)

In this chapter a Neighborhood Relation Diagram [EPGH11], which represents a completely different approach, is introduced in order to represent results of indicators of sustainability. Based on the geometric construction of Voronoi diagrams and in contrast to the grid cell-based approach in Sections 4.5.6 and 5.4, the NRD defines census tracts as neighborhoods and therefore offers the possibility to apply calculated indicator results to the original Census data structure. Facing the fact that sometimes the necessary data is stored in an unstructured format (census tracts), it would be a huge effort to get the required information out of this data. Therefore the major goal of this approach is to insert new census data (from an unsystematic structure) directly into the system without any preceding standardization in a regular grid.

Techniques such as cartograms and weighted Voronoi diagrams (Section 3.4) usually utilize global mapping and representation. Furthermore, they do not visualize multiple non-spatial parameters in an adequate way. In contrast, this chapter introduces a novel method to construct a diagram based on the local mapping of non-spatial parameters. To depict multiple non-spatial parameters, multiple diagrams can be overlaid. The computation of this Neighborhood Relation Diagram is based on the geometric construction of Voronoi diagrams (Section 3.4.3). According to the local topology, each cell is constructed in a way that the cell's shape reflects the relations to the non-spatial parameters of neighboring cells. This locally weighted approach is novel and exhibits robust properties, in particular constrained cell expansion.

6.1 Application demands

The objective for this application is to visualize partially spatial data by preserving spatial relations (global topology) and optimally depicting local differences in non-spatial information. By assuming the general case of unstructured partially spatial data (i.e., both spatial and non-spatial information is unevenly distributed), as it is in particular the case within the context of this work, the data exhibits

- high global differences and
- both high and low local differences

in non-spatial information, as well as unstructured spatial locations. Common approaches in geovisualization - color coding techniques, cartograms, or weighted Voronoi diagrams - visualize non-spatial information in global relations. Inherent requirement of these approaches: a global normalization of non-spatial parameters has to fit the visual mapping process. This global scaling prevents a local comparison if non-spatial information is unevenly distributed. Spatially unstructured data makes for an even greater challenge. The effects of normalization of non-spatial parameters are highly dependent on the parameter's distribution. If high global differences in these parameter values are presented, the mapping is less expressive in regions of low local differences and more expressive in regions of high local differences. In Figure 6.1, the depiction of low local differences in non-spatial information becomes diminutive after global normalization. Those results are an understatement of the original differences in non-spatial information between neighboring regions. When the spatial assignment of non-spatial parameters exhibits many local maxima, the derivation of a suitable global mapping function is proving difficult. In terms of carbon footprint data, this is particularly the case e.g. in regions including airports, financial or shopping districts as well as desert regions in which the absolute carbon footprints vary greatly.

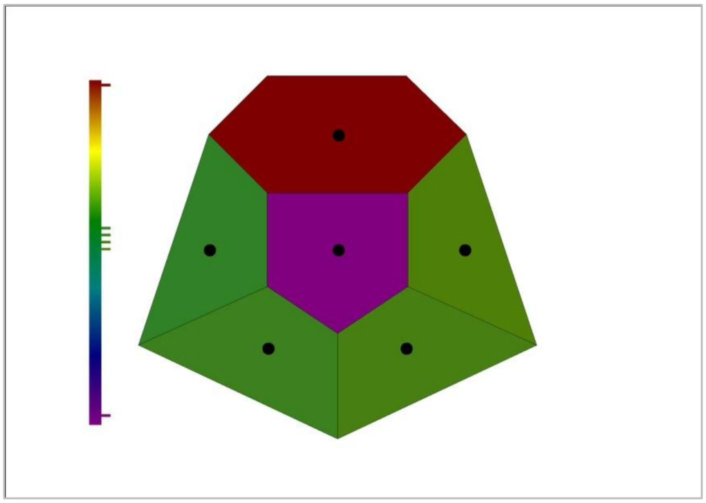


Figure 6.1: Global normalization leads to unexpressive mapping for unevenly distributed non-spatial information. Consequently, small differences (here only in slight color nuances) are hard to depict. This makes global mappings unsuitable for local comparison [EPGH11].

In the case of high local differences in non-spatial information, cartograms and weighted Voronoi diagrams may easily overstate those differences to a degree that a change in spatial topology is induced. Consequently, the spatial information of those regions is altered to an extent where mental references to the original map are easily lost or, in the most undesirable case, the neighborhood is lost completely. This problem is formally stated and investigated [KNP04].

The distortion of topology also leads to the inevitable conclusion that an overlay of multiple cartograms or weighted Voronoi diagrams cannot be utilized to visualize multiple non-spatial parameters. When the spatial reference is lost, an interpretation of different layers is not possible. Color coding, cartograms and weighted Voronoi diagrams only visualize a single non-spatial parameter. However, in many applications multiple non-spatial parameters are of interest to planners.

Based on this discussion of related problems, it can be concluded that a new technique is necessary in order to visualize partially spatial data and achieve a suitable local comparison.

This technique should

1. use local mapping for non-spatial information to achieve a more expressive local comparison,
2. preserve the global spatial topology to keep the mental reference of spatial information and
3. handle multiple non-spatial parameters.

As established, neither size nor color can reflect pairwise neighborhood relations well enough for planning applications. Therefore, similar to weighted Voronoi diagrams, non-spatial information is visualized in a diagram. However, instead of using size, relations between non-spatial parameter values are depicted by altering the shape of each region in direct relation to its neighbors. By following this approach, a local comparison is achieved through a local mapping in shape. Although constructed differently, the result can be illustrated in the same way as a force-directed approach in which each boundary of a region expands in the direction of its neighbor with the force of their pairwise relation between non-spatial parameter values. This force of transformation is contained within this neighborhood to achieve a preservation of topology. Furthermore, the spatial distance between the center locations of neighboring regions is incorporated in this transformation to ensure a stable behavior and to keep the mental references of spatial information. In the following section, the geometric computation of this diagram is explained in full detail.

6.2 NRD Algorithm

A diagram that fulfills the requirements discussed in Section 6.1 is weighted (non-spatial parameter) and consists of cells that display pairwise relationships to their neighboring cells' weights. The effect of this weighting, however, has to be constrained in a direct neighborhood of unstructured generator points and weights, illustrated in Figure 6.2. The red arrows represent the orientation and intensity of deformation for each cell face according to the relative relationship in weighting. As established in the previous sections, this is not achievable by common approaches.

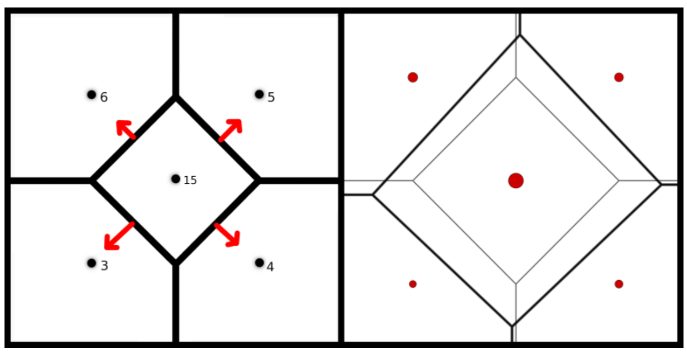


Figure 6.2: Left: In contrast to common weighted Voronoi diagrams, our approach utilizes weights to depict pairwise neighborhood relations. This is achieved by a direct and constrained cell deformation (the arrows illustrate the magnitude and direction of cell boundary expansion that describes these local relationships). Right: The resulting Neighborhood Relation Diagram for the same weight configuration [EPGH11].

The main idea to solve this problem is based on the geometric principles of Voronoi diagrams but applies a different weighting scheme. Instead of incorporating weighting into the metric, the positions of edge perpendiculars are being influenced by the weighting. As mentioned in the previous section, the vertices of a planar Voronoi diagram are the circumcenters of the corresponding Delaunay triangles. Those circumcenters are computed by the intersection of perpendiculars to the edges of Delaunay triangles which lie at a ratio of $\frac{1}{2}:\frac{1}{2}$ on the edge of each triangle. Those perpendiculars intersect at one point and form a vertex in the resulting diagram.

In Neighborhood Relation Diagrams, the position of perpendiculars is defined by a weighted ratio which reflects the pair wise local relation between the generators' weights. For two neighboring generators with spatial (Euclidean) distance e between them and their non-spatial parameter values w_1 and w_2, this ratio is defined as

$$\frac{d}{d+e} : \frac{e}{d+e} \tag{6.1}$$

where d equals $\sqrt{(w_1 - w_2)^2 e^2}$. The distance measure e adds a constant to the ratio which keeps the spatial reference, balances high non-spatial value differences, and scattered spatial locations.

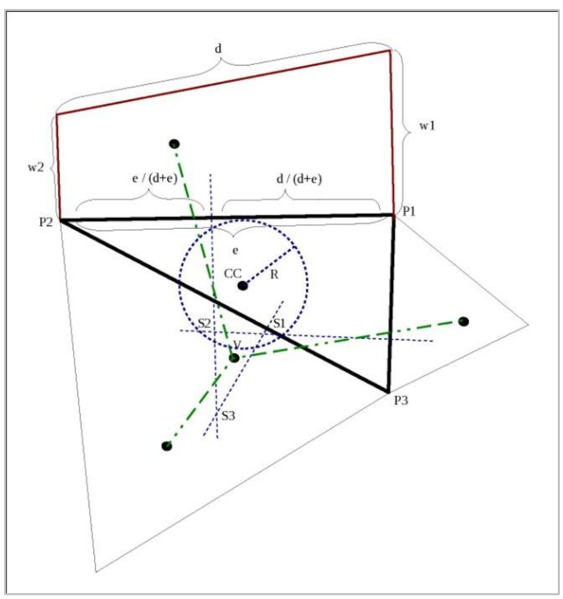


Figure 6.3: Illustration of the geometric computation. Based on a local neighborhood consideration, the position of the perpendiculars of each of the triangle's edges are shifted [EPGH11].

Figure 6.3 illustrates the geometric computation as described below. The generator's weights are represented by scaled normal vectors to the diagram's plane. For a given Delaunay triangulation, the following steps for each triangle are computed in order to compute the cell's vertex V:

1. Calculate the circumcenter CC of the triangle and its inner radius r.
2. Compute perpendiculars to edges at a ratio of $\frac{d}{d+e}:\frac{e}{d+e}$
3. Calculate intersection points S1, S2 and S3 of perpendicular lines.
4. Compute the center point V of the triangle defined by S1, S2 and S3.
5. Constrain the placement of V by a distance from the CC (e.g., by R).
6. Compare the resulting line segment with the neighboring segments to prevent overlapping cells.

The diagram is build by the straight-line-connection of each triangle's vertex V with the vertices of its neighboring triangles, as illustrated by the green lines in Figure 6.3.

In contrast to the geometric construction of Voronoi diagrams, perpendiculars shifted according to their neighborhood relations, in general, no longer intersect in a single point, but form a triangle by their intersection points. In contrast to a global approach, this reflects the local pairwise relationship of the locations' weights. The center of the resulting triangle in which the perpendiculars intersect as the triangle's vertex is used, since it best reflects the impact of the weight distribution in the triangle and it is fast to compute.

Although the Delaunay triangulation maximizes the minimal angle within each triangle, the quality of the triangle's initially calculated vertex is dependent on the quality of the Delaunay triangulation. This is due to the fact that the smaller an angle in a triangle of the triangulation gets, the further away possible intersection points of (more and more parallel) perpendiculars are located. Therefore, the initially chosen vertex is constrained by a maximum distance to the triangle's circumcenter.

It appears noteworthy that a different weighting of one generator affects the position of the perpendiculars of its edges and shifts each along the edge (towards or away from the generator) within the boundary of the edges. This reflects a change in the intersection points with the perpendiculars of the other edges of the triangle, resulting in a change of the center point for the triangle formed by the intersection points. Thus the position of the triangle's vertex is changed within a fixed boundary of possible center points, which is then constrained by a maximal distance to the triangle's circumcenter.

This distance represents a variable for changing the impact of weighting and thus for differing from unweighted Voronoi diagrams. While this could be a global distance measure, a combination of local variables (like the outer or inner circle's radius) should be preferred. This study has found that the radius of the inner circle of each triangle is a good representation for the individual degree of freedom for the triangle's vertex.

By constraining the impact of weighting, degenerate triangles of a Delaunay triangulation are handled, resulting from unstructured spatial locations of generator points. However, in some cases, this restriction is not enough to impose regularity on the diagram.

Depending on the triangulation, a triangle's vertex may lie in a neighboring triangle and vice versa. To prevent the resulting unattractive 'flips' (illustrated in Figure 6.4) which lead to the overlapping of cells, the orientation of the calculated vertices of neighboring triangles can be compared to the orientation of their circumcenters. A flip occurs if the dot product between these vectors is not positive. In that case the vertices for both triangles are merged to a single vertex positioned at the center of the line formed by the original vertices. By the incorporation of the Euclidean distance in the neighborhood relation, the local effects of weighting the cell's structure are balanced, and rendering this technique seems more robust for unstructured spatial locations.

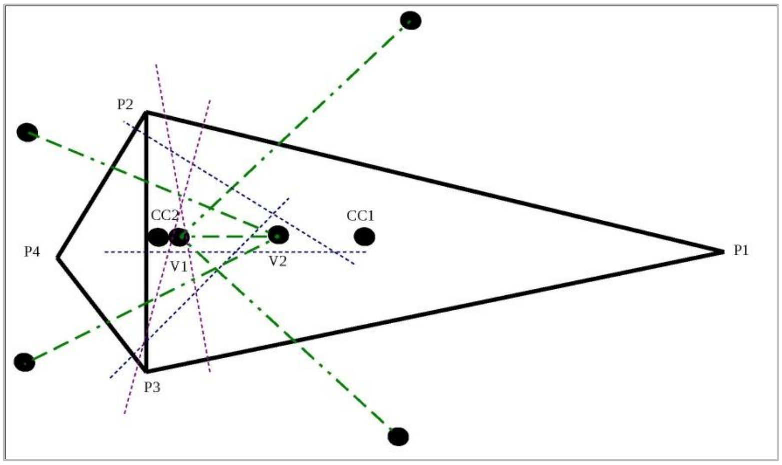


Figure 6.4: An illustration of overlapping cell expansion resulting in a misorientation (flip). Criterion: $\overrightarrow{CC_1CC_2} * \overrightarrow{V_1V_2}$ [EPGH11]

It can also be noted that $\frac{d}{d+e}$ never reaches zero for any weighting of two different generators and that the perpendicular lines never lie on a generator of the corresponding edge. Therefore, this method is also continuous in the regard that small changes in weighting lead to small changes in the diagram.

The following properties of the Neighborhood Relation Diagram can be summarized:

- The cell's deformation describes the relationship to its neighbors, enabling a direct comparison.
- Weights have a locally constrained impact (only on the direct neighboring cells). Therefore, no spatial distortion of topology is induced, even by large weight differences.
- This also allows of overlay of multiple diagrams. A display of multiple non-spatial parameters is possible.

- Through the relative consideration of the neighborhood, a local mapping of non-spatial information is achieved. Globally marginal but locally important differences are depicted.

6.3 NRD for indicators of sustainability

This section presents a comparison to existing methods and further demonstrates the advantages of this method for the visualization of indicators of sustainability within the scope of this work. Case studies for both carbon footprint and urban sprawl indicators are performed in which patterns for downtown Phoenix, Arizona, USA, are analyzed with the help of our technique.

6.3.1 NRD vs. other methods

In the following, a discussion of advantages and disadvantages compares the NRD diagram to related techniques. This section also refers to the merits, contributions, and applications of Neighborhood Relation Diagrams (NRDs) to the field of geovisualization. As motivated in Section 6.1, the merits of using local mapping of non-spatial information are numerous when the goal is to depict relations between the non-spatial information of neighboring spatial regions. NRDs are topology preserving, its cells do not overlap and are constrained by the fixed spatial locations of their neighborhoods. This is especially useful in applications where spatial data is to be displayed and mental references of those spatial locations are to be kept. Another highly beneficial factor of this property is that an overlay of different diagrams can be utilized to visualize multiple non-spatial parameters in a single view. An example of this is given in Figure 6.8 later in this chapter.

The second advantage of using NRDs is that the shape of their cells displays neighborhood relations effectively without exhibiting issues due to scaling. The force-directed shape transformation of cells allows for an intuitive and fast visual assessment of neighborhood relations. Last but not least, the NRD requires no optimization process for its construction. It is straight-forward to implement and its added algorithmic complexity, if compared to a Delaunay triangulation, is negligible.

Although the outcome may appear similar, cartograms differ from NRDs in every aspect mentioned above. Cartograms use global mapping, display non-spatial information by area instead of shape, their regions cannot be constrained within a neighborhood. They are thus known to lose spatial references and distort topology. They especially have problems with unstructured data and are constructed by an iterative optimization process. These properties are well established, for example, by Keim et al [KNP04]. An advantage of using cartograms in other applications could be the fact that they are more flexible. Cartograms work on any spatial region definition (2D-mesh) and can always create a subdivision if only spatial locations (points) are provided. In contrast, the approach in this study is based on subdivision and would first have to be adapted to work with meshes. The same comparison applies to color coding. Color coding differs from this approach in terms of the mapping process used. This may be locally less effective for unstructured data due to global scaling, which is discussed in section 6.1. Although shape is an effective descriptor for neighborhood relations, the mental identification process of colors is faster than that of shapes and the technique is well established in today's society. The technique is also straight-forward, intuitive, and computationally very fast. Because of these strong advantages, color coding may very well be preferable in some situations. However, a mapping to color is not accessible to many users since a notable part of the population is color blind. Additional complications arise when an underlying (colored) reference map is used in the visualization.

These maps are often desirable in urban planning. Most importantly, color coding can only visualize a single non-spatial parameter. Since the overlay of multiple color maps is not possible, the visualization of multiple non-spatial parameters cannot be achieved by this approach. These disadvantages greatly limit the application of color coding and strongly speak in favor of researching of alternative techniques.

6.3.2 Case study A: Carbon Footprint in Phoenix, Arizona

In order to demonstrate the benefits of this approach, downtown of Phoenix, Arizona was chosen to be the study area. The city of Phoenix, county seat of Maricopa County and capital of the state Arizona, is also the largest city of Maricopa County, with 1.4 million people [Usc11]. The focus of this approach lies on an alternative structure detached from the rigid grid structure used in Chapters 4 and 5. Therefore, the NRD approach also requires a new delineation of neighborhoods. Since the input data is originally based on census data (see Sections 4.2 and 5.1) provided by the US Census Bureau, this approach takes advantage of their guidelines and use census tract boundaries to delineate the neighborhoods. Census tracts are small, relatively permanent statistical subdivisions of a county which are delineated by local census statistical areas committees. Their spatial size varies greatly depending on the density of settlement (usually between 2,500 and 8,000 persons), but they are designed to be homogeneous with respect to population characteristics, economic status, and living conditions [Usc11]. The chosen census tracts in this case study represent a typical residential area in the center of Phoenix and reflect a reasonably varied distribution of different household categories, illustrated in Figure 6.5. They are located north of the downtown area and include tracts with dense population as well as tracts with recreation space or public facilities. Based on the carbon footprints results in Chapter 4.5.6, Figure 6.6 illustrates the carbon emissions for the average household categories in a schematic map for the chosen census tracts.

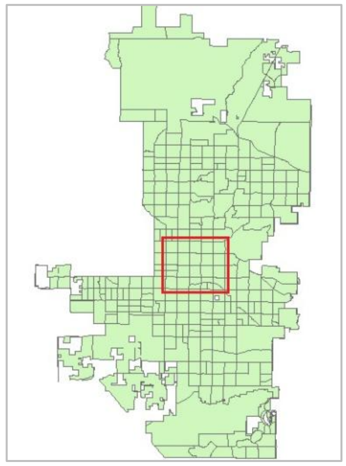


Figure 6.5: Census tracts of the city of Phoenix provided by U.S. Census Bureau [Usc11]

A major benefit of the NRD approach is the provision of carbon footprint information by focusing on cell deformations for each neighborhood. The sizes of the resulting new cells represent the carbon footprint distribution for the census tracts in relation to the adjacent neighborhood cells. It is possible to immediately locate potential effects in CO_2 emissions in the neighborhood cells by, for example, applying planning projects such as housing reconstruction or resettlements.

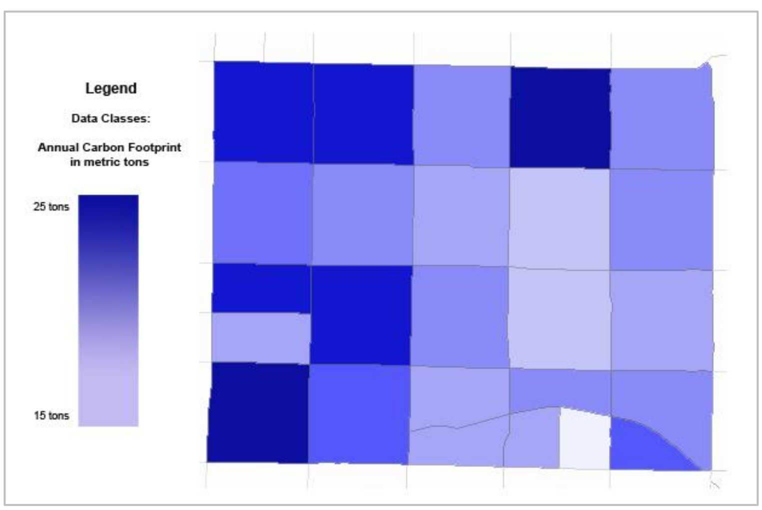


Figure 6.6: A traditional color map-based visualization of the carbon footprint for average household categories per census tract.

Figure 6.7 shows the resulting spatial subdivision diagrams based on average household carbon footprints for the census tracts. The average distribution represents the carbon footprint of the most common household category in the tract. The aggregated carbon footprint for the tract, then, integrates the actual number of housing units in that census tract. That means that the aggregated values are the result of multiplying the average values by the number of households.

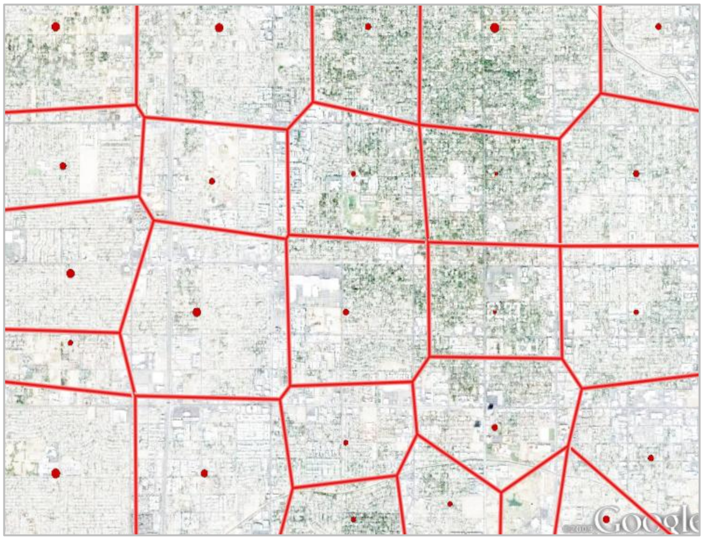


Figure 6.7: The average results of household carbon footprints with an underlying map adopted from Google Earth [Goo11]

An underlying background map of this particular section of Phoenix, adopted from Google Earth, is included in order to provide planners and decision makers with better orientation. The sizes of the center points also differ depending on these result values. As already mentioned, average and aggregated values are distinguished in order to interpret the resulting cell sizes correctly.

Figure 6.8 includes both average (black) and aggregated (red) resulting cells and it can quickly be determined that both household categories and numbers of households are big contributors to the resulting cell deformation. Instead of a background map, the original Voronoi Diagram in light gray was provided to concentrate on the different cell sizes. To highlight the advantage of this approach, refer to cells P, Q and R. By looking at the average results, it is obvious that the average household type in cell P has a higher carbon footprint compared to the specific household types representing cells Q and R. Cell P, representing census tract 1,072.02 Maricopa County, has an average household carbon footprint of 22.2 tons/year. Cells Q (census tract 1,069) and R (census tract 1,072.01) have an average household carbon footprint of 20.6 tons/year and 19.4 tons/year.

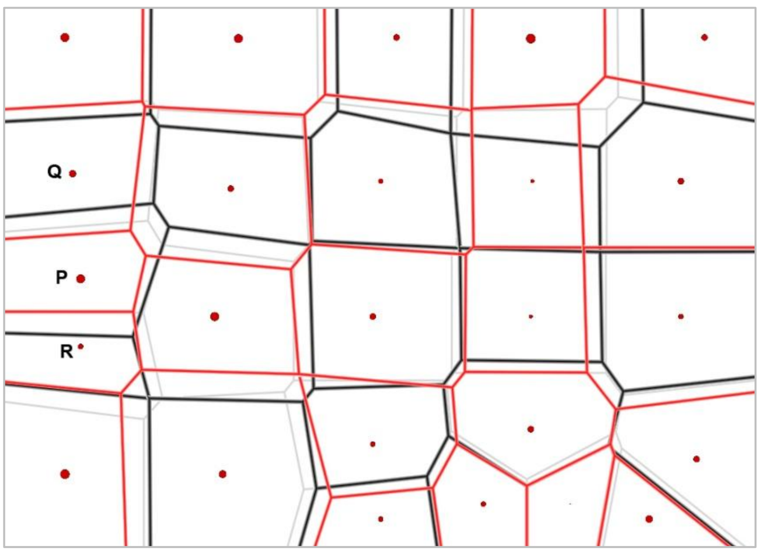


Figure 6.8: The resulting diagram for average (black) and aggregated (red) household carbon footprints.

The NRD immediately provides visual information on this relation. But by multiplying these carbon footprints with the total number of households per cell, the weighting as well as the connected subdivision diagram (red) change significantly, due to the higher number of households in cells Q and R (total household carbon footprints of cells P = 31,102 tons/year, Q = 45,567 tons/year, R = 29,739 tons/year). Therefore, it is important for planners and decision makers to distinguish between both analysis approaches and thus avoid misleading conclusions.

6.3.3 Case study B: Urban Sprawl in Phoenix, Arizona

The second case study which benefits from the NRD is dealing with the phenomenon of urban sprawl. Based on results provided in Chapter 5 this section illustrates urban sprawl indices for the same study area (downtown Phoenix, AZ) described in Section 6.3.2. Since the NRD is calculating on the basis of census tracts which are located in the center of the city, urban sprawl indices are reduced in a way to exclude the dimension centrality.

Figure 6.9 shows the resulting spatial subdivision diagram based on total urban sprawl indices for each census tract.

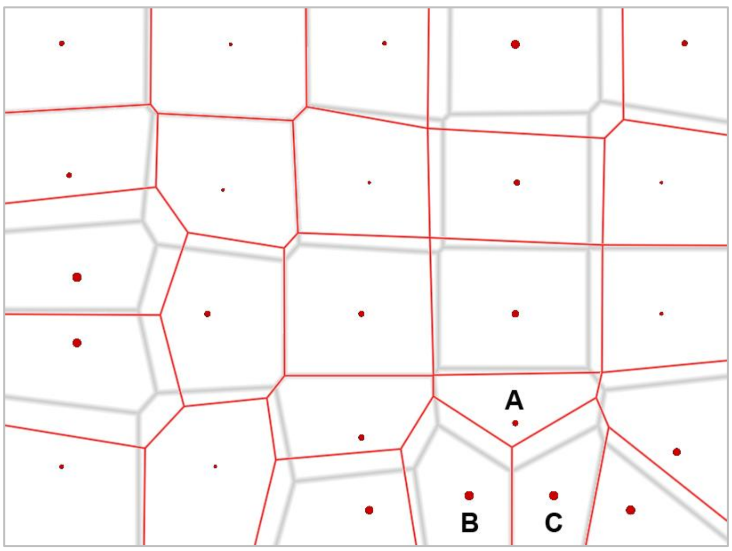


Figure 6.9: The resulting diagram for Urban Sprawl Indices

Areas with low sprawl indices can be easily detected by a) the size of the center points[1] and b) the cell deformations towards their direct neighbor cell. To highlight the advantage of this approach, refer to cells A, B and C. Cell A (census tract 1088,02; 1,717 households) with a low urban sprawl index (0.473) is directly

[1] Small diameter = low sprawl, large diameter = high sprawl

influenced among others by cells B (census tract 1088,01; 1,039 households) and C (census tract 1087; 0 households) with high urban sprawl indices (B = 0.872; C = 0.886). Relatively equal sprawl indices in cells B and C, despite of a huge gap between their household densities, indicate once more the multi-dimensional approach in establishing an urban sprawl index. Since this NRD shows the local relation between neighboring cells only, it is possible to locate sprawl situations on a very small scale and detached from the global situation of the metropolitan area. Therefore tendencies of urban sprawl in a neighborhood can be detected in an early stage in order to assist for policy and planning decisions.

6.4 Urban Sprawl vs. Carbon Footprints

Referring to Chapter 5.5, an adequate visualization of two different phenomena which strongly differ in terms of their result units (urban sprawl indices range from 0 to 1 while carbon footprints go up to thousands of emission tons) is hardly to achieve. Approaches such as overlays of respective surfaces (see Figure 5.19) demonstrate the ability to provide both result numbers within one illustration but they have also proven that there are still deficits to overcome concerning visibility issues.

One of the major benefits in using NRDs is the ability to show multiple data sets within one representation. Neither color coding nor cartograms can achieve this. Therefore, NRDs seem to be a suitable visualization technique in order to visualize the relationship between urban sprawl indices and carbon footprints. Consequently, Figure 6.10 illustrates both urban sprawl indices (red) and carbon footprints (blue) for the study area utilized in both case studies above.

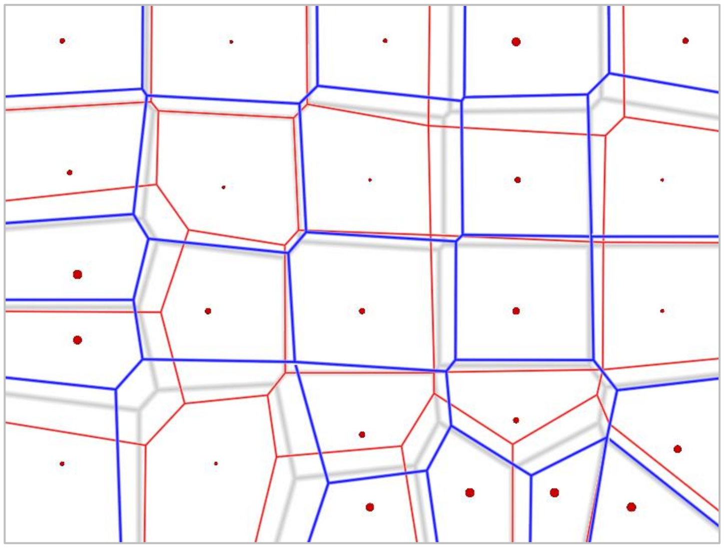


Figure 6.10: The resulting diagram for urban sprawl indices (red) and aggregated household carbon footprints (blue)

6.5 Discussion

This chapter provides a novel visualization technique for the depiction of local relations between non-spatial parameters within a neighborhood of unstructured partially spatial data. The method builds upon the geometric construction of Voronoi diagrams. Each cell in the resulting diagram is constructed according to a local neighborhood metric that reflects the relation of non-spatial parameters to neighboring cells. The resulting diagram contains non-overlapping cells that are constrained within their neighborhood and are shaped to depict a local mapping of relations. This mapping is more effective than global approaches, exhibits no complications of topology distortion, loss of mental references, and allows for the depiction of multiple non-spatial parameters.

This method contributes to the field of geovisualization by providing an effective local mapping of multiple non-spatial parameters. This local mapping enables the visual representation of indicators of sustainability at the level of urban neighborhood districts, thus enabling the investigation of green house gas emission and land use patterns.

To summarize it can be concluded that the requirements of this application - a meaningful visualization of indicators of sustainability between neighboring regions - are well met by this technique. However, disadvantages should also be noted. The strong application focus of the method has driven the development of an effective local mapping. Inherent in this focus, this strength is also the biggest weakness of the technique. Since NRDs completely focus on local relations, a global comparison is not possible within such a diagram. While other approaches are able to visualize both local and global relationships (with the discussed problems and limitations), the focus on neighborhood relations limits the employment of this approach to other applications. NRDs can only visualize local differences, patterns, and relations - although better than the common approaches in geovisualization compared above.

Another drawback of using cell based deformations in general is the spatial resolution. In contrast to the grid cell structure, this method can only visualize small regions. Visualizing the total picture of resulting indicators using NRD for whole Maricopa County is restricted in terms of the visibility of the output.

However, this study provides a helpful tool to deal with such complex analysis which is also able to illustrate this important information and therefore also allows for an efficient comparison of different data sets. The focus is not on the global scale, but shows possible effects of planning projects on the neighborhood scale. Therefore, this approach is able to illustrate multidimensional data within one representation, and is unique, more efficient, and less time consuming, in contrast to other visualization techniques like color coding or cartograms.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

The motivation of this dissertation was to establish metrics and visualization techniques in order to deal with indicators of sustainability – carbon footprints and urban sprawl - in Maricopa County. Based on a regular gridcell structure (1 mile x 1 mile) metrics for both chosen indicators were development at the urban neighborhood scale. In other words, in contrast to scholars Glaeser and Kahn [GK08] and Shammin et al. [SHHW10] or respectively Galster et al. [GHRW+01] and Ewing et al. [EPC03], this study focused on gridcell-based indicator results what has never been done so far.

Regarding carbon footprints this thesis provided a detailed approach of measuring CO_2 emissions for individual households, distinguishing three different emission contributors for households – operational energy, embedded energy in consumables and energy used in travel. Furthermore the resulting carbon footprints could be distinguished by different household categories, dependent on attributes income, race and household sizes. Results showed that income, household size and location of households are huge contributors to the resulting carbon emissions while attribute race did not show any significant influence. Nevertheless by utilizing a linear regression model, the resulting carbon footprints per different household category could be applied to output data of UrbanSim and therefore offered the possibility to forecast carbon footprints for Maricopa County for future years and different scenarios. Results clearly showed the demand for future policy decisions in order to handle future increasing carbon emissions. Furthermore individuals and families could be informed about the impacts of their consumption behavior.

Regarding urban sprawl this thesis provided a similar gridcell-based approach to detect urban sprawl within a metropolitan area. In contrast to Galster et al. [GHRW+01], whose indicator approach can be considered as the basis for the approach in this thesis, the results clearly showed that it has to be distinguished between urban sprawl at the level of metropolitan areas and the level of neighborhoods. However this study found consensus in Galster et al. [GHRW+01] and Tsai [Tsa05] by highlighting the importance of measuring urban sprawl based on different dimensions. It is not possible to reduce such a complex phenomenon to only one aspect such as density or distance to the next city center.

By establishing a three-step-based visualization method in order to visualize indicator results, this thesis addressed the predefined requirements for a good geovisualization. Therefore, this surface-visualization, based on Coons Patches, can be considered as a combination of the advantages of common GIS representation and the increasing demand of three-dimensional representation techniques within the field of urban planning. Since detached from commercial software packages such as ArcGIS, this visualization tool is individual adaptable as well as reproducible.

In addition, especially in terms of communicating the results to the public, a graphical user interface (GUI) was included to access the resulting visualizations depending on indicator, scenario, year and visualization method. By providing two separated viewports, the user can immediately compare different results and see possible relations between different indicators of sustainability.

Chapter 6 provides an alternative approach in measuring and visualizing both indicators by utilizing a Neighborhood Relation Diagram (NRD), based on weighted Voronoi diagrams. Despite of being able to compare direct impacts of indicator results on the neighboring cells, it also offers a suitable tool to finally compare both phenomena – carbon footprint and urban sprawl – with each other.

7.2 Future Work

This dissertation represents a complete approach for modeling and visualizing indicators of sustainability, but there is still some potential for extending and improving those results in future research. Since UrbanSim and therefore the input data of presented calculations for both indicators is based on U.S. Census data from 2000, it would be interesting to apply this study to the recent U.S. Census 2010. To date this data is not available yet but once it will be accessible it could be applied in order to validate the findings of this thesis.

Another future research could be the adaptation of those indicators of sustainability metrics and visualization techniques to other application or research areas which could benefit from this kind of approach, especially in terms of visualization.

In general the adaptation of the “planning metaphor” to other research areas is not new. Especially in software visualization the use of metaphors becomes very important. But due to complexity of software systems and individual user perceptions the choice of an adequate metaphor becomes an essential part of this process. In software visualization most techniques and tools are based on the graph metaphor [PBG03]. But in order to provide understandable visualizations of software information to different user groups with different information backgrounds, a more interactive form of data representation might be more adequate e.g. in terms of navigation, switching between overview and detail or user centered representations. In general most of alternative graphical illustrations are facing the absence of an intuitive interpretation. Comparable to UML (unified modeling language) which can be stated as the standard software modeling language, users have to be trained in the fundamentals in order to understand them. In contrast metaphors which can be found in the real world already provide an understandable and intuitive graphical design [PBG03].

Scholars such as Panas et al. [PBG03], Balzer et al. [BNDL04] or Wettel and Lanza [WL07] have already shown that a landscape or city metaphor can be useful in order to visualize software metrics. By visualizing entities, relations and software structure in general those studies initiate potential future discussions on applications such as quality management of software systems. Similar to the planning metaphor the utilization of a 3D metaphor can be a suitable way for visualizing software systems. While the use of three-dimensional representations are naturally connected to visualization techniques capturing the city metaphor in Section 7.2, scholars such as Andrews et al. [AWP97], Marcus et al. [MFM03] or Knight and Munro [KM00] further are presenting approaches to visualize software in 3D.

Since an overlap between this thesis and software engineering can be detected in terms of visualization, it would be interesting to see, if there is also some potential future work in terms of the indicator approach. Since the metrics of the chosen indicators of sustainability in this thesis are not adaptable to the field of software engineering at a first glance, the main idea can be stated as similar: Finding indicators in order to measure a specific phenomenon. In software engineering indicators are particularly utilized within the scope of quality management and, within embedded systems, also in software safety. Literature is vast in terms of definitions for the term “software quality”. Following the IEEE Standard Glossary of Software Engineering Terminology, software quality can be defined as a) “the degree to which a system, component, or process meets specified requirements” and b) “the degree to which a system, component, or process meets customer or user needs or expectations” [IEEE90]. In order to make this term operable and measurable, indicator-based quality models are introduced [Bal08]. In general one can distinguish between GQM models [RB87] (goal-question-metric model) and FCM model [Bal08] (factor-criteria-metric model). Here one has to distinguish between functional and non-functional criteria.

Comparing those indicators with e.g. indicators of urban sprawl, one can immediately find consensuses. Household densities per gridcell number could be associated with the amount of LOC (lines of codes) per method number within a software system. Furthermore the term density could be defined as the number of defects within the size of a software system (usually measured in LOCs) or within embedded systems in order to detect critical system components Therefore density would become on that note an indicator for measuring the system quality. Since density is only one dimension for measuring urban sprawl it is obvious that it cannot be a standalone indicator for measuring software quality. Therefore one can raise the question if it would be possible to apply other dimensions such as continuity or diversity to the measurement of system quality? If yes, it would be interesting to transfer the metric of urban sprawl indicators to software metrics.

Since software visualization usually maps the software metrics into a grid structure (e.g. treemaps) a possible alternative could be to map software metrics into the regular grid structure, presented in Chapter 4 and 5. If this is possible software visualization could benefit not only from alternative visualization techniques but also in terms of neighborhood-based representations. Point of interests could be created - hierarchies depending on highest LOC or highest number of methods - which again can be analyzed for supporting quality management. In other words by mapping quality metrics (e.g. LOC, number of functions or inheritance depth) into the grid one could analyze the criticality and how those metrics correlate with each other.

As presented in chapter 6, Voronoi cell tessellations represent another possibility to visualize indicators of sustainability. Balzer et al. [BDL05] present an application of Voronoi cells on software systems by providing Voronoi treemaps. In other words the hierarchical structure of software entities are illustrated by Voronoi cells based on an underlying treemap. Since this approach was reduced to hierarchical illustrations it would be interesting to apply this kind of visualization into quality management, where for example the cell sizes represent the error urgency. Since those Voronoi cells are interested in relations to “neighborhoods”, one could raise the question if it possible to illustrate neighboring lines of codes, which are located next to “error lines”.

In conclusion the adaptation of the findings in this thesis into the field of software engineering would open the door to manifold research areas in the future, especially regarding visualization of software quality.

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Curriculum Vitae

PERSONAL IDENTITY

Name	:	Sebastian Petsch
Place/Date of Birth	:	Traben-Trarbach / February 20, 1980
Nationality	:	German

EDUCATION

- **01/2008 – to date** Graduate student at the International Research Training Group (IRTG 1131)
- **10/2001 – 09/2007** Study of “Spatial and environmental planning” at the University of Kaiserslautern
  Degree: Diplom-Ingenieur (Dipl.-Ing.)
  Thesis: Noise Visualization in 3D Models
- **10/2000 – 09/2001** Study of “Techno-Informatics” at the University of Kaiserslautern
- **1990 - 1999** Grammar school ”Gymnasium Traben-Trarbach”,
  Certificate: General Qualification for University Entrance (Abitur)
- **1986 - 1990** Elementary school Briedel/Pünderich, Germany

WORK EXPERIENCE

- **06/2003 – to date** Student research assistant, Department of Computer Science, Computer Graphics and HCI Group, University of Kaiserslautern
  - Development of 3D Models
  - Supervising Exercises in ”Computergrafik” and ”Human Computer Interaction”

Publications

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