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Urban Form and Greenhouse Gas Emissions

Findings, Strategies, and Design Decision Support Technologies

Michael West Mehaffy

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Urban Form and Greenhouse Gas Emissions

Findings, Strategies, and Design Decision Support Technologies

Stedelijke Morfologie en Broeikasgasemissies

Bevindingen, Strategieën, Ontwerpbeslissings-ondersteunende Technologieën

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus, prof.ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op

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Door
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and err again,
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- Piet Hein, "The Road to Wisdom"

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I am also greatly indebted to my fellow researchers. The software engineer Ward Cunningham has been essential to this research, and a huge influence on my thinking and understanding of the technology and its issues. The modelling system I have proposed herein relies exclusively upon Ward's foundational insights and key technological developments, notably his "federated wiki" technology.

My other co-researchers and co-authors of some of the work herein include my Promotor Andy van den Dobbelsteen; Tigran Haas of KTH in Stockholm; and Sergio Porta and Ombretta Romice of The University of Strathclyde in the UK. My colleague Nikos Salingaros, Professor of Mathematics at the University of Texas, gave me invaluable advice and insights, particularly in the area of network science. My colleague Emily Talen, Professor and Senior Sustainability Scientist at Arizona State University, has also given me important advice and guidance.

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I have been profoundly influenced by the work of Christopher Alexander, my former professor and collaborator, and educated as a mathematician and physicist before he became an architect. He has also given me invaluable advice in this work. I have also been greatly inspired by the work and friendship of the biologists Brian Goodwin and Stuart Kauffman, both formerly of the Santa Fe Institute. Less directly, my work has been profoundly shaped by people I did not know, or know well, including Jane Jacobs, Kevin Lynch, Alfred North Whitehead, and others too numerous to mention here.

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Contents

Summary

The research reported in this dissertation contains three complementary and overlapping parts:

One, "findings": It assesses the factors of urban morphology that contribute to increased rates of greenhouse gas emissions per capita, and the ways they interact. It finds a significant but under-represented set of factors, distinct from but relating the factors at the individual building scale and the scale of regional transportation systems.

Two, "strategies": It assesses the methodologies by which such findings might be put to use in identifying and achieving reductions through changes in urban design, and proposes new strategies to do so using innovative forms of design decision support tools.

Three, "design decision support tools": It then proposes a specific new technology, namely a new class of open-source scenario-modelling tool, embodied in new prototype software. The tool utilizes a new kind of "federated" web-based wiki technology incorporating design pattern languages, which was developed in collaboration with the software engineer and wiki inventor Ward Cunningham.

As part of this research, it has been necessary to examine fundamental methodological questions, and to account for limitations of current data as well as current significant gaps in research.
In the process, this research has made a modest contribution to the state of knowledge about additional research needed.

For me, this work has also highlighted the need for urgent and effective reforms to current "business as usual" practices. The need is all the more urgent given unprecedented rates of urbanisation – much of it sprawling and resource-inefficient – taking place in many parts of the world today.

Samenvatting

Het onderzoek beschreven in dit proefschrift bevat drie complementaire en elkaar overlappende delen:

Eén, "bevindingen": Dit deel beoordeelt de factoren van stedelijke morfologie die bijdragen aan een verhoogde uitstoot van broeikasgassen per hoofd van de bevolking, evenals de manier waarop ze op elkaar inwerken. Het vindt een significante, maar ondervertegenwoordigde reeks van factoren, verschillend van de factoren die betrekking hebben op de schaal van het individuele gebouw en de omvang van regionale transportsystemen.

Twee, "strategieën": Dit deel beoordeelt de methoden waarmee dergelijke bevindingen kunnen worden ingezet bij het identificeren en het bereiken van reducties door veranderingen in het stedelijk ontwerp, en stelt nieuwe strategieën om dit te doen met behulp van innovatieve vormen van ontwerp- en beslissingsondersteunende instrumenten.

Drie, "ontwerpondersteunende instrumenten": Dit deel stelt een bepaalde nieuwe technologie voor, namelijk een nieuwe klasse open-source scenariomodelleringsinstrument, belichaamd in een nieuw prototype software. Het instrument maakt gebruik van een nieuw soort 'samengebrachte' webgebaseerde wiki-technologie die ontwerppatroontalen integreert. Deze werd ontwikkeld in samenwerking met software-engineer en wiki-uitvinder Ward Cunningham.

Als onderdeel van dit onderzoek is het noodzakelijk geweest om fundamentele methodologische vragen te onderzoeken en rekening te houden met de beperkingen van de huidige data en met de beperkingen van het onderzoek. In dit proces heeft het onderzoek een bescheiden bijdrage geleverd aan de stand van de kennis en over benodigd aanvullend onderzoek.

Voor mij heeft dit werk ook gewezen op de noodzaak van dringende en effectieve hervormingen van de huidige 'business as usual' praktijken. De noodzaak is des te dringender gezien het ongekende tempo van verstedelijking - veel daarvan onbeheerst uitdijend en inefficiënt wat betreft het gebruik van grondstoffen – die in vele delen van de wereld van vandaag plaatsvindt.

1 Introduction: Research Framework

§ 1.1 Background and Context

Arguably no problem facing the human species today is more daunting – and at the same time, more pressing – than the reduction of greenhouse gas emissions to mitigate the increasingly grave threat of climate change. While the science is still unclear about the range of alternative pathways to mitigation and adaptation, there is now an unequivocal consensus within atmospheric science and related disciplines that the phenomenon is occurring, and that it is already beginning to bring – and without remedy is likely to bring with increasing severity – a series of human catastrophes (IPCC AR4 SYR, 2007).

Yet it is also surely true that greenhouse gas emissions are only one aspect of an even wider human problem of unsustainable resource depletion and degradation. Both topics raise deeper issues still about the ability of humans to respond effectively in the face of inherently uncertain scientific knowledge about critical future events, and the often-associated (and increasingly problematic) consequences of political controversy and inaction.

It is encouraging to observe, however, that we humans *have* acted effectively on occasion to manage just such future events, under just such conditions. Perhaps the most relevant example is the so-called Montreal Protocol in 1987, an international treaty to control emissions of substances that deplete the planet's critical ozone layer. The treaty, together with a series of follow-on actions, has been widely hailed as a positive example of global environmental management (UNEP, 2014).

However, when it comes to the reduction of emissions of greenhouse gases (hereafter termed GHGs) the problem appears much more daunting. First, it is evident that there are many more economic and political disincentives against taking strong action, shared by many more interests – notably including developing countries, who often see such action as a serious threat to their own pressing economic and human development goals.

More deeply, as I will discuss in this dissertation, there is a high degree of uncertainty arising from the sheer complexity of the systems that shape consumption and emissions – most notably, the urban systems in which we move, consume, waste, and otherwise generate most of the ultimate demand for resources and emissions. It is safe to say that the dynamics of these systems – that is, the systems that comprise cities, suburbs and towns, together with their hinterlands – are among the most complex of any we know. They include myriad variables, many of them obscure, together with their myriad interactions. The situation is even more complex because urban systems are affected by perhaps the most notoriously difficult variables of all, those of human behaviour.

Yet precisely because urban systems act as concentrated sources of GHG emissions, they present an especially attractive target for management. The wide variations in per-capita emissions between cities with different forms – for example, the high GHG emissions associated with sprawling

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suburban forms, relative to more compact urban forms – does suggest this is an important area for investigation and development.

Furthermore, precisely because urban systems are complex, progress in understanding their dynamics in the formation of GHG emissions may well produce other insights about the dynamics of urban systems and related phenomena, with potential applications beyond the specific problem of GHG emissions mitigation. (I will discuss this point further in the Conclusion chapter.) In this sense, the problem of urban dynamics and GHG emissions may well be a kind of "lens" issue, whose examination may help to bring into focus other so far intractable challenges in our time. Although this lofty aim was certainly not our specific goal in the research reported herein, our work has indeed suggested that this is the case, as I will discuss in the summary and conclusions.

§ 1.2 The role of city form – and urban design

The specific research reported in this volume was motivated by my own recognition of a significant lacuna in the research on emissions from urban systems. In 2009 I was invited to participate in the IARU Scientific Conference on Climate Change in Copenhagen, a lead-up to the unsuccessful climate treaty negotiations of that year. I was asked (by a colleague and session organiser who was a member of the Intergovernmental Panel on Climate Change) to present some survey research on the role of urban form that I had previously conducted (Mehaffy, 2009). My recognition of the immature status of the research at the conference, and the failure of the subsequent treaty negotiations, convinced me that important research work remained to be done to support and to inform policy and practice in the future. Only with a more solid evidence-based foundation could we make progress in an otherwise lethargic world of policy and practice.

Specifically, I found that there is a relatively mature body of research on building systems, their emissions sources, and potentially effective strategies for management. At another, larger scale, there is also a relatively mature body of research on the emissions generated by transportation systems, notably automobiles and other vehicles. These two components do account for a significant percentage of urban-generated emissions, and indeed all emissions generated from consumption activities – perhaps as much as half, depending on the methodology used to measure emissions generation. They offer important opportunities to lower emissions in the short term, through lower-emissions or even zero-emissions systems (for example, zero-emissions vehicles).

However, I found that an important part of the picture is incomplete. It was readily apparent that these two components do not cover the full set of urban factors that affect emissions, and there is a range of significant if smaller urban factors between them that are much less well understood. They include infrastructure systems (including streets) and their patterns of scale and connectivity, infrastructure operating energies and transmission losses, patterns of sun and wind, patterns of distribution of uses and activities, and patterns of consumption, among others – in short, the many factors that constitute and are shaped by urban form beyond the individual building scale, but short of the scale of transportation systems per se. Crucially, this intermediate zone also connects building systems to the systems of transportation, and helps to explain how they are interrelated through urban form. Thus, it is a key part of a complete picture of the role of urban form.

The urban factors in this intermediate zone – the factors of urban morphology – are shaped by the discipline of urban design, which happens to be the area of my own expertise. Thus it became apparent to me that a contribution of research to address this lacuna could be useful to my own discipline, and to the seminal human problem of greenhouse gas mitigation. That motivation was the inception of my research agenda.

There was a second crucial piece of that agenda. I recognized that to be useful in practice, my research project must do more than identify a set of findings, which were likely to remain abstract. It must provide tools to actually guide design in practice – or at least, provide the basis for them, allowing further development and improvement by others – in the form of decision support and scenario-modelling tools. While the complete development of such a resource must be a long-term process that will necessarily span beyond the scope of this current phase of research, it requires a foundation of findings and methodology on which to build. That is an important purpose of the research reported herein.

§ 1.3 The urgency of the problem

This topic is particularly urgent because, as my earlier research suggested, alternative models of practice and supporting policy could achieve significant emissions reductions from current baselines. By contrast, "business as usual" development models are likely to result in dramatic *increases* of rates of emissions. This is because these inefficient models are now guiding development in many emerging economies around the world – a condition that is likely to further accelerate dangerous levels of emissions in the decades ahead.

Yet as noted previously, progress in reversing these trends has been stymied by geopolitical problems, inherent scientific uncertainties, and incentives against action – as the 2009 Copenhagen treaty negotiations demonstrated. In North America, which has become a model emulated by other regions, there is relatively poor comprehensive guidance for policy and design, and a low level of action in response. Project methodologies abound (for example, ratings systems like LEED-ND) but, as I discuss further in Chapter 8, they have been criticised for their lack of basis in evidence (Abdalla et al., 2011; Humbert et al., 2007; Sharifi and Murayama, 2013).

Thus there is an urgent need for concrete advancements in effective mitigation science, translated into effective practice and policy. Specifically, there is a need for effective modelling of the dynamics of emissions from urban form, and the results of specific urban design and policy choices available. Only then can actions be tied to outcomes, including new incentives and new drivers of effective changes to policy and practice. This research must be inter-disciplinary in nature, combining climate science, urban morphology, urban design, behavioural economics, software engineering technology and other disciplines. That is the broad context of our specific research project, and the specific research framework on which it has developed.

§ 1.4 The magnitude of the potential opportunity

While I was deeply concerned by what I learned initially about the magnitude of the problem, I was also equally impressed by preliminary evidence for the magnitude of the potential opportunity. My initial research showed a striking correlation between urban form and rates of emissions per capita in cities around the world – correlations that were not readily accounted for by other evident factors such as climate, demographics, cultural variations or other expected variables. Of course, correlation is not cause, and the work remained to tease out the factors and show how they are causative, as part of a coherent explanatory model. That task comprises the bulk of the middle section of this dissertation (chapters 3-5).

The striking early evidence that I found played a key role in the early formulation of my research hypothesis prior to commencing this work. It would then remain to substantiate the hypothesis with findings, and then to ask how the findings could support changes to “business as usual” urban development, by offering a new kind of design decision support technology. That latter task comprises the concluding section of this dissertation (chapters 6-8).

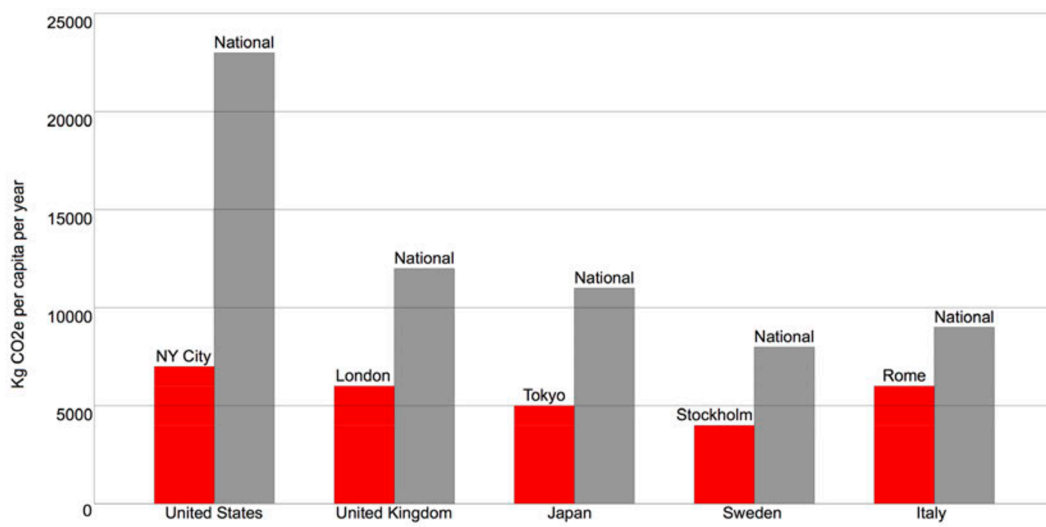

FIGURE 1.1 Comparison of country (gray) and city (red) GHG emissions per capita. Data is from 2005-2007 national inventories gathered under UNFCC standards. Source: World Bank (2011)

Figure 1.1 is a typical example of the initial evidence that played such a major role in motivating, and later articulating, my core research hypothesis. It shows a striking divergence in emissions per capita between five cities, and the averages of the very same countries in which those cities are located (using data from national inventories in 2007-2009). The emissions for those countries as a whole include other smaller cities, of course, as well as suburban and rural populations. But as can be readily seen, there is a major delta – on the order of 200% or even considerably more – between per-capita emissions in dense, mixed, multi-modal cities like New York, London, Tokyo, Stockholm and Barcelona, and average emissions per capita in the United States, the UK, Japan, Sweden and Spain overall. The latter high rates would appear to reflect the strong influence of their rural and especially their suburban populations, whose settlements are lower density, more fragmented by use, and generally dependent on a single mode of transport..

The comparison between countries is also revealing, in spite of national differences. For example, the per-capita emissions for the United States as a whole are on the order of 300% higher than those of Sweden. This delta cannot easily be explained away by obvious factors such as economic prosperity, since Sweden has a higher per-capita income than the USA. Nor is climate an obvious factor, since Sweden's winter climate is harsher on average. There are indeed other factors that might account for some of the delta, such as contributions of non-emitting energy sources and the like. But it became apparent to me that none of these factors could readily account for the magnitude of the delta. The one consistent variable was a great divergence of urban form, from dense, mixed, multi-modal cities to much lower density, dispersed, mode-dependent settlements.

Perhaps the most sobering delta of all was that between the USA as a whole and the city of Stockholm – an astonishing 600% increase in per-capita emissions. I pondered the meaning of this divergence. Was the average citizen of the USA six times more prosperous, healthy or happy in their life choices? There was certainly no available evidence to suggest that. Or, as seemed much more likely, were US citizens simply squandering over 80% of their GHG-emitting energy resources without receiving any real benefits? Was part of this profligate waste coming from the influence of urban forms? If so, how could this be documented, and what could be done to reverse it – particularly in view of the rapid urbanisation now taking place in many parts of the world?

These are the broader questions that motivated the research reported in this dissertation, and the specific research framework on which it has developed.

§ 1.5 Problem Statement

The problem-statement of this research is therefore as follows:

There is a need to reduce greenhouse gas emissions from urban consumption sources by identifying the factors that are shaped by urban design, and by guiding design towards decisions that will achieve the reductions. This must be done with a new generation of design decision support tools tools, currently lacking, that integrate the disparate sources of research from rigorous, peer-reviewed processes, and apply the results within an evidence-based, self-correcting methodology.

The problem-statement can be subdivided into the following sub-problems:

"Business as usual" urban design practice and policy is responsible for large-magnitude emissions compared to feasible alternatives, as demonstrated in comparative analyses;

1. There is currently no comprehensive method to integrate fragmented research findings into a form that can guide design practice and urban policy toward significantly lower emissions;
2. There are instead a series of aspirational targets and certification systems, and not sufficient methodologies that are transparent and capable of evolutionary improvement;
3. Current practice and policy relies primarily on immature or obsolete conceptual models, lacking an evidence-based approach to emissions reduction (as well as mitigation of other impacts);
4. A major but poorly studied variable is the relation of urban form to consumption behavior and demand;
5. Progress in mitigation is therefore slow or even stagnating.

My hypotheses about the causes of these problems are:

1. There is no adequate evidence-based design tool to identify the impacts and benefits of design decisions, and to drive policy, practice, and choice inicentives;
2. The research that might contribute to identifying impacts and benefits in operation is fragmented and, from a practical point of view, essentially inaccessible to designers and policy-makers;
3. The aspirational targets and certification systems are a "best response" by practitioners who are sincere about improvements, but lack the necessary data-driven, evidence-based modelling tools;
4. Current immature or obsolete conceptual models are driven more by outmoded mechanical or artistic visions of the future than by contemporary scientific understanding of urban dynamics;
5. Consumption behavior and demand are highly complex and highly variable (though not mysterious, and not intractable);
6. All of these interrelated causes point to a deeper inability to effectively model the dynamics of urban processes and their policy-driving benefits, and the lack of a methodology that is capable of learning from evidence and improving its efficacy over time.

§ 1.6 General objectives and sub-objectives

I identified the following general objective:

To develop the basis for a minimally accurate, effective and improvable decision support tool that will guide urban design best practice and policy in achieving potentially significant GHG reductions from feasible changes to urban morphology (including modifications for new construction, and retrofits of existing construction).

- Identify the various sources of emissions and their magnitudes;
- Identify their interactions and the factors that modulate these interactions, including behavioural factors;
- Evaluate and/or develop design and policy strategies to achieve meaningful and sustained reductions.

The sub-objectives are as follows:

- Identify the interacting influences of economic, socio-political, ecological and technological factors;
- Develop the model to address more unified information systems, including web-based scenario models;
- Develop the model to facilitate a more efficient design process;
- Raise awareness of the problem.

The final products are as follows:

- Clear research findings demonstrating the relation of factors of urban form on GHG emissions and the potential reductions from variations in urban form design;
- A theoretical model of variable urban form and its effects on GHG emissions, reflecting and explaining the research findings;
- Prototype of a design decision support tool that incorporates (and may further refine) the above findings;
- Publication of at least four journal papers documenting the above (at this writing, five have been published and one is in peer review).

My thesis, supported by initial survey research, is that there is a major delta of global GHG reduction that is achievable by systemic changes in urban morphology, and that it may be on the order of one-third of all emissions – possibly much greater, particularly in relation to future emissions based on business-as-usual trends.

I further hypothesize that these reductions can be achieved through a series of methodologies pursued with the assistance of new modelling and assessment resources to be developed in the course of the research.

I further hypothesize that, through exploitation of emerging design, policy and economic strategies and tools, these methodologies are economically, socially and politically feasible.

The following boundary conditions apply for the area of investigation:

- ***Emissions measurements and sources considered:*** Consumption-based sources, as opposed to production-based sources (e.g. manufactured goods consumed elsewhere); emissions measured per capita; emissions measured in CO2 equivalent in metric tonnes; emissions measured by the methodology established under the United Nations Framework Convention on Climate Change (UNFCC).
- ***Level of scale considered:*** Neighbourhood, district and city scales, as distinguished from building scales on the one hand, and regional/national/global scales on the other;
- ***Emissions systems considered:*** Urban form, as opposed to buildings systems on the one hand, and transport systems on the other (although some discussion of their linkages will be discussed);
- ***Scope considered:*** Models of new development within growing metropolitan areas (including developing economies) with a secondary emphasis on retrofits within existing areas;
- ***Parameters considered:*** Reductions of greenhouse gas emissions, as distinguished from reductions of energy or resource consumption per se (which do not always generate GHGs);
- ***Approach focus:*** Reductions from changes to urban morphology (e.g. spatial distributions, circulation networks, patterns of use, etc.) as distinguished from reductions from specific building and energy systems (which are partially considered, but only in relation to the former).

The main research questions are these:

1. What are the key variables of urban morphology that drive carbon emissions, and how can they be manipulated (together with their interactions) through design changes, and related policy changes?
2. How can this opportunity for reduction be managed through a new class of urban design decision support tool?
3. How can this class of tool be developed, and made more accurate and useful over time?

Sub-questions regarding the key variables and their manipulation through design:

- What are the various sources of emissions, and what are their interactions?
- How do they interact with other economic, socio-political, ecological and technological factors?
- How can these interactions be integrated into a model?
- What existing policies and best practices, which might be revised as part of the decision support tool, result in higher than necessary emissions?
- What is the role of behavioural factors, and social feedback effects such as "induced demand?"
- What innovative new policies and practices are feasible? What does the model suggest about the feasible reductions from their use?

Sub-questions related to the creation and development of a specific tool:

- What are the modelling systems that are most appropriate (computer, web, open-source, Wiki)?
- What other available technology may be useful?
- Where is the data to be found (or gathered)?

Background questions are as follows:

- What other work has been done in the field, and how can this work make a unique contribution?
- How can this work be most useful in meeting current urban challenges, e.g. rapidly-developing urban environments in the developing world (both formal and informal)?
- How can this work exploit new advances in other fields, such as economics, computer science, et al.?

§ 1.7 Approach and Methodology

The research has been organised into the following six steps:

1. Survey of current research and assessment of prospects (problem-statement)
2. Assess interactions with other economic, socio-political, ecological and technological factors
3. Integrate the role of behavioural factors, and social feedback effects such as "induced demand"
4. Develop an early version of the proposed decision support tool
5. Assess the decision support tool in relation to existing policies and best practices to reduce emissions: conduct "reverse forecasting" assessments to make preliminary evaluations of the predictive accuracy of the decision support tool
6. Draw conclusions for current best practice

The methods of research are as follows:

1. Literature survey research
2. Interviews, symposia, collaborative research (e,g, software engineering)
3. Research by design and evaluation
4. Research and development of software
5. Generation and evaluation of research test results
6. Peer evaluation and comment

I am grateful to the many advisors and collaborators who have contributed to this project and/or provided advice, as listed in the dedication page.

§ 1.8 Relevance

Societal relevance: Mitigation of climate change, and related resource issues; increased awareness of the problem and its likely solutions.

Scientific relevance: Integration of disparate and inconclusive current findings into a new and synthetic finding; research and development of a new modelling tool for urban design best practice and policy.

Projected innovation: A new conceptual framework; a new software innovation; and a new (prototype or "alpha test") urban design scenario modelling tool.

Embedding in research programmes and relationship with other research projects: This work extends and connects existing research in transportation, buildings, energy generation and related fields. As such it involves investigators from these areas and their research in the search for an integrated model or models for the role of urban morphology and the magnitude of impact of its variation, to guide design and policy.

This work also extends and connects my own research and policy work with UN-Habitat in advance of Habitat III (in partnership with Ax:son Johnson Foundation and Project for Public Spaces) and the key role of urban morphology in general, and public space networks in particular. In addition, it extends my previous research and interaction at the International Alliance of Research Universities' International Scientific Congress on Climate Change in 2009, where I presented the initial survey research that would form the impetus for this research.

Relationship to other Delft research: This PhD research has been part of the Green Building Innovation research programme (theme of carbon neutrality) as well as the Urbanism programme. It is particularly related to PhD work by Rob Roggema (Climate adaptation and spatial planning) and Nico Tillie (Fossil energy free, liveable cities). Close relationship is made with the European Network for Sustainable Regions (ENSR) and its involvement in the EU FP7 research programme of City-zen.

§ 1.9 Scientific publications and chapter structure

The chapters herein were previously published as peer-reviewed research, with the exception of the introduction, conclusion and a portion of the validation report in Chapter 8. To avoid repetition and follow a logical order, some chapter material is drawn from multiple papers, and some introductory or clarifying text has been added. The papers published and their relevant chapters are as follows:

Chapters 2, 7

Mehaffy, M. W. (2013). Prospects for scenario-modelling urban design methodologies to achieve significant greenhouse gas emissions reductions. *Urban Design International*, 18(4), 313-324.

Chapters 2, 6
Mehaffy, M. W. (2014). Counting Urban Carbon: Effective modelling of resource-efficient urban design solutions under uncertain conditions. *International Journal of Architectural Research:* ArchNet-IJAR, 8(2), 20-35.

Chapter 3
Mehaffy, M., Haas, T., & Dobbelsteen, A. v. d. (2014). Unpacking density: Exploiting urban design variables in carbon reduction strategies. *Nordic Journal of Architectural Research,* 26(2).

Chapter 4
Mehaffy, M. (2015). The Choice Architecture of Neighbourhood Design. Currently in peer review, *Journal of Planning Education and Research.*

Chapter 5
Mehaffy, M. W., Porta, S., & Romice, O. (2015). The "neighborhood unit" on trial: a case study in the impacts of urban morphology. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability,* 8(2), 199-217.

Chapter 8, Appendix
Cunningham, W. and Mehaffy, M.W. (2013). Wiki as Pattern Language. In *Proceedings of the 20th Conference on Pattern Languages of Programs (PLoP'13)*, Monticello, Illinois, USA (October 2013). 15 pages..

Related peer-reviewed research papers that have contributed background information

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2 Counting Urban Carbon: Baseline and Boundaries of Current Findings

Chapter Summary

This chapter describes the baseline of findings from current research and identifies relevant boundaries. Particular attention is given to the inherent complexity and uncertainty of urban systems. Nonetheless, consistent factors are identified for further refinement and incorporation into a decision support tool.

This chapter incorporates the first half of the peer-reviewed publication "Counting Urban Carbon" (Mehaffy, 2014) as well as additional material from the paper "Prospects for scenario-modelling urban design methodologies to achieve significant greenhouse gas emissions reductions" (Mehaffy, 2013). This material covers the boundaries and methodology for gathering and assessing current research findings. The second half of the paper "Counting Urban Carbon" deals with the methodology behind the decision support tool discussed later, and it appears as part of Chapter 6, Modelling Methodologies.

As noted in the introductory chapter, the dynamics of urban systems are among the most complex of any system we know. They include myriad factors and interactions, including perhaps the most complex of all factors: those of human behaviour. If we are to make headway in the stated aim of mitigating greenhouse gas emissions with new urban design decision-making tools, we need to be able to analyse the urban systems in question, and clearly identify, in a useful way, the factors that can be varied by design to produce the preferred results. We must also identify, to the extent they will substantially change the results, how those factors interact, possibly producing unintended consequences.

This in turn will require a very clear understanding of current emissions and their trends; evidence for the urban factors that account for emissions reductions (on conversely, increases); their potential interactions; the methodologies that can model potential reductions or increases with useful accuracy; the factors that introduce uncertainty into current measurements; and the strategies to deal with inherent uncertainty, in both the current measurements and the evidence-based models of future emissions.

In short, we need a clear "road map" of the current state of knowledge about greenhouse gas emissions, and the complexities and uncertainties that must be accounted for in development and application of our ultimate goal, an effective design decision support tool. That is the goal of this chapter.

One significant problem is that there are well-documented complexities and ambiguities in the way we measure emissions, as this chapter will discuss in more detail. In greenhouse gas emissions as in other scientific subject areas, there are characteristic phenomena of uncertainty in measurement which must be accounted for. Moreover, there are potential problems of confusion between kinds of measurements, such as production-based emissions and consumption-based emissions (Hoornweg, Sugar and Gomez, 2011; Satterthwaite, 2008).

Moreover, there is inherent uncertainty and even randomness in the way these emissions will actually occur, which makes prediction a problematic, possibly even self-deceptive exercise (Taleb, 2005; Kahneman, 2011). In part this is because the systems themselves are not static but are self-modifying, posing a fundamental challenge to both science and policy (Mayumi and Giampietro, 2006). We will discuss this particular challenge in more detail in a later chapter (Chapter 6, Modelling Methodologies).

§ 2.1 Inventory data sources and boundaries

Before we consider these deeper complexities, the first task is to identify the sources of emissions data and their relevant boundary conditions, so that we may draw usefully reliable findings. There are in fact many distinct inventories of GHG emissions, including local inventories gathered for specific purposes. (Examples include corporate inventories used to measure progress against goals, inventories developed for specific research projects (an example of which is the Vulcan Project) and inventories generated by specific measurement technologies (such as NASA's Orbiting Carbon Observatory 2, or the Japanese Aerospace Exploration Agency's Greenhouse Gases Observing Satellite, or GOSAT).

However, we must be careful not to mix data from different sources, which may be measured under different protocols or boundary definitions. We must also be careful to describe the boundaries of our own analysis, and what is being measured and what is not. Chapter 1 set out the boundary conditions of the research. For the work reported in this chapter we must further define the boundaries of measurement as follows:

1. ***Emissions per capita.*** The research will not look at emissions per geographical unit, per economic sector, or other kinds of units. Per-capita emissions data has the advantage of focussing on a global standard unit – one human individual – and the effects on emissions from that unit as the urban form and other conditions around it vary.
2. ***Consumption activities.*** The research will not look at emissions from production activities per se, but will account for them as the consequence of demand and consumption originating with individual consumers. This too helps to focus on the influences on activities of individual consumers from varying urban forms. There are of course significant factors that lie outside of this boundary: for example, policy decisions to shift to non-emitting production sources, changes to regulatory policies or technologies limiting production emissions, and the like. Though potentially very important elements of a wider GHG mitigation strategy, these factors will not be considered in this research.
3. ***Emissions measured according to a single global standard protocol.*** The research will not consider local inventories that define their own methodologies, since they may not be commensurable with other inventories. A single standard, regardless of flaws it may embody, does at least have the ability to reveal significant variations in emissions in response to other variables, including urban form.
4. ***Emissions measured as "CO2 Equivalent" in metric tonnes.*** This methodology accounts for the varying greenhouse effect and atmospheric persistence of different gases such as methane and chlorofluorocarbons, and expresses them as equivalent units in carbon dioxide of their "global warming potential" (GWP). It uses the measurement unit of "metric tonnes" which is widely accepted.

For this purpose, perhaps the most comprehensive set of inventories, and the most useful, is the set of national inventories that are provided under standardised technical specifications according to the

United Nations Framework Convention on Climate Change (UNFCCC). In turn this framework uses the ISO 14064 standard for measuring, quantifying, reporting and verifying emissions. From this set of inventories, this research will draw on the CO2 Equivalent per capita reports.

§ 2.2 Inventory uncertainties

If we are seeking to develop a useful predictive model for design decision support, we must also assess whether the data on which we rely to develop the model and to measure its effectiveness is accurate enough to provide the basis for usefully accurate prediction. To the extent the data is unreliable, our predictions will also likely become unreliable. In this regard, there are several well-recognized problems to take into account.

Many authors have documented inherent uncertainties with current greenhouse gas inventories, which may result in errors as high as 20% (Rypdal and Winiwarter, 2001). These errors are even more significant when distinctions are not kept clear between production-based and consumption-based values. Hoornweg, Sugar and Gomez (2011) demonstrate that per-capita emissions can vary significantly for the same resident of a city or country depending on whether these are production- or consumption-based values. Such distinctions are often confused, or comparisons are not made between consistently defined values.

Satterthwaite (2008) presents evidence that the emissions generated by residents within cities are overstated in current methodologies, relative to residents of other regions. Moreover, he notes, it is important to tease out the different kinds of residents within cities and their consumption habits, in order to get an accurate understanding of emissions sources. Dodman (2009) makes a similar finding, showing that the factors accounting for emissions are complex and not well understood at present.

Jonas and Nilsson (2007) find that scientific uncertainties are inherent in greenhouse gas accounting, and that (particularly under treaties such as the Kyoto Protocol) a verification framework is essential, but to date does not exist. Lieberman et al. (2007) observe that recognising high levels of uncertainty is necessary to improve inventories and manage risk in policy actions, such as carbon emissions trading schemes.

Many of these authors make the point that uncertainty cannot be removed, but it can be recognised and accounted for so as to produce more usefully reliable inventory measurements. Indeed, to that end the Intergovernmental Panel on Climate Change has produced practice guidance on uncertainty management in national inventories (Moss and Schneider, 2000). Rypdal and Flugsrud (2001) are among investigators who have developed methodologies to reduce or manage uncertainty in inventories. Moss and Schneider (2000) also have issued guidance to IPCC lead authors to reduce uncertainties through more consistent assessment and reporting procedures.

All of these investigators point out an inherent component of uncertainty in greenhouse gas data, illustrating the need for models that are sufficiently robust to be useful in spite of this uncertainty. What is critical, then, is that the basis for comparison is equivalent, and that it has a logical relation to the opportunities for reduction. For example, the allocation of GHG emissions per capita, and to the activities of individuals as they generate varying levels of demand, may provide better access to the behaviours that actually generate emissions in manufacturing, agriculture, energy generation and other sectors. Of course, it is in urban settings of varying kinds and intensities that most of these activities occur.

§ 2.3 Uncertainty regarding urban form as a factor in greenhouse gas emissions

Among the factors that influence human-generated emissions of greenhouse gases, the evidence gathered for this research indicates that urban morphology may be one of the most significant – and yet paradoxically, one of the least well recognized and understood. This state of affairs has profound consequences for present-day policy and best practice (Ewing et al., 2007).

On the one hand, we have compelling phenomenological observations that cities with significant differences in urban morphology also have significant differences in per-capita GHG emissions (World Resources Institute, 2009, Energy Information Administration, USA, 2010). We can generally account for "apples to oranges" factors such as climate, culture, economy and the like, and yet it is difficult to account for more than perhaps half of the significant observed difference in emissions rates. Yet our current models are unable to account for such a large difference from urban morphology alone (Mehaffy, 2009).

This research lacuna is in contrast to the much more mature body of research on the effects of building systems and their components, which do provide useful guidance for policy and best practice in the form of energy codes, tax policy and the like. At the other end of the urban scale, there is an equally mature body of research on transport-related emissions and their variables, with applications to policy strategies such as transportation planning and pricing. But there is at present a weak understanding of the connection between the two scales – the region with its transport system (and other emissions sources) on the one hand, and the building with its resource-using systems on the other.

This gap in understanding is likely because the effects of urban form can appear modest when looked at in isolation, even if they may be significant when aggregated, or especially, when interacting within a dynamic, synergetic system. Moreover, these factors often interact in exceedingly complex, systemic and sometimes subtle ways, and they are "masked" by other variables, such as variations of climate, income and behaviour. It is therefore difficult to tease out the various local factors that may be attributable to urban form (such as end consumption) from more global ones (such as initial production) and to recognize them as variable factors in their own right (Dodman, 2009; Wilbanks and Kates, 1999). As discussed previously, the picture is further obscured by incompatible variations in the boundaries of different measurements and inventories, creating inconclusive "apples to oranges" comparisons (Mackay, 2009; Brown, Southworth and Sarzynski, 2008).

Nonetheless, the literature contains a growing body of work that examines the detailed contributions from urban morphology, and as a result, some specific elements of the system are slowly becoming clearer. For example – and as we discuss in more detail below - a number of investigators have examined causative relationships between urban form and specific emissions sources, such as personal automobile use and housing energy use (Ewing et al., 2007; Brown, Southworth and Sarzynski, 2008).

But it is fair to say that there is still no comprehensive assessment of the full set of causative factors, their relative magnitudes, and their relation to other influencing factors (Satterthwaite, 2008; Kates et al., 1998). This uncertainty within the research community translates into uncertainty and inaction in mitigation policy. Indeed, real doubt has been expressed in leading professional publications about whether overall greenhouse gas emissions levels can be altered significantly through feasible changes in urban form at all (Technology Review, 2009).

However, the incomplete research discussed here does strongly suggest that the cumulative and systemic effects of urban form may well be major contributors to greenhouse gas emissions; that there is reason to conclude that feasible changes in urban form can and must play a central role in effective mitigation strategies (especially so for the developing world); and that there remain important gaps in knowledge that will need to be filled by ongoing research to guide effective policy and best practice (Intergovernmental Panel on Climate Change, 2007). This paper is an early effort to assess the opportunities within this subject area.

More specifically, as we will discuss later in this dissertation, the research suggests an important opportunity to develop very useful new scenario-planning tools to guide the specific features of urban design at the neighbourhood and district scale. If successful, these tools might do more than simply identify static quantities of reductions that could then be achieved. They might, by providing a dynamic feedback capability, be able to make incremental improvement in the efficacy of the design strategies, and over time, through empirical evaluations, contribute useful research data leading to improvements in their own effectiveness (Hopkins, Lewis and Zapata, 2007).

§ 2.4 The specific challenges of analysing urban systems

As noted, it is in the nature of analysis that we have a much better picture of the behaviour of individual components of urban systems acting in isolation, than we do of their behaviour as part of a complex, dynamic urban system (Condon, Cavens and Miller, 2009). Yet it is clear that this systemic context is an essential parameter of performance, without which we may achieve emissions reductions in one component, but find those reductions offset or even exceeded by increases in systems overall.

This "Whack-a-Mole" phenomenon (so named for the children's game, which solves one problem only to see another one pop up elsewhere) can often be seen at work when individual urban components such as buildings and automobiles are treated as isolated variables. Gains from the efficiency of a component in isolation are often erased when that component is examined within its larger urban system. For example, there are notable cases of "green buildings" in more remote locations that require significantly higher transport energy for their users, erasing gains from building technology. (Environmental Building News, 2007)

It is certainly true that it is more difficult to quantify these systemic impacts, and our potential leverage over them, than to quantify the impacts of individual components. Urban systems by definition contain myriad factors that interact in exceedingly complex ways – and they can be greatly affected by human behaviour, one of the most complex of all factors. Furthermore, it is difficult to quantify the impact of relative trade-offs in "apples-to-apples" fashion, because they are often masked by other variables – for example, the effects of climate or demographic variables.

Lastly, we are discussing greenhouse gas emissions as they are driven by activities within urban systems, but often the emissions are actually generated in remote power generation facilities or manufacturing plants. These emissions vary by type of fuel, and, in the case of hydro, wind and nuclear, emissions are very low (but not zero, because of concrete used in manufacturing, etc).

In addition, resource use driven by urban activities can drive emissions in other complex ways. The shipping of goods is itself a remote generator of emissions. High consumption of meat can result in wood-burning for clearing that is not replaced with new growth, and higher release of methane from livestock. The process of concrete production is an emissions source in its own right. (MacKay, 2009)

Thus we must distinguish firstly between those sources of emissions that occur within the urban system itself (like gas-fired boilers, say), and those that are driven by consumption activities within the urban system, but occur remotely. Secondly, we must distinguish between the metrics of energy and resource use, which is a major driver of GHG emissions, and the metrics of GHG emissions per se. These generally correspond closely, but can have important variations. In this dissertation we will refer occasionally to the combined concept of "energy use and GHG emissions" while understanding this implicit distinction.

In spite of these systemic challenges, research is beginning to establish a much clearer understanding of the important ways that the dynamics of urban systems, with buildings as their sub-systems, affect energy use and GHG emissions (Ewing et al., 2007). Indeed, as this paper will summarize, the research indicates that important conclusions can be drawn, and that they point the way to dramatic reductions in emissions, through feasible changes to urban form.

§ 2.5 Current understanding of the urban morphology factors in GHG reductions

As we have noted, in spite of the weaknesses in this area of research, a number of contributing factors to GHG emissions from urban form have been previously identified (U.S. Environmental Protection Agency, 2010). Significant ones have been clearly identified, while other, lesser ones are more poorly understood.

Another remaining problem is that there has been little work to assess their aggregate effects in combination, or the systemic interactions between them. Nonetheless, there is sufficient data to begin putting together the factors of urban form, as elements of an eventual modelling tool.

A first step for our assessment is to summarize these factors, and what is known about them at present. From there, we can begin to identify the specific, coordinated guidance that an urban scenario planning tool would provide to achieve likely reductions.

Residential density

Many authors have found a close correspondence between lowered residential density (usually corresponding to detached single-family residential buildings, and low ground cover) and increased GHG reductions. Most of the conclusive work in this area relates to personal transportation by car, which is relatively easy to translate into GHG reductions. For example, Holtzclaw et al. found a striking correspondence between residential density and "vehicle miles traveled per household" within parts of three American cities (Holtzclaw et al, 2002).

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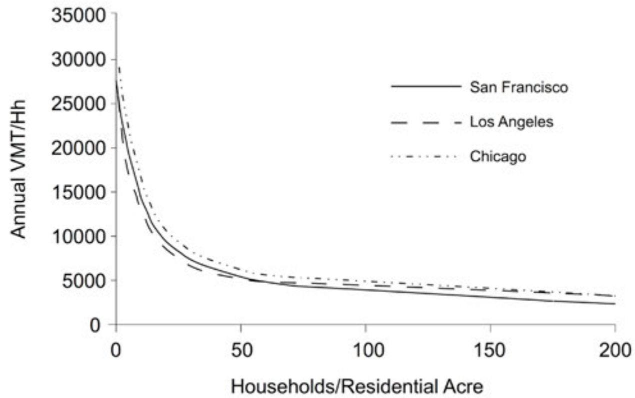

FIGURE 2.1 Driving versus residential density. Source: Holtzclaw et al. (2002)

Kenworthy and Laube found very similar results when looking at the evidence from many cities internationally. Their metrics were different (motor spirit consumption per person instead of distance driven, and urban density per person instead of per household); nonetheless their results were almost identical. Indeed, their research showed a doubling of density is associated with a reduction in energy use per capita of approximately 30% (Kenworthy and Laube, 1999).

Other studies showed a similar pattern. In US research (Holtzclaw et al., 2002) the reduction is from about 15,000 miles per year (9,000 kilometres) at a residential density of 12 units to the acre (5 to the hectare) down to about 5,000 miles per year (3,000 kilometres) at 75 units to the acre (30 to the hectare). A frequently cited study in the field (Kenworthy and Laube, 1999) also demonstrated that transportation fuel consumption per capita declines by one-half to two-thirds as urban densities rise from four to twelve persons per acre (1.6 to 4.8 persons per hectare).

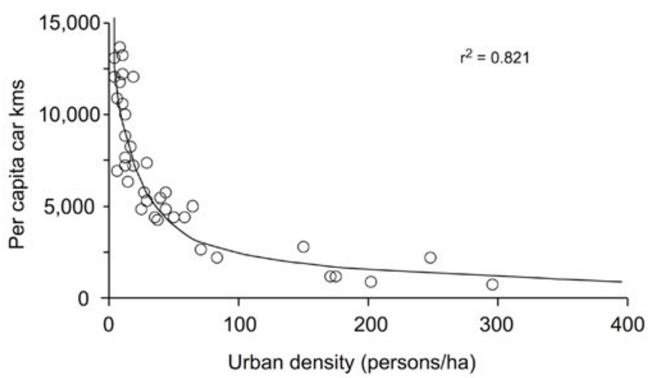

FIGURE 2.2 Urban density (persons/HA). Source: Kenworthy and Laube (1999)

A similar pattern is observable from non-transportation sources of GHG emissions (e.g. Norman, MacLean and Kennedy, 2006; Ewing and Rong, 2008). The components studied include infrastructure, transmission distribution and losses, characteristic housing stock and its heating and cooling demands, and heat island effects, among others. While transportation factors are easier to analyse, and therefore tend to dominate the literature, a growing body of work is already establishing a clear association between residential density and greenhouse gas emissions from non-transportation sources.

These findings are compelling, providing strong evidence that an effective urban design path to lower greenhouse gas emissions is to increase residential density. Nonetheless, of course, "density" is an aggregate variable that includes a number of other factors, and these must be teased out if we are to have more accurate design guidance for effective reductions (Norman, MacLean and Kennedy, 2006). Among them, as identified by the research, are:

Proximity of daily needs and activities

An optimum mix and distribution of workplaces, retail, offices and other daily destinations results in significantly shorter trips per day on average. The most optimum pattern follows a "power law," e.g. many small and close, few large and distant, and a range between." A mature body of literature demonstrates this association with proximity to daily needs and activities through "jobs-housing balance" and "retail-housing mixing" (e.g. Kenworthy and Laube, 1999, Cervero and Duncan, 2006.) This criterion is associated with typological diversity (a mix of different building types allowing different uses).

An urban morphology meeting this criterion would feature an optimally distributed pattern of uses, with "neighbourhood center" uses (such as limited groceries and everyday conveniences) tightly distributed (e.g. 400m to 800m or ¼ to ½ mile), "town center" uses (general groceries and shopping, other regular services and employment centres) distributed somewhat less tightly (e.g. 800m to 3200m or ½ mile to 2 miles), and "urban center" uses (specialty shopping and services) distributed in fewer and more centralized locations (e.g. 3km-7km or 2 miles-5 miles). (Mehaffy et al., 2009.)

Walkable neighbourhood design

Research is confirming the many important benefits of a neighbourhood structure that accommodates high rates of walking, including the energy efficiency and GHG emissions reductions from walking, which consumes approximately 150 kilojoules per passenger-kilometer, compared to 4,200 kilojoules per passenger-kilometer for an average single-occupancy passenger sedan (Hydro-Québec, 2005.) (It is worth noting that walking trips fuelled by a significant meat diet can be somewhat higher.) Moreover, the beginning or end segment of a public transport trip is almost always a walking segment. Therefore a neighbourhood morphology that obstructs walkability is likely to obstruct transit use as well.

"Walkability" must be defined in precise morphological terms in order to be sufficiently specific for an urban design methodology. A growing body of research demonstrates a strong correlation between walkable neighbourhoods and such factors as high intersection density and short blocks, and diversity of close-by destinations (e.g. Leslie et al., 2005, Berrigan, Pickle and Dill, 2010), and walking infrastructure and aesthetics (e.g. Cerin et al., 2006). That is, a walkable neighbourhood will offer attractive, comfortable, well-connected pathways on short blocks (no more than 120 meters or about 400 feet per side, 360 meters or about 1200 feet total perimeter) to a mix of nearby destinations.

Bikable neighbourhood design

Biking is also a low-energy (and low GHG emissions) form of transport, just 60 kilojoules per passenger-kilometre when fuelled by a vegetarian diet, and somewhat higher when fuelled by meat (Hydro-Québec, 2005).

A small but growing body of literature shows that the morphological characteristics of a bikable neighbourhood are similar to those of a walkable neighbourhood: close-by destinations, connectivity, intersection density, adequate infrastructure and attractive aesthetics. In addition, there is evidence that bikability requires a pathway safe from vehicles, close to buildings and "eyes on the street," and generally free from major grade changes (generally above 5% for more than 90m or 300 feet). Typically this requires a set of quieter secondary through streets that are closely spaced, with attractive aesthetics such as vegetation and detailed building architecture (Saelens, Sallis and Frank, 2003, Wahlgren and Schantz, 2010).

Availability of effective, safe and convenient public transport

An average single-occupancy passenger sedan consumes 4,200 kilojoules per passenger-kilometer, while a 40% occupied subway consumes 280 kilojoules per passenger-kilometer (just 6.7%). A 50% occupied diesel bus consumes 800 kilojoules per passenger-kilometre. (Hydro-Québec, 2005.) The urban morphology to support this reduction must be sufficiently dense, typologically diverse, and (as noted above) supportive of walking to stops.

The vehicles themselves contain embodied energy and resources (Welbanks et al., 1999). Thus a greater number of cars per capita will translate into greater embodied energy and resources, and greater emissions. A younger fleet (vehicles replaced more often) will also increase the embodied energy and resources as well as emissions per capita, other things being equal. (However, an example of the complexity of such an analysis is that at present a younger fleet is also likely to have higher fuel efficiency, lowering emissions.)

The urban morphological characteristics of effective public transport systems are the subject of a mature body of literature. Generally, a minimum residential density of 8 units per acre, or 20 units per hectare (translating to about 50 persons per hectare) is accepted, and stops must be no more than 800 m or ½ mile apart, and must form a well-connected network with minimal detour requirements. Service must also be frequent, convenient and comfortable. (Berrigan et al., 2010; 37. McNally and Kulkarni, 1997; Johnston and de la Barra, 2000.)

Urban network

An integrated rather than fragmented urban network results in shorter trips on average, and proportionately lower energy use and emissions per trip. It also promotes walking, as average walking trips are also shorter. (Pushkar, Hollingworth and Miller, 2000, Dill, 2004). There is also evidence that the dynamics of networks allow for resource efficiencies from combined and synergetic interactions, resulting in additional efficiencies and reductions of GHGs. (This phenomenon, which has been termed the "resource spillover," is one that I have identified for future research.)

This factor also requires a morphology with a small-grained, interconnected street pattern (Berrigan et al., 2010).

Neighbourhood Vehicle Infrastructure

Neighbourhoods that have a low demand for only occasional automobile use (e.g. for transporting large purchases) can support reduced numbers of shared automobiles. The result of reduced fleets will be a reduction of embodied emissions and energy from manufacture per person (Sullivan , Costic and Han, 1998). Neighbourhoods whose morphologies allow an efficient distribution of daily destinations without the need for high-speed automobiles (e.g. freeway travel) can support fleets of low-impact vehicles, such as Neighbourhood Electric Vehicles (NEVs) (Marshall, 2009). This is a synergetic benefit from the other urban morphologies discussed above (density, typological diversity, interconnected street pattern).

Beyond the effects associated with transportation, there are many other lesser but also evident factors of urban form that directly influence greenhouse gas emissions. Some of these factors are only poorly understood at present – particularly as they may aggregate and interact with other factors. Therefore the magnitudes of their contributions to emissions, both in aggregation and in interaction, present a ripe area for further exploration. Following is a brief review.

Infrastructure efficiency

It is intuitively obvious, and confirmed by research, that higher density reduces the allocation of required infrastructure per person:

- ***Infrastructure construction and maintenance.*** A one-block street segment that embodies a typical 100 million BTUs (approx. 100 gigajoules) will be allocated across 8 households at 12 million BTUs (approx. 12 gigajoules) per household. But the same street segment serving 20 households will be allocated at only 5 million BTUs (5 gigajoules) per household (Allen, Bruce and Benfield, 2004).

- ***Operating energy.*** This includes lighting, pumping, signals, irrigation, and other urban infrastructure energy systems. Higher density neighbourhoods require proportionately less operating energy per capita (Hydro-Québec, 2005).

- ***Transmission efficiency and loss***. Losses from transmission can be as high as 7% or more, and there is a clear association with urban form. Higher density means shorter distances and more efficient distribution (Dong, 2006; Suresh and Elachola, 2000).

- ***Cogeneration and district energy opportunities.*** These can be much more efficient than individual building systems – over 25% more efficient – and they can also significantly reduce transmission losses (Allen, Bruce, and Benfield, 2004).

In addition to higher residential density, infrastructure efficiency is increased with an urban morphology that includes other intensive activities, diverse and complementary uses (e.g. demand occurs at different times of day), and dense spacing of network nodes for greater efficiency (Dong, 2006; Ewing and Rong, 2008).

Ecosystem Assets

Approaches to infrastructure which replace GHG intensive engineered solutions with ecosystem services show great promise in a wide variety of socioeconomic settings:

- ***Protection and restoration of ecosystem services.*** Urban form can be designed to maintain or restore natural systems that are performing water filtration, carbon sequestration, air purification and other valuable services. These eliminate the need for engineered equivalents which would generate high energy use and emissions (Knapp et al., 2005, Bolund and Hunhammar, 1999).

- ***Local and urban agriculture.*** Other factors being equal (e.g. requirements for greenhouse heating), local and organic food systems appear to offer the ability to reduce energy, petrochemical use and GHG emissions associated with food growing, storage, and transportation. Urban form can be used to support adjacent extra-urban agricultural lands and to promote urban agriculture on rooftops, in greenhouses, in yards and open spaces, and in underutilized areas (Knapp et al., 2005).

- ***Sustainable water systems.*** Urban form can be designed to facilitate systems approaches to water catchment, purification, and distribution, as well as to stormwater, graywater, and wastewater treatment, re-use, and infiltration. These approaches can greatly reduce GHG emissions associated with conventional water purification and wastewater treatment plants, including pumps and mechanical filtration systems (Hellstrom, Jeppsson and Kärrman, 2000).

- ***Heat island/albedo/vegetative cover per person***. Low-density auto-dominated development is typically associated with relatively high loss of vegetative cover per person. Areas of extensive pavement and hard surfaces tend to increase heat island effects, with an increased demand on cooling equipment in warm areas and seasons. In addition, low albedo in pavement and roofing increases warming, and loss of vegetative cover reduces CO_2 absorption – both of which aggravate warming effects over time, and increase cooling demands yet further. These can be mitigated with a more compact urban form that reduces such surfaces per person, and preserves surrounding ecosystems. The urban environment can also be supplemented with "cool roofs" or green roofs, and greater levels of urban vegetation (Akbari and Levinson, 2008; Akbari, Menon and Rosenfeld, 2009).

Clearly, urban morphologies that are more compact are likely to consume less of the surrounding land that would otherwise perform ecosystem services. In addition, urban morphologies that afford places for on-site water reinfiltration, green roofs, urban agriculture and mitigations of heat island/albedo effects (reduced paving areas, lighter paving, roofs and buildings, etc) can improve performance by measurable percentages.

Interface between urban form and building form

Urban areas that include multi-family and attached dwellings – particularly those with advantageous solar orientations – have a number of energy efficiency and GHG emissions advantages:

- ***Urban building type, exposure, and orientation.*** According to U.S. DOE data, space-heating requirements are roughly 20 percent less on a square foot basis for dwellings in multi-unit buildings, compared to detached structures. (Allen, Bruce and Benfield, 2004; Ewing and Rong, 2008)

- ***Prevailing size, and associated economic factors.*** Residential units in higher-density areas are typically smaller on average, in part because of the higher prices commanded by greater proximity to nearby employment, amenities and services. This results in a proportionate decrease in heating, cooling, and other energy loads. The increased cost of homes also may cause a shift away from other forms of energy-intensive consumer spending, toward home care and improvement. (Allen, Bruce and Benfield, 2004, Ewing and Rong, 2008)

- ***Embodied energy in building materials.*** Smaller residences will also have a proportionate decrease in embodied energy for building materials, which translates into reduced GHG emissions in manufacture and construction – assuming that the number of people per square foot is not also reduced even more. In addition, attached dwellings have an average of 5% lower embodied energy per unit of floor area than detached dwellings (Allen, Bruce and Benfield, 2004). (But it is worth noting that as buildings grow beyond about 5 stories in height, there are disproportionate increases in embodied energy per unit of net residential area due to losses to building circulation systems and non-linear changes in structural requirements (Treloar et al., 2001). The lesson is that all factors must be weighed systemically.)

Urban morphologies performing well in this category feature relatively low-rise, compact residences, with good solar characteristics (exposure, deciduous trees, etc). Other non-residential buildings are generally well-integrated into the neighbourhood structure, and also compact and well-oriented to solar exposure.

Though it is beyond the scope of this paper, we note there is evidence that tall buildings have a number of drawbacks, including relatively high embodied energy, poor exposure to wind and sun, inefficient floorplans due to egress requirements, and other factors. These do not appear to be offset by increased density, the benefits of which seem to diminish above a more moderate density. In addition, there are significant effects of tall buildings on the other buildings and environments that surround them, such as shading, wind effects, and "canyon" effects (trapping heat and pollutants). (See e.g. research cited in Mehaffy, 2011.)

Other indirect factors

There are other topics that are more difficult to quantify, but may be critical in accounting for observed GHG emissions – and in developing new strategies for reduction:

- ***Induced demand.*** This is a well-known perverse effect of efficiency (also known as Jevon's Paradox). As systems become more efficient, they also tend to become less expensive. The result is that people may be more likely to use them more, partially or wholly erasing the gains from efficiency. It will be critical to develop policy approaches that prevent the induced demand effect from erasing potential decreases in GHG emissions. (Allen, 2001; Johnston, 2006; McNally and Kulkarni, 1997).

- ***Cognitive and behavioural factors.*** To what extent will the quality and conviviality of the built environment and associated open spaces displace demand for forms of consumption associated with high levels of GHG emissions? How does this interact with a wide range of cultural factors? What will promote lower resource use and emissions habits and choices? Much more research is needed in this important subject, but we know that the success of neighbourhoods in attracting and retaining residents over time depends on attractive architecture, durable high-quality construction, and access to parks and natural areas (Holtzclaw, 2001; Ramaswami et al., 2008).

- ***Resilience and performance over time***. New technology that is meant to improve performance will clearly do little good if it breaks down or becomes rapidly obsolete. In such a condition the embodied energy of its production can easily exceed any savings from its introduction. So too, buildings need to be able to adapt to new uses, while remaining durable and easy to repair and maintain. There is also evidence to suggest that buildings that reflect local identity are more likely to be found appealing and worthy of care. (Allen, 2001.)

We suggest this is an important category that deserves much more investigation. Though the significance of these factors is inherently harder to quantify, since they relate to the complexities of behaviour and perception, nonetheless they may play a major role in consumption and therefore emissions per capita.

For the moment, we note evidence suggesting that an urban morphology that is compact, connected, diverse, varied, and fractally patterned, as well as less dependent on systems that are prone to induced demand (i.e. more reliant on passive approaches) will contribute to improved performance in all these factors. Not surprisingly, such a morphology has many of the characteristics that were well-adapted to an era prior to extensive mechanization of transport and relatively inexpensive fossil fuels: a small and flexible grain of development, permeable pedestrian networks, diversity and proximity of uses, typological diversity, complex layering of public and private realms, and other factors.

There remains the problem of how to incentivise development of these and other beneficial morphologies, aside from making clearer changes to best practice standards. One way would be to monetize the savings from GHG reductions, as well as other resource conservation benefits. But that again begs the question of how to quantify such reductions – and actually to capture them through changes in form once they are quantified.

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3 Unpacking density: Translating findings into urban design variables for carbon reduction strategies

Chapter summary

The last chapter identified a range of factors that contribute, individually and in common, to increased GHG emissions per capita. These factors are typically associated with comparatively denser urban forms. This chapter moves beyond density to identify the more particular variables of urban form, and urban design, that can achieve the identified reductions. The chapter examines those factors and their translation into three key urban design variables.

This paper is drawn from "Unpacking Density" (Mehaffy, van den Dobbelsteen and Haas, Nordic Journal of Architectural Research, 2014).

As we saw in the previous chapter, a growing body of research has demonstrated an intriguing correlation between urban density, particularly residential density, and the conservation of energy and other resources, as well as the reduction of greenhouse gas (GHG) emissions (Anderson, Kanaroglou and Miller, 1996; Kenworthy and Laube, 1999; Ewing and Rong, 2008). A number of studies have shown a striking correlation between higher residential density, expressed per capita, and lower energy use and greenhouse gas emissions, also expressed per capita (e.g. Norman, MacLean and Kennedy, 2006). A particularly clear connection has been demonstrated between residential density and transportation energy, beginning with a widely cited study by Newman and Kenworthy (1989).

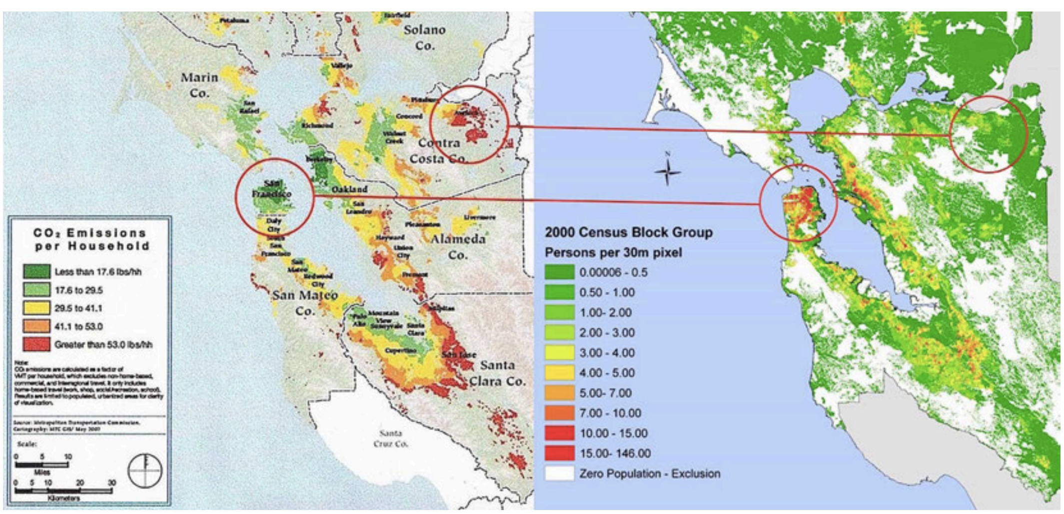

FIGURE 3.1 The striking inverse relationship between density and emissions from transportation is readily visible in this comparison. On the left, a map of the emissions per household from transportation, with green showing lower emissions and red showing higher emissions. On the right, residential density, with dark green showing lower density and red showing higher density. Sources: Left, Metropolitan Transportation Commission, 2007. Right, U.S. Department of the Interior, U.S. Geological Survey.

But progress has been slower to demonstrate the causal structural components and their interactions at play. As Berg, Granvik and Hedfors (2012) have pointed out, the effects of densification have not been sufficiently evaluated so as to tease out effective planning strategies. Mindali, Raveh and Salomon (2004) begin to look at individual variables of density in the Newman and Kenworthy research, and conclude that it is not density alone that is responsible, but other factors of morphology. While some likely contributions related to scale seem intuitively obvious and relatively well-supported by research (such as the reduction of distances travelled), other less scale-dependent components, such as patterns of distribution, are less clearly understood. Moreover, the pattern of interaction of these factors can be complex and difficult to isolate (Randolph, 2008). In turn this gap in evidence has made it more difficult to exploit these factors so as to establish more effective policy, best practice, and incentive approaches to achieve the goal of more resource-efficient cities (Ewing, et al., 2011).

Thus, there is a compelling need to research the question of the most salient factors, and moreover, how they interact within an urban system, as part of a variable design framework. It is not enough to understand such factors in isolation; what is necessary, as a useful guide to policy and practice, is an essential understanding of their structural dynamics within an interacting system. This is the key research question for the current study.

Specifically, in this chapter we will analyse a framework of three potentially significant factors already identified in research, together with the state of research for their analysis, and we will consider the basis for evaluating their interactions. We will then draw conclusions of implications for urban best practice as well as further research needed.

First, we will examine the structural distribution of uses and destinations – a factor we will refer to, in short, as the *web of destinations* – and assess what is known about the importance of characteristic patterns of distribution for resource efficiency.

Second, we will examine the provision of viable pedestrian-based multi-modal pathways – what we will refer to as the *web of transportation* – and the characteristics that they are known to require.

Third, least understood but perhaps most intriguing, we will examine the effects of what we term the *neighbourhood network* that appear to arise from the dynamics of network structures such as pedestrian pathways.

Lastly we will examine these factors as an interactive group, so that we can begin to understand the structural dynamics by which they interact. By varying these structural factors in relation to one another, we may thus be in a position to achieve significant reductions of greenhouse gas emissions as well as other benefits.

It is important to state at the outset that such a framework is only the beginning of a longer iterative process of evaluation, refinement and greater efficacy. But it is in the nature of complex systems, including cities and city design, that relatively simple and robust decision-making models, informed by research, and improved by iterative cycles of empirical application, evaluation and adjustment, are capable of achieving remarkable and promising levels of effectiveness (Dawes, 1979).

§ 3.1 Implications of Previous Research

As noted, previous literature has already identified a significant number of factors that play a role in the apparent benefits of compact urban environments. At this point it is fair to say, however, that as individual components they have not been able to account for the magnitude of empirically observed effects upon conservation of energy and resources, or reduction of greenhouse gas emissions per person.

Indeed, some investigators have suggested that, while compact urban environments can produce beneficial results, the actual magnitude of benefits may be so marginal that they do not rise to the level of a useful strategy for policy or practice. In a notable example, the US National Research Council (2009) attracted significant attention in its conservative finding on the impact of greenhouse gas emissions as a result of densification. However, Ewing, et al. (2011) noted that the study also made quite conservative assumptions which were, at best, not warranted by the evidence, and may have reflected an academic bias. In addition, the study looked only at greenhouse gas emissions reductions from private vehicle travel, which is only one of a number of factors. By contrast, Ewing, et al. argued that the evidence does suggest that a densification strategy could achieve significant results, but more work is needed to tease out the factors.

Other investigators have raised notable counter-arguments to the specific claims for the benefits of compact urban environments altogether. Neuman (2005) is typical of those who have pointed out that, whatever the benefits may be from densification, there are negative impacts as well that are often ignored, and that may well offset the benefits. Moreover, Neuman and others challenge what they argue is an implicit conception of cities wholly in terms of their form, rather than in terms of their processes.

Rebutting the work of Neuman, however, Hillier (2009) and other researchers using the framework of "Space Syntax" have demonstrated that the morphology of spatial networks (including, in part, their density) does have important implications for resource use and greenhouse gas emissions.

Furthermore, the fact that densification may have negative impacts cannot by itself be a disqualification for this strategy, since almost any design strategy is likely to result in a mix of negative and positive impacts. It is precisely the role of a study such as this one to provide useful predictions of the outcomes of such strategies. From that point, informed practitioners have the responsibility to apply this knowledge to achieve the best outcome in a given context, as defined by the stakeholders and verified through empirical observation and refinement.

The contrarian research may therefore suffer from a failure to observe "the forest for the trees". Ample research does show large variations in magnitude of greenhouse gas emissions, at least associated with – whether or not yet proven to be caused by – variations in urban form. For example, as documented by the World Resources Institute (2009) and others, the magnitude of observed differences in greenhouse gases between cities and their country averages in different countries can be readily observed to be as much as six-fold – an enormous magnitude indeed. It is, at the very least, difficult to account for this magnitude, apart from very evident differences in urban form. It follows that an effective strategy to achieve changes in urban form – while recognizing the need to balance other factors and their effects – remains a promising subject of investigation.

It also follows that the challenge remains to identify the factors that have been shown by previous research to have substantial impacts, and to explore how aggregations and interactions of such factors may indeed help to explain – and to achieve – significant reductions.

Among the most thoroughly investigated factors to date are:

Jobs-housing balance. The work of Cervero and Duncan (2006) is typical of studies that showed that this factor is particularly important, and more important than availability of retail and consumer facilities.

Mix of uses. Brown, Southworth and Stovall (2005) pointed out that a variety of uses is also important, and related to the distribution of destinations discussed further below. Dobbelsteen and Wilde (2004) demonstrated that a mix of multiple uses in space promotes more efficient land use, particularly when combined with intensification (i.e. higher density in both residential and non-residential uses).

Multiple uses over time. Dobbelsteen and Wilde (2004) also demonstrated that spaces that can be used in multiple ways also promotes more efficient land use, since a single facility can be used to accommodate multiple activities (e.g. a school used for evening community meetings).

Viable multi-modal transportation. Research by Bovy and Hoogendoorn-Lanser (2005) and others has shown that, other things equal, a well-coordinated multi-modal system including convenient public transport supports lower-energy transport modes. See also Hydro-Québec (2005).

Role of infrastructure embodied and operating energy, and transmission losses. The operating energy of pumping and lighting systems can be significant, as well as the energy and resources lost in transmission. These effects are generally sensitive to compactness of form (Rong, 2006; Hydro-Québec, 2005).

Ability to exploit district-scale energy efficiency and demand management. Many energy systems are able to produce significant efficiencies through co-generation and waste heat use, as well as through district-scale management of energy demand (Rosen, Le and Dincer, 2005; Marshall, 2008).

Behavioural and economic factors. It is reasonably well established that compact environments tend to be associated with smaller homes and more resource-efficient behaviours, relative to others (Liu, et al., 2003; Ewing and Rong, 2008). However, while the association has been well-documented, the causal mechanism or mechanisms (such as, perhaps, the "choice architecture" of different environments, as discussed further in Chapter 4) have not been. Nonetheless, the magnitude of the embodied energy and resources consumed as a result of these factors is large (Lenzen, Wood and Foran, 2008).

Meta-analyses and multi-disciplinary analyses have also been done for these factors, notably by Clifton, Ewing and Knaap (2008). The authors concluded that there are a number of advantages to urban form that is mixed and compact, but there is also a need for more standardisation in research protocols. Moreover there is a need for normative principles and policies to be crafted at multiple scales, and carefully designed to address the disparate issues that arise at each scale. This is a key sub-goal of the research herein.

§ 3.2 Identifying salient urban design factors and their interactions

For urban designers, there is a particular need to translate the factors identified to date into useful urban design variables that can be used to analyse and model options. One key problem with the factors identified to date in the literature is that they are generally considered in isolation, and it is difficult to understand, in a useful way for urban designers, how they interact in practice. This results in the familiar problem of proliferation of unintended consequences: one variable may be optimised while others are neglected, often reducing or erasing the benefit. For example, in what is known as Jevon's Paradox, increasing the efficiency of devices reduces their cost of operation, which tends to increase demand, thus reducing or erasing the gain from efficiency.

Thus it is of central importance to identify the salient factors that interact, so as to understand them usefully within a system of design elements, while accurately modelling the complexity of the system. In a sense, we want the optimal balance between simplicity and complexity, such that our models are simple enough to operate in a comprehensible way, but complex enough to model actual urban phenomena in a sufficiently accurate way. This is of course the ultimate challenge of all modelling.

Here we propose a morphological framework of just three factors, which aggregate and integrate the factors above in a way that they can be more easily understood as individual factors, and in their patterns of interaction with one another. The details of these interactions are discussed later in the paper.

It should also be noted that in any urban design process, many other criteria must be considered, including particular aspects of the local context which vary greatly. There is all the more reason, then, to maintain a manageable number of factors, so that any other necessary factors can also be considered. In this way, individual criteria (including GHG emissions) are not considered in isolation, but within a comprehensible and comprehensive model that can address other factors.

The three aggregated factors mentioned in the outset of this chapter, and discussed in more detail below, are:

Web of destinations: This factor combines jobs-housing balance, mix of uses, and multiple uses over time. It describes (as far as research to date makes known) the optimal distribution of destinations so as to minimize travel and maximize efficient use of resources. It is intended to be useful in identifying patterns of optimal spacing that urban designers may use in preparing design scenarios for comparison and analysis.

Web of transportation: This factor combines viable multi-modal transportation, embodied and operating infrastructure energy, and behavioural and economic factors. It describes (as far as research to date makes known) the optimal integration of modes of transportation, beginning with pedestrian travel and integrating other modes most efficiently into a viable multi-modal network. Again, this factor is intended to be useful in identifying patterns of optimal integration of multi-modal transportation systems, in a way that urban designers could use in preparing design scenarios.

Neighbourhood Network: This factor combines district-scale energy, infrastructure embodied and operating energy, and behavioural and economic factors. It describes (as far as research to date makes known) the optimal form of a neighbourhood to maximise so-called network effects, and minimise resource use and GHG emissions. This factor is intended to be useful in optimising the overall structure of a neighbourhood both internally and in relation to adjacent neighbourhoods, as part of a comparative analysis of design scenarios.

These are certainly not the only factors that one might identify in urban design scenario-modelling. Other factors include building size and orientation, unit types and sizes, building-scale technologies, and many others. But our research has convinced us that these factors are most in need of clarification, and subsequent integration into a useful urban design scenario-modelling approach. They may also serve as the first elements of a wider modelling approach, based in part on the work described herein.

Below we consider each of the three factors in more detail.

§ 3.3 Web of Destinations: The role of efficient distribution of destinations

A growing body of research confirms the logical supposition that certain distributions of regular travel destinations (such as work, retail, services, recreation and civic uses) will result in more energy and resource consumption per capita than others (Handy, 1996; Clifton, Ewing and Knaap, 2008). For example, the highly dispersed destinations of a rural environment will, other things held equal, require an increase of energy for transportation, relative to a dense urban environment. But a similar requirement will hold for inefficient distribution of urban destinations, such as highly centralized retail cores.

Much of the understanding of efficient patterns of distribution has come from network science, graph theory and Space Syntax, notably the work of Hillier (2007), Hillier and Hanson (1984) and others who have followed on that work. Marcus (2007) demonstrated how Space Syntax helps to account for the social performativity of a given spatial distribution pattern. Ståhle, Marcus and Karlström (2005) explored the geographic accessibility provided by a range of distribution patterns under analysis by Space Syntax.

Additional evidence for the effects of various distribution patterns comes from research on the distribution of destinations as a result of so-called “self-organizing” processes that tend to achieve efficiencies (such as economic processes that seek the lowest available cost).

In the field of spatial econometrics, or the economic effects of geographic pattern, there has been extensive work on the spatial distribution of land uses and their consequences. Irwin and Bockstael (2002) described a process whereby agents interact with each other and with externalities to produce characteristic and economically efficient urban forms, including the distribution of destinations. It is important to note that the forms may be efficient from the point of view of economic interactions, but not necessarily with regard to resource consumption and other so-called “externalities”. Indeed, this disparity between efficient economic processes and inefficient externalities like resource consumption seems to account well for the phenomenon of urban sprawl.

Similarly, White and Engelen (1993) applied a model of cellular automata (agents following rule-based interactions) to describe a self-organising distribution process, resulting in a characteristic “fractal” pattern of uses (i.e. patterns that are self-similar at larger and smaller scales). Similar work by Batty (2001) shows how the self-organising processes of urban settlement create fractal distributions that follow a power law (that is, they follow an exponential distribution curve with a few large elements at one end, and many small ones at the other).

Hillier (1997) proposed a related theory that human movement itself shapes a fractal pattern of destinations over time, which continue to self-organize into a more efficient "movement economy". For Hillier, one of the most problematic results of modern planning and zoning models is that they greatly inhibit this self-organizing pattern.

An important implication is that fixing the destinations by planning directive may be far less efficient than developing a process whereby the destinations can be allowed to self-organize. But as Hillier notes, in order for this to occur, the initial movement network must also be provided in an efficient pattern, which he describes as a deformed grid (Hillier, 1999a).

FIGURE 3.2 Sherford, a new community in the UK designed by Paul Murrain and other associates, using Space Syntax analysis over several iterations of design refinement. The blue lines are principal streets, the smaller red circles are neighbourhood centres, and the larger dotted grey circles are their pedestrian catchment areas. The analytical technique of Space Syntax guides a more efficient synthesis of urban form. Source: Paul Murrain Ltd. and The Prince's Foundation for Building Community.

For city planners and designers, this creates a conundrum: How do they know how to establish the characteristics of such a movement network? Hillier's Space Syntax analytical method (2007) proposes a methodology. The analysis process allows development and testing of alternate scenarios. The successful scenario is one that is most likely to accommodate an efficient distribution. Once the street network is constructed, it is not necessary to assugn the uses through zoning or other top-down mechanisms. An efficient web-like pattern will spontaneously develop – the same process of urban self-organization that has occurred in cities throuhout history.

A relatively mature body of work has demonstrated how these web-like patterns function to provide a range of benefits, including resource efficiency and GHG reduction. We previously mentioned Hillier's work in Space Syntax applied to resource efficiency and sustainability (2009). Marcus and Colding (2011) also used network concepts to describe a "*spatial morphology of urban social-ecological systems*."

These tools of network analysis allow the development of efficient networks, by serving as tools to iteratively explore the likely outcomes of design scenarios. In so doing they do not seek to replace self-organization, but rather to serve as a facilitator of it. In this sense the job of planners and urban designers is not so much to allocate the elements of urban structure efficiently, but to provide the framework to facilitate their efficient growth by other actors.

§ 3.4 Web of Transportation: The role of viable pedestrian-based multi-modal pathways

As noted previously, investigators such as Bovy and Hoogendoorn-Lanser (2005) have demonstrated that multi-modal transport systems play an evident role in resource-efficiency and GHG emissions reductions. But there is a deeper question of what morphology such systems require for optimum function. To tease this out, we can begin by assessing the specific role of pedestrian pathways within the larger multi-modal network.

It can readily be seen that this role is fundamental, since almost every trip by any mode begins and ends with a pedestrian trip. If users are not able to walk to transit stops, or to convenient parking for vehicles or bicycles, then they are not likely to find that mode of transport viable. Moreover, the ability to use more resource-efficient modes such as walking and biking may in itself result in greater resource efficiency overall. Thus the question of the functionality of pedestrian-based transport pathways (also accommodating bicycles and perhaps other modes) is an important one for research.

Significant work has been done on the characteristics of well-used pedestrian-based pathways. A growing body of research demonstrates a strong correlation between walkable neighbourhoods and such factors as high intersection density and short blocks, and diversity of close-by destinations (e.g. Leslie, et al., 2005; Berrigan, Pickle and Dill, 2010).

Investigators such as Law, Chiaradia and Schwander (2012) and Samaniego and Moses (2008) have explored the web-like structure of multi-modal pathways from the perspective of graph theory. As with other findings from network science, the pattern of interconnections of pathways is critical, as is the relationship between paths and nodes. As with related work in Space Syntax, the findings establish a useful set of criteria for assessing and modelling complex urban design options.

Another important component is the aesthetic character of the walking environment. Cerin, et al. (2006) showed that the presence of vegetation is associated with greater walking. Other investigators found similar results for both walking and biking (Saelens, Sallis and Frank, 2003, Wahlgren and Schantz, 2012)

Related findings come from environmental psychology. A classic study by Ulrich (1984) showed that a view of natural scenery from a window could produce a measurable improvement in patient outcomes. Follow-up studies established a number of remarkable effects from natural, "biophilic" characteristics such as vegetation, water and natural geographic features. The design of healthcare facilities has exploited these insights through what is known as "therapeutic horticulture" (see e.g. Sempik, Aldridge and Becker, 2003).

There is evidence that the benefits of these biophilic characteristics extend well beyond the patient healthcare context. Parsons, et al. (1998) described the role of vegetation in reducing stress among urban commuters. Nikolopoulou and Steemers (2003) reported that the experience of thermal comfort in urban areas varied not just according to actual temperature, but also according to experiential factors such as presence of vegetation and ability to control the environment. Other research has shown that the experience of other people and animals, even if only sensed behind a window or wall, has restorative effects (Kaplan, 1995).

Salingaros (2010) argued that such biophilic characteristics are also generated by buildings themselves, and specifically by their fractal, ornamental and other geometric characteristics. It is not just adding trees and shrubbery around buildings that is important, but creating the geometric characteristics of natural environments that humans find naturally pleasing and restorative: complexity, variety, layering, "prospect and refuge", symmetry, grouping, and other "natural" characteristics.

At the level of a streetscape, these geometric characteristics create interest and appeal for pedestrians. They maintain a range of scales to view at different distances, and they entice pedestrians to continue an enjoyable walking trip. They present an endlessly changing vista, with layers of experience containing other people, animals, vegetation, sunlight, water and other appealing factors.

All of these findings are reinforced by research into actual increases in walking and biking activities, and the factors demonstrated to be most closely associated with those increases (e.g. Saelens, Sallis and Frank, 2003).

§ 3.5 Neighbourhood Network: The role of urban "network effects" as they affect behaviour, demand and resource consumption

An intriguing area of investigation is the role of particular connective patterns within the urban system, in relation to others – a domain in mathematics known as graph theory, also commonly known as network theory (Borgatti, et al., 2009). This topic is clearly important for the evident reason that some patterns of connections make possible some forms of exchange of resources, while other patterns do not.

In biological systems, network theory helps to account for the way that certain flows of biological products promote "metabolic" efficiencies, that is, efficient use of chemical products to promote the growth of more complex structures (Stelling, et al., 2002). These processes are highly sensitive to the connective patterns of the flows, and network theory – specifically, "metabolic network modelling" – helps to understand how they inter-connect, and how they achieve their efficiencies. For example, Ko, Bentley and Weigand (2004) describe "*an integrated metabolic modelling approach to describe the energy efficiency of Escherichia coli fermentations*". As they note, this network model helps to explain efficiencies that are beneficial in industrial fermentations.

A strong corollary can be found in economics, where networks of interactions can promote "spillovers", or interactive exchanges of knowledge and other resources. This topic has been the subject of considerable research within economics and economic geography (Glaeser, 2009; Desrochers and

Leppälä, 2011). The question has begun to be explored how this network "spillover effect" might also apply to urban resource efficiencies as well (Mehaffy, 2011).

Other investigators have explored the role of network structure within urban systems, and their implications for movement and interaction (e.g. Cullen and Godson, 1975). The aforementioned work on Space Syntax by Hillier et al. relies explicitly on network theory concepts such as centrality (Hillier, 1999b). Batty (2008) calls for an integrated theory of how cities evolve, linking urban economics and transportation behaviour to developments in network science and related fields, and he gives an outline of what is known, while pointing out the urgent need for more work.

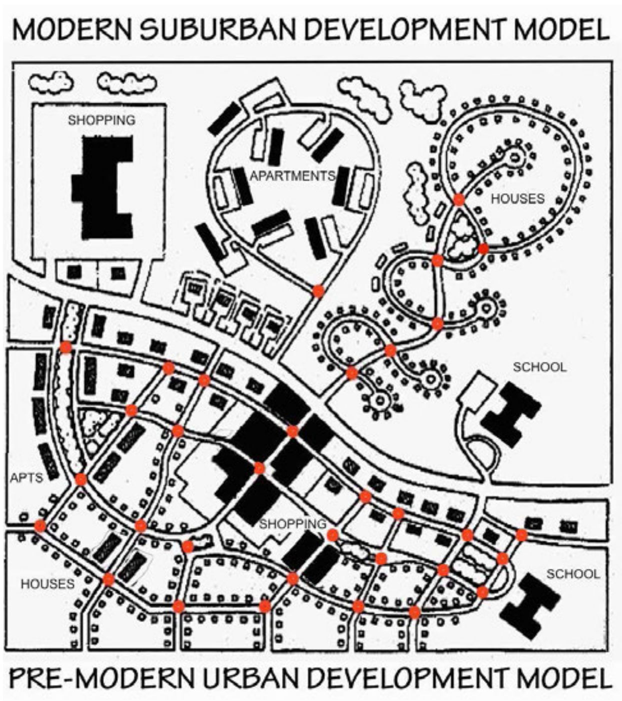

FIGURE 3.3 The street system at the top of this diagram follows a "mathematical tree" structure – few if any of the "branches" inter-connect. The lower structure is a "mathematical lattice", with many more redundant inter-connections, shown in red. It can readily be seen that average trips between any two random destinations in the "tree" form will be longer than average trips in the "lattice" form. It is notable that the ingredients are the same in the top and the bottom, but only the pattern of connectivity varies. Source: University of Miami (2013).

Hillier is also careful to note that cognitive effects can play a role that overrides mere network effects alone (Hillier and Iida, 2005). Salingaros (2005) also makes extensive use of neuroscience as well as network theory to understand the dynamics of urban interactions. It is not only our movements that are connected in patterns of networks, but our spatial experiences. Such work points the way to a kind of "place network theory" that integrates physical, cognitive and behavioural factors.

More specifically, how can we account for the relation of network theory to resource efficiency? One simple example begins to suggest an avenue for exploration. In the morphology of street systems, it is possible to have alternate designs with very different degrees of inter-connection. At one extreme is what is known as a "mathematical tree" – a branching hierarchy with very few inter-connections (Figure 3, top). An alternative model is what is known as a "lattice" – a structure that has many interconnections (Figure 3, bottom).

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It can readily be seen that average trips between any two random destinations in the "tree" form will be longer than average trips in the "lattice" form. It will be more likely that a "shortcut" is available in the lattice, relative to the tree structure.

Common urban design models of the 20th Century made extensive use of the "tree" form as a way of enhancing vehicular mobility (Mehaffy, Porta and Romice, 2014). Because it was assumed that most trips would be made with vehicles powered by relatively cheap energy, only secondary consideration was given to the characteristics of pathways for other modes, or their degree of inter-connection. Such morphological differences have had profound consequences on the pattern of mobility and resource efficiency of these urban areas (Pushkar, Hollingworth and Miller, 2000).

Moreover, it is not just transportation networks that are affected by network relationships. In a highly influential paper, Alexander (1965) argued that the tree-like relationships introduced by modern planning models constrain many other aspects of city life. Alexander pointed out that historical cities tended to have the characteristics of a "semi-lattice", with many inter-connected relationships. These inter-connected relationships extended to many different components of the urban environment.

Alexander used this mathematical argument to mount a powerful critique of existing planning models based on hierarchical "tree" organizations. "*The enormity of this restriction is difficult to grasp*", he noted, "*It is a little as though the members of a family were not free to make friends outside the family, except when the family as a whole made a friendship*" (Ibid., p. 58).

Alexander went on to make a crucial structural conclusion: "*It must be emphasized, lest the orderly mind shrink in horror from anything that is not clearly articulated and categorized in tree form, that the idea of overlap, ambiguity, multiplicity of aspect and the semi-lattice are not less orderly than the rigid tree, but more so. They represent a thicker, tougher, more subtle and more complex view of structure.*" (Ibid., p. 58)

Alexander's words foreshadowed the later work on metabolic network modelling as well as the related work on urban economies discussed previously. But the question remains for further investigation: Apart from simple density, how does the structure of such network relationships actually produce resource efficiencies, and related benefits such as greenhouse gas emissions reductions?

One such benefit has already been suggested: The redundancy of connective relationships allows optimization of more efficient pathways. As we saw, this holds true for transportation networks, but it seems plausible that the same would hold true for other kinds of interconnected, redundant relationships. For example, redundant relationships between a user and that user's available destination types would allow a more efficient generation of combined trips, across an average of randomized lists of destinations, if those destinations were inter-connected into a semi-lattice structure.

Another apparent benefit is that, at the scale of a pedestrian network, a user has a greater choice to explore more efficient activities, and a greater incentive to do so. Because of the personal energy investment in walking, there is a greater incentive to combine trips, and to find shorter paths. An inter-connected pathway provides those shorter paths and combined trips. By contrast, a vehicle-based trip to more distant destinations over a more centralized, "dendritic" street system is likely to promote even less efficient travel behaviour.

It is at this point that, as Hillier and others have noted, we must recognize the role of cognitive factors, beyond a mere structural configuration. What a person experiences within a pedestrian network will be different from what a person in a vehicle will experience. The structure of choices before them – what behavioural economists refer to as the "choice architecture" – will be notably different. There is evidence that this difference will have an impact on the form and degree of consumption, with implications for resource use and greenhouse gas emissions (Johnson, et al., 2012).

It is plausible to hypothesize that a compact, walkable urban network will, for the reasons discussed, tend to offer a more inherently efficient choice architecture than a dendritic, vehicle-dependent system, which will tend to promote a much higher level of consumption of fuels and other consumer products. The empirical evidence of consumer behaviour tends to confirm this hypothesis, although this subject is in need of much more detailed investigation.

§ 3.6 Modelling the interaction of the three urban design factors

It can readily be seen that the previous three factors do not function in isolation from one another, but work together within an urban system. Clearly the presence of pedestrian-based multi-modal pathways within a neighbourhood will inter-depend with the distribution of its destinations, and in turn both of these factors will inter-depend with the structure of their connective network and its interactive effects. For accurate and effective guidance of policy and best practice, these dynamics must be identified and understood. The goal of research, in that light, is not to tease out these factors merely to treat them in isolation, but to better see, and model, their useful combinations into larger models of planning and policy. Though much more work will be required to fully establish the dynamic relationships involved, we can begin to map them here (Table 3.1).

For example, we can ask what happens when there is a viable multi-modal pathway, but the distribution of destinations is uneven and inefficient. It seems logical that the multi-modal pathways will then be under-utilized, and modes that are able to convey passengers more quickly over longer distances (with higher consumption of resources) will predominate. For automobiles conveying one or two passengers, this implies an even higher level of resource consumption.

In fact we do find that in a comparison between cities with concentrations of destinations and those with more dispersed destinations, even when both have multi-modal pathways, the rates of consumption are notably higher in the former (Pushkar, Hollingworth and Miller, 2000; Cervero and Duncan, 2006). In this way we can confirm and refine such a framework, drawing on additional research as it becomes available.

Similarly, it seems very likely that when there is no viable multi-modal pathway, the network effects on consumer interaction and behaviour will be affected. Bettencourt (2013) finds this to be the case, and notes that cities that "*remain only incipiently connected will typically under-perform better mixing cities in terms of their social outputs*".

In those cities where increased automobile travel is a widely available alternative, it seems very likely that the result will be more travel over longer distances, and a tendency to consume "drive-through" "fast-food" product offerings that are far less resource-efficient – for example, processed foods, meat products, products with high amounts of disposable packaging waste, and so on.

Indeed, research does show a correspondence between travel distance and increasing rates of consumption (for example, Carlsson-Kanyama and Linden, 1999). This tendency is also described by research in so-called "choice architecture", described further in Chapter 4. There is evidence to suggest that the structure of choices visible to a consumer – such as the selction of drive-through food products for an automobile driver – will greatly influence consumption patterns (Lockton, Harrison and Stanton, 2009).

Lastly, it seems that cities with an inefficient distribution of destinations will also suffer from a diminution of the otherwise beneficial network effects on behaviour and demand. The research does tend to bear this out. Bettencourt (2012) points out that a city is a "social reactor" and that socioeconomic outputs (such as creation of new enterprises) are proportional to local social interactions within public spaces. This network phenomenon (first suggested by Jacobs (1961), and further established by Glaeser (2009) and others) presupposes an essential level of connectivity and power-law distribution.

With three factors, there are seven possible combinations of factors, depending on which of the three factors is present. (A, B, C, AB, BC, AC, ABC). It is then possible to map out what are the likely outcomes of combinations of the factors when combined optimally. Table 3.1 provides a summary of how such a framework could offer increasingly accurate predictions of reductions, which are shown only as initial plausible approximations at this time.

Just as removing one of the three factors reduces the benefits gained by the others, so too, adding one of the factors produces greater benefits. But there is evidence that such benefits are not linear, that is, not a function of simple addition (therefore not producing a "linear" graph, or a straight line on a graph). They often produce so-called "super-linear" results, which are greater than the sum of their individual effects. This makes intuitive sense when one understands that the elements of such a system reinforce each other, and produce synergistic and compounding effects.

The magnitude of such a superlinear result within urban systems is known to vary according to many factors, including scale (Batty, 2008; Bettencourt, 2013). It is not uncommon to see a ratio of about 1:1.1, or about ten percent more benefit than the addition of the individual benefits alone would be expected to produce.

Thus an initial reduction of, say, 10% per factor, might well yield more than 20% for two factors combined, or 30% for three factors combined. In this example, following the ratio of 1:1.1, we show a plausible estimated super-linear result of 22% for two factors, and 33% for three.

Greater accuracy will require further research and empirical refinement, as well as adjustment for local conditions. But as we noted previously, such a relatively simple framework, able to be iteratively and empirically improved, can have robust effectiveness in modelling decision-making under surprisingly complex conditions, as Dawes (1979) and other authors have shown.

We stress that the status of the research in this area is immature, and more research is needed to fill in the picture and establish more reliably predictive patterns of interaction. Even so, we trust that this first step clarifies the nature and importance of the type of model indicated, and thereby makes substantial progress in answering the key research question posed in this study.

1 DDE *Destination Distribution Efficiency*
2 MMN *Multi-Modal Network*
3 NNE *Neighborhood Network Effects*

DDE	MMN	NNE	Predicted Outcome	Initial Predicted GHG Reduction From Baseline*	Notes
X			Driving distances/trips are marginally lowered	10%	*Baseline transportation, neighborhood type*
	X		Trips by other modes are marginally increased	10%	*Baseline destination cluster, neighborhood type*
		X	Consumption is marginally lowered	10%	*Baseline destination cluster, transportation types*
X	X		More benefits; consumption is still moderately high	22%	*Baseline neighborhood type*
X		X	Transportation energy per capita is still moderately high	22%	*Baseline transportation types*
	X	X	Transportation activity per capita is still moderately high	22%	*Baseline destination cluster*
X	X	X	Optimal outcome	33%	*Spatially integrated at optimal scales*

Per capita based on estimates from statistical averages and predicted superlinear behaviour; to be verified and refined on the basis of further empirical evaluations. Baseline assumes all other factors are held equal and are typical for the urban development type in question.

TABLE 3.1 Simplified model for the interaction of the factors and their results.

§ 3.7 Conclusion

The mitigation of greenhouse gas emissions from urban systems presents a profoundly complex problem that can, it now appears, only be solved with effective new methods, bridging the gaps between disciplinary specializations, and between research and practice. Those methods must be simple enough to be useful in practice, but robust enough to be empirically effective. They must have the capability to iterate, refine and "learn" within a complex and uncertain environment.

But we would be unwise to apply such methods in isolation from other current and age-old criteria for good city-making. A "compact city" – or any other single factor – is not a guarantee of benefits, and, depending on the relation of other factors, it could well be negative. Those who pursue abstract planning goals in isolation – including greenhouse gas reduction – should certainly take note that many factors must be successfully integrated to produce a well-performing urban environment of any sort. As Neuman (2005) and others note, for example, there is the fundamental but elusive factor of "liveability": It bears remembering that the theoretically best-performing urban environment will not perform well in practice if people simply do not choose to live there, or do not thrive there.

The challenge, then, is to provide pragmatically useful modelling tools and strategies to practitioners, policymakers and citizenry, which can predict reasonably well the actually observed structural dynamics of interacting urban design factors such as those presented here. Such tools need not – and cannot – be perfectly precise. However, they must have the capability to adapt and evolve in response to empirical results and local variations. The framework developed here is meant as a step toward that important goal.

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4 Varying Neighbourhood "Choice Architecture": Exploiting behavioral economics in urban form to achieve further emissions reductions

Chapter Summary

When evaluating the factors of urban form that contribute to emissions, we must also consider the difficult but critical subject of human behaviour and choices of consumption. There is indeed a body of research findings that gives us guidance on the "choice architecture" of neighbourhood design. This chapter examines the evidence and draws conclusions for the decision support tool.

This chapter is drawn from a completed paper that is, at this writing, in peer review at the Journal of Planning Education and Research.

One of the promising topics of investigation into GHG mitigation has been the opportunity to achieve significant reductions through changes in behavior and consumption, with a notable focus on the household scale (Gowdy, 2008; Dietz et al., 2009). This work is informed by new developments in the field of behavioral economics, and, as we discuss in more detail below, the topic of "choice architecture" – the effect that transparent changes in the structure of choices can have on behavior (Thaler, Sunstein and Balz, 2010, Kahneman, 2002). It seems that the pre-arrangement of choices can, without necessarily *removing* choices, have a marked effect on the actual choices made – and as a consequence, on GHG emissions.

We investigate here the same question at the neighbourhood scale. That is, can feasible changes to the "choice architecture" of neighborhoods – that is, of urban design – offer an additional strategic pathway to achieve significant reductions in per-capita GHG emissions? If so, the implications could be far reaching, and extend beyond the topic of GHG mitigation to include other social policy goals and strategies. Our investigation concludes in the affirmative – although we note that this is an early finding, and significant further development awaits.

§ 4.1 Methodology

One method to conduct the investigation would be to perform detailed comparative experiments on various features and their effects on demand behaviours. Further regression and hedonic analyses could be performed to tease out the factors and draw conclusions. This research methodology is common in economic analysis of buyer preferences and the like.

The drawback of this approach is that any one study is likely to paint a very limited, context-dependent picture. Given the complexity of the local variables that may skew results, it is only when a significant body of literature has been developed that reliable general conclusions can likely be drawn, sufficient to guide modelling tools in design practice (the goal herein).

Another approach is to survey the literature of existing studies on resident behaviours relative to consumption patterns – particularly those affecting travel modes and other potentially high-consumption activities – and to re-interpret them through the lens of choice architecture, drawing potentially useful conclusions about new strategies. Subsequently these conclusions can be further evaluated through more direct empirical studies.

Accordingly, we survey a number of topics relative to neighbourhood consumption patterns, and the findings of previous peer-reviewed research. We assess the results through the lens of choice architecture, allowing us to draw conclusions about likely tools and strategies for relatively non-controversial changes in demand. We conclude with a discussion of the incorporation of tools and strategies into revised urban design models, as a basis for updated best practice.

§ 4.2 The controversy over urban-scale mitigation actions

We must start by noting that debate has raged over the potential magnitude of GHG reductions that are actually available from variations in urban form. In one well-known example, a paper published by the National Academy of Sciences (2009) argued that the individual factors that can be varied are not significant contributors in themselves, and that, because urban form changes slowly, meaningful GHG reductions from changes in urban form are not available in the short term.

However, a rebuttal by Ewing et al. (2011) argued that the individual magnitudes were under-stated in the NAS paper, and that their significant cumulative effects were ignored. Other research (summarized by Mehaffy, 2013) also supported the view that, taken together, the factors of urban form account for very large variations indeed in per-capita GHG emissions – up to 30% or more. Furthermore, while changes in urban form do indeed occur slowly, the corollary is that they are long-lasting. If they do generate large variations in emissions, then it matters even more, over longer spans of time, what characteristics of urban form we choose.

But the relationship between variations in demand and changes to urban form remains a topic for deeper investigation. For example, do people tend to choose to drive more in some neighborhoods with certain characteristics of form, all other things held equal? Do they choose to consume more energy-intensive, high-emissions products?

We already know from other forms of intervention that demand can be a problematic variable. For example, the actual performance of many energy-efficient buildings has been shown to deviate substantially from predicted levels, in part because of variations in anticipated demand (Newsham and Birt, 2009, Montanya and Keith, 2011).

As discussed previously, the problem is especially acute because demand is an elastic variable, subject to the phenomenon known as "induced demand." While other variables are optimized, demand can increase significantly as a consequence, erasing the benefits of efficiencies. In transportation, the phenomenon can be seen when widening of roads draws more drivers, eventually eroding the mobility benefits of the widening.

Merely making a technology more resource-efficient can also result in induced demand. As we discussed in the last chapter, an example is the variation known as Jevons' Paradox, which observes that as efficiency goes up, cost tends to go down, which tends to result in increased consumption demand. This phenomenon has been observed as an unintended consequence of increased energy efficiency (Polimeni, 2008). The result is an unexpected increase in emissions, relative to what would be expected.

The actual magnitude of Jevons' Paradox and related effects has been the subject of significant controversy in the field of energy-efficient technology (e.g. see Sorrell, 2009). But the principle has been widely established in the economics literature since economist William Stanley Jevons first observed it in 1865, and it illustrates a wider challenge for GHG reduction. Consumption demand is a crucial variable that can greatly distort or even erase achievements from other efforts, including narrow technological responses. It follows that we must take a comprehensive approach to greenhouse gas reductions, along with the other beneficial outcomes we seek in neighbourhood design.

In order to find effective methods to confront the challenge of consumption demand head-on, we must look for the behavioral factors that shape it more directly.

§ 4.3 "Choice Architecture" in Behavioral Economics

In recent years the field of economics has increasingly turned to psychology to explain behaviours that are not predicted by standard economic models, notably by the "efficient market hypothesis" (Sent, 2004; Wilkinson, 2008). That is, human beings often make choices that are based on limited information, and limited ability to make rational judgments – a condition termed "bounded rationality" by the economist and psychologist Herbert Simon (1956). The result is that choices are distorted by the limits of human cognition – limits that, according to Simon, often have their origin in the structure of the environment and the psychology of its experience.

Building on that key insight, the concept of "choice architecture" was introduced in 2008 by behavioral economists Richard Thaler and Cass Sunstein (Thaler, Sunstein and Balz, 2010) to describe the influence on decision-making of the predetermined structural configuration in which choices occur. The clear implication is that alterations in that structure may alter the outcomes of decision-making. Since its introduction, work on the topic to date has focused on the intersection of consumer behavior and public policy, e.g. choices for healthy eating (Johnson et al., 2012).

From a more pragmatic perspective, commercial businesses have already compiled an extensive body of knowledge about the factors that influence consumer behavior in retail environments, including visibility and access from the street (Gibbs, 2011). While this research does not focus on "choice architecture" by name, it examines the same kinds of questions: for example, what placement of signage, window displays, driveway access and other factors is most likely to encourage patronage? What is most likely to discourage patronage, and reduce likelihood of success in a given location?

It is not a major leap to investigate the next question: what placement of neighbourhood elements will influence consumption behavior, and in what ways? How can we, as choice architects, make changes to those placements so as to affect consumption behavior? Here we begin to suggest a set of likely topics for preliminary use in modelling of urban design strategies.

§ 4.4 Choice Architecture and Transportation Behaviour

There is a mature body of research documenting the contribution of vehicular transport (notably personal automobile transport) as a significant factor in global per-capita GHG emissions, particularly so in developed countries (Dodman, 2009). This factor appears likely to gain in significance as countries like China and India continue to develop car-dependent urban forms (Calthorpe, 2013). To the extent that the "modal split" (the percentage using different forms of travel) can be shifted away from vehicle use and towards walking and/or bicycling, there is a concrete opportunity to achieve measurable reductions in energy and resource consumption, and in GHG emissions per capita, in combination with other opportunities (Pacala and Socolow, 2004).

This opportunity appears especially attractive because walking or bicycle transportation requires minimal energy and resources – largely limited to the food that a walker or bicyclist consumes – whereas single-occupant automobiles traveling over the same distance can consume as much as 250 ml of motor spirit per kilometer, and emit up to 600g of greenhouse gas per kilometer as well as other pollutants. (Other modes, such as public transit and car sharing, generally consume fewer resources per kilometer than single-occupant automobiles, though they are higher than walking and bicycling.)

In addition, the embodied energy and materials in automobiles and infrastructure further increase the average emissions per unit of distance (Mehaffy, 2013). This is because greater vehicle operation and Vehicle Miles Travelled (VMT) on average requires manufacture of a greater number of automobiles, and more construction, maintenance and operation of roadways, all of which contribute to resource consumption and GHG emissions. In addition, roadways and other infrastructure generally remove vegetation and pervious cover, further exacerbating the problem.

Therefore, if changes to neighbourhood choice architecture can have a significant effect on modal split, then such a strategy may assist with achieving significant per-capita reductions of GHG emissions as well. But before we can examine changes, we must assess the choice architecture of existing neighborhoods and the places where changes might be made.

There is a growing body of evidence showing that the basic features of neighbourhood form do affect choice of transportation mode. Jiao, Moudon and Drewnowski (2011) showed that greater distance between retail and employment destinations was strongly correlated with a greater mode share of automobiles (in addition to longer trips, by virtue of the greater distance). Other elements of choice architecture also tended to increase modal split in favour of automobiles, including the presence of larger parking lots at grocery stores, lower density of streets, and percentage of single-family homes (Ibid.).

Krizek (2013) also showed that neighbourhood form is correlated with changes in travel behaviour for new residents moving into a neighbourhood. This is an important finding in that it excludes demographic characteristics per se, and demonstrates that neighbourhood form alone does have an influence on transportation behaviour.

Following is a more detailed examination of the choice architecture of various neighbourhood types, and their specific characteristics of choice architecture.

§ 4.5 Choice Architecture in Auto-Dependent Neighbourhoods

We begin with a common development type in affluent countries: neighborhoods in which most trips, by virtue of the neighbourhood design, must occur by automobile. The density may be too low to support public transit, destinations may be too far to be practical for walking or biking, and other provisions for walking or biking may not exist. (We consider these features in more detail in the next section.) We refer to these neighborhoods as "auto-dependent" in that residents must depend upon automobile transportation for essential trips.

First, we need to investigate what choice architecture is created by the automobile itself, once it is in use. The most obvious is the capacity to continue driving for longer distances, and the often cumbersome disincentive to stop the car and switch to other modes of transportation. The latter requires identifying an appealing mode of alternative transportation, finding a space in which to park the car, going through the process of manoeuvring the car, and finally unbuckling, exiting and securing the car – all of which take considerably more effort than remaining in the car. The bias toward operating the car is thus a form of "induced demand" that can result in increased VKT and increased fuel consumption and emissions, along with other factors.

The economic literature provides evidence of this phenomenon at work. In work on the effect of "search costs" (Smith, Venkatraman and Dholakia, 1999) it was shown that consumers may not have adequate information about the full costs versus benefits of continuing a "search" (e.g. pursuing an alternative mode or destination) and may therefore default to the current choice. This is a manifestation of the phenomenon of bounded rationality noted by Simon (1956).

The phenomenon of "switching costs" in economics carries a similar implication: the costs of time and opportunity in searching for parking, manoeuvring and securing the car are known, whereas the benefits of making the switch are unknown, with the result that the switch is less likely (Dobbie, 1968). The result may well be that a driver will make what in retrospect appears to be an apparently irrational decision to drive to a store that offers cheaper products, even though the cost of the fuel burned may be even greater than the savings. In the terms of this analysis, the driver's rationality is "bounded" by the choice architecture of the environment.

In addition, it is evident that automobiles also create a choice architecture that greatly limits social interaction with others encountered during the trip. There are findings that suggest that this reduced interaction affects not only the trip itself, but overall levels of social interaction for neighborhoods in which a greater percentage of trips occurs by automobile (Nasar, 1997; Freeman, 2001; Leyden, 2003). This may be because of the cumulative effect of frequent trips by automobile (although more work needs to be done on this question).

Secondly, we can ask what choice architectures are created within the infrastructure system that is designed to accommodate the automobile: the service station convenience stores, drive-in fast-food restaurants, drive-to shopping centres, and other related facilities. It is perhaps not surprising that they exploit the opportunity to present high-consumption choices to a captive market, using sophisticated behavioral psychology to do so (Smith, 2004; Chandon and Wansink, 2010).

Lastly, we can ask what is the unintended choice architecture of a car-dependent neighbourhood on other modes of transportation. There is ample evidence that the engineering changes needed to accommodate automobiles can (and often do) conflict with the safety and comfort of pedestrians and bicyclists (Pucher and Dijkstra, 2003). In turn, there are negative impacts on public transit users, who must walk or bike to and from transit stops. This negative impact increases with the degree of car dependency and use, resulting in an increasingly dangerous and uncomfortable environment for non-auto users.

Put differently, the findings demonstrate that auto dependency tends to produce more auto dependency, within a feedback cycle. The cycle is accelerated via the reinforcing influences of a changing neighbourhood choice architecture.

§ 4.6 The choice architecture of walkable and bikeable neighborhoods

At the other end of the transport consumption spectrum, the literature also helps us to identify elements of a neighbourhood choice architecture that influence rates of walking and biking. There is evidence that neighborhoods with higher rates of walking and biking exhibit trip-substitution from longer-distance automobile travel (Ewing and Cervero, 2001). This in turn implies reduced GHG emissions per capita, an implication that is supported by other studies on city GHG emissions (Ewing et al., 2008; Cervero and Murakami, 2010). It thus appears that increasing walking and biking trips is an attractive "stabilization wedge" in GHG reduction strategies (Pacala and Socolow, 2004) and an attractive target for a choice architecture strategy.

As might be expected, research has demonstrated higher rates of walking in neighborhoods with more walkable design, even adjusting for other factors such as self-selection (Frank et al., 2007). In particular, the literature shows a strong correlation between rates of walking and short blocks with high intersection density (Leslie et al., 2005, Berrigan, Pickle and Dill, 2010). As the investigators note, short blocks lessen the average distance between any two destinations, making walking a more attractive choice. In addition, shorter blocks present a more varied and visually interesting walking path, with more frequent changes of vistas, as compared to longer, unbroken blocks. At the opposite extreme, so-called "dendritic" street patterns can make walking nearly impossible because of the excessively long, indirect paths for most trips (Figure 4.1).

Short blocks and high intersection densities are also associated with greater rates of bicycle use, for the same evident reasons (Winters et al., 2003). A "permeable" street network shortens average trip distances, and also gives bicycle users a greater opportunity to use alternate streets that are safer and with less traffic. Moreover, such a permeable network is likely to reduce the concentrations of traffic overall, and reduce the number of areas of dangerous traffic with which a bicycle might have to contend – particularly if secondary streets can be used for bicycles (Mehaffy et al., 2010).

Another evident factor is the provision of well-designed pavements (also known as sidewalks in the USA) and bicycle lanes. Nelson and Allen (1997) showed that there is a correlation between the total length of lanes and the rates of bicycling. Cao, Mohktarian and Handy (2007) showed a relation between safe and well-designed pavements and bike lanes, and increased rates of walking and biking with reduced rates of driving. It seems probable that these well-designed systems shift the choice architecture for residents towards changes in travel behavior.

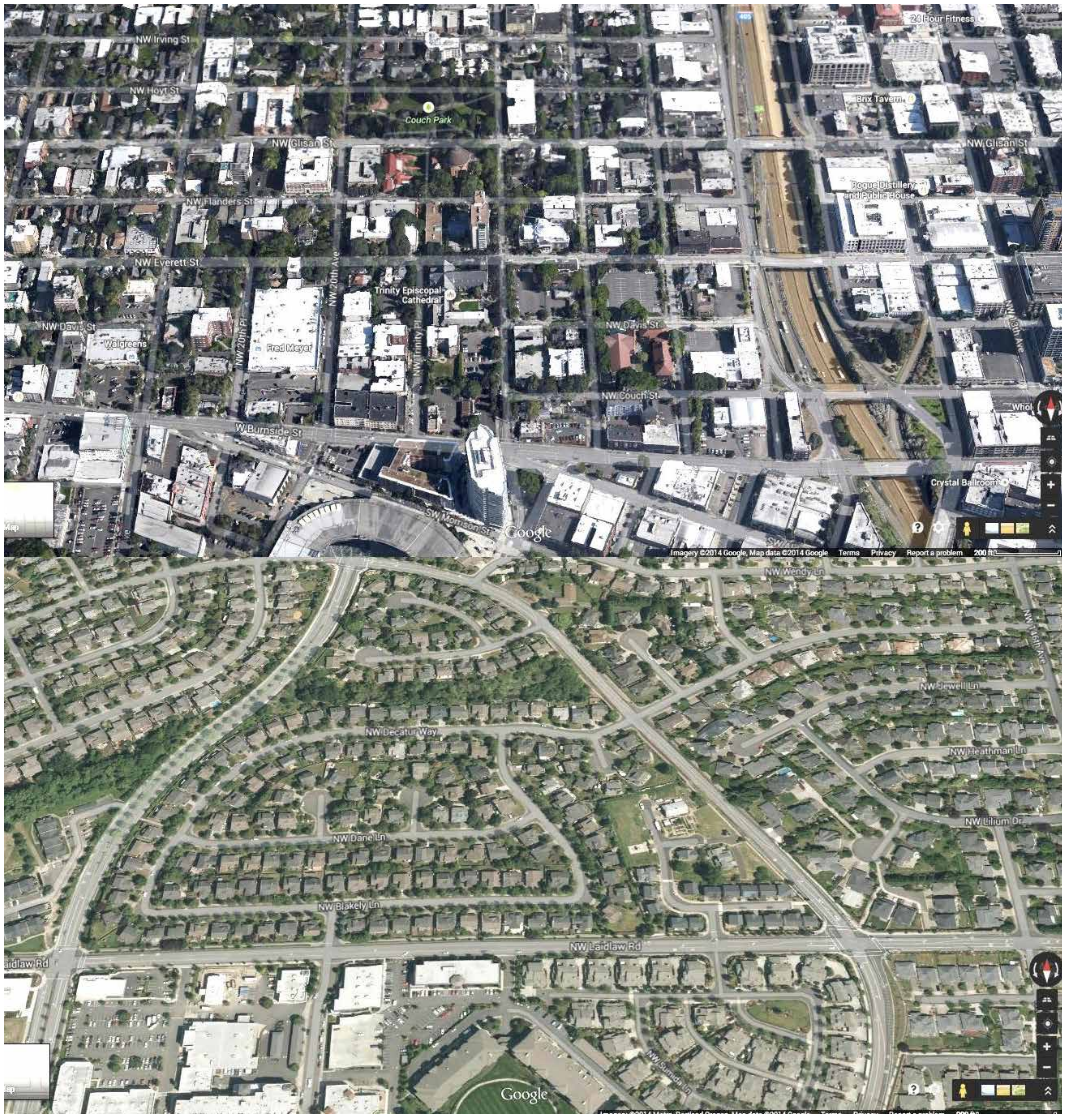

FIGURE 4.1 Two very different street patterns shown at the same scale. Above, short blocks and a high density of intersections invites walking, and allows combined trips. The highway is not allowed to sever the walkable fabric; instead it is submerged below bridges that continue the walkable street grid. Below, long uninterrupted blocks and "dendritic" or tree-like street patterns make walking unappealing and difficult for most trips, resulting in greater numbers of longer, point-to-point driving trips. Photo Credit: Google Maps..

Another important component is the aesthetic character of the streetscape itself, including vegetation, interesting small-scale details, mix of uses and activities, and user experiences of beauty. Cerin et al. (2006) showed that the presence of vegetation is associated with greater walking. Other investigators found similar results for both walking and biking (Saelens, Sallis and Frank, 2003, Wahlgren and Schantz, 2012). Wahlgren and Schantz (2012) also found that user experiences of beauty and greenery both served independently as stimulating factors for bicycle commuting. This finding suggests that beauty in buildings (as experienced by users) as well as natural areas can improve the choice architecture to favour bicycle use.

Of course, the question of what specific design characteristics a walker or bicyclist is most likely to find beautiful must also be ascertained, and this research is not mature. But Cold (1998) surveys literature concluding that such environmental preferences are not subjective but are rooted in evolutionary history. In particular, the perception of beautiful environments is strongly associated with environments that combine coherence with complexity. This combination affords curiosity, enticement and an opportunity to penetrate hidden layers. Neighborhoods with these factors are indeed associated with measurably higher rates of walking and bicycling (Saelens, Sallis and Frank, 2003).

§ 4.7 The choice architecture of public transit use

Through this lens, we can also ask what are the characteristics of neighbourhood choice architecture that will tend to encourage public transit use. To the extent such use displaces equivalent trips by automobiles on an equal basis, there is strong evidence that it results in lower per capita GHG emissions (Poudenx, 2008; Mehaffy, 2013). We will not consider here the many factors relating to transit frequency, connected destination network and other factors that are within the control of the transit service management. Rather, we consider what factors within the neighbourhood itself might encourage transit use.

Foremost among them is the walkability or bikeability of pathways to transit stops, which will affect the willingness of residents to make the initial journey to the transit stop (Frank and Pivo, 1994; Cervero and Radisch, 1996). Closely related to this factor is the distance to the transit stop from an average point of origin (Zhao et al., 2003).

A second factor affecting transit use is the attractiveness and comfort of the transit vehicles and facilities themselves. Although this factor is often overlooked, it seems likely that a part of the relative stigmatization of bus travel in particular is in its aesthetic character, and the identity it carries of a "second-class" form of transportation (Audirac and Higgins, 1984; Poudenx, 2008).

Lastly, there is evidence that the immediate environment of the transit stop is important. If it contains other adjacent uses – particularly services that are likely to attract waiting passengers – it is likely to be more frequented (Schmenner, 1976; Kim, Ulfarsson and Hennessy, 2007). In addition, if there is shelter from inclement weather, this amenity signals to potential riders that they will be comfortable while awaiting their transport (Law and Taylor, 2001).

As in other areas, these findings lend support to the concept that modifications to the choice architecture of a neighbourhood can have substantial impacts on the actual choices made to use public transit.

§ 4.8 The choice architecture of neighbourhood housing types

The design of neighborhoods inevitably affects and limits the design of housing, including the size of lots, the configuration of attached housing, and less directly, the size of homes. In turn, these structures present a choice architecture to residents that, as evidence discussed below will suggest, greatly affects domestic consumption patterns.

First, there is evidence that the size of homes and lots plays a major role in consumption demand (Ewing and Rong, 2008). Aside from the obvious reduction of space required to heat, cool and light the home, residents also have more limited choices to purchase high-consumption household and backyard goods. Residents who "downsized" homes do have a lower demand profile (Erickson, Chandler and Lazarus, 2012).

A second, related finding is that residential water use is notably lower in more compact neighborhoods (Chang, Parandvash and Shandas, 2010; House-Peters and Chang, 2010). By contrast, larger-lot suburban residents may experience reinforcement of attitudes and behaviours associated with high water consumption (Corbella and Pujol, 2009). This water use disparity carries implications for GHG emissions in two respects: one, the water itself requires energy and other resources for pumping, storing and purifying; and two, the rates of water use tend to closely track rates of energy used in water heating, clothes washing, lawn care and other household activities.

The analysis of geographic data on energy and resource consumption shows striking patterns of variation, but more work is needed to integrate models of household sources of consumption in relation to regional sources of production (Baynes et al., 2011). For now it seems very likely that the home itself creates a choice architecture favouring greater per capita consumption and greater GHG emissions (Høyer and Holden, 2003). In turn neighbourhood form creates the context in which household-scale choice architecture occurs.

§ 4.9 The choice architecture of recreational activities

In addition to its evident health benefits, active outdoor recreation is a low-carbon activity in relation to other activities that it typically replaces – for example, sedentary consumption activities within the home. If outdoor recreation is within walking distance to the home, there is reason to hypothesize that walking trips to recreation may also replace longer trips by vehicle, possibly to other higher-GHG emitting activities. But at present this is an immature topic needing further development.

It also seems clear that the presence of nearby parks, in addition to making convenient recreation available, may also provide a choice architecture in which residents are more likely to engage in park use activities (Groth et al., 2008). Conversely, the absence of such facilities within the neighbourhood, even when residents have the means to access more distant ones readily by vehicle, is associated with lower active recreation by residents (McCormack et al., 2010).

§ 4.10 The choice architecture of food consumption

There is evidence that the structure of a neighbourhood has a notable influence on the pattern of food consumption by residents. In turn there are implications for resource intensity of the food consumed, the amount of waste packaging, and contributions to landfills – all of which drive greenhouse gas emissions per capita.

Neighbourhoods whose choice architecture favours driving can create a "cycle of dependence" (Handy, 1993) in which smaller, more local retail is replaced with more distant regional "volume" shopping centres, along with "big box," fast-food and other "drive through" convenience retailers. These facilities benefit from a captive automobile-based market, in the form of buyers who must, if they are not satisfied with the selection, go to the trouble of returning to their automobiles and initiating the cumbersome process of driving to another facility. For this captive market, businesses have become adept at utilizing brightly coloured packaging and signage, and high concentrations of salt, fat, sweets and processed foods, which entice buyers to engage in high-consumption purchases (Smith, 2004, Chandon and Wansink, 2010).

Another example of negative neighbourhood choice architecture is a lower-income neighbourhood that does not have any reasonable access to affordably priced healthy food outlets for its residents. Such a "food desert," as it has been called, is associated with poorer diets and lower measures of health (Wrigley et al., 2002). Many residents of such neighborhoods have been observed to shift to higher consumption of so-called "junk foods," including more resource-intensive foods sold at drive-in fast-food and service station convenience store outlets (Walker, Keane and Burke, 2010).

As an alternative, Larsen and Gilliland (2009) report that adding farmers' markets to such food deserts resulted in measurable declines in the cost of foods overall, and increases in the consumption of healthy foods. Younger et al (2008) found that farmers' markets "ease the burden of food production on GHG emissions by decreasing the distance goods are transported and the demand for deforestation."

We can also see examples of positive choice architecture in sidewalk-facing markets that present appetizing healthy food in a way that is visible to pedestrians and bicyclists, creating a very different choice architecture (Figure 4.2). Of course it is possible to present unhealthy foods in the same way, but it is notable that the close proximity of the food to pedestrians and bicyclists in effect "levels the playing field" and allows fresh fruit and produce to be shown in a most appealing way.

FIGURE 4.2 The choice architecture of a street in Oslo, Norway. The neighbourhood form facilitates choices of walking, multi-modal transport, healthy and relatively low-emission foods, and combined trips. Photo Credit: Author.

§ 4.11 Several methodological and ethical questions

Before we can proceed with a strategy to implement the tools of choice architecture at the neighbourhood scale, we must ask several key questions regarding the validity of the analysis presented herein.

One, how do we know that the gains in choice architecture in one area will not be offset or even overtaken by losses in other areas of behavior? For example, there has been criticism that the relative low-carbon lifestyle of urban residents is offset by their demand for externalities such as foreign-manufactured products, or by other activities such as jet travel.

The answer is that we must always operate, as much as possible, on a per-capita, apples-to-apples basis. While it may be the case at any time that individuals engage in new activities and new demands that offset the reductions achieved in other activities, the question is always whether the other activities *in themselves* are creating induced demand, or whether they would otherwise create additional consumption if the mitigating actions did not take place.

Another question regards whether we can focus effectively on greenhouse gas reductions while ignoring other needs and priorities, such as community health and well-being. Can we avoid creating unintended effects with such a narrow focus? The answer, of course, is that we can't, and furthermore, it is perfectly possible to achieve multiple objectives with a comprehensive approach to neighbourhood form, as a number of investigators have demonstrated (e.g. Younger et al., 2008).

It is equally important to recognize a looming question in this assessment: on what basis are neighbourhood "choice architects" any more suited to judge the choices that are desirable, than the citizens who are making decisions about the course of their own lives -- however flawed we may judge those decisions to be? This question was notably raised by Selinger and Whyte (2010) and as they noted, it raises a core methodological issue of the competence of planners and urban designers to make decisions on behalf of others. For example, even if we agree that the pursuit of greenhouse gas reductions is a laudable goal, how can we trust urban choice architects not to create other unintended and sometimes deleterious effects on the well-being of residents?

This question was also considered earlier by Kevin Lynch (1984). He argued that norms of good and bad are an inevitable ingredient of planning and design decisions. That is, it is of the essence of such decisions that some people are making choices on behalf of others. What is vital, Lynch argued, is that these processes are transparent, and that the normative theories behind them are explicit, so that they can be evaluated within a democratic and professionally accountable process. When such values lie unexamined, he argued, they are dangerous.

In that sense, the test for an urban choice architecture lies in whether or not it serves to achieve the values that the community itself has defined in its pursuit of its well-being *as a whole,* as opposed to the values that various sub-groups have defined in their own interest, be they professional, economic or otherwise. In that sense, urban choice architecture is no different than any other aspect of urban design: there is a professional responsibility of transparency, accountability, and democratic review.

§ 4.12 Conclusion

We can now summarize, for the purposes of this exploratory assessment, the identified elements of a neighbourhood choice architecture suitable for a GHG reduction strategy (without limiting such a strategy from the pursuit of other goals and benefits). We also list in parentheses the specific factor that contributes to GHG reduction, as shown by the cited research discussed above.

1. A tightly connected street network, utilizing relatively small blocks (increased walkability, bikeability).
2. Beautiful streetscapes, defined according to user preferences (increased walkability, bikeability).
3. Safe routes, free from vehicular danger (increased walkability, bikeability).
4. Visually appealing transport stops, offering services and/or shelter (increased public transport use).
5. Visually appealing transport vehicles, offering dignified and comfortable transport (increased public transport use).
6. Close proximity to active recreation areas (decreased indoor consumption activities).
7. Close proximity to healthy and local food outlets, with active streetfront displays (decreased consumption of high-embodied energy and processed foods).

It is worth noting that, apart from a GHG reduction strategy, many of these elements offer evident benefits on their own, and few are in themselves politically controversial, or inconsistent with market demand for neighbourhood amenities. (They may however be inconsistent with some developer biases.) These findings do suggest that a neighbourhood choice architecture strategy can be entirely consistent with open, democratic and politically feasible neighbourhood planning models.

How can we get an assessment of the possible per-capita GHG emissions reductions available from the implementation of such a choice architecture? Of course the implementation would necessarily be slow, but as we noted previously, the corollary is that its effects would be persistent and cumulative. One way to gauge the potential magnitude of reductions is to compare existing neighborhoods with and without the features, and – excluding other identifiable factors as much as possible – to examine the variations in their per-capita emissions.

Indeed, we find quite dramatic differences in per capita emissions in different cities and countries around the world, as described in the introduction section of this dissertation (World Bank, 2011; Olivier, et al., 2013). The enormous variation in GHG emissions per capita – up to a five-fold difference or more – is currently not explainable by common factors such as a warm climate or an impoverished economy (as can be seen with cities like, say, Stockholm). A behavioral model does point a strong finger of suspicion at the variations in behavioral choices created by urban form.

In fact an examination of the urban form of places like Stockholm does reveal a structure of relatively small blocks, with beautiful, safe walkable streetscapes, attractive transport facilities, well-distributed recreational spaces, proximity to healthy food choices, and relatively small homes, including a high percentage of attached homes.

What percentage of the reductions might be attributable to this difference in choice architecture per se? It is of course difficult to isolate those factors from the other factors with which they interact. But on the basis of the enormous difference from urban form, and the known effects of behavior on emissions, we believe it is reasonable to start with a hypothesis that at least ten percent reduction is possible, perhaps more, as a starting point for further investigation.

Of course this is only a conceptual evaluation, and more detailed comparative research needs to be done. Given the variability of demand and its sensitivity to other factors, this is likely best done within specific local studies and pilot projects that must be part of a larger process of iteration and learning. But we believe we can identify sufficient support in the literature for the GHG reduction benefits of each of these choice architecture factors, at a level that is already sufficient to motivate experimental implementation in policy and practice.

FIGURE 4.3 An inviting, walkable pathway leading to convenient, attractive public transit. Photo: the author.

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5 Avoiding Negative Impacts from Urban Morphology: Case study of the "Neighbourhood Unit"

Chapter summary

A design decision support model must not only account for elements of urban form that help to reduce per-capita GHG emissions, it must also account for elements of urban form that work to increase those emissions. This chapter examines the case study of a very prevalent urban design model, the so-called "neighbourhood unit", and evaluates its impact on urban form as well as emissions.

This chapter is drawn from the peer-reviewed publication "The Neighborhood Unit on Trial" (Mehaffy, Porta and Romice, 2014).

It may well be that within modern urban planning and design, no single practice has had greater influence – and in some quarters, greater controversy – than the use of the "neighbourhood unit" as a standardized increment of urban structure.

The best known example of planning by neighbourhood unit – and one that is still widely influential almost a century later – is that of Clarence Perry, proposed in 1929 for the First Regional Plan of New York, under the auspices of the Russell Sage Foundation (Figure One; Perry, 1929a). His model, like a number of other variations, standardises the components of a neighbourhood, together with their geometric distribution and their relation to perimeter street patterns. To some degree, as we will discuss, Perry's neighbourhood unit also seeks to standardize social populations and their interactions, though this is a distinct and variable element.

As we will discuss, Perry's model is not the only attempt to standardize neighborhoods into units, or to segregate their parts. Standardized and segregated neighbourhood unit planning has roots much deeper in the history of planning – often with accompanying controversy. Nonetheless, it is Perry's model that has been most influential, and the most controversial, on modern planning practices up to the present day.

An indication of the degree of influence (and controversy) of Perry's model even today can be readily be assessed from a sampling of recent communications by prominent urban planners. On the home page of the US-based Form-Based Codes Institute website in August 2011 is a lecture by noted Florida planner Bill Spikowski, in which he argues for the famous 1929 model of Clarence Perry's neighbourhood unit: "I tend to like Perry's view… this stuff is mostly still valid today" (Spikowski, 2007). But in a vociferous 2010 exchange between New Urbanism co-founder Andres Duany and London urban designer Paul Murrain, co-author of the classic design manual *Responsive Environments*, Murrain was sharply critical of his friend Duany's promotion of the Perry model: "I condemn Perry because like you I observe, and I have observed the destruction of integrated urbanism across the developed world to a staggering degree courtesy of the model you promote." (Personal communication copied to the authors and used with permission, October 14, 2010.)

Duany, for his part, has strongly defended his use of the Perry diagram. As he stated to the authors, "I selected Perry's as the chassis for the first generation of New Urbanist diagrams. This was a rational move as it was the most famous diagram in the history of American planning…" At the same time, Duany acknowledged historical problems with Perry's model, but made clear his view that it remained a useful framework: "By close comparison, it served to point out the many subtle differences between old and new urbanist practices." (Personal communication to the authors and used with permission, June 14, 2011.)

This and other recent debates reflect the enduring international legacy of neighbourhood unit planning in general (as we describe below), and Perry's 1929 proposal in particular – as well as its more recently modified versions. The persistence of the debate also reflects the high stakes involved for modern planners, under pressure to respond more effectively to a daunting set of increasingly complex challenges: threats to economic viability, social vitality, public health and well-being, ecological integrity, resource depletion, climate change, and other topics that are increasingly grouped under the heading of "sustainable urbanism." The debate, in this sense, centres on to what extent the neighbourhood unit concept is part of the solution to this set of challenges, or part of the problem – and on whether a modified neighbourhood unit, or indeed some other alternate model, offers the most effective way forward.

This debate is only the most recent in a long history of controversy over neighbourhood unit planning. Indeed, as a number of authors have documented (e.g. Banerjee and Baer, 1984; Silver, 1985; Rofè, 1995; Ben-Joseph, 2005; Lawhon, 2009; Rohe, 2009) the extensive history of neighbourhood unit planning brings with it an equally extensive legacy of debate. Lewis Mumford, a major figure in 20th Century planning in his own right, noted in 1954 that while "during the last two decades the idea of planning by neighborhoods has been widely accepted… a counter-movement has come into existence" that has been "drawing up for battle" (Mumford, 1954). This counter-movement included harsh critics of neighbourhood-unit planning such as Reginald Isaacs, whose prominent 1948 paper "The neighbourhood theory: An analysis of its adequacy" drew a spirited rebuttal from Mumford (Isaacs, 1948; Mumford 1954).

§ 5.1 Neighbourhood unit planning: a pervasive contemporary practice

In even a cursory examination of the history of neighbourhood unit planning, one fact quickly becomes apparent: as Mumford noted, the model has had a profound effect upon the thinking and practice of planners since at least the early twentieth century, and up to the present day. Lawhon, surveying historical US planning literature, cited the extensive record demonstrating that "the neighbourhood unit has widely served as the primary design concept for new residential neighborhoods" (Lawhon, 2009). Nor has that influence faded: Solow, Ham and Donnelly, in a 1969 survey of American planners, reported that "half the [surveyed] group thought the neighbourhood unit concept useful, valid, and ideal for public policy. Nearly 80% used the concept in practice" (Solow, Ham and Donnelly, 1969). Lawhon himself, in a much more recent survey of American planners active in smaller cities and rural areas, found that "fifty seven percent of those familiar with the neighbourhood unit agreed or strongly agreed with the statement that 'the neighbourhood unit is still a valid model to guide residential development design in my community and other communities'" (Lawhon, 2009).

The international literature also documents the pervasive global influence of neighbourhood unit planning, as Murrain's observation to Duany suggests. Mumford, writing at mid-century, also pointed to the then-recent British New Towns as an implementation of what he termed "planning by neighborhoods" (Mumford, 1954, p. 256). Azab, writing from Bahrain in 2006, noted that "the concept has proved to be the backbone for most practices within planning, design and policy making arenas." But as his paper made clear, he shared Murrain's misgivings about its global effects: "Scholars and professionals have widely used – or could we say, 'abused' – the idea without questioning its validity for both practice and/or education" (Azab, 2006). In China the next year – and it would seem, with significant import in view of that country's rapid development – the publication "Chinese Planner's Guide to Western Urban Planning Literature" presented and discussed the neighbourhood unit, and did so uncritically (LeGates and Zhang, 2007).

The neighbourhood unit has also been profoundly influential in countries allied with the former Soviet Union, where the "microrayon" was a closely related form of unitised neighbourhood planning. (Miao, 2003). For example, a similar model, the "danwei," was extensively used in China (Lu, 2006).

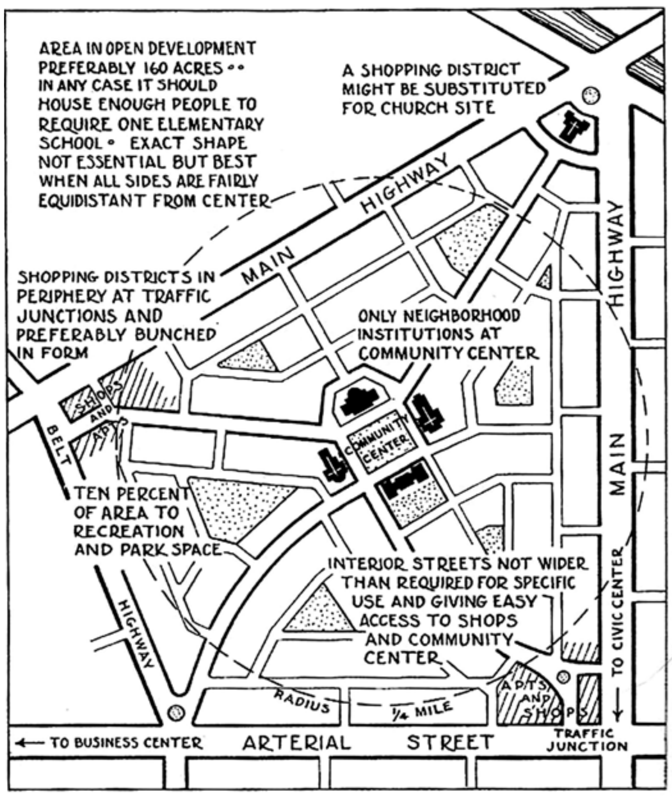

FIGURE 5.1 The Clarence Perry 'Neighborhood Unit' diagram of 1929. Note the size, roughly 1/2 mile or 800m in diameter. Neighborhood institutions at the center were segregated from commercial uses at the edges. The unit's discontinuous streets were largely impermeable to through traffic, which was concentrated at the relatively fast-moving (and therefore relatively pedestrian-unfriendly) arterial edges." Source: New York Regional Plan, Vol. 7 (1929).

Much of this 20th Century influence can indeed be traced – often explicitly by name – to Clarence Perry, the proponent of the landmark 1929 proposal (Figure 5.1), the one that Duany described to Murrain as "the most famous diagram in the history of American planning". Perry did not simply offer his model, but promoted it in a dizzying number of tracts, touted its many benefits as he saw them, and offered refutations of criticisms (e.g. Perry, 1926, 1929b, 1930). In just one such publication he argued for the traffic mitigation benefits of the neighbourhood unit interior, its social cohesion (and what we would term today "social capital"), its ability to support a local school within walking distance, its usefulness as a model for slum rebuilding, and its profitable mix of amenities offered to buyers, among other benefits (Perry, 1929b).

The scale of Perry's Neighborhood Unit was of particular importance. It spread across an area of ¼ mile radius, that is, roughly ½ mile wide and ½ mile long, surrounded by fast-moving arterials. At the center of this unit were placed civic uses such as schools and parks. At the edge were placed commercial activities such as groceries and other retail. Within the neighbourhood unit, the streets were discontinuous, making it difficult for cars to pass through the center of the neighbourhood; through-traffic was intentionally discouraged.

As his writings make clear, one of Perry's overriding concerns was to accommodate the automobile by creating a separation between fast vehicles and much slower pedestrian-dominated residential areas. As he writes:

"The automobile is working a great change in our city maps. To accommodate the ever growing stream of cars the engineers, in practically all our large cities, are building boulevards, parkways and super-highways. These wide, deep channels are cutting up residential sections into irregularly-shaped islands around which raging streams of traffic will soon flow. Should we not take some steps to formulate the size and the contents of these residential islands? If we permit highway specialization in the interest of the motorist, why should we not insist upon equal municipal care and forethought in the interest of the pedestrian and the resident?" (Perry, 1929b, p. 99)

As we shall see, this advanced concession to the coming "raging streams of traffic" is very much at the core of contemporary controversies. Perry clearly conceives here that the conflict is an inevitable one, and the only alternative is to segregate these two functions by creating functionally demarcated "residential islands." In this sense Perry was promoting a form of segregation by function, a hallmark of early modern planning, and a central feature of use-based or "Euclidean" zoning codes. Drawing from his own words, we can conclude that Perry's intent was to complement traffic engineers' automobile-oriented road planning with a pedestrian-oriented residential precinct.

Lewis Mumford also saw this segregation as inevitable: "Perhaps the first question of importance is what degree of isolation should be accorded the neighbourhood, apart from the inevitable separation made by major traffic arteries." (Mumford, 1954, p. 267). It was thus no surprise that Mumford's partners in the Regional Planning Association of America founded in 1923, Henry Wright and Clarence Stein, developed their influential super-block based layouts for Sunnyside (1924) and Radburn (1929) as a clear anticipation of Perry's diagram under the label of "The Motor Age Suburb". For Mumford, this was clearly a necessary accommodation to the realities of modernity: "Neighborhood unit organization seems the only practical answer to the gigantism and inefficiency of the over-centralized metropolis." (*op.cit.,* p. 266)

This accommodation to automobiles (and to gigantism) was certainly a major theme in the highly influential Radiant City concept of the Swiss architect Le Corbusier. Indeed, according to Samuels et al. (Samuels, Panerai, Castex, & Depaule, 2004) Le Corbusier's thinking has strong parallels to Perry's neighbourhood unit model. For example, Le Corbusier's plan for Chandigarh, conceived since 1951, is entirely based on residential reservations, variously called "sectors," or "neighbourhood units," bounded by urban arterial roads on a 1,200x800 meter grid. The concept was already fully established in the "Ville Verte" (1930) and "La Ville Radieuse" (1935). Other colleagues of Le Corbusier within the *Congrès International d'Architecture Moderne* (CIAM) promoted a similar "superblock" model (Birch, 2011).

Thus it should not come to any surprise then that when the first criticism of orthodox modernist planning started to emerge in the early 1960s, the neighbourhood unit was shortly brought to the center of the battlefield. For example, the highly influential urbanist Jane Jacobs, in her landmark 1961 critique *The Death and Life of Great American Cities*, assaulted the legacy of Le Corbusier and his influences in promoting "the superblock, the project neighbourhood, the unchangeable plan, and grass, grass, grass" (Jacobs, 1961, p. 22). She also assailed the logic of functional segregation and its devastating effect on modern cities, to the point that "today a land-use master plan for a big city is largely a mapper of proposed placement, often in relation to transportation, of many series of decontaminated sortings" (Jacobs, 1961, p. 25).

§ 5.2 Functional and social segregation in Perry's Neighborhood Unit

This functional segregation was not simply a segregation of speeding automobiles from residential neighborhoods. As Mumford argues, the neighbourhood unit is the centrepiece of a wider strategy of zoning by segregated use. "Perry's concept of the neighbourhood unit carried further the earlier notion, first used in Germany, of dividing a city into specialized zones." Perry establishes the neighbourhood unit as one kind of "nuclear" domestic zone: "Treating the domestic quarters of a city as a functional zone, to be differentiated in plan, because of its different needs, from the commercial and industrial zones, he established likewise the need for a nuclear treatment of the domestic zone... All this seems like such elementary common sense that one wonders that anyone should seriously challenge it." (*op.cit.,* pp. 263-264.)

But challenge it they did; as noted previously, Reginald Isaacs' 1948 paper in the Journal of the American Institute of Planners titled "The neighbourhood theory: An analysis of its adequacy" was typically withering (Isaacs, 1948). In this and other cases, Mumford was eager to rise to Perry's defence, making note tersely in this case of "a Mr. Reginald Isaacs," and "one of his attacks on the neighbourhood unit principle" – specifically, the need of a typical family to seek services much farther afield than a neighbourhood unit can provide. Mumford responds that a large number of these services can still be provided within the neighbourhood unit: "the health clinic, the library, the movies, a church, a park, a playground, a variety of shops... there is not one of these activities that could not, with benefit, be relocated in a neighbourhood unit" (*op.cit.,* p. 264).

In fact this is one of the chief criticisms of contemporary critics like Paul Murrain, who question whether such an internalized concentration of shops, clinics, libraries and other amenities could be viable for such a small population (Murrain, 2011). Influential studies today point to the link between the amount and type of facilities on the one hand, and the urban scale at which they should be provided on the other. The distribution is scalar, not compartmentalized, and there is a link between higher services and public infrastructure, which implies an open and integrated relationship between neighborhoods (Urban Task Force, 1999). Indeed, it seems highly improbable that the service needs of contemporary lifestyles will be exactly congruent with the services offered by such a uninitialized, standardized, neighbourhood structure.

Mumford also rejected accusations that neighbourhood units would serve the purpose of "segregation by race or caste or income," which he argued "have nothing whatever to do with the neighbourhood principle" (*op.cit.,* p. 256). Unfortunately, one of the people who apparently disagreed with him on this point was none other than Clarence Perry:

> "[The neighbourhood unit scheme] illustrates a method of producing homogeneity. When the real estate plan is dangled before the public, automatically it draws together a group of people of similar living standards and similar economic ability to realize them. McKenzie has pointed out that the segregation of a city population "along racial, economic, social and vocational lines" is a normal process and one which is constantly at work. Already cooperation in housing schemes is being taken up by various occupational groups. There are also signs of racial and religious ventures in the same direction. The use of a neighbourhood formula in suburban building and slum rebuilding schemes is going to promote this grouping process." (Perry, 1929b, p. 99)

Whether we favour this tendency or not, Perry concluded, it is a fundamental social phenomenon and one we need to accommodate, much as we accommodate the inevitability of "raging streams of traffic" that will be "cutting up residential sections." Hence for him the neighbourhood unit is once more the logical response to an inevitable demand.

A somewhat different social goal for neighbourhood unit planning came later from New Urbanist planners, who explicitly sought a "sense of community" from the bounded physical layout of the neighbourhood. Such a bounded layout might also help to supply the missing identity and "sense of place" within modern suburbia. But as noted in an influential critique by Talen (1999), the question remained whether such a sense of community would also engender a sense of exclusion and social segregation, alone or in combination with other factors.

§ 5.3 The roots of neighbourhood unit planning

While in the history of planning the neighbourhood unit is most closely associated with Clarence Perry's 1929 diagram, there is abundant evidence that Perry's contribution only formalized, albeit in a profoundly influential way, the ideas of a much older tradition of thought and debate.

Mumford, in his 1954 paper on the neighbourhood unit *(op. cit.)*, testified to this common lineage, and described an even deeper foundation in the European and American social reform movements that were associated with Garden City planning: the "community center" movement, the "Social Unit" movement and others. Mumford concluded that "though Perry no more discovered the neighbourhood unit than Le Corbusier discovered modern architecture, the work of each of them has had a dramatic value in crystallizing many diffuse efforts" (Mumford, 1954).

Architectural historians Donald Leslie Johnson (2002) and Eran Ben-Joseph (2005) have traced Perry's neighbourhood unit concept to Chicago planners associated with the City Beautiful movement, to the Garden City movement, and to the rise of city planning as a professional discipline around the turn of the century. They noted the contemporary influence of Daniel Burnham's 1909 Chicago Plan (completed with planner Edward H. Bennett), a seminal document of City Beautiful planning. As Jane Jacobs noted, Burnham's plan also segregated elements of the city into their own units – in his case, civic elements – "the whole being treated as a complete unit, in a separate and well-defined way" (Jacobs, 1961, p. 24).

These ideas were certainly not unchallenged in their day. Johnson documented heated contemporary controversy over Burnham's lavish new civic district from several camps. Social reformers of the day, including Jacob Riis, George B. Ford, and Benjamin C. Marsh, were bitterly critical of what Marsh termed the plan's "gigantic cost" for "civic vanity" and "external adornment." Designers were no less critical: architect Cass Gilbert dismissed the superficiality of the plan and noted "if it is to be city beautiful it will be one naturally." Prominent landscape architect Jens Jensen slammed the plan as "a show city" and "a city of places" (quoted in Johnson, 2002, p.229, 230).

Around the same time, and on the other side of the Atlantic, Ebenezer Howard's Garden City proposal was certainly no less influential in the history of neighbourhood unit planning – and no less the subject of intense debate (Birch, 2002). Howard's proposal featured a series of residential "wards" which were strikingly similar to Perry's units. Raymond Unwin, the planner who implemented Howard's ideas in Garden City realizations such as Letchworth (1903) and Welwyn (1920) – and who was later to travel to the USA and interact with Perry – introduced in the plans of these two cities Perry-like enlarged urban blocks (the direct precedents of modernist super-blocks), dead-end service streets or cul de sacs, and inward-turning, back-on-street cottage building types.

Silver (1985) anchored neighbourhood-based planning in an even older tradition of social reform, noting that "interest in the neighbourhood idea and in enhancing its potential through planning has been an enduring feature of American thought for at least the past 100 years" – i.e. since at least 1885 (Silver, 1985). As Lewis Mumford pointed out in his 1954 defense, the neighbourhood unit in particular was at no point a wholly new invention; there are clear parallels to European *quartier* planning. "Paris, for all its formal Cartesian unity, is a city of neighborhoods… the sense of belonging to a particular *arrondisement* or *quartier* is just as strong in the shopkeeper, the bistro customer, or the petty craftsman as the sense of being a Parisian." Likewise, he said, Venice "is a city of neighborhoods, established as parishes in relation to a dominant church or square; and by its very constitution it reminds us that the medieval city was composed on the neighbourhood principle…" (Mumford, 1954, pp.256-257)

Why, then, Mumford asked, is it necessary to introduce a new concept into planning practice? Why did spontaneous neighbourhood grouping, "so well defined before the seventeenth century," as he put it, tend to disappear in more recent plans? Mumford gave two reasons: "the segregation of income groups under capitalism," and "the increase of wheeled vehicles and the domination of the avenue in planning." As new arterials cut through "urban tissue that had once been organically related to neighbourhood life," as he puts it, "the city as a whole became more united, perhaps; but at the cost of destroying, or seriously undermining, neighbourhood life" (*op.cit.*,p.258-259).

Mumford highlighted a critical distinction between earlier *quartier* planning and the neighbourhood unit: the latter would find an accommodation to the new vehicular traffic by creating a more isolated, functionally segregated neighbourhood island. This island would be connected to other islands through the arterial traffic of vehicles – but not through the old pedestrian connections. This was a fateful transition, fundamentally altering the connective fabric between neighborhoods, and heavily favouring one dominant mode of travel – the automobile.

§ 5.4 Contemporary criticisms of neighbourhood unit planning

It was clear, then, that one key goal of the neighbourhood unit for both Perry and Mumford was the protection of residential neighborhoods from the disruptive vehicular traffic of modernity. As Perry argued, if we must accept the inevitability that modern arterials will cut apart a series of irregularly shaped residential islands, then we must "take some steps to formulate the size and the contents of these residential islands" (Perry, 1929b, p. 99). In his case, these islands were to be roughly ½ mile (800 mts) square. But we now know that the geometry of this spacing is highly dependent on the scale of pedestrian mobility, and getting the scale wrong is likely to have significant consequences (e.g. Mehaffy et al., 2010). In fact, the geometric basis for this argument has been called into question by a number of critics since then.

One of the most incisive structural criticisms came from Jane Jacobs, in her 1961 argument against what she termed "the curse of border vacuums." These vacuums, she argued, are created by the abrupt edges of large single uses, including the residential "superblocks" of Perry and others. The challenge for urban designers, as she saw it (and drawing on an earlier argument from Kevin Lynch) was to convert these edges into "seams" which would serve to connect the two sides, creating greater cross-movement of diverse populations, and "normal city cross-use of their territory by people from outside it" (Jacobs, 1961, pp. 257-269; p. 394).

Clearly this was not at all what Clarence Perry had in mind for his homogeneous "protected residential cell" (Perry, 1929b, p. 99). But Jacobs argued that this pervasive model of inward-turning neighborhoods was devastating to cities, and to their economies:

> "Unfortunately orthodox planning theory is deeply committed to the ideal of supposedly cozy, inward-turned city neighborhoods...[This is] the point of departure for nearly all neighbourhood renewal plans, for all project building, for much modern zoning... This ideal of the city neighbourhood as an island, turned inward on itself, is an important factor in our lives nowadays [but] it is a silly and harmful ideal... Whatever city neighborhoods may be, or may not be, and whatever usefulness they may have, or be coaxed into having, their qualities cannot work at cross-purposes to thoroughgoing city mobility and fluidity of use, without economically weakening the city of which they are a part." (Jacobs, 1961, p. 114-115)

Yet this was precisely the model that planners used to develop post-war US cities like Phoenix (as shown in Figure 5.2). The model of the neighbourhood unit was married with the "functional classification system" – a hierarchy of fast-moving arterial street grids feeding into more fragmented collectors within the neighbourhood unit, feeding in turn into highly fragmented local streets – all centring upon a half-mile square neighbourhood unit.

A more recent strain of criticism has come from network theory, especially as it has been applied to street networks. For example, Hillier et al (2010) provided an analysis of connectivity patterns that reinforced Jacobs' criticism of "border vacuums" around neighbourhood units that are too large and disconnected. Porta et al (2011) have cited evidence from recent research in complex networks that demonstrate that large, isolated residential islands disrupt universal dynamics in the relationship between space and service/retail location in cities. Their evidence shows that community services and shops reinforce each other in urban systems (of all kinds and ages) most effectively, when they are spatially associated with main streets and thoroughfares, which allow them to exploit the so-called "movement economy" (Hillier et al, 1993). Uses that are not so located tend in the long term to struggle, or fail altogether.

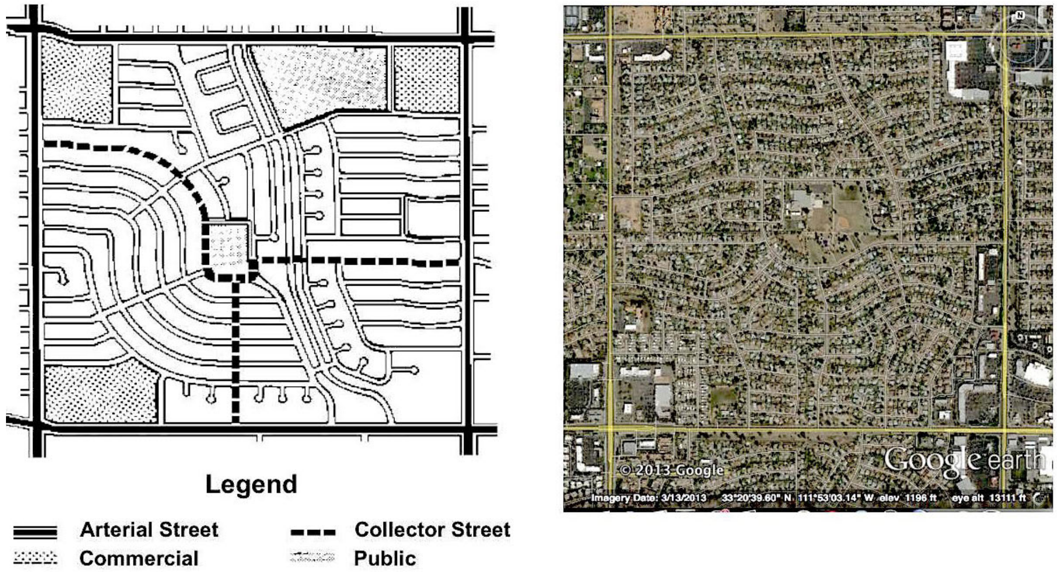

FIGURE 5.2 The Neighborhood Unit integrated with the US Functional Classification System (left) which became the model for development in cities like Phoenix (right). Areas of minimum ½ mile in width interrupted through traffic, which was concentrated in perimeter arterials. Central uses were limited to neighbourhood institutions, like parks and schools. The perimeter arterials fed largely discontinuous collectors, which led into highly discontinuous local streets. Sources: fhwa.gov, Google Earth.

Recent transportation advocates (e.g. Hall 2011) have also argued that the old arterial models, rooted in the outmoded engineering logic of the tree-like "functional classification system," are no longer viable. The latest models, by contrast, follow the diffusion logic of networks, and the elastic, adaptive dynamics of agent-based systems. Vehicle drivers are not like molecules of water in a pipe, but can choose their mode and route. The more engineers provide wide, fast arterials for automobile-dependent transportation, the more they "induce demand" and generate ever more congestion. Meanwhile, wide and fast arterials sever the pedestrian connectivity between neighborhoods, by creating disruptions along their borders.

Reform-minded transportation engineers today are therefore focused less on "mobility" as an absolute goal, and more on balancing *mobility* with *access*. They do so by creating a *diffusion network*, and by reducing the need for trips, and offering alternate transportation choices. Jacobs, Macdonald and Rofé (2002) argued that fast single-mode arterials have a viable alternative in the form of multi-modal, multiway boulevards. Hall (2011), a New Urbanist traffic engineer, served as a co-author on the Institute of Transportation Engineers' recommended practice guide, Walkable Urban Thoroughfares (ITE, 2010). He noted that the new approach no longer requires isolated neighbourhood units -- what he termed "pedestrian petting zoos." The answer to Perry's "raging streams of traffic" is thus not to turn our backs on them, but to engage them, and convert them into a more context-sensitive, pedestrian-friendly "diffusion network" of much calmer, narrower, streets and boulevards. At the same time, residents need to be offered multiple travel modes, a complement of ordinary daily destinations that are well-distributed and, where car travel is still desired, a more integrated and adapted form of automobility (Hall, 2011).

A key problem for Perry, according to some prominent transportation critics, is in creating viable public transit service. One such critic is Shelley Poticha, former senior urban advisor for the Obama administration, and previously executive director of the Congress for the New Urbanism (CNU). At a 2008 CNU conference session, she gave a very public critique of the fragmentation of transport in an updated version of Perry's model proposed by New Urbanist practitioner Doug Farr (Poticha, 2008).

Farr removed the segregation of civic from commercial uses, but otherwise left the features of Perry's scheme intact (see Figure 5.3).

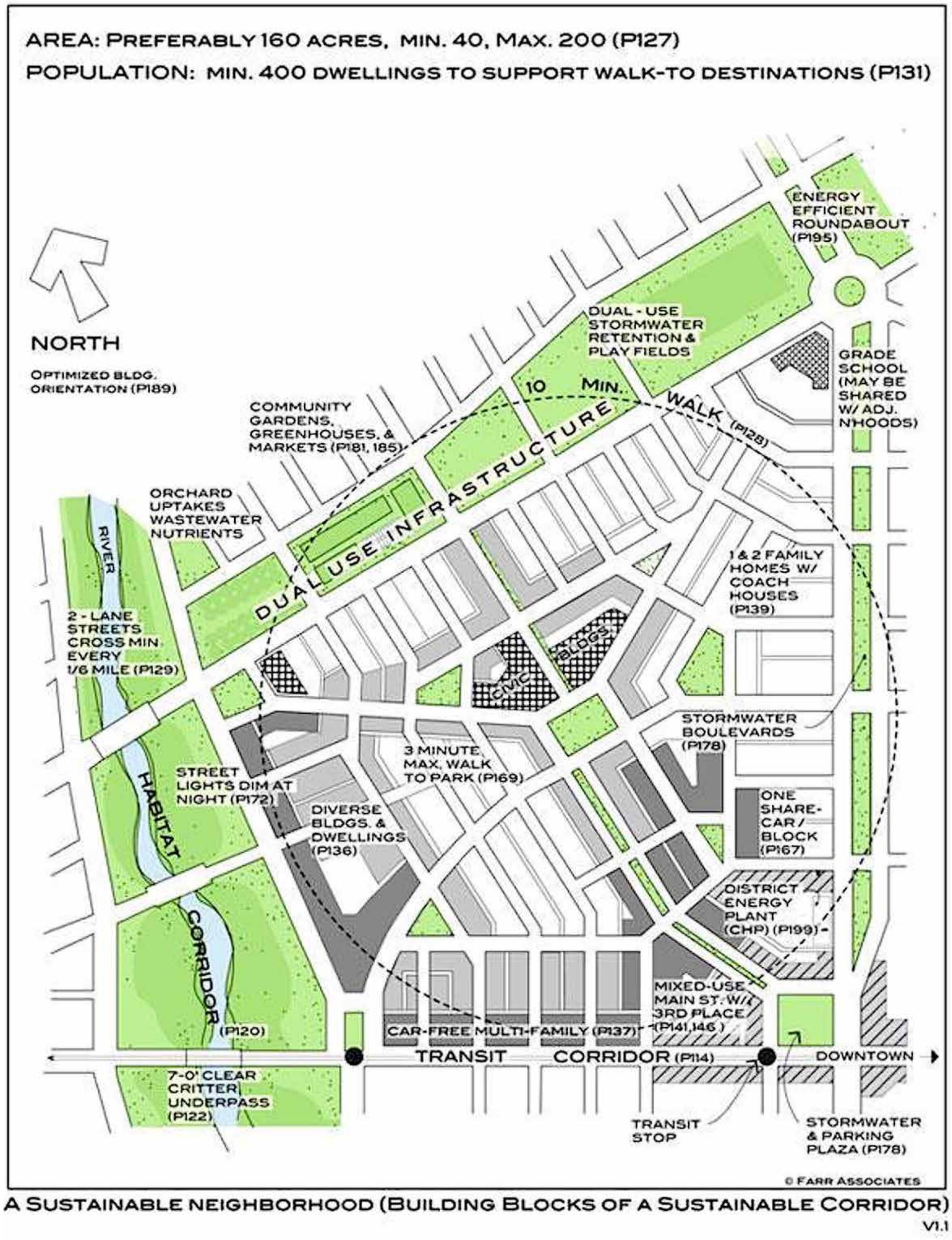

FIGURE 5.3 An updated version of the Clarence Perry Unit, shown in Doug Farr's 2008 book *Sustainable Urbanism.* The segregation of civic from commercial uses has been removed – but the relatively impermeable ½ mile square unit bounded by more concentrated, comparatively fast-moving arterials, remains. So do the connectivity issues across these arterials – and also between the units, and across the larger city. Source: Farr and Associates (2008).

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The criticism by Poticha and others is as follows: By not centring neighborhoods on arterials, the Perry model and its variants create a fragmented transit service area that cannot be serviced cost-effectively. According to such critics, this failure has a significant impact on the viability of a public transit system, and on the resulting ability to reduce carbon emissions from urban transportation.

Australian urban designer Chip Kaufman, in an email to Andres Duany and others, described such a problem in "a surreal tropical siting of a Perry-inspired English new town." Before presenting his solution, Kaufman showed the existing condition "to show Perry's influence even this far from the UK. Who could support such an influence?" The trouble, he says, is that the unitary neighborhoods do not allow transit at their centres, which would be far more efficient; instead, the transit must effectively zig-zag around their edges, which is highly inefficient. (Personal communication, copied to the authors and used with permission, October 14, 2010).

Ultimately, criticism of Perry's diagram, and indeed of the neighbourhood *as a design unit,* has come from the discipline of urban morphology. For example, Mehaffy et al. (2010) have raised the argument that in its initial conception the neighbourhood unit fostered a fundamental flaw in *the scale* of the city, which informed the construction of the modern city and contributed to many of its key failures. The neighbourhood unit size has always been tailored around the size of a pedestrian catchment area, i.e. the typical 5 minutes walk or ¼ mile (approx. 400 meters), by fixing this distance as *the radius* of the circle inscribed in the unit's boundaries. As a consequence, major urban arterials placed at the borders of these units are set ½ mile (800 meters) apart. By contrast, cities in history have been built, to a remarkably consistent degree, at roughly *half* that scale - that is, they have a remarkably consistent network of through streets that are spaced at about ¼ mile or 400 meters apart. The scale of this urban network, as we argued, has impacts on a number of critical factors influencing urban life and dynamics, such as vehicular diffusion, connectivity, navigability, accessibility to shops and services, pedestrian mobility, and a more integrated vehicular mobility. The historical act of *doubling* this measure (and thus quadrupling the areas involved) now can be seen as having a major deleterious effect on the structure of walkable cities, and advancing excessive automobile dependence. In short, this "alteration in scale" has been devastating to the multi-modal integrity of cities.

There is one other criticism of neighbourhood-based planning that is well worth mentioning: the notion that a neighbourhood is even properly regarded as an artefact to be created by planners, as a formulaic unit or otherwise. Baird et al (2010), in a more specific version of Jacobs' "fluidity of use" argument, propose that it was exactly the continuity of the urban fabric that enacted the self-organizing, continuously changing, adapting formation of neighborhoods in historical cities -- at least until the advent of "professional" theories of urban design in the 20th century. The neighbourhood, they argue, is essentially a social construct, made of ever-changing and layered systems of personal and collective links within and across cultural boundaries.

Research in environment behavior studies on what contributes to residential preferences, place attachment, and place identity, has also established that neighborhoods are psychological concepts, and that often there is no correspondence between this conceptualization and the pre-established physical boundaries of a neighbourhood (Gifford, 2002).

Research has also uncovered an important link between neighbourhood satisfaction and broader concepts such as personal satisfaction with the city as a whole, psychological well-being, and satisfaction with quality of life in general. Important non-spatial determinants of perceived quality include participation in organizations outside the neighbourhood, as well as other physical, cultural, personal and societal factors (Gifford, 2002).

Lastly, as Hall, Porta and others have noted, it is doubtful whether "walkability" is a meaningful concept when confined to isolated residential pockets, "cut apart" from one another by "raging streams of traffic" (in the words of Clarence Perry). More likely, it seems that such pockets will be little more than what Rick Hall dubbed "pedestrian petting zoos" – providing very poor access to essential services and destinations.

Therefore, the design of urban space can contribute to neighborhoods, most importantly, by assuring continuity of accessibility across a larger urban field. Within this field, neighborhoods can emerge under the "attraction" of central services, but still more or less spontaneously. That continuity is in fact essential to enable the purely social dynamics of neighborhoods to occur, and it can't be severed without fundamentally undermining the social cohesion of urban communities, their identity and place attachment – and ultimately, the identity and vitality of the city as a whole.

§ 5.5 Empirical evidence for the poor performance of the neighbourhood unit

As we have seen clearly from the discussion of the Perry proposal, the neighbourhood unit in 20th Century practice proceeded from the assumed inevitability of large-scale, automobile-dominant transportation systems as requirements for modern mobility (Perry, 1929a, 1929b; Mumford, 1954). But this assumption is increasingly open to question in an age of resource depletion and environmental damage, and as policy has turned markedly toward greater diversity in transportation modes and destinations. In that light, a more rigorous re-assessment of the impacts of the neighbourhood unit, viewed as a ubiquitous element of modern urban morphology, seems overdue.

Though empirical research on neighbourhood units per se is still relatively immature, and direct causal links are weak, the circumstantial evidence already available suggests significant impacts. Research on areas planned according to neighbourhood unit theory – including very large suburban areas across the USA, Australia and other countries – shows lower rates of walking, higher rates of obesity, lower rates of social interaction, and higher rates of social isolation and exclusion, relative to older areas with more continuous urban fabric (see e.g. Power, 2001; Frumkin, 2002; Dannenberg et al, 2003; Berke et al., 2007; Diez Roux and Mair, 2009). There are surely other factors involved as well, but we suggest that there is enough evidence to shift the burden of proof onto the defenders of the neighbourhood unit.

Calculations of ecological footprints also show a heavy current imbalance between consumption of productive land in developed and developing countries, with North America, Canada and Northern Europe featuring the greatest values, and a dangerously speedy trajectory towards the overall depletion of productive land. This depletion is closely tied to the growth of automobile-based suburban development, within which neighbourhood unit planning has played a historically prominent role (Frey and Yaneske, 2007). Though causal evidence is incomplete, once again it seems the burden of proof must be on the proponents of continued neighbourhood unit planning, to justify its continued use as an ecologically responsible practice.

Research is also indicating a significant increase in greenhouse gas emissions per person in suburban areas that have extensively used neighbourhood unit planning, such as Phoenix and other US cities (Brown, Southworth and Sarzynski, 2008). Hankey and Marshall (2010) presented evidence that 15–20% of projected cumulative emissions in the USA could be reduced through feasible changes in urban form, including more continuous walkable fabric. This benefit was from transportation efficiency alone; when adding other factors such as infrastructure and associated building type, the feasible reduction amount could well be significantly more.

Though this circumstantial evidence needs confirmation with more direct causal evidence, it seems sufficient to conclude at this point that with regard to greenhouse gas emissions and related challenges of resource consumption, neighbourhood-unit planning is, at best, problematic. The disruption of continuous walkable urban fabric may well perpetuate over-reliance on the automobile, and reduce the capacity for more inherently efficient, self-organizing urban patterns. This would be entirely consistent with Jane Jacobs' critique, and with the new insights of network science – but it does merit further evaluation and confirmation.

§ 5.6 Evidence from empirical examples for the feasibility of continuous walkable urbanism

Paul Murrain and other critics of modern neighbourhood unit planning argue that the mobility demands of modern cities *can* be met, even as they maintain a continuous fabric of diverse walkability. As evidence, they point to a large number of empirical examples of successful modern cities that do a reasonably good job of the latter.

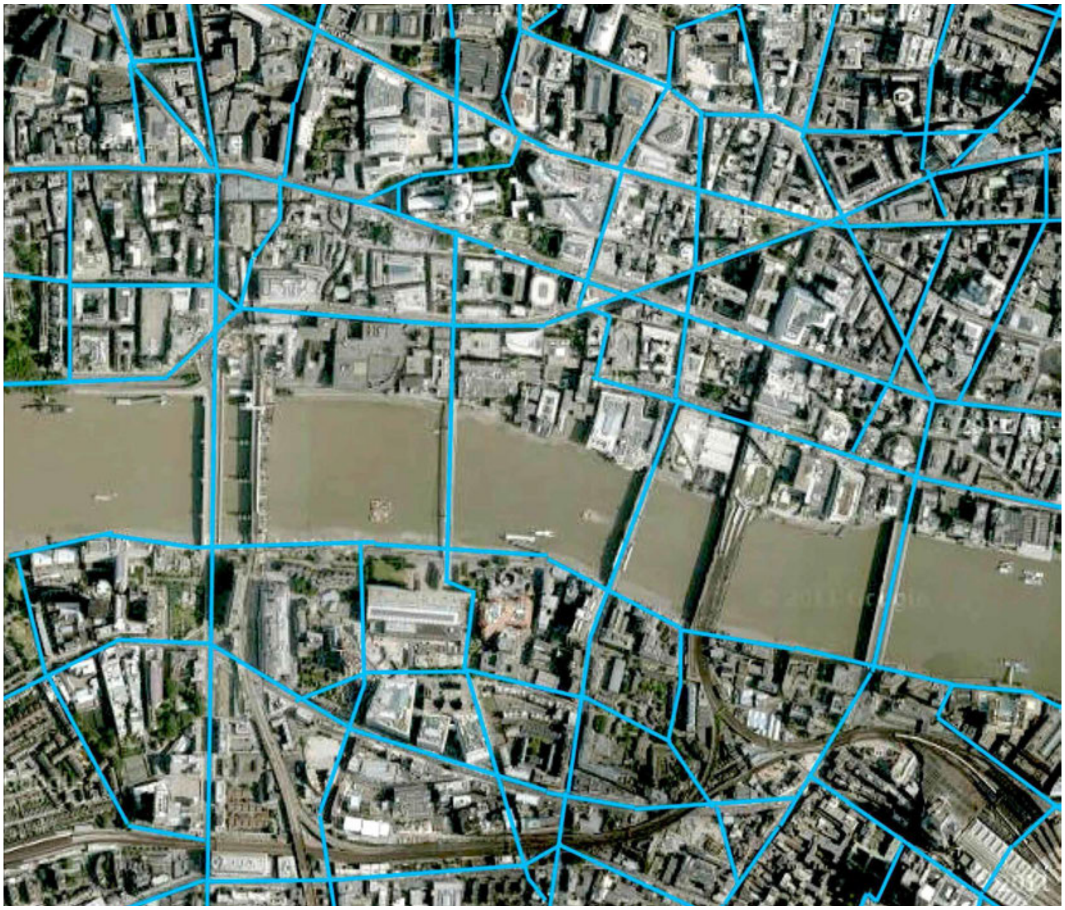

FIGURE 5.4 An aerial of central London showing a portion of its pedestrian-permeable network, at no more than 1/4 mile (400m) nodal spacing for the multi-modal through street network. Source: Google Earth, drawing by S Porta (2012).

Critics like Andres Duany argue that modern cities require a balance of mobility with access, and therefore, except within the neighbourhood unit itself, vehicular mobility must supersede pedestrian mobility. But many modern cities (as we discuss below) do maintain a surprising degree of large-scale pedestrian mobility, while simultaneously providing vehicular mobility and vehicular access. Again, the question is one of balancing the scales of integration, especially between pedestrian and vehicular modes.

Murrain, for his part, has brought to Duany's attention the example of London, which maintains continuous walkable fabric in one of the most modern and economically successful cities in the world. Instead of being cut up into isolated residential islands, London manages to submerge the more damaging uses – again, freeways, railroads, subway lines – and maintain a remarkably small-scale, fine-grained urbanism in many areas. As Murrain notes, he is able to walk from his home in Southwark to many parts of the city – and does so frequently -- without encountering any significant pedestrian barriers. (Figure 5.4.)

Another intriguing example – and a darling of many New Urbanist planners on both sides of the Perry debate – is Portland, Oregon. By accident of history, and by virtue of later visionary planners inspired by Jacobs, Portland's central core (not to be confused with its suburbs) has managed to achieve many of Jacobs' key "generators of diversity:" mixed use, small blocks, a mix of old and new buildings, and (at least by US standards) concentration of population and activities (Figure 5.5.) It does so while maintaining a relatively successful modern economy that presents no evidence of a deficit of mobility.

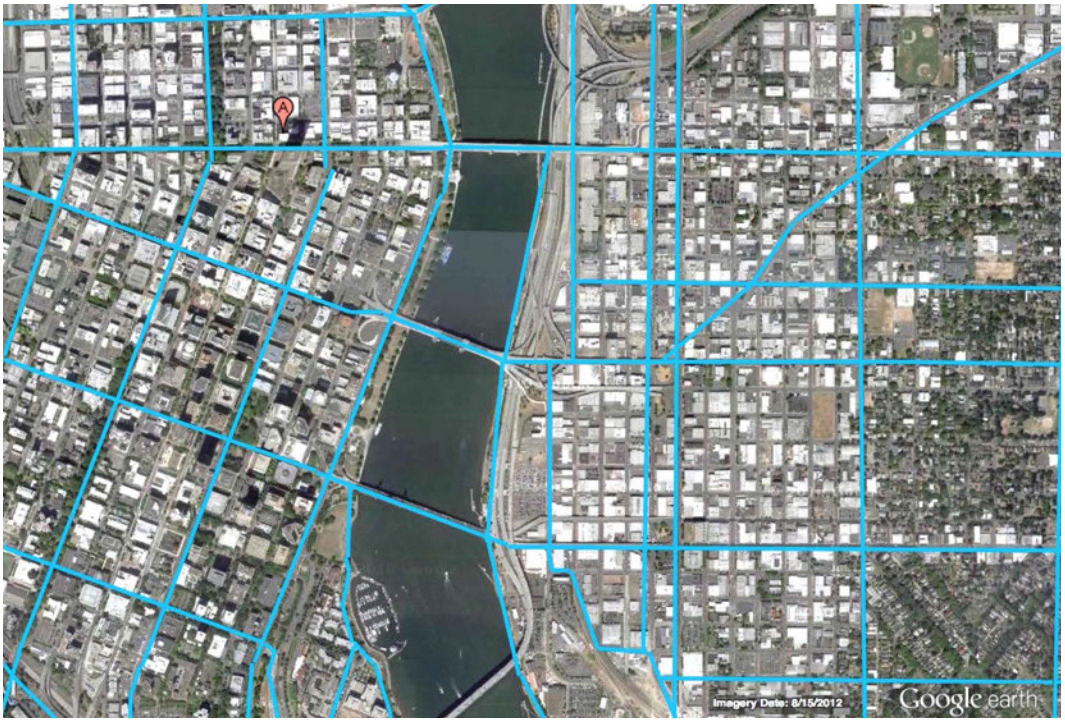

FIGURE 5.5 An aerial photograph of Portland, Oregon showing its pedestrian-permeable network of relatively low-speed arterials at a maximum 1/4 mile (400M) spacing, which continues at grade across the river as well as much of the central freeway system. The interstitial areas within the grid, which are interrupted with traffic-calming features designed to discourage cut-through traffic, are roughly half the size of a Perry Neighborhood unit. This more diffuse, permeable, multi-modal network aids in what Jacobs called "thoroughgoing city mobility and fluidity of use. Source: Google Earth, drawing by S. Porta (2012)

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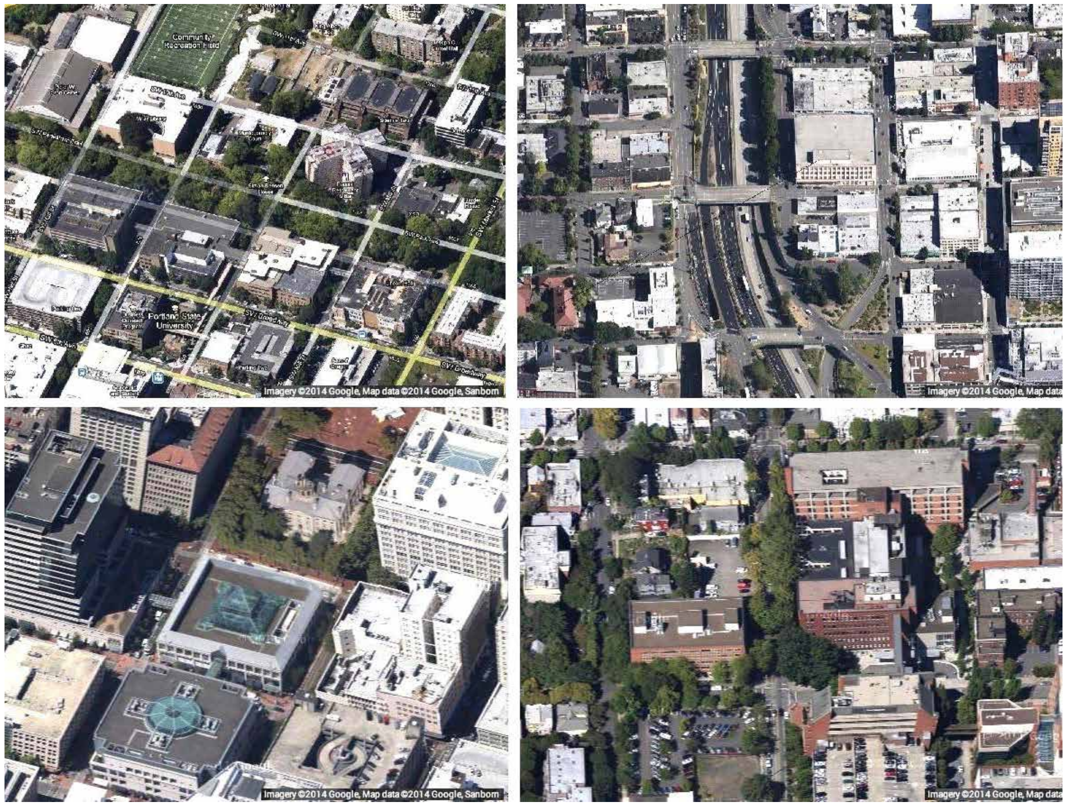

FIGURE 5.6 More viws of Portland's grid of pedestrian-friendly thoroughfares, and its permeability at no more than ¼ mile, across the river, a park, and local freeways, as well as other areas that are usually assumed to be impermeable. The neighbourhood unit's typically fast ½ mile arterial grid surrounding a superblock-like impermeable cluster of local streets is missing. Indeed, typical "campus" uses are seamlessly integrated into a fluid grid. Upper left: a university district, home of Portland State University's 25,000 students. Lower left: Pioneer Place, a shopping mall spread over three blocks. Upper right: a typical flex industrial zone, with pedestrian-friendly thoroughfares passing at grade above a freeway. Lower right: Good Samaritan hospital district. Source: Google Maps.

Portland has also managed, to a remarkable degree, to maintain a continuous walkable urban fabric, even across the kinds of barriers that Jacobs warned against: rivers, freeways, large parks, schools, industrial areas, even shopping malls and hospitals (Figure 5.6). As it has done this, it has also accomplished the remarkable feat of providing vehicular mobility *and* access.

By continuing the walkable small-block grid through these uses – and often allowing them to span the grid with bridges and tunnels spaced at approx. ¼ mile – the city demonstrates that large-use specialist functions ***can*** be integrated within small-grained urban areas, thereby avoiding what Jacobs called "border vacuums." The most challenging uses, freeways, are submerged in key neighborhoods, while the street grid continues overhead (Figure 5.6, upper right). The same challenges are met in the case of rivers, and other large disruptions. Other large uses (hospitals, universities, shopping malls, industrial districts) also function well within a modern economy, while simultaneously integrating a permeable pedestrian network.

This tactic was also implemented in Barcelona after the Olympics, therefore achieving a higher level of integration between local neighborhoods that were previously severed on both sides (Figure 5.7).

Portland's urban form has allowed it to support an unusually high modal share of walking, biking and transit relative to automobile trips – one of the highest for walking and biking combined in the US, according to the US Census Bureau's 2010 survey. The city has also achieved an impressive reduction in greenhouse gas emissions, according to the Climate Action Plan report of the City of Portland and Multnomah County (2009, p. 12). That report indicates that the per capita emissions in 2008 were 19% below 1990 levels. Whether this impressive achievement has been the result (at least partially) of the fluidity of pedestrian and bicycle mobility across neighborhoods remains to be fully demonstrated. However, the arguments presented herein outline a powerful case in the affirmative, in our view.

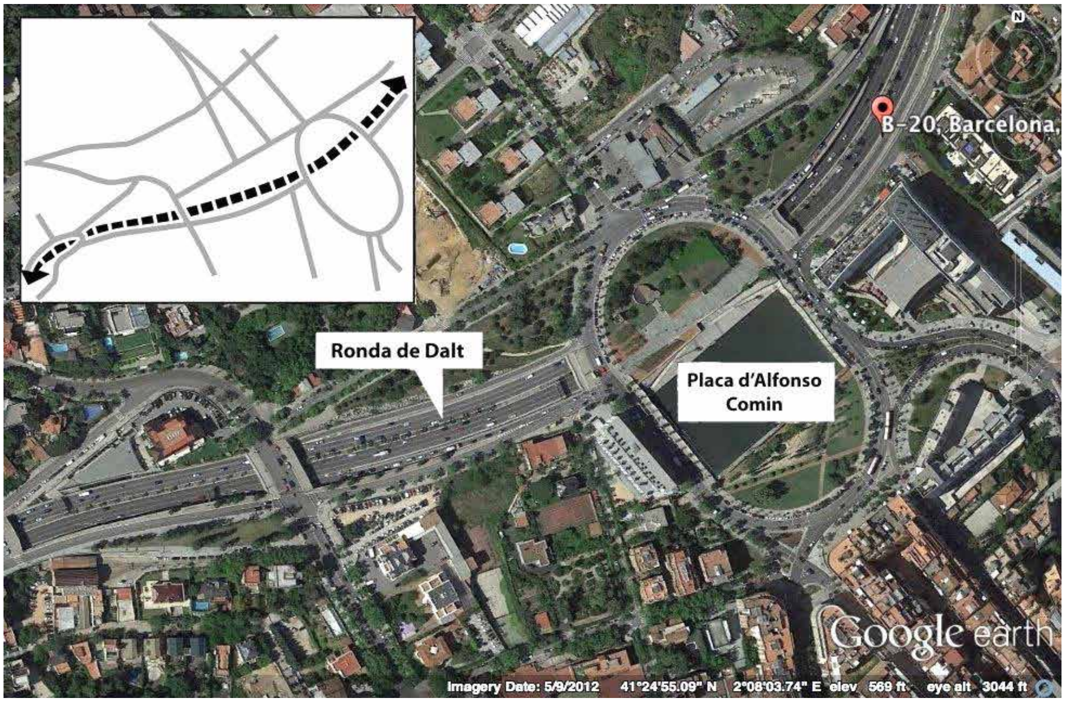

FIGURE 5.7 Barcelona's pedestrian network was integrated across a freeway as part of the 1992 Olympics. Source: Google Earth.

§ 5.7 Conclusion

As we have seen, vigorous and even impassioned debate over use of neighbourhood unit planning continues today among prominent planners. New questions have arisen about the effect of standardized neighbourhood unit planning on viable public transportation, cross-neighbourhood walkability, social diversity, movement economics and other critical parameters. Critics now claim - with the preponderance of evidence on their side, as we have seen - that it is time to discard the neighbourhood unit as a best-practice model. We have examined here an alternate model that has empirically demonstrated advantages.

In drawing conclusions, it must be noted that there is a distinction to be made between the transportation functions of a neighbourhood, and the social interactions and groupings that occur there. However, these two factors are clearly inter-dependent, and to the extent that the physical geometry of a neighbourhood constrains the social interaction there, the result seems likely to be a predictable set of negative social effects. (As we noted, Clarence Perry accepted social segregation, and he was evidently not concerned that neighbourhood units might reinforce or increase this trend.)

On the other hand, a physical structure that is conducive to what Jacobs called "city mobility and fluidity of use" in turn would seem to have positive impacts on economic vitality, equity, and other social and environmental factors. The empirical evidence, while incomplete, tends to support this claim. Thus, the question of planning by neighbourhood unit appears to be one with profound implications for the long-term vitality of a neighbourhood, and its ability to self-organize into an economically and socially productive system.

We have also noted the incomplete but already strong circumstantial evidence that neighbourhood unit planning contributes significantly to environmental externalities and related impacts. As we noted, among other factors, there are new and disturbing questions about the increased rates of greenhouse gas emissions per capita associated with (and possibly caused in part by) neighbourhood-based planning.

Our conclusion is that an approach to neighbourhood structure "beyond the neighbourhood unit" – one that provides an appropriately scaled framework on which a more continuous, more spontaneous urban pattern may be formed -- is possible, and moreover necessary. The evidence does suggest that a much more optimum balance can indeed be achieved, seamlessly combining an essentially continuous walkable city fabric with the mobility functions afforded by modern transportation systems like arterials and railways.

As we have argued, the critical issue is one of scale: specifically, the scale of pedestrian mobility must be matched to the scale of vehicular mobility, within an integrated framework for fluid movement and growth (Mehaffy et al., 2010). Although more research is surely needed, examples from Portland and elsewhere do tend to show that such a goal can be reached. The preponderance of evidence also already strongly suggests that the neighbourhood unit, as a standardized repetitive element at a specified scale, fails this essential test.

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6 Modelling Methodologies: Opportunities and Limits

Chapter Summary

This chapter describes in detail the methodologies of modelling and their limits, as a preparation for exploring the specific model to be proposed and evaluated.

This chapter is drawn from the peer-reviewed publication "Counting Urban Carbon" (Mehaffy, 2014).

Before we can turn to the specifications of a new urban design decision support model, we must first ask fundamental questions about methodology. After all, there is a profound problem facing anyone seeking to develop models to guide design choices. It lies in the epistemological limits of all models, which we will discuss here in more detail. Following that discussion, we can examine some of the modelling methodologies that have been developed in part to respond to these limitations, and to provide the more robust capability that we seek.

First, we must recognize that a modelling tool is, by definition, a prediction of what will happen in the future, when conditions in reality are sufficiently aligned with the parameters of the model. But the data on which such a model relies for its development is, by its nature, from the present or the recent past. In relying upon previous data, we must apply our own theories – the predictive elements of our model about how the system will behave – to generate a prediction. If our model is not a simple extrapolation (which is rarely correct), then we must rely upon a more complex set of abstract ideas about the interaction of factors.

Of course, any such abstraction is precisely that – an abstraction, which is fundamentally "an omission of part of the truth," in the memorable words of the philosopher and mathematician Alfred North Whitehead (1938). Our challenge is not to create a perfect copy of reality, but to apply such abstractions (including models) in a way that their corresponding features provide useful guides to the structure of the phenomenon of interest, without their omissions becoming problematic. This standard of usefulness must ultimately apply to all models.

However, Whitehead warned, we must be clear about what our abstractions can and cannot do, and the need to attain what he termed a "right adjustment of the process of abstraction". Failure to do so may lead us to what he called "the fallacy of misplaced concreteness" – the often mistaken assumption that aspects of our abstractions will correspond to aspects of reality. An example is the tendency to over-estimate the predictive validity of a theoretical model – a common problem in a number of professions today (Taleb, 2005; Kahneman, 2002; Tversky and Kahneman, 1974).

Whitehead's work is part of an extensive literature on the epistemology of modelling, and the broader capabilities and limits of abstract systems – including language itself – whose cautionary lessons must form the foundation of the robust modelling methodology we seek. In particular the Twentieth Century brought important work in identifying the inherent incompleteness of information as a fundamental limitation of any such model.

Especially notable among this literature is the work on undecidability and incompleteness by the mathematician Kurt Gödel (1931). Gödel famously applied a brilliant analysis of symbolic logic to Whitehead's own logical system, presented in his masterwork *Principia Mathematica* (developed with his colleague Bertrand Russell, 1912). Somewhat ironically, in view of Whitehead's own later work, it was Whitehead and Russell's intention to create a complete logical system to represent all of mathematics. But Gödel proved, with unassailable logic, that it must be incomplete – and so too must any such formal system. The implication is that any referential system – that is, any system that refers by formal representation to some other system, including any model – must be incomplete. Furthermore, this incompleteness is not a trivial distinction, but it goes to the core of any referential system.

The philosopher Ludwig Wittgenstein (1953) made a similar observation about the nature of language itself. In his earlier work (1921) he had built on Russell's own work to develop a theory of the correspondence of linguistic acts to structures in the world, as maps correspond to the regions they represent (a "picture theory" of language, as he put it). His later work, however, recognized that there is no such simple mechanical coupling of a linguistic model to its subject; indeed, he formulated a "rule-following paradox" that showed, not unlike Gödel, that language could not be generated by a rigid set of rules of correspondence to reality. Rather, the linguistic system must function as a kind of "game", or an analog system with its own internal rules, in which useful but quite loose correspondences may (or may not) occur. To think otherwise, Wittgenstein warned, is to fall victim to a kind of "bewitchment of intelligence", of just the sort that language (and especially the misuse of language) is prone to encourage.

Unfortunately we can still see examples of Wittgenstein's "bewitchment of intelligence by means of language" and Whitehead's "fallacy of misplaced concreteness" in many modelling methodologies today – or what is just as unfortunate, in their uncritical application by over-specialized professionals. These faulty outputs become the uncritical basis for rigid, poorly optimized design decisions, with little scope for refinement and fine-grained support.

As the urban theorist Jane Jacobs (1961) pointed out, such models actually fail to account sufficiently for what she described as "the kind of problem a city is" – a problem that has the dynamic behaviours of living systems and their processes. Such systems cannot be entirely reduced to linear, single-variable analyses or statistical models – though these approaches have their limited place. However, she argued that their misuse by planning specialists damages the inherent capacity of these cities to self-organize in benign ways. The inevitable result is the grim damage that is readily observable in great cities of the 1960s, as she documented in her landmark work *The Death and Life of Great American Cities*.

§ 6.1 Accounting for Complexity and Self-Organization

Jacobs' analysis alluded to yet another fundamental problem with the modelling of complex phenomena like urban systems. It is that the phenomena we are modelling do not sit frozen, but have the unfortunate habit of self-modifying in response to dynamic events, and in unpredictable ways. That is, they are complex adaptive systems that are continuously evolving and, to some degree, self-organizing. While some of their features may remain relatively static, many of them – particularly those relating to socio-economic interactions – are exceedingly dynamic. Often they have "non-linear" characteristics, i.e. their behaviour is not proportional to the quantitative factors that influence it. Clearly we must somehow account for this dynamism in any model as well.

The development of transportation modelling illustrates the nature of the problem.   Earlier transportation models treated the actions of individual vehicles as simple and predictable elements that seek only to continue on their current path at the maximum possible rate. The errors of these models, and the failures of the systems constructed in response – particular the failure to alleviate traffic congestion for any but a short period – are now well documented (Supernak, 1983). Of course, human beings are decision-making agents in their own right, and they are able to decide to take alternative routes based upon dynamic conditions – or not to travel at all.   One consequence of this dynamic environment is the phenomenon of induced demand: the more supply is increased, the more demand may grow in order to consume more of it (Noland, 2001).

The same limitation affects the systems that generate greenhouse gas emissions. As Mayumi and Giampietro (2006) pointed out, the socio-economic systems that are ultimately responsible for greenhouse gas emissions are themselves self-modifying, and because the number of variables is large, the ability to predict actual outcomes is greatly reduced.

Jacobs (1961) noted the importance of large numbers of variables in playing a role in the complexity of cities. But she argued that it is not only the number of variables, but the way they are interrelated within a structural characteristic she referred to as "organized complexity." She noted the progress made in the life sciences in understanding how the elements of a system modulate one another's behaviour so as to form an "emergent" pattern.

In the subsequent decades, this progress accelerated notably, as problems in many fields were seen to be understandable as problems of complex adaptive and self-organizing systems. The progress was perhaps most dramatic in the field of biology and genetic processes. For example, Farmer et al. (1987) were able to show how so-called "network models" could explain the complex interactions of immune systems and other biological phenomena, and they applied the insights to other systems as well. Kauffman (1993) also showed that self-organisation processes are capable of accounting for the evolution of complex biological structures. But self-organisation was readily seen in other systems. Nicolis and Prigogine (1977) described the self-organisation of non-equilibrium chemical systems. Kauffman (1995) described broader insights from self-organisation and complex adaptive systems.

FIGURE 6.1 Self-organisation is seen in many natural systems including this bird flock. Each bird follows a local set of rules to adjust its position to the other adjacent birds, and the system "self-organizes" into an ordered structure. Similar phenomena have been extensively studied in urban systems and their economies. Photo credit: Titus Tscharntke

A number of authors have also applied these lessons to urban systems since Jacobs. Salingaros (1998, 2005) described the "urban web" as an interactive network with dynamic and self-organizing aspects. Batty (2007, 2009) described the complex and fractal structure of cities, and proposed modelling methodologies to account for this structure. Allen (1997) described cities and regions as self-organising systems, arising from the complex interactions of individual agents. Portugali (1999) described self-organization processes in cities as a form of rule-based "game".

In these and related findings, the topic of self-organisation poses profound epistemological limitations – but also opportunities (Kauffman, 1995). If we can understand the dynamics of these processes, we might well find ways of enhancing their desired results, and suppressing their undesired results. This indeed has been a fertile area of research. In fact, a number of modelling methodologies have been developed so as to account for and exploit these dynamics. We discuss several of them in more detail below, followed by a discussion of their relevance for carbon reduction urban design modelling more specifically.

§ 6.2 Methodologies for modelling under complex and uncertain conditions

In recent decades a number of innovations in modelling methodology have emerged to incorporate the epistemological insights of earlier decades. We survey several of the most relevant up to the present day, and draw conclusions for current work in development of urban design support modelling.

§ 6.2.1 Bayesian Methodology

One of the most important developments in the methodology of statistical modelling has been the development of Bayesian methods, originated by the English mathematician Thomas Bayes and further formalised by the French mathematician Pierre LaPlace via what is known as Bayes' Theorem. Subsequently a methodology has been developed around the use of the theorem with applications to modelling, known as Bayesian methodology (Rupp, Dey and Zumbo, 2004).

In contrast to "frequentist" methodology, which seeks to confirm or reject a predictive hypothesis purely on the basis of the frequency of data, Bayesian methodology allows for successive estimations of the probability of truth of such a hypothesis. There is a strong relationship to what is known as "fuzzy logic" in the field of logic, but there is one key difference: whereas Bayesian methodology is concerned only with uncertainty around a given set of data, fuzzy logic accepts the premise, for strategic reasons, that the logical consistency of the data itself may not hold (Zadeh, 1973). Fuzzy logic is an important development in complex systems and decision processes, but it is less applicable here than Bayesian methodology.

In Bayesian methodology, a crucial element of the calculation is the knowledge of probability *prior* to the current data calculation, known in the field as the "Bayesian prior." This key assessment can be made on the basis of what is known, or only believed, about the probability of the predictive hypothesis. This can include an explanatory theory of how the system in question is predicted to behave, or even a heuristic that is drawn from past experience. The methodology relies upon iteration, and at each successive step the Bayesian prior will be updated on the basis of new information and new assessments. In this way, a Bayesian methodology is capable of learning and growing more accurate over time.

It is a crucial feature of the methodology that the initial accuracy of the Bayesian prior probability need not be high for the process to provide useful results – as long as the system is capable of improving based upon later outcomes. (This idea is captured in the elegant little poem titled "The Road to Wisdom," by the physicist and mathematician Piet Hein: "To err and err and err again, but less and less and less.")

Comparisons have been drawn between Bayesian methodology and the iterative way that the scientific process itself works. As we will see, there is also a comparison to the use of design patterns and pattern languages, which function as "structured essays" that can be improved iteratively over repeated usage, testing and improvement. (See Appendix.)

§ 6.2.2 "Improper" linear models

Although linear models – those that simplify a prediction to a simple linear scale of probability – are often significantly inaccurate, they may still be more accurate than human judgment alone, including the judgments of highly trained professionals (Kahneman, 2002). This may be because, like all models, linear models combine inaccurate features with features that may be accurate enough to be useful in some decision-making contexts. The question is not whether they have any inaccuracy – all models must, as Gödel demonstrated – but whether they nonetheless provide useful capabilities.

The usefulness of so-called "improper linear models" was made clear in a very highly cited paper by the psychologist Robyn Dawes, titled "The robust beauty of improper linear models in decision-making" (1979). In it he demonstrated that, in certain contexts, "improper" models (that is, models in which the variables are not properly weighted in relation to one another) can nonetheless be useful. These contexts are typically where data is limited and "noisy" (inaccurate) and where there may also be many variables of data. In such a case it may be more effective to simply aggregate the factors without giving them weight. In fact, the research shows very clearly that such models can be remarkably effective, and considerably more accurate than human judgment, even highly trained expert human judgment.

It is a remarkable fact that this is so. The reason, according to Dawes, is rooted in the subject of epistemological limits as we discussed previously. While models can suffer from inability to cope with complexity and dynamic self-organization, it appears that human judgment is even more prone to error. As later work by Kahneman (2011) showed, we make decisions with cognitive systems that are extremely vulnerable to biases and distortions. When it comes to phenomena like climate change, these biases can result in the familiar patterns of inaction and apparently irrational response. In such cases improper linear models, for all their limitations, often perform better than human judgment.

A rudimentary example of an improper linear model, according to this definition, is the urban sustainability rating system known as LEED-ND, or Leadership in Energy and Environmental Design for Neighborhood Development. The system uses a point system for scoring a range of urban sustainability metrics. It has been criticised, probably rightly on the merits, for ranking the points in an arbitrary way – "improperly" according to this definition (for example, in the critique of Sharifi and Murayama, 2013). Yet Dawes' work suggests that LEED-ND may well be a good interim model to use, at least until such time as better models are developed.

§ 6.2.3 System Dynamics Modelling

AltThe fundamental problem of dynamic interaction and feedback was recognized in the 1950s by Professor Jay Forrester of the Massachusetts Institute of Technology (1957, 1961). His methodology, called "system dynamics," explicitly built in recognition of the effects of feedback and time delays with the behaviour of systems, and the methodology sought to capture and predict the outcome of such interactions.

Forrester's stepwise, iterative modelling methodology can be described as follows:

- First, define the boundary of the phenomenon to be modelled, using existing boundaries as much as possible.
- Second, identify the most important "stocks" (metrics) and the flows (movements of quantities) that will change these stock levels.
- Third, identify inputs that will influence the flows.
- Fourth, identify the feedback loops in the flows and the inputs.
- Fifth, draw a "causal loop diagram" that links the stocks, flows and inputs.
- Sixth, write equations (or computer programs) that will calculate the flows.
- Seventh, estimate the parameters and initial conditions, using the best information available.
- Eighth, run the simulation of the model and analyse the results.
- Finally, if iterations are required, cycle back to the point of the next iteration.

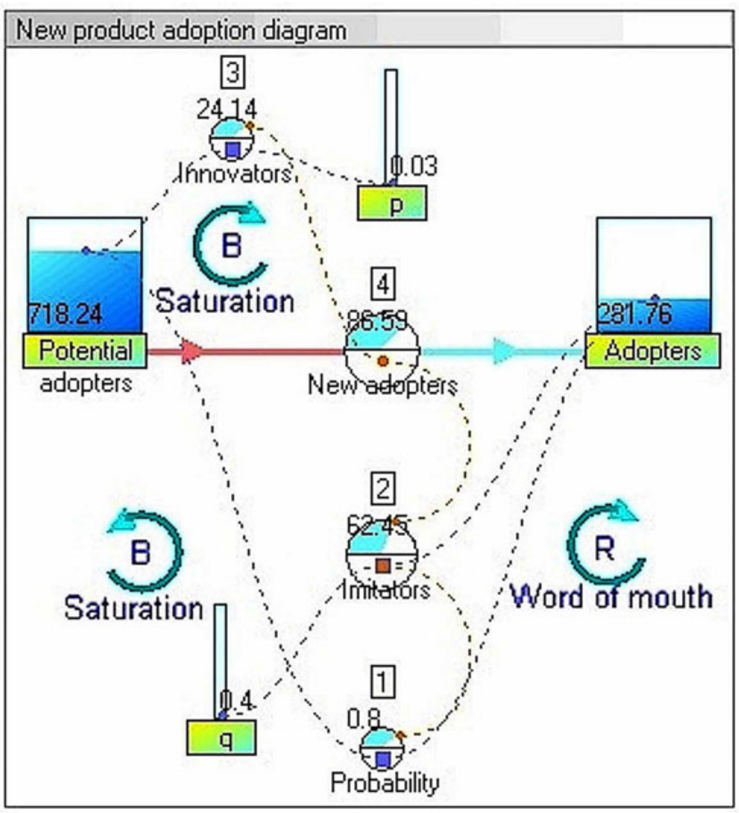

FIGURE 6.2 Diagram of a dynamic model of the interaction of factors in the adoption of a new product, as it is influenced by word of mouth, imitation, innovation, and other factors. Source: Patrhoue/Wikimedia Commons, After Sterman, 2001

.Forrester's modelling methodology became popular in business management and industrial process engineering, notably as a tool to optimise quantities and delivery times. Initially a manual method, the process was computerized in software such as SIMPLE and DYNAMO, and it became an industry standard tool. The modelling was expanded into urban systems when Forrester was asked by Boston mayor John Collins to collaborate on a project at MIT, resulting in the book *Urban Dynamics* (Forrester, 1969).

Forrester was drawn into global systems modelling in his work for The Club of Rome's 1972 report *The Limits to Growth*. That work certainly focused public attention on the ecological parameters of socio-economic systems, and the implications of their limitations. But its notable inaccuracies of prediction (for example, it under-estimated ecological capacity) also did damage to the reputation of such large-scale models. In fact, the following year, a "requiem for large-scale models" was published in the *Journal of the American Institute of Planners* (Lee, 1973).

Other critics pointed out the value-laden assumptions in Forrester's modelling. Kadanoff (1971) published a critique of Forrester's book *Urban Dynamics*, making the argument that Forrester's choice of modelling elements shaped the outcome. Harris (1972) argued that single projections, including those proposed by Forrester, are extremely unreliable because their boundary definitions isolate the entity under study from its environment. He suggested that Forrester's modelling, while highly influential in business process planning, had little effect on urban planning practice.

§ 6.2.4 Artificial Neural Networks and Bayesian Belief Networks

The recognition of limitations imposed by self-organizing phenomena has inspired a class of models that are able to self-organize on their own, and, in effect, "learn." Notable among these are "artificial neural networks," which seek to mimic the learning processes of neurons in biological systems (Rumelhart and McLelland, 1986). This approach to modelling is "connectionist" – that is, it relies upon the evolving set of connections between the elements of the model, which are not defined statically as in Forrester's system dynamics.

This work has begun to be applied to modelling, and to greenhouse gas modelling specifically. For example, Radojević et al. (2013) published a report on a project to forecast greenhouse gas emissions in Serbia using artificial neural networks. However, much more remains to be done in this promising area .

Bayesian belief networks are similar in that they have the capacity to learn by identifying and evaluating inferences within a modelling environment of uncertainty. But they do so using Bayesian methodology, which as we have seen, deals with uncertainty not by identifying "true-false" relationships, but (evolving) degrees of probability based on incomplete knowledge and belief. In such a model, a certain quantitative relationship between A and B might be probable to a certain degree (say, residential density and number of kilometres driven), and another relationship between B and C might also be probable to a certain degree (say, number of kilometres driven and types of automobiles owned), but with variable degrees of probability. The resulting network can model the total degree of likelihood for the condition in which A, B and C interact (say, how residential density relates to types of cars owned, and how both affect kilometres driven).

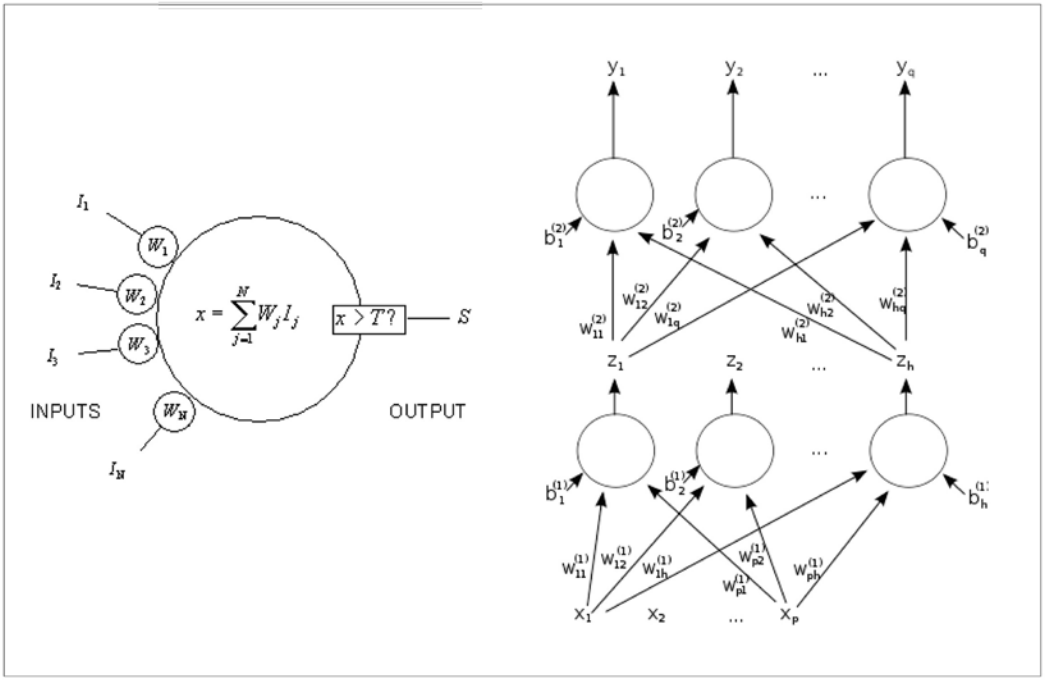

FIGURE 6.3 Artificial Neural Networks solve optimisation problems by mimicking the way natural neurons work. Left, each neuron receives inputs from other neurons and decides whether to "fire" based on a threshold value. Right, the network of neurons is able to "learn" the pattern that produces the intended output. Source: Left, after Ivan Galkin, U. Mass Lowell. Right, M.C. Strother.

Bayesian belief network models have been used in ecological modelling and conservation (Marcot et al., 2006) and the effects of variable greenhouse gas emissions on sea ice and polar bear populations (Amstrup et al., 2010). A Bayesian Belief Network has also been used successfully to model land use decision behaviours (Aalders, 2008). Again, more remains to be developed in this promising field.

§ 6.2.5 "Dynamic Structural Models"

Several fields, notably econometrics, apply the concept of a "dynamic structural model," in which the behaviour of an individual (a person or object) is predicted based upon a dynamic interaction of structural conditions and preferences (Aguirregabiria, 2011). In this sense, the individual person or object is embedded within a dynamic system and their behaviour is understood as an interaction with the other factors.

In computer systems engineering and other related fields, the same term is used to describe an "object-based" modelling process. The systems that are modelled are not seen fundamentally as collections of discrete mechanical elements, but rather, as whole systems that are "decomposed" into smaller systemic wholes according to their functional sub-systems. These elements of "dynamic structural models" are more readily able to retain the larger systems attributes that are essential in the generation or "instantiation" of new applications (IBM, 2014).

§ 6.2.6 Pattern Languages

In software, one of the best known such object-based modelling systems is pattern language programming (Coplein and Schmidt, 1995). Pattern languages, developed by architect Christopher Alexander, have been used successfully as object-based models of software design since the early 1990s. In fact they are now ubiquitous within computing, and they form the basis of many common software systems (such as the Apple Mac OSX and the iPhone Cocoa language). Pattern languages have spread into many other domains as well, including human-computer interaction, service design, business administration, education, and many other fields. In some cases innovations in software design have led to innovations in other fields; a notable example is the development of the "Scrum" and "Agile" methodologies, which began in the software world and spread to become mainstream management methodologies (Beedle et al., 1999; Mehaffy 2010).

The reason that pattern languages, invented for architectural design, fit so well within the object-based approach of computer software is that they were explicitly developed as flexible, networked, language-like design models (Mehaffy, 2010). Their inventor, architect Christopher Alexander, was trained as a mathematician and physicist before earning the first Ph.D. in architecture at Harvard University. However, he spent time working on early generations of computer decomposition software. He also worked closely with leading cognitive psychologists at MIT, including George A. Miller, and his Ph.D research included cybernetics, cognitive psychology, linguistics and philosophy.

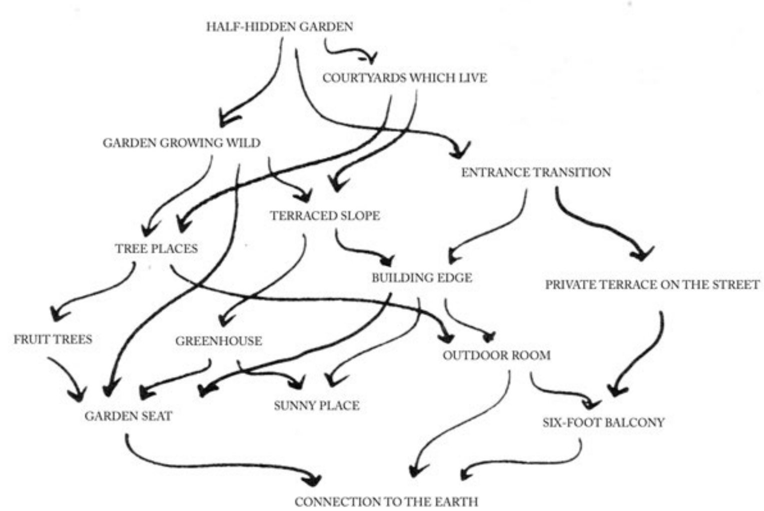

FIGURE 6.4 Pattern languages have been used in many fields of software and hardware design, following their invention in the field of architecture. The elements and their linkages form a web-network, which usefully mimics the web-network structure of design problems. (Credit: Christopher Alexander.)

Like Wittgenstein, Alexander became convinced that language was not a perfect decomposition of an orderly hierarchical reality, but more like a "game" with its own set of objects and rule-based interfaces, only loosely coupled to the world to which it referred. It had ambiguities, overlaps, and the complexity of web-networks – as did, too, the phenomena it sought to describe.

So, too, designs must not seek to be perfectly rigid hierarchical structures made up of collections of elements, but rather, they must be systems with language-like ambiguities (Alexander, 1965). The value of such a design model was in its ability to capture the same web-like structure of the world, and to be able to explore a wide range of design possibilities in a powerful and flexible way – not unlike the power and flexibility of natural languages.

Each pattern is, in a sense, an element of a predictive model which asserts that a given configuration will work in a predictable way, within a context of other patterns. Crucially, the pattern is able to be tested and falsified, and then modified to become more accurate. In this sense, a pattern states a kind of Bayesian prior, which can be used to create a prediction of whether a given design will actually work. Over time, and within a community of users, the patterns can become more accurate and effective.

One of the developers of pattern languages in software, Ward Cunningham, took this capability a step further. He developed a flexible new tool for collaboration, using easily editable pages as hyperlinked objects. His invention, Wiki, is also now a ubiquitous tool, leading to the development of Wikipedia and thousands of other corporate and private Wikis (Mehaffy, 2010).

For Cunningham, a Wiki page *is* a kind of pattern, and a Wiki compendium is, in a sense, a pattern language. In both cases the pages are "structured essays" that describe what is asserted to be a valid relationship. But in both cases, that relationship can be tested, corrected and made more accurate over time (see the Appendix for more discussion of this central software methodology).

It is a key capacity of pattern languages that, like natural languages, they are shared and evolved by a community of users. For Cunningham, this capability was an essential strength of Wiki, and was clearly a critical ingredient of the success of Wikipedia. Cunningham is now working on a new generation of Wikis that will, in addition, have the capacity of data management and manipulation, as well as a more distributed, "federated" structure (Mehaffy, 2013; Cunningham and Mehaffy, 2013).

The next chapter will describe the workings of this Wiki structure in more detail, and will examine a prototype decision-support tool that utilizes its capabilities. First it is necessary to examine another existing methodology for evaluating design solutions – one that will also form a part of the basis for the new tool we will discuss.

§ 6.2.7 Scenario modelling

A simpler modelling methodology that is also able to incorporate aspects of the other methodologies discussed herein is the use of so-called "scenario-modelling". This methodology has become more common in recent years (Schoemaker, 2004; Mehaffy, 2013), notably in the fields of urban design and planning. This is in large part because a range of concrete possibilities can be more readily explored and evaluated, not only on the basis of one criterion like greenhouse gas emissions, but with a balance of broader criteria.

As with all design, the goal is not merely to create some wholly new structure with desirable attributes, but – as the noted design theorist Herbert Simon famously described it – to effect a course of action that successfully changes an existing state into a preferred one (Simon, 1962). This implies an ability, on the part of the designers, to explore a range of alternative design decisions and their likely outcomes, so as to judge their preferability. That is, it implies a capacity for usefully reliable prediction.

It is in this environment that scenario modelling has arisen as an urban design decision-support tool . In essence, a designer, or design team, prepares a series of design alternatives, which serve to outline the range of choices that are believed to be available for the design. The modelling process then provides a set of comparative predictive results of those choices, and thereby provides guidance in directing the design process. In so doing, the process works to solve an optimization problem with regard to a set of inter-dependent variables – such as greenhouse gas emissions, residential density, urban paving area and the like (Condon, Cavens and Miller, 2009).

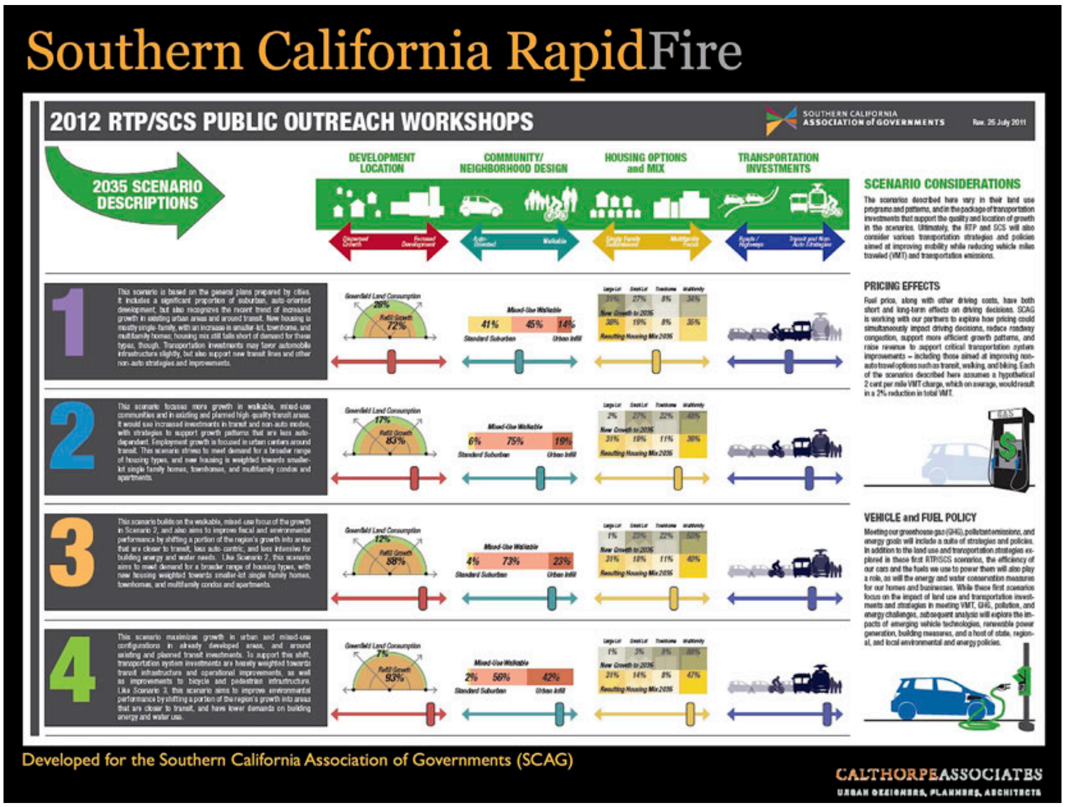

FIGURE 6.5 Scenario modelling has been developed on computer platforms using open-source methods, such as RapidFire, shown here, developed by Calthorpe Associates for use in California's greenhouse gas reduction planning work. In this user interface, stakeholders are able to choose their preferences within comparative scenarios, and then see the predicted results of their choices. Credit: Calthorpe Associates.

A question immediately arises as to which variables are selected, and how the preferential condition is determined – and by whom. By definition, the designers are optimizing relative to normative definitions of "preferred states" that they themselves have accepted. For example, more reduction of greenhouse gas emissions is better, but perhaps not at the expense of an excessive level of residential density, which may be an "unpreferred state."

But the next question must be, of course, on whose authority do they choose those normative definitions? This was the problem raised by urban design pioneer Kevin Lynch, writing in his book *Good City Form* (1984). He argued that such normative values are an inevitable part of all design, and what is critical is that they are transparent, critically examined, and subject to democratic process. The goal is not to have "the right model" of good city form in any objective, predetermined sense, but to have a model that has been openly and critically assessed, with the benefit of public scrutiny and evaluation.

A key strategy for doing so has been to employ scenario-modelling tools within so-called "public involvement" processes, where citizens and stakeholders have at least a theoretical opportunity to participate in shaping the normative values of the urban design modelling and decision-making process. Examples are so-called "envisioning" processes, where stakeholders are brought into a process of design scenario development and given choices about preferred outcomes, which are then analysed with predictive modelling (Lemp et al., 2008). Subsequent iterations can refine the outcomes according to the preferences of those engaged in the stakeholder involvement process, as well as other required parameters of the outcome (e.g. legal and regulatory requirements).

These public involvement processes can take the form of collaborative workshops or "charrettes" (Condon, 2007). The goal of these charrettes is to actually engage a range of designers, technical experts, and stakeholders, in developing, assessing and refining design ideas. In a sense, the charrette process is in the business of assessing design scenarios, and for this reason the scenario-modelling process has been found to be well suited to the charrette workshop (Condon, Cavens and Miller, 2009).

It is important to emphasise that the achievement of a preferable state, as Simon described it, need not be accomplished entirely by one act, by one process, or even by one agent. Indeed, in practice this rarely happens. As Gigerenzer described it (2004) we are in an environment of "ecological rationality" and must rely in part upon "fast and frugal" heuristic decision-making methods. Progress will be achieved through successive iterations that often involve multiple parties, who can then learn from the results and refine the successive iterations to become more effective.

This means that in modelling of such design actions, what is necessary is to have generally reliable, but not necessarily precise, guides to actions that are likely to take us sufficiently in the preferred direction with each iteration, while avoiding the reversal of progress by any other factors. Through successive iterations we can get closer still, and at the same time, we can use the feedback we gain to hone the accuracy of our predictions as we progress. Through successive iterations and by many participants, these actions can be refined and improved over time: the process can "learn" and grow more effective. This is an aspect of design that mirrors phenomena in the natural world, as Simon (1962) and other planning and design theorists have described (e.g. Jacobs, 1961; Alexander, Neis and Anninou, 1987).

Another fundamental challenge of modelling is the selection of data and the methodology by which the predictions are generated. As we will discuss in more detail below, the issue of political controversy and inaction in the realm of GHG reductions remains especially acute because the complexity and inherent uncertainty of the information obscures the set of decisions that would likely make progress possible, relative to other goals. Our models, often reliant upon large data sets and statistical inventories, are highly sensitive to small errors in initial assumptions – for example, incorrect selection of relevant factors to compare on an "apples to apples" basis (see e.g. Rypdal and Winiwarter, 2001). These errors become magnified to produce large-scale errors at worst, or inconclusive results at best (Cullen and Frey, 1999). Inconclusive or erroneous results are then cited by self-interested parties to support their policy arguments, leading to greater confusion (Morgan and Henrion, 1990). The result is that there is very little progress, and a great deal of uncertainty, false hope, paralysis – and worse, false claims for failing methods. This undesirable cycle is self-reinforcing and self-accelerating.

§ 6.3 Conclusion

Building on the advances of these existing methodologies in other fields, we can now state the requirements of an effective modelling methodology for resource-efficient urban design decisions, working under the uncertain conditions with which we must cope:

1. ***Such a methodology will be iterative.*** It will not be applied in a single iteration to any degree of effectiveness, but will improve with successive iterations.
2. ***It will be able to regularly make comparisons with empirical results and adjust its predictive data accordingly.*** The iterations will be of little benefit if they do not allow a periodic comparison with empirical results so as to verify or refine the model.
3. ***It will utilize the iterative participation of a community of users in an "open-source" format.*** In this way the improvements can be distributed across a larger community, and the cycle of improvements can be accelerated.
4. ***It will include the most readily identifiable factors, and add other factors as they can be established accurately.*** The accurate weighting of the factors is less important than their inclusion within the model as it goes through iterative refinement and empirical adjustment.
5. ***It will account for the dynamic interactions between factors, without becoming overly complicated.*** The best way to do that is to use a more flexible, web-networked, language-like approach, rather than a mechanical approach to constructing components within a linear or reductionist scheme.
6. ***It will draw on the best available data – but it will also compensate for the inherent uncertainties of the data.*** This means using methods to draw inferences and improve them iteratively (such as Bayesian methodology) and other compensations. It will also mean that the result is treated as provisional and incomplete, but nonetheless, a useful basis for incremental improvement.

It will be noted that the previously discussed modelling methodologies do contain some or all of the features specified above, to varying degrees. But an opportunity now appears to combine the varying benefits of different approaches into a next-generation methodology, as outlined here. For example, in what ways might pattern languages be able to function as artificial neural networks, capable of learning in problem-solving – particularly with the open-source capabilities of a Wiki community? What capacity might such a technology offer for developing more effective design models, and more effective problem-solving capability for complex contemporary challenges?

Such a synthesis methodology therefore suggests the possibility of a promising new kind of design technology – or perhaps it is more accurate to say, an existing technology, given useful new capabilities. That is the opportunity we will examine in the next chapter.

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7 Decision Support Tool Structure: Software options and methodologies

Chapter Summary

This chapter describes a distinct new class of scenario-modelling urban design tools, and it discusses a specific prototype tool generated as part of this research.

This chapter is drawn from the peer-reviewed paper "Prospects for scenario-modelling urban design methodologies" (Mehaffy, 2013). As noted previously, another section of that paper forms the conclusion of Chapter Two, "Counting Urban Carbon."

How can we develop a useful design decision support tool that can quantify the magnitude of GHG emissions through scenario-modelling? We now have some evidence about the factors that are likely to influence the results, which we can use as "Bayesian priors" within our methodology. We also have the elements of a methodology based upon existing scenario modelling and other approaches.

Clearly the contribution of the different factors will vary significantly based upon specific local conditions. Any modelling strategy will need the capability to express variations in these local conditions. More detailed research is needed to be able to account for these variations, and the ways that they interact. At the same time, some of this research will have to be highly localised (Johnston et al., 2000, Kates et al., 1998).

Moreover, a modelling tool will also have to account for the fact that these different factors do not merely aggregate, but also interact. Reductions from one factor, such as dwelling size, may then limit the available reductions from another factor, such as whether a dwelling is attached or detached. Some factors may also increase the available reductions from other factors. This means that the elements of the model will need to be able to interact with each other through mathematical functions operating not just in series, but within an interactive network. We discuss the strategy for developing such an interactive modelling structure below.

In spite of these variations, the evidence we have summarised does suggest that the total effect of such factors is likely to be a large one – taken together, perhaps in the range of one-third of all GHG emissions from human activity (Mehaffy, 2009). This helps to account for the actual observed difference in per capita emissions between cities, which is difficult to account for apart from urban morphology (World Resources Institute, 2009).

Of course, being able to account for and thereby model the relative reduction that is theoretically available between two theoretical urban morphologies is one thing. Actually changing the morphology of new urban developments to achieve significant reductions – let alone existing urban developments – is quite another challenge (Ewing et al., 2007). This will depend upon how much new development is occurring (a significant amount in developing countries like China and Brazil), and how much "retrofit" development is occurring elsewhere (and the extent of possible changes in morphology as a result). In any case, the first requirement is clearly the ability to account for and to model such a difference.

Also significant is that feedback from such a model can be tied to implementation strategies and incentives, which will make it more likely that the reductions shown in the model can actually be achieved. Various scenarios can be modelled, not only for their greenhouse gas reductions (and possibly other metrics of interest), but also for their feasibility. In this way, an optimum path can be identified through the testing of alternate "scenarios" in a stepwise, evolutionary process (Hopkins and Zapata, 2007).

There are two benefits from such a process. One, the alternatives identified by the model can serve to improve the likelihood that beneficial changes in morphology can in fact be made. And two, the outcome of such changes can itself be modelled, and the results can be used to fine-tune the model, and thereby improve its accuracy and usefulness (Condon, Cavens and Miller, 2009).

This situation presents a significant opportunity to develop new models that do just that. More specifically, they allow urban design scenario planning, with real-time evaluations of the various factors that might be able to be varied in the design. As we will discuss, such a methodology allows local evaluation, experimentation, and customised implementation. Over time, it allows the kind of evolutionary improvement of the model that we have described.

Moreover, such a system can itself be developed and improved by many collaborators, using so-called "open-source" collaborative methodologies. In such a system, different collaborators are able to make local incremental improvements, increasing the quality of the result. There are promising examples of such systems whose efficacy has been well demonstrated in the software development world, including software such as Linux and so-called "Wiki" systems such as Wikipedia. (von Hippel and von Krogh, 2003; de Laat, 2007; Voss, 2005).

Thus, such a modelling system, tied to a cycle of research feedback and empirical results, could in principle improve in accuracy and effectiveness over time: in effect, the system would "learn."

§ 7.1 Computer modelling, open-source methodology and design patterns

Thus, there is considerable evidence to suggest that a computer-based scenario-modelling system is needed, and one that allows collaborative open-source development.

Among planners, the practice of using open-source software to develop and apply new methods of scenario modelling is already well advanced (Condon, Cavens and Miller, 2009; Holway, 2011). Modular software packages are being applied and developed further, including *Envision Tomorrow* by Fregonese Associates, and *UrbanFootprint* by Calthorpe Associates. These and other systems are explicitly written to work with "modules" written by others, which can be developed to model more specific or local features of the urban environment.

Such a modular approach is in fact a useful and often-used feature of software design, including software designed according to "design pattern" protocols (Gamma et al., 1995). As discussed in the previous chapter, design patterns are guides to software developers that provide information about the design elements that are most likely to be effective in a given context. Not only are there entire packages of software that function in this modular format, but even small parts of the software system consist of modular "patterns" that work together according to grammar-like rules (hence the term "pattern *language*"). This "object-oriented" flexibility provides much of the programming power for the methodology.

As noted previously, the development of design patterns also led directly to the development of Wiki, which can be thought of as a set of pages (originally, patterns) that can be collaboratively developed, edited and exchanged (Leuf and Cunningham, 2001). As the pages are developed, their information tends to grow more useful and (in the case of modelling information) more accurate. The best-known example of this phenomenon is the widely-used on-line encyclopedia, Wikipedia (Voss, 2005).

However, it is important to recognize that, under the right circumstances, Wikis are themselves capable of serving as modelling methodologies. In a sense, a page on Wikipedia is a model of a portion of human knowledge, expressed in relation to other knowledge via hyperlinks to other Wikipedia pages. Just as human knowledge can be refined, errors can be corrected, and more knowledge can be added, so Wikipedia is capable of refinement, correction and improvement. (This requires a degree of rigour in the methodology, as we discuss in the Appendix.) As we will see, this capability will prove useful in the software now under development.

§ 7.2 A scenario-modelling methodology based upon open-source software

Armed with these insights – and with the broader modelling methodologies previously specified in Chapter 6 – we are now ready to discuss the specific structural specifications of a scenario-modelling urban design methodology. The system will have the following attributes:

1. It is web-based, making it available to a wide community of users as well as developers;
2. It is simple enough to be user-friendly, but robust enough to be effective;
3. It is able to model different scenarios, with a range of input values, relatively quickly and effectively;
4. It is evidence-based and transparent – that is, the sources of evidence can be identified, further examined, and if superseded with new evidence, replaced;
5. It is developed and refined through an "open-source" process – that is, it is open to improvement by those who have the expertise or the evidence base on which to do so (this is particularly valuable in achieving refinements over time);
6. It has a capacity for interactive network modelling and whole-systems characteristics.

Such a technology would offer a notable advance in modelling capability. Most computer-based modelling systems today are "black boxes" – it is difficult or impossible to follow the calculation process, and there is typically no readily identifiable relationship to the research on which the calculations are based. Furthermore, even for open-source systems, the development of new features requires possession of the original source code as well as considerable programming expertise. Lastly, modelling systems typically require exceedingly complex calculations that are highly sensitive to initial conditions, which can produce erratic and unreliable results.

As we have discussed previously, software technologists have produced several innovations in recent years that are relevant to our needs:

1. ***Wiki.*** As we have seen, this web-based content-sharing platform is simple and powerful, and applications like Wikipedia (perhaps the best known example) are able to evolve rapidly through open-source development. Hyperlink capability allows elements to be networked, and provides the capacity to link to citations of peer-reviewed research and other evidence for examination and possible revision.
2. ***Data interchange and calculation plug-ins.*** Web pages can now handle relatively sophisticated calculations with new modular data-interchange formats like Javascript Object Notation (JSON).
3. ***Federated open-source.*** Instead of open-source development on a single master copy (like the centralized copy of Wikipedia) federated open-source is a "next-generation" innovation that allows simultaneous development and differentiation of multiple local copies. Beneficial developments can be re-migrated to other copies, or back to the original. New applications can be quickly developed that do not just explore new uses of the original source code, but alter it. The result is faster and more diversified development of innovations.
4. ***Design patterns and pattern languages.*** As discussed in Chapter 6 and further in Appendix 1, pattern languages can be thought of as modular elements of design that have been shown to be effective within a definable context, and that can be combined more quickly, easily and reliably into a relational network. Wiki is itself an elementary form of pattern language structure, developed as part of the larger development of design patterns in software

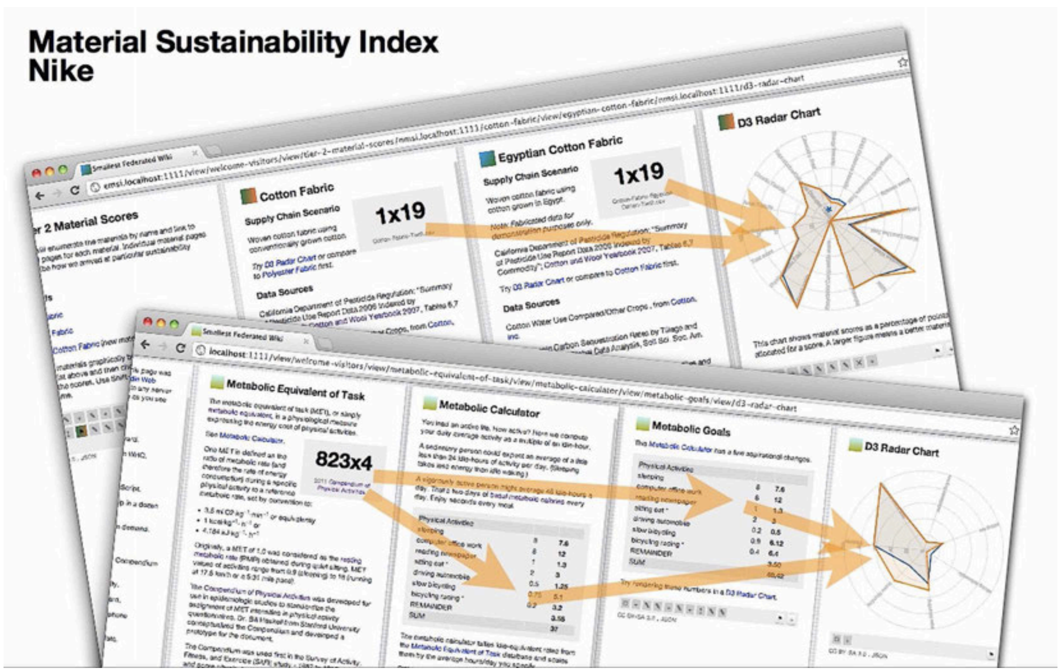

FIGURE 7.1 Ward Cunningham's "Federated Wiki" as developed to provide design outcome scenario-modelling for Nike apparel designs. [Source: Cunningham (2012a).]

§ 7.3 Federated Wiki – a promising new scenario-modelling technology

The research herein has been conducted in collaboration with the software engineer Ward Cunningham, who is the original developer of Wiki as well as a co-developer of design patterns. Cunningham has developed a new generation of Wiki with data exchange and calculation capabilities, the goal of which is, as Cunningham states, "to do for numbers what the first Wiki did for words."

A second crucial innovation is that the new Wiki has a federated structure, allowing faster and more differentiated open-source development. In practice this means that a scenario-modelling system like WikiPLACE that is altered by one user can be shared and altered by another user, and any useful innovations can be migrated back to the first user.

A third key innovation is that the new Wiki exists entirely on the web, in a contextual "drag and drop" page format. Elements from one Wiki page can be quickly and easily dragged to another page. Its hyperlinks function contextually on the web, and they will update in response to the context in which they are placed.

The central importance of this innovation must be emphasized. The pages and elements exist within a language-like web that depends upon their context, just as natural languages do. The elements are not fixed, but depend upon their context, without which they can be ambiguous. This key point warrants explanation by an example.

In a natural language, if one speaker uses the term "she", speaking to another, the intended referent of the term will likely be understood even though it is structurally ambiguous and entirely dependent on context. It could be that "she" is a person previously identified in the conversation, or, alternatively, "she" might be a new referent in the discussion. The person spoken to will look for an identifying context for the person to whom the speaker is referring. If there is no new identifying information, the context will imply that "she" is the person to whom the speaker previously referred.

This ambiguity and flexibility is in fact a powerful capability of language (Chomsky, 2002). It allows the network of references to become infinitely extensible, forming an open-ended modelling system that can include many different aspects of interest. We can speak of "she," and also "her briefcase," and subsequently "it," and so on – ultimately encompassing an infinite web of entites and sub-entities within our descriptions.

By contrast, a linguistic system that lacked this flexible ambiguity would be very limited in its usefulness. We would have to re-state with monotonous precision every term and every relation – e.g. Mary who has the briefcase that contains the letter, and so on – greatly limiting the flexibility and agility of the language.

There is a strong corollary with the agility of Federated Wiki. The simple but powerful use of contextual variables places a given element within an ultimately infinite web of contextual relationships – just as natural languages do.

Contrast this structure with, say, the structure of spreadsheet data, where the failure to precisely specify the location of even a single point of data, or its operation, can cause the entire spreadsheet to malfunction. This failure of rigid specification systems is a key driver of innovations like wiki, by Cunningham and others, leading to the development of what has come to be known as Agile Methodology. (See the Appendix section for more on this subject.)

Of course there is a risk with such a language-like flexibility, as ambiguity can cause its own kinds of failures in data. However, the benefits are much more significant than the limitations, as several examples will demonstrate.

In fact, as we shall see, the scenario-modelling capability of such a system is very well suited to the Bayesian approach that we discussed in Chapter 6.

§ 7.4 Federated Wiki and the Nike sustainability rating system

Many current-generation environmental design sustainability assessment systems (such as BREEAM and LEED-ND) rely on a "checklist" format, and there has been criticism of the weak correlation between the points awarded and actual performance (Humbert et al., 2007, Abdalla et al., 2011). Indeed, criticism of such assessments' arbitrary construction and weak basis in evidence has grown in recent years (Tolksdorf, Peterson and Ulferts, 2014).

In product manufacturing, there has been a similar effort to account for environmental as well as social impacts from materials and manufacturing choices, which often occur across the lifecycle of the materials. One typical response was developed by the footwear manufacturer Nike, their "Nike Materials Sustainability Index" (or Nike MSI). A key aim of the index was to allow apparel designers to compare choices of design elements, and to produce comparative design scenarios in which the impacts of materials production from "cradle to gate" (that is, from extraction to product delivery) could be identified (Nike, 2012).

The Nike report describes the process as follows:

> "Nike MSI calculates relative material scores for each of the more than 80,000 materials available to Nike product creation teams from 1,400 suppliers. These scores then feed into the Nike Apparel and Footwear Sustainability Indexes, helping designers to select materials with lower environmental impacts, as measured by Nike MSI."

In essence, designers were being asked to construct scenario models of various materials choices, and identify a more optimum mix of materials choices. However, with 80,000 materials the process was a complex one, and not particularly user-friendly. In addition, updates to the database were limited by the number of people who had access – in practice, very few. This was in spite of the fact that Nike had decided to open the data to inspection and review by third parties. This meant, in principle, that the data could be revised, corrected and extended by a larger community of users.

In 2012 Nike hired Ward Cunningham as their "Open Data Fellow" and asked him to develop a Wiki system that would allow greater collaboration, sharing, and user-friendly use of the Nike MSI system. As an outgrowth of that system, Cunningham developed a new generation of Wiki which he called "Federated Wiki." This research has been carried out in part on behalf of Nike corporation, with potential application to its apparel manufacturing systems. (Cunningham, 2012a; Zaino, 2012).

In the Nike model, Wiki pages (scaled to be used easily on a handheld device) could be quickly combined and substituted to construct scenario models of different materials for a design (say, a shoe design). The metrics of those materials – cost, energy in manufacturing, water use, GHG emissions et al. – could be quickly tracked and displayed. The different variables could be coordinated with each other, and even correlated (for example, cost of energy correlated with GHG emissions). In this way, users could quickly explore a number of components through scenario planning, and assess their impacts in each case. (Cunningham, 2012b)

Just as important, the Federated Wiki makes it easy for a community of users to develop, refine and improve both the system, and the underlying data on which it relies. Because of the hyperlink structure of the data, it is possible to examine the source of a given piece of data, refine it, correct it, or add more data.

It is also possible to re-write small elements or even entire portions of the Wiki, which will appear on the local copy of the "federated" original. If these improvements are seen as valuable by the original user or by other users, they are also available to be re-incorporated.

This "federated" approach bears further explanation. It has become common in open-source software development, where it has proven effective. Although the approach is decentralised, it is nonetheless highly structured, following specific protocols of refinement. While anyone is free to "fork" their own copy of a software program (or in this case a wiki) from elsewhere, and make whatever changes they care to, those changes cannot be "pulled" back to the original unless the original author agrees.

There is also a function of "curation" – that is, a host organisation can ask trusted individuals (known as "committers") to peer-review content for its accuracy and suitability. This is how Wikipedia, for example, maintains and improves the quality of its content. (While Wikipedia is not a federated wiki, its curation function works in roughly the same way.)

Toward an urban design decision support tool based on Federated Wiki

Conceptually, it is not a large leap to envision a system that does the same thing for urban design. The components of a shoe (fabric, sole, laces etc) might simply be replaced with the components of a development (homes, commercial spaces, etc). The modular "pattern language" approach means that each of these can be further broken down into smaller components, with modelling of their interactions. An element of say, GHG modelling information, could form a "pattern" that could then be combined with other patterns (say, other GHG inputs) within a larger set of modular and coordinated tools, or a "pattern language."

The critical function is the passing of metrics from one pattern (or page) to the next, together with the appropriate function as indicated by the research – for example, attaching dwellings will result in a predictive delta of reduced emissions, as will higher density. Because the system is open-source and Wiki-based, it is relatively easy for different users to test, refine and exchange improvements, and build up the base of information to become more reliable and more useful. As we discussed previously, just such an evolutionary improvement is what has in fact occurred with Wikipedia (see also the discussion in Appendix 1).

The advantage of such a system, then, is precisely what we seek: the ability to easily and rapidly model different scenarios, analysing variables that facilitate implementation; and the ability to use such a process to make further refinements in the result, to improve accuracy and usefulness. This is therefore, we conclude, a most promising new research agenda.

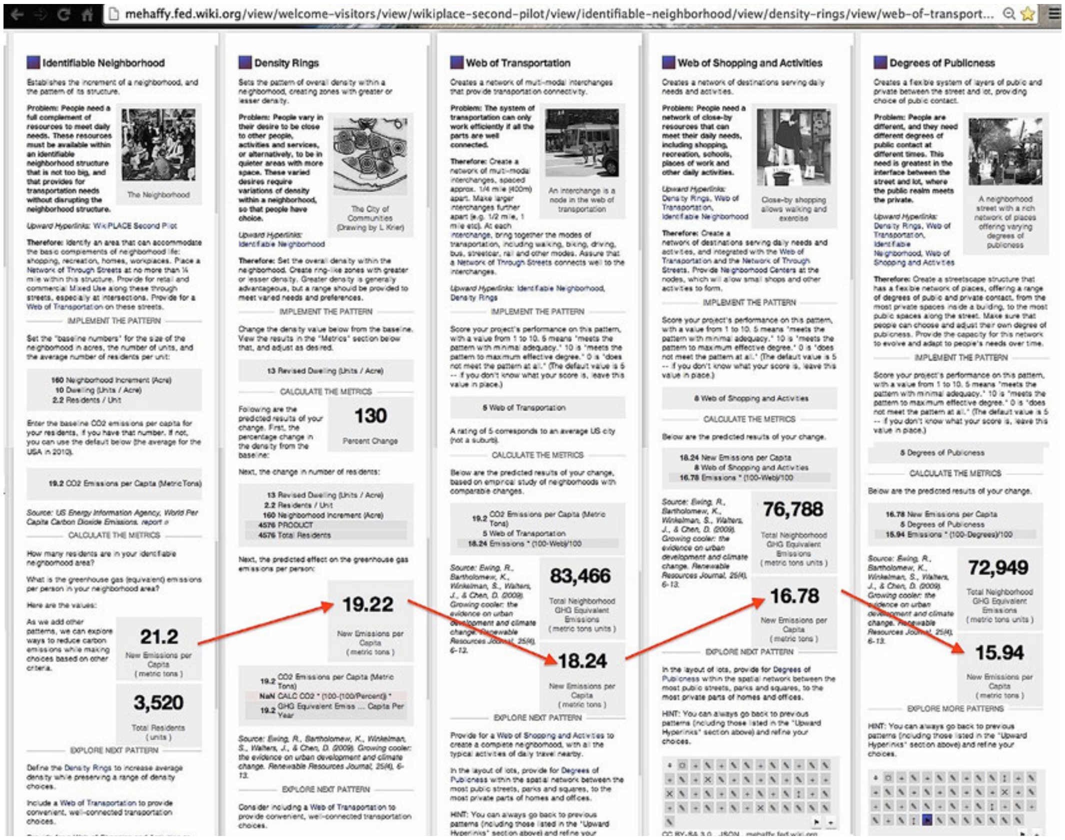

FIGURE 7.2 Early demonstration by Cunningham and Mehaffy of WikiPLACE, a scenario-modelling tool based upon the Smallest Federated Wiki architecture. Such a tool could in principle fit as a module within other scenario-modelling tools. [Source: the author.]

The example above (Figure 7.2) shows a nominal neighbourhood of 100 residential units, and other metrics of baseline GHG emissions per person, number of persons per household and so on. Additional "patterns" (urban design elements) are chosen (via hyperlinks at the bottom of each page) to assemble the full scenario model: in this case single family detached residences, attached residences, increasing density, etc. As these and many other patterns are chosen, the model applies a predictive calculation at each step, acting as a "delta" on the metric with each new pattern. The challenge for the accuracy of the model is to ensure that the delta follows empirical research, and accounts for potential interactive effects.

The links to such research are given, as are all calculations. The point of the process is that it is transparent and accessible, allowing other collaborators to spot errors, add more accurate data, and improve the model over time. For specific user communities, it is also easy to substitute specific local information for the broader baseline information, thus "calibrating" the scenario-modelling to local conditions.

Cumulative effects are relatively easy to model – as for example, the cumulative sources of emissions, or the average deltas of a given design pattern. More difficult to model are interactive effects, which will require more complex and carefully constructed functions (as we discuss below).

In this way, a group of users can develop and test alternative urban designs relatively quickly, manipulating the parameters of building type, density, network, orientation and many others to produce an increasingly accurate predictor of GHG emissions. In principle, it would be relatively straightforward to use a software module to analyse a specific design drawing, and report back on its predicted performance.

A key benefit is that the process is real-time and relatively user-friendly. The tool could be used in a group setting such as a collaborative workshop or charrette, or a public involvement design process. As the demand for public involvement grows, this potential benefit should not be underestimated. (Indeed, it represents a tantalising opportunity for further research.)

It is also important to note that, using the same conceptual approach, other metrics besides GHG emissions can be modelled instead, or in addition.

§ 7.5 Beyond aggregations: Towards modelling (and capturing) the synergetic effects of whole-systems networks

As should now be evident, the evolutionary capability of such a model, with its ability to progressively incorporate more successful strategies based upon tighter feedback cycles with empirical results, offers a tantalizing capability: to gradually evolve functional models of dynamic interactions that are effective and useful resource toward achieving a given goal within a highly complex and uncertain system (such as the reduction of greenhouse gas emissions from urban sources).

It bears stressing that, based on the findings discussed previously, this outcome should be possible with such a methodology *even if the set of mechanisms is not well understood beforehand.* As the model is adjusted to correspond with such observations, it can in principle grow more accurate in its capacity to represent the complex dynamics that are characteristic of urban systems – perhaps even before a theoretical model of the mechanism at work has been abstracted. (Such a process could even hasten the identification of new and more detailed theoretical models, thus serving as an important research tool.)

One such promising dynamic may be in the cyclical flows of resources that capture synergetic effects, greatly increasing the efficiency of a resource system. Such a dynamic is well understood within "metabolic" systems in biology, and promising strategies have been developed to capture them within the growing field known as "industrial ecology." The essence of such strategies is to plug resource flows into cyclical networks, to maximise their synergetic recombinations. Though it is beyond the scope of this research, we believe it is important to note including that the same opportunity may well exist for urban resource networks (Codoban, 2008).

In this light it is also important to recognise that a design pattern is, in essence, an element of a whole-systems network, which is more completely modelled by its larger pattern language. There is a close correspondence to the way that a natural language can serve as a useful model of a part of the world,and it does so in part as a whole-systems network whose parts are interdependent. In both cases the network is capable of redundant relationships, which are not accidental features but in fact crucial to the dynamics of the system as a network.

A scenario-modelling system that utilises design patterns will consider each pattern as a scenario element, and then the assembly of patterns is the larger scenario. If the system is able to handle quantitative data and its transformations (as indeed we must seek) then it is simply necessary that the transformation of data between patterns is also a model of what is happening in the phenomenon in question – for example, a decrease in greenhouse gas emissions per capita. (We will discuss this in more detail in Chapter 8, where we present the actual scenario-modelling software and its functioning.)

§ 7.6 Conclusion

As we discussed in Chapter 6, the challenge of urban design decision support goes to the heart of modelling methodology, and the nature of modelling processes in a complex and uncertain context – an inevitable characteristic of almost any urban system. If we are to avoid the problems we discussed of "whack-a-mole" (solving one problem only to see another one produced) then it seems clear that we must develop a new generation of tools that are suited to the whole-systems nature of our challenges.

Indeed it is not too much to say that the question goes to the methodologies of science itself, and how scientific findings can be translated into efficacious designs. It seems clear that this must be done pragmatically and iteratively, following Bayesian logic, and without the expectation of linear precision.

As with the process of scientific discovery and refinement as a whole, this is not, and cannot be, an automated technological process. Rather, it must be a process of "curation" of knowledge – that is, an ability to review and evaluate information as it is generated, and to test and adjust the result accordingly. The ability to improve accuracy depends upon this curation. The same principle of curation must apply to open-source software technologies – including wiki – if they are to grow more useful and accurate.

In the present challenge of urban form and greenhouse gas emissions, by following such a methodology, we may begin to tease out very important factors within the patterns of consumption and waste, that do in fact relate directly to urban morphology. Such a modelling process would be an extremely helpful guide in both evaluating design scenarios, and in establishing the policies, tools, incentives and practices needed to implement them. This is the tantalizing research and development opportunity ahead.

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8 Evaluating WikiPLACE: A prototype decision support tool for urban design

Chapter Summary

This chapter describes the new WikiPLACE urban design decision support tool that was developed as an outgrowth of this research. It applies the prototype to "back-cast" the GHG emissions of a range of known examples of urban systems. It compares the resulting predictions with known measurements to provide an initial evaluation of the efficacy of the tool.

Portions of this chapter are drawn from the peer-reviewed paper "Wiki as Pattern Language" (Mehaffy and Cunningham, 2013) which is also included in full in the Appendix. Additional portions are specific to this dissertation.

A key part of this research has been to develop a prototype design decision-support tool that embodies the findings, strategies and methodologies developed during this research. While it must be noted that this research is not a software development project per se, nonetheless the software tool that was developed does represent a key implementation of a new *class* of technology that has been advanced herein. It is therefore important to present the tool as an instance of the technology, and to evaluate its performance as part of the overall evaluation and validation of the research herein.

The tool, developed in close collaboration with the software engineer Ward Cunningham, is called WikiPLACE – an acronym for "Wiki-based Pattern Language Adaptive Calculator of Externalities." Before presenting the structure of the tool, it may be helpful to explain the significance of the terms in this acronym.

The aim of the tool is to identify the predicted magnitude of **externalities**, that is, factors that are not normally calculated within economic transactions. In this research project, the externality of interest is greenhouse gas emissions from urban sources; however, as mentioned previously, other kinds of externalities could also be readily calculated by such a tool (e.g. resource depletion, future tax burdens, etc).

The tool functions as a predictive **calculator** based upon the previous research on how the factors being measured are most likely to generate externalities, following the modelling methodologies described previously.

The tool is **adaptive** in two ways: it is able to modify and adapt its calculations in response to variations in the chosen design scenarios; and it is able to modify and adapt its own structure through open source development, peer review, sharing, modification and evolution over time.

Lastly, the tool uses the structure of design patterns and **pattern languages**, which as we have seen have proven efficacious in the design of software, where robust but flexible design alternatives can be explored and assembled into larger proposed designs with reasonable reliability. In the context of the

Wiki, each Wiki page functions as a pattern, which as Cunningham describes it, is "a structured essay" that makes a falsifiable, revisable prediction about the relationship between design elements and the outcome they produce.

WikiPLACE is thus well-suited to function as a pilot example of the scenario-modelling tool discussed in this research, with specific application to the findings on greenhouse gas emissions and urban design decision support. A great advantage is that it can be tested on actual urban designs to evaluate how well it performs relative to known GHG emissions measurements. The last section of this chapter reports on three such test cases, and makes an assessment.

§ 8.1 The structure of WikiPLACE

The core of WikiPLACE is a collection of design patterns that, together, constitute an urban design scenario. For example, one pattern might establish the residential density, another the mix of uses, another the modal mix of transportation, and so on. (Indeed, these and other patterns are included in the initial "Alpha Test" version, as we will discuss in more detail below.)

Again it is important to emphasise that the deign patterns are, by their nature, not individual variables in abstraction, but whole-systems representations of particular kinds of urban pattern, forming contextual elements of a larger design scenario. This is key to the methodology, discussed previously, to model contextual scenarios rather than fragmentary variables in isolation – and thereby, to get a more robust prediction. Nonetheless, portions of each pattern are in fact defined by precise metrics which can be narrowly varied within alternate scenarios to assess their potential impact (for example, variations of residential density).

These design patterns together form the design scenario, in the form of the "project pattern language" - in other words, an integrated network of design elements and their relationships.

Each pattern applies a "predictive delta" to the metric or metrics of interest – that is, a prediction of how the metric(s) will change in practice, if that design pattern is applied in that way. This predictive delta is a mathematical formula or function (in other words, a mathematical model) that corresponds to the previous findings of peer-reviewed research. (Importantly, this research can be viewed through hyperlinks.) For example, if research shows a pattern of decreasing GHG emissions per capita from vehicle travel in relation to increasing residential density, then a function that describes that pattern will be applied to the metric of GHG emissions per capita, to produce a delta that corresponds to the research findings.

As discussed, it is relatively easy to examine the source of data, and, if desired, to make revisions. (For example, if changes or "calibrations" are believed warranted as a result of local testing and refinement.) The federated structure allows revisions on a local copy of WikiPLACE which, if found to be more reliable, could be used to replace other local copies, or – if the original author or curator agrees – the original from which it was derived.

Within each pattern, it is possible to vary an input metric (say, residential density) and explore changes in the prediction for outcome (say, GHG emissions per capita). It is technically possible to compare this to other "tradeoff" metrics – for example, changes to the average cost of each dwelling – although for this research that capability has not been developed.

Subsequent patterns repeat the cycle, applying the relevant predictive delta on the metric(s) of interest. These are selected from a series of hyperlink menus in each pattern that lead to subsequent pattern choices.

At some point, it is likely that two or more patterns will not just perform together in a linear way, but interact through a feedback process. For example, one pattern may produce, say, a 110% increase, and the second may produce a 110% increase, but the two together will not produce an increase of 121% (1.10x1.10) as might be expected; because of their interaction, they will produce, let us say, 121% x .95, a factor of their interaction.

This interaction factor must also be modelled within the system. There are two ways that WikiPLACE can do this. One is to build the interaction into the formulas that each pattern calculates, in such a way that the patterns will interact dynamically, reflecting the interaction between the factors being modelled. This method corresponds to the methodology of *system dynamics modelling* discussed in Chapter 6. In effect, the patterns form a network of stocks and flows which interact.

The other method is to apply a scaling factor to the result at a final step – a "network analyser" that adjusts the result in approximation of such a feedback dynamic. This is a "shortcut" method, but one that can be effective under the right circumstances. In fact, the circumstances correspond to the methodology also discussed in Chapter 6, an *improper linear model*. As such, it constitutes a pattern in its own right, and one whose function is to account for the interactive effects of other patterns.

Thus, by selectively choosing and defining patterns, WikiPLACE can quickly generate alternate scenarios. The user can model different scenarios by changing the value of individual patterns, or by employing different patterns altogether. These can be opened in different browser windows and placed side by side, if desired.

§ 8.2 Using WikiPLACE in practice

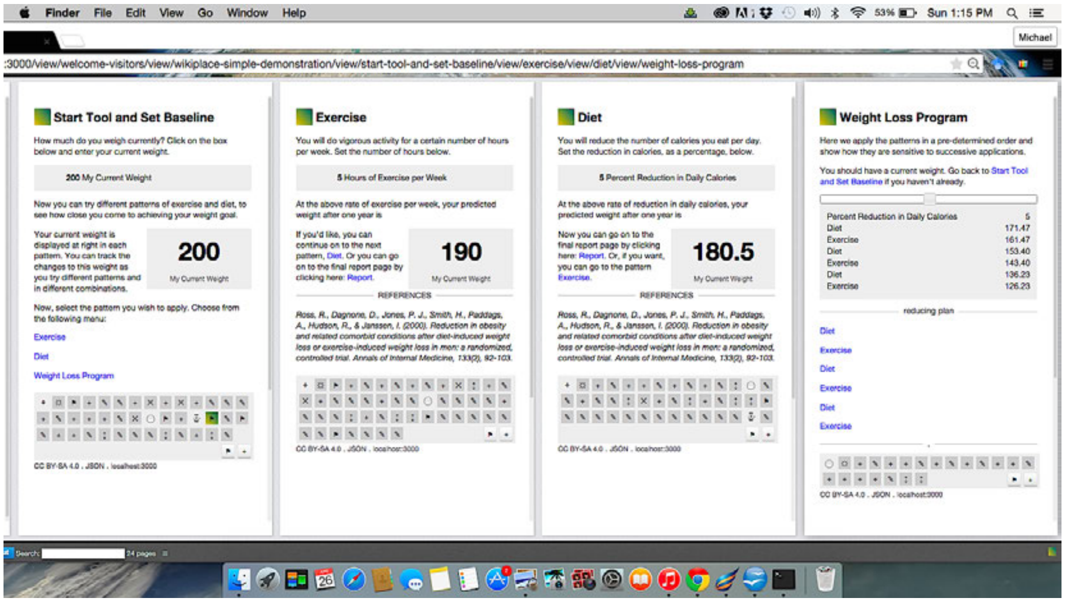

FIGURE 8.1 A simple example of how WikiPLACE works, using patterns for losing weight. This is the desktop view with the four pages open. Left to right: "Start Tool and Set Baseline" allows the user to enter their current ("baseline") weight; here the user has first selected "exercise" and entered 5 hours per week, with the resulting weight displayed after one year; next the user has selected "Diet" and entered a 5% reduction in calories, with the resulting weight displayed after (the same) one year; and finally, a page allowing the user to experiment with different combinations of patterns and "loading orders."

The simplified example above will conceptually illustrate how the underlying software actually works (Figure 8.1). In this example, we will be interested in the metric of personal body weight, and how we might achieve a weight-loss goal (analogous to lowering GHG emissions per capita). In this extremely simplified example, there are just two patterns – exercise, and dietary restrictions.

The first step in using the WikiPLACE tool is to set the baseline values for the design in question. The user does this by calling up the "Start Tool – Set Baseline" pattern from within the browser window. (This first pattern is accessed from a welcome page that appears on startup of the tool.)

Over a series of subsequent steps, the user will identify a series of design patterns to apply to the design, each of which will generate a predicted delta on the metric(s) in question – in this case, weight loss. The predictive deltas will be derived from research findings, which point to a relationship between the value of the design element and the outcome of the metric in question (in this demonstration they are fictional).

The user will then select the value or values of the design parameters – in this case, how many hours of exercise per week or how much reduction in consumption of calories per day – and the predictive delta for each patterns is applied to the metric and the result is updated.

Then the user selects the next pattern and repeats the process, with the results displayed as before. In this case, with only two patterns, the user can only proceed in one of four ways: Pattern A alone, Pattern B alone, Pattern A then B, or Pattern B then A. But in practice, with many more patterns, a user could quickly and easily try different patterns, back up, or even start again. All this could be done on one browser page, while another browser page is displaying a very different scenario (which could also be perhaps constructed by another user within a group). In this way, quick and user-friendly scenario-modelling is possible.

The final page shown here is an example of how the scenario can be revised and further analysed. On this page the user can combine a number of different sequences of diet and exercise, applying them in different sequences or "loading orders," and quickly view the result. The slider element at the top allows the user to experiment quickly with input values across a range of possible values.

This is only one of a number of methodologies that the Federated Wiki software provides to create a final step of analysis within the modelling system. As we will see with the WikiPLACE model, the important goal is to display the predicted value along with a summary of the method by which it was produced.

§ 8.3 The WikiPLACE prototype patterns

This prototype or "alpha test" version of WikiPLACE contains just four patterns, capturing four key conclusions of the research (documented through references to peer-reviewed research in each pattern). I have chosen four patterns in part because that is a sufficient number to see how collections of patterns behave within a modelling scenario. It also allows a minimally complete system on which to evaluate initial performance of the decision support tool, which we report in the conclusion of this chapter. However, it is theoretically possible to include any number of patterns, or have access to repositories of much greater numbers. (In the field of software design, this is currently how design patterns are accessed and shared.)

The four design patterns in this alpha test are derived from the research reported in previous chapters, and summarized below. The logic of their structure is a core outgrowth of the methodology described earlier, reflecting Bayesian, heuristic and iterative methods. As discussed, their structure also reflects a "systems approach" to urban design, rather than an attempt to model narrow variables in isolation. As we have seen, that approach is overly sensitive to initial conditions, and prone to produce "garbage in, garbage out" results. Instead the methodology here reflects the earlier discussions of "improper linear models," "Bayesian belief networks" and related advances in identifying usefully approximate knowledge.

Each pattern is a description of a design configuration, stated as a proposed solution to a design requirement. This structure follows from the logic of design patterns and pattern languages (Buschmann, Henney and Schimdt, 2007). The design requirement is not simply a narrow goal in isolation, such as "reduce greenhouse gas emissions." After all, the most direct response to such a narrowly defined goal might well be to cease all activity! Instead the goal of reducing greenhouse gas emissions is placed in the context of a larger urban design goal, as stated in the problem-statement of the pattern.

In the same way, WikiPLACE could model other quantitative externalities of interest to urban designers, such as the cost of development to the public, or the value of ecosystem services. Again, it could do so within a broader scenario of design, rather than as an isolated set of variables.

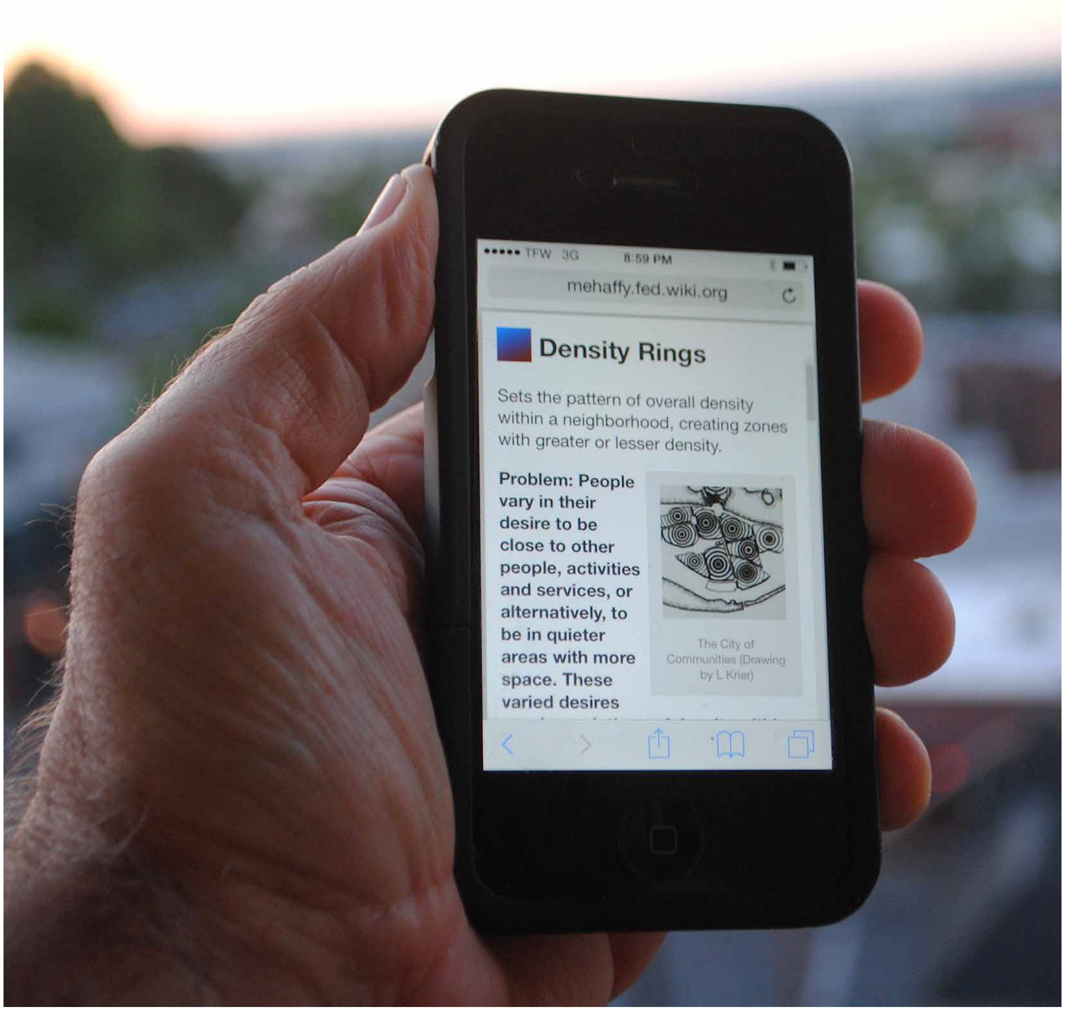

FIGURE 8.2 The WikiPLACE system is designed to be user-friendly. Here a pattern is visible on an iPhone that could be used at a field site. In this format it is possible to simply scroll between the patterns within a model for quick and easy use. It is also possible to select new patterns from a menu, and thereby to quickly construct a new model. As with any wiki system, it is also possible to edit the patterns, or even to write wholly new ones that are shared over a "federated" network.

For this prototype, my software development colleague Ward Cunningham and I have borrowed the pattern format, and even specific pattern names, from the classic 1977 book, *A Pattern Language*. There are three reasons for this. First, the book is extremely well known and studied, with over 3,700 citations on Google Scholar (2015). Second, the book's user-friendly format is evidenced by its perennial bestseller status across a wide audience; according to the US website Amazon.com, the book remains, in 2015, the number one bestselling book in the architecture category, some 38 years after its publication (Amazon.com, 2015). Third, the format is a familiar benchmark that has been successfully adapted to other fields, notably software (Buschmann, Henney and Schimdt, 2007).

However, we have varied the detailed structure of the patterns to fit the specific needs of WikiPLACE – an evolution that is perfectly appropriate to the deeper logic of pattern languages, as software users and researchers have demonstrated (Mehaffy and Cunningham, 2013). In this case the patterns have been written to capture the findings of the research, as we have discussed previously. Following are the four patterns together with their detailed structure.

PATTERN 1
IDENTIFIABLE NEIGHBOURHOOD NETWORK

This pattern captures the factors described in Chapter 3 as neighbourhood network – that is, a measure of the density of inter-connectedness of neighbourhood infrastructure, both within systems (e.g. street patterns) and between systems (e.g. waste-to-energy). It then asks users to score the degree to which their scenario conforms with that model. If there is a match, then a corresponding prediction of emissions reduction is applied to the metric. If there is no match, or a lesser match, then a prediction of a proportionally lesser reduction (or no reduction) is made. This is not to say that reductions might not be made with other urban forms, or indeed with a variety of other measures – but that the model is simply not reflecting those probabilities.

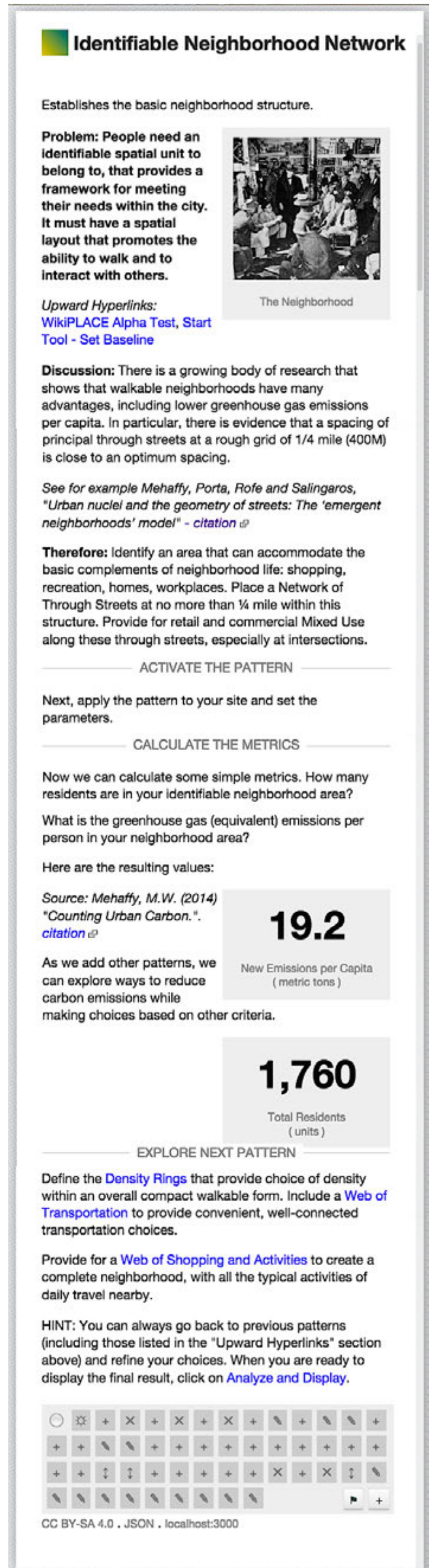

FIGURE 8.3 The pattern Identifiable Neighbourhood Network as it appears on the web browser screen of a desktop computer. Normally only part of the full height of the pattern is visible, and the user scrolls down to view the lower part.

PATTERN 2

DENSITY RINGS

As we saw in Chapter 2, one of the most significant findings regarding greenhouse gas emissions and urban morphology is that the variable of residential density is strongly correlated, inversely, with emissions, particularly (but not exclusively) from transportation sources. However, as we have also seen, it is not density as a variable in isolation that is causative – a dense residential area separated from offices and other needs by a long commute would not perform well – but rather, we are concerned with density in relation to urban pattern. Thus, the pattern defines an overall density while encouraging variations of density across gradations, or "density rings."

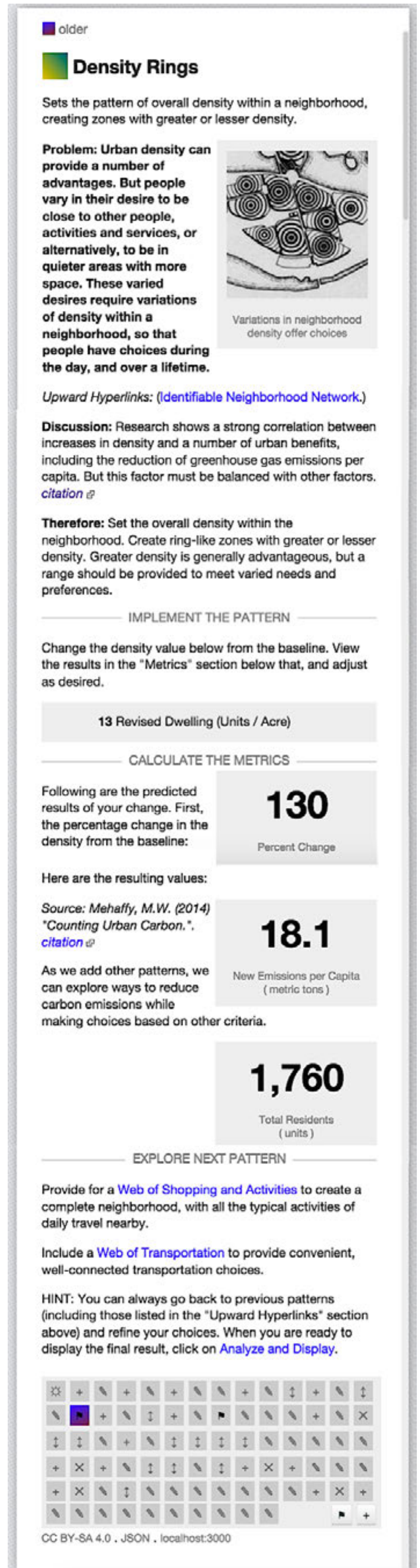

FIGURE 8.4 The pattern Density Rings as it appears on the web browser screen.

PATTERN 3

WEB OF SHOPPING AND ACTIVITIES

The Web of Shopping and Activities is also based on the research findings described in Chapter 3, and a factor referred to as the web of destinations – that is, the structural distribution of uses and destinations. Again the pattern describes an optimum condition described in the research, and again it asks users to calibrate the degree to which the design scenario achieves this pattern. A high calibration corresponds to a fine-grained mix of elements, while a low score corresponds to a baseline of segregated urban form.

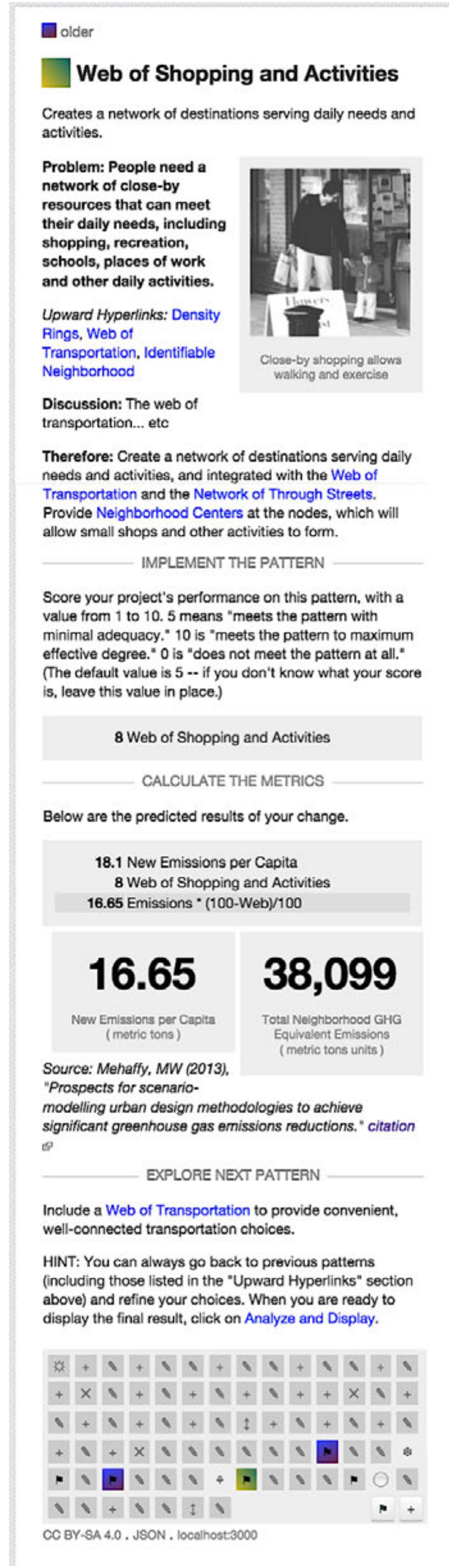

FIGURE 8.5 The pattern Web of Shopping and Activities as it appears on the web page.

PATTERN 4

WEB OF TRANSPORTATION

As we also saw in Chapter 3, the network of multi-modal transportation, or what was termed the "web of transportation," is also an identifiable factor in GHG emissions per capita. The term defines the provision of an integrated network of viable pedestrian-based multi-modal pathways. The pattern describes the best-performing condition that is identified in peer-reviewed research, and then it asks the users to calibrate the degree to which the design scenario achieves this condition, or alternatively, a baseline of more conventional, more fragmented, auto-dominated transportation system.

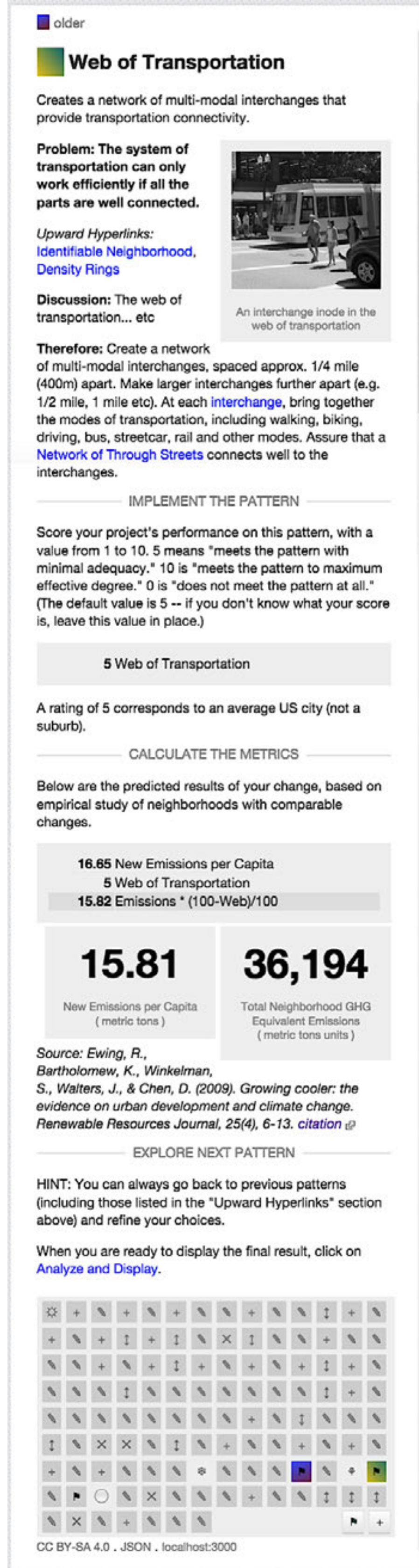

FIGURE 8.6 The pattern Web of Transportation as it appears on the web browser screen.

SUMMARY DISPLAY PAGE WITH (OPTIONAL) ADDED ANALYSIS OF RESULTS

The last display page provides a summary of the results (see last panel to the right in Figure 8.7). An alternate experimental version of the software has featured an opportunity to calculate interactive network effects between the patterns. Because the interactions are relatively simple in the case of this WikiPLACE Alpha Test version, and the order is fixed, the interactive adjustments are not significant at this stage and we have eliminated them from this preliminary model. A more complex version we have begun to develop will allow the patterns to interact dynamically, forming a dynamic structural model. Further development of this capability is one goal of postdoctoral research.
However, it should be remembered from the discussion of "improper linear models" in Chapter 6 that greater precision is not always the same as greater accuracy, and that approximate models can sometimes be better decision-making guides (Dawes, 1979). With that in mind, it is useful to see how the WikiPLACE model performs against actual data.

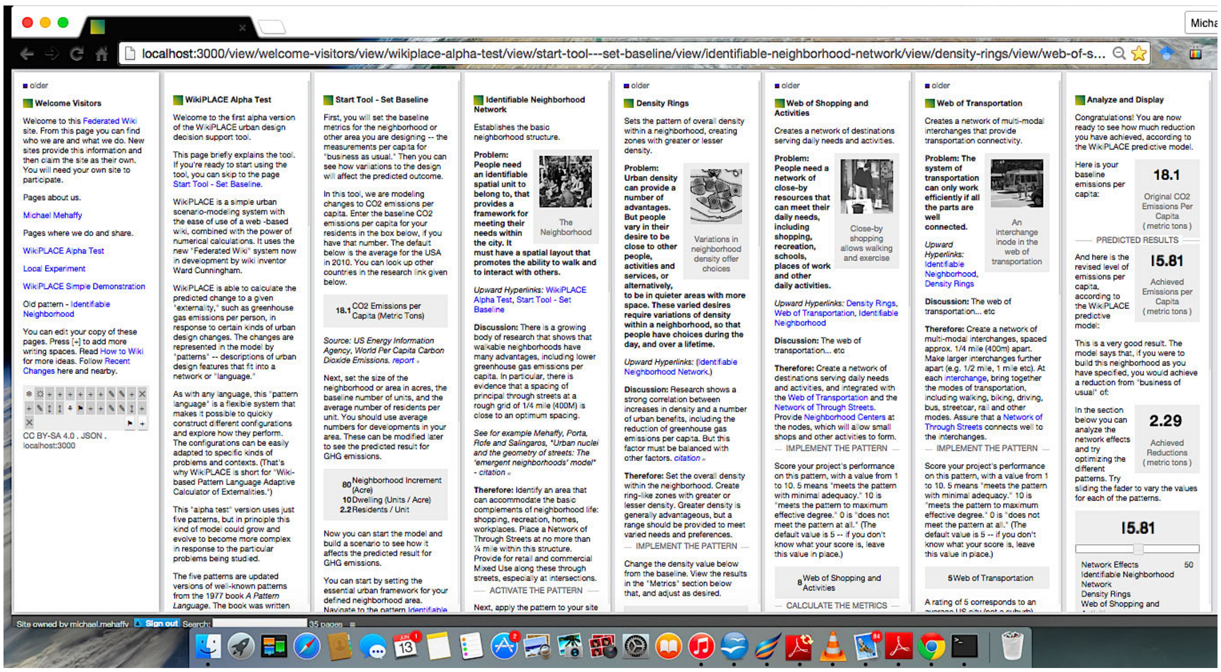

FIGURE 8.7 The complete structure of WikiPLACE as it appears in maximum zoom out on a desktop, showing all the patterns in the alpha test version. From left to right, the introduction and startup page, the Start Tool – Set Baseline page, the four patterns, and the final display page. Users can adjust the values of the patterns, or change the order or number of patterns. Following the protocol of a wiki, users can also edit the patterns as they desire, or even write new ones on their own local copy (which can be shared with others, if desired, throught the federated network).

§ 8.4 Preliminary evaluation of the WikiPLACE tool

As an initial evaluation of the tool and its modelling methodology, I conducted a "reverse forecasting" test – that is, a test of forecasting accuracy by comparison with known examples. By comparing a range of known examples, we can get an approximate gauge of the predictive performance of the tool relative to real-world inventory results.

Here, however, we encounter an important problem in this analysis: the previously discussed problem of inconsistent inventory methodology, and "apples to oranges" comparisons (see Chapter 2). In this research I have carefully chosen to define emissions as measured per capita, generated by consumption activities of people living in neighbourhoods. This is distinct from in-boundary and aggregate emissions. As discussed, this is an important boundary definition because it enables us to examine how people, living and working in neighbourhoods of different morphologies, might consistently vary their emissions based upon those morphological differences – as indeed the evidence herein has shown.

However, consumption-based, per-capita inventories at the neighbourhood scale are uncommon. Where they exist, they cannot be easily correlated with other comparable neighbourhoods within the same or other cities, or with their average country emissions. This is, in fact, an important need that I intend to develop further in post-doctoral research.

Therefore, the approach I have taken in this initial evaluation is to use three different types of reverse forecasting comparisons, and assess the performance of the model as an average across these comparisons. That is, I will start with the known parameters of one entity, and then use the model to predict the emissions of the second entity based on its morphological differences.

It is essential that as many other emissions-influencing factors as possible, beyond urban morphology, be excluded, so that the results are not skewed by these outside factors. Thus, as much as possible, the comparisons should hold steady for climate, economic prosperity, demographics, governmental systems, mix of fuels and zero-emissions sources, and so on.

The three comparisons generally do hold these factors steady, and any variations are further averaged out over the three different kinds of analysis. (As we discussed in Chapter 6, aggregation is always helpful in improving predictive power.)

The three comparisons are:

1. **Countries compared to cities within them.**
2. **Different cities compared within the same country.**
3. **Different neighbourhoods compared within the same city.**

For each model run, I used a consistent weighting of the patterns, but I varied the score of each pattern based upon the change of morphology. I used a ranking from 1 to 9, where 5 is the midpoint of no change, 9 is the highest score representing a full implementation of the pattern, and 1 is the lowest score, representing a complete lack of presence of the pattern.

In later iterations of the model, specific attributes could be measured and calculated more precisely as desired. For example, density could be measured as number of persons per hectare, or a similar metric. For this initial proof-of-concept, I have used a rough approximation of the variations based upon the findings of the research reported earlier.

I also calibrated the "deltas" of the patterns – the magnitude of possible GHG reductions from the full implementation of each of the patterns – from the findings of the research. Though this is a very rough estimate at this stage, it should be remembered that the purpose of the wiki-based system is to allow further refinement and evolution of the model and its accuracy. (Its purpose is also to encourage more development and comparison of consumption-based inventories at smaller scales.)

§ 8.4.1 Countries compared to cities

The country-city pairs were selected because they have greenhouse gas emissions inventories that have been developed through standard UNFCC inventory methods and data (as reported in Dodman, 2009). To do the evaluation, I set the baseline per capita emissions according to national per capita inventory data for each of five countries. I then ran the model to calculate predicted per-capita emissions for each of five cities within those countries, whose parameters of urban form were then assessed according to the four patterns within the model. I then compared the results to the actual greenhouse gas inventories for those cities, as an initial assessment of the degree to which the tool does accurately predict per-capita reductions.

It is important to note here an important issue regarding in-boundary versus consumption-based inventories. The UNFCC methodology relies on in-boundary inventories. While they typically show similar results to consumption-based inventories in cities where production and consumption are roughly balanced, in-boundary inventories provide misleadingly high results for those cities that do large volumes of manufacturing and exporting of goods that are consumed (and demanded, through purchasing behaviours) in other parts of the world. Examples are cities in China, which for that reason have not been considered for use in this reverse forecasting test.

For cities that do not have an unusual concentration of export manufacturing – or equally unhelpful for our purposes, an unusual scarcity of it – there is a relatively close correlation between in-boundary and consumption-based numbers. For example, in the US state of Oregon, which has done comparative analyses of both, in-boundary emissions are 15.8 metric tons per capita per year, while consumption-based emissions are 18.8 metric tons per year – meaning that 3.0 metric tons per year of emissions generated by Oregonians occur in other parts of the world, such as goods manufactured in China. This represents an increase of 18.9% over in-boundary emissions. (McConnaha et al., 2010.)

Although most inventories are in-boundary, not consumption-based, if an in-boundary national inventory is compared to an in-boundary city inventory, both of which are typical for intensity of manufacturing and balanced import/export, the result will at least be "apples to apples" and should give a useful approximation of the magnitude of consumption-based emissions reduction, or "delta," to provide an indication of the performance of the model.

Another limitation is that the comparison of the model results here is to cities, not to neighbourhoods. We know from research on the dynamics of cities that their efficiencies derive partly from the interactive behaviour of the city as a whole, and individual neighbourhoods cannot easily be separated from the characteristics of the overall city. Put differently, this should indicate to us that a model applied to a neighbourhood in isolation should not predict a magnitude of reduction that is equivalent to that of a city as a whole.

For purposes of this experiment, then, we should expect this model to get a lower magnitude of emissions reduction for the given cities than we see in the full-scale cities in question.

The cities and countries were chosen with the following goals in mind:

1. ***Each city is reasonably typical for its country*** in climate, economy, demographics, political and legal system, and mix of fuels (including zero-emissions sources) as well as other GHG sources, so that those factors are generally equivalent in the comparisons.

2 ***Each city is typical of its country's mix of manufacturing and import/export,*** so that the in-boundary measurements are not artificially skewed by demand occurring in other locales. (For this reason, Chinese cities have been excluded.)
3 ***The city-country pairs are relatively diverse,*** representing different continents, parts of the world, country sizes, climates, etc.

The five city-country pairs are:

1 **London, and the UK *(Europe).***
2 **New York City, and the US *(North America).***
3 **Barcelona, and Spain *(Europe).***
4 **Tokyo, and Japan *(Asia).***
5 **Rio de Janeiro, and Brazil *(South America).***

I scored the cities on the degree to which they met each of the four patterns, so that the delta to be applied by that pattern could be calculated. In scoring each pattern, I evaluated the approximate degree to which each city's morphology varies from the average city or town in that country. For example, London, while a very dense city that meets the patterns very well, is more like the average U.K. City or town than, say, New York City is like the average American city or town. Thus it does not score as high in the evaluation for that pattern.

The following table shows the scoring I gave to each city relative to its national baseline:

Pattern Scoring - Country to City Comparison

Country (City)	***Neighborh. Network***	***Score 1-9***	***Density Rings***	***Score 1-9***	***Web of Activities***	***Score 1-9***	***Web of Transport.***
UK (London)	Low	6	High	8	Moderate	7	Low
Spain (Barcelona)	Low	8	Very High	9	High	8	Low
US (New York)	High	9	Very High	9	High	9	Moderate
Japan (Tokyo)	Moderate	7	Very High	9	Moderate	7	Moderate
Brazil (Rio de Janiero)	High	8	Very High	9	High	9	High

TABLE 8.1 Scoring for the country to city comparison.

I then ran the WikiPLACE model, applying the maximum delta for each pattern to the score for each pattern. For example, the maximum delta for Pattern 1 is 20%, but London scores 6 on the 1-9 scale, so the actual delta applied is 5%.

The output of each pattern then supplied the input for the next pattern, and so on through the sequence of four patterns.

The last output forms the final predictive value for emissions, which is then compared to the actual inventory value. The deviation value and percentage are also shown.

WikiPLACE Output – Country to City

Country (City)	*Init. Value (Baseline)*	*Pattern 1 Score 1-9*	*Pattern 1 Max. Delta %*	*Output Value*
UK (London)	11.19	6	20	10.63
Spain (Barcelona)	10.3	8	20	8.76
US (New York)	23.92	9	20	19.14
Japan (Tokyo)	10.59	7	20	9.53
Brazil (Rio de Janiero)	8.2	8	20	6.97

Country (City)	*Input Value*	*Pattern 2 Score 1-9*	*Pattern 2 Max. Delta %*	*Output Value*
UK (London)	10.63	8	30	8.24
Spain (Barcelona)	8.76	9	30	6.13
US (New York)	19.14	9	30	13.40
Japan (Tokyo)	9.53	9	30	6.67
Brazil (Rio de Janiero)	6.97	9	30	4.88

Country (City)	*Input Value*	*Pattern 3 Score 1-9*	*Pattern 3 Max. Delta %*	*Output Value*
UK (London)	8.24	7	20	7.41
Spain (Barcelona)	6.13	8	20	5.21
US (New York)	13.40	9	20	10.72
Japan (Tokyo)	6.67	7	20	6.00
Brazil (Rio de Janiero)	4.88	9	20	3.90

Country (City)	*Input Value*	*Pattern 4 Score 1-9*	*Pattern 4 Max. Delta %*	*Output Value*
UK (London)	7.41	7	20	6.67
Spain (Barcelona)	5.21	8	20	4.43
US (New York)	10.72	9	20	8.57
Japan (Tokyo)	6.00	7	20	5.40
Brazil (Rio de Janiero)	3.90	9	20	3.12

Country (City)	*Final Predicted Value*	*Actual Inventory Value*	*Deviation*	*% Deviat.*
UK (London)	6.67	6.20	0.47	7.09%
Spain (Barcelona)	4.43	3.40	1.03	23.21%
US (New York)	8.57	7.10	1.47	17.18%
Japan (Tokyo)	5.40	4.80	0.60	11.18%
Brazil (Rio de Janiero)	3.12	2.30	0.82	26.34%
Average Deviation =				**17.00%**

TABLE 8.2 The results of the WikiPLACE reverse forecasting experiment for five city-country pairs. WikiPLACE was able to predict the reduction within an average deviation of 17.0%.

The results are reasonably accurate, with an average deviation across the five city-country pairs of 17.0 percent.

§ 8.4.2 Cities compared to cities

The next comparison is to city pairs that differ in the parameters of urban form, particularly density. The baseline is taken from an analysis of energy use in cities that, working from the results, developed a life-cycle analysis model of four cities in the USA: Orlando, Phoenix, Austin, and Seattle (Nichols and Kockelman, 2015). It is important to note that Nichols and Kockelman looked at energy, not emissions, and therefore did not consider fuel sources or emissions (including zero-emissions sources). However, the analysis does provide a reasonably good "apples-to-apples" comparison of these cities. This is because their mix of fuel sources and zero-emissions sources is comparable, and other factors are comparable.

Nichols and Kockelman's model shows the following percentage change in energy use for the four cities:

1 **Orlando 0% *(Baseline)***
2 **Phoenix -11.8%**
3 **Austin -16.0%**
4 **Seattle -16.8%**

Taking these values as reasonable approximations of GHG emissions deltas, we can generate a table of four per capita GHG emissions measurements for these four cities. Using the USA baseline of 23.92 for Orlando, we derive:

1 **Orlando: 23.92**
2 **Phoenix: x -11.8% = 21.10**
3 **Austin: x -16.0% = 20.09**
4 **Seattle: x 16.8% = 19.9**

I then scored the deviation from the Orlando baseline standard for the four cities. They generally have comparable urban form (a relatively dense mixed-use core surrounded by auto-dependent sprawl) but they vary in density, as Nichols and Kockelman noted. Thus I scored changes to the density pattern, but not to the other three patterns (with the sole exception of Seattle, which I scored higher on its web of transportation).

Pattern Scoring – City to City Comparison

City	*Neighborh. Network*	*Score 1-9*	*Density Rings**	*Score 1-9*	*Web of Activities*	*Score 1-9*	*Web of Transport.*	*Score 1-9*
Orlando	Baseline	5	8.2	5	Baseline	5	Baseline	5
Phoenix	Comparable	5	10.7	6	Comparable	5	Comparable	5
Austin	Comparable	5	11.3	6	Comparable	5	Mod. Higher	6
Seattle	Comparable	5	16.8	7	Comparable	5	Mod. Higher	6

** Persons per acre*

TABLE 8.3 Scoring for the four cities based on Nichols and Kockelman data. Orlando is the baseline for the comparison of the other three.

Taking these values as inputs to the WikiPLACE model, I generated the following results:

WikiPLACE Output – City to City Comparison

City	*Init. Value (Baseline)**	*Pattern 1 Score 1-9*	*Pattern 1 Max. Delta %*	*Output Value*
Orlando	23.92	(Baseline)		23.92
Phoenix	23.92	5	20	23.92
Austin	23.92	5	20	23.92
Seattle	23.92	5	20	23.92

** Orlando baseline*

City	*Input Value*	*Pattern 2 Score 1-9*	*Pattern 2 Max. Delta %*	*Output Value*
Orlando	23.92	(Baseline)		23.92
Phoenix	23.92	6	30	22.13
Austin	23.92	6	30	22.13
Seattle	23.92	7	30	20.33

City	*Input Value*	*Pattern 3 Score 1-9*	*Pattern 3 Max. Delta %*	*Output Value*
Orlando	23.92	(Baseline)		23.92
Phoenix	22.13	5	20	22.13
Austin	22.13	5	20	22.13
Seattle	20.33	5	20	20.33

City	*Input Value*	*Pattern 4 Score 1-9*	*Pattern 4 Max. Delta %*	*Output Value*
Orlando	23.92	(Baseline)		23.92
Phoenix	22.13	5	20	22.13
Austin	22.13	5	20	22.13
Seattle	20.33	5	20	20.33

City	*Final Predicted Value*	*Actual Inventory Value*	*Deviation*	*% Deviat.*
Orlando	23.92	(Baseline)		0.00%
Phoenix	22.13	21.10	1.03	4.64%
Austin	22.13	20.09	2.04	9.20%
Seattle	20.33	19.90	0.43	2.12%
Average Deviation =				**5.32%**

TABLE 8.4 The results of the WikiPLACE reverse forecasting experiment for four cities compared. WikiPLACE was able to predict the actual results within an average deviation of 5.32%.

§ 8.4.3 Neighbourhoods compared to neighbourhoods in the same city

The third reverse forecasting experiment also uses data from Nichols and Kockelman (2015). They gathered data for five different neighbourhoods in Austin, Texas, with notably divergent characteristics of urban form. Other typical factors were generally comparable – namely, climate, economics, political and legal system, and mix of fuels and zero-emissions sources.

Nichols and Kockelman completed an inventory of energy use per capita, combining both operational and embodied energy. Because zero-emissions sources are a negligible component of Austin energy, the level of energy consumption per capita is generally representative of GHG emissions per capita. Therefore on this basis we can impute a GHG value variation from a theoretical baseline, here taken from the USA average given previously. The actual number is not what is of interest to us here, but the relative comparison between the numbers as measured and the prediction of WikiPLACE

Austin Neighborhood Data from Nichols and Kockelman (2015)

Neighborhood	*Operational*	*Embodied*	*Combined*	*Delta from WL Baseline*	*Imputed GHG Value*
Westlake	101	23.99	124.99	0.00%	23.92
Anderson Mill	94.46	22.14	116.6	6.71%	22.31
Hyde Park	77.18	11.99	89.17	28.66%	17.06
Riverside	60.97	7.41	68.38	45.29%	13.09
Downtown	54.67	3.78	58.45	53.24%	11.19

TABLE 8.5 Operational and embodied energy in five neighbourhoods in Austin, Texas, and imputed greenhouse gas emissions for each.

I then scored the five neighbourhoods according to the four patterns, noting in particular the data on density, and the other factors:

Pattern Scoring – Neighborhood to Neighborhood

Neighborhood	*Neighborh. Network*	*Score 1-9*	*Density Rings*	*Score 1-9*	*Web of Activities*	*Score 1-9*	*Web of Transport.*	*Score 1-9*
Westlake	Baseline low	5	962	5	Baseline low	5	Baseline low	5
Anderson Mill	Low	5	6148	6	Low	5	Low	5
Hyde Park	High	7	5713	6	Moderate	6	Moderate	6
Riverside	Moderate	6	17249	9	Moderate	6	Moderate	6
Downtown	High	7	4857	6	High	8	High	8

TABLE 8.6 Scoring of the five neighbourhoods based on their attributes of urban form. Westlake is identified as the baseline for the other four.

Taking these values as inputs to the WikiPLACE model, I generated the following results:

WikiPLACE Output – Neighborhood to Neighborhood

Neighborhood	Init. Value (Baseline)	Pattern 1 Score 1-9	Pattern 1 Max. Delta %	Output Value
Westlake	23.92	(Baseline)		23.92
Anderson Mill	23.92	5	20	23.92
Hyde Park	23.92	7	20	21.53
Riverside	23.92	6	20	22.72
Downtown	23.92	7	20	21.53

Neighborhood	Input Value	Pattern 2 Score 1-9	Pattern 2 Max. Delta %	Output Value
Westlake	23.92	(Baseline)		23.92
Anderson Mill	23.92	6	30	22.13
Hyde Park	21.53	6	30	19.91
Riverside	22.72	9	30	15.91
Downtown	21.53	6	30	19.91

Neighborhood	Input Value	Pattern 3 Score 1-9	Pattern 3 Max. Delta %	Output Value
Westlake	23.92	(Baseline)		23.92
Anderson Mill	22.13	5	20	22.13
Hyde Park	19.91	6	20	18.92
Riverside	15.91	6	20	15.11
Downtown	19.91	8	20	16.93

Neighborhood	Input Value	Pattern 4 Score 1-9	Pattern 4 Max. Delta %	Output Value
Westlake	23.92	(Baseline)		23.92
Anderson Mill	22.13	5	20	22.13
Hyde Park	18.92	6	20	17.97
Riverside	15.11	6	20	14.36
Downtown	16.93	8	20	14.39

Neighborhood	Final Predicted Value	Actual Inventory Value	Deviation	% Deviat.
Westlake	23.92	(Baseline)		0.00%
Anderson Mill	22.13	22.31	-0.19	-0.85%
Hyde Park	17.97	17.06	0.91	5.05%
Riverside	14.36	13.09	1.27	8.84%
Downtown	14.39	11.19	3.20	22.25%
Average Deviation =				**7.06%**

TABLE 8.7 The results of the WikiPLACE reverse forecasting experiment for five neighbourhoods. WikiPLACE was able to predict the reduction within an average deviation of 7.06%.

As can be seen, the results of these reverse forecasting experiments are encouraging. The results for the city-country pairs, for example, are reasonably accurate, with an average deviation across the five city-country pairs of 17.0 percent. In that case it will be noted that each of the WikiPLACE predictions was not as great as the actual difference – that is, the WikiPLACE predictions were more conservative than the actual measurements. This is likely to be because of other benefits of cities that the model does not account for – or does not yet account for. The use of such tools may in fact serve as a useful research tool to uncover these other factors.

The run for city-to-city comparisons gives even more accurate results. That is in part because the variations are focused on changes in density, while other factors are not as varied. Density is also the variable that Nichols and Kockelman studied, so it is not surprising that WikiPLACE has given a very similar result. Nonetheless it is encouraging to see a satisfactory performance.

The result for the neighbourhood to neighbourhood comparison, an average deviation of 8.82%, is also encouraging. The largest deviation was for Downtown Austin, which is still relatively low in residential density. This may suggest that the other factors can be more significant when density is low. However, this question remains for investigation. Nonetheless it demonstrates how WikiPLACE can be an aid in uncovering interesting research questions.

§ 8.5 Conclusion

It must be stipulated that this is a very preliminary experiment with limited data. As I noted, this research has made clear to me the need for more data at the neighbourhood scale, with apples-to-apples comparisons of sources, boundaries and other parameters. More data would make it easier to verify the results of the WikiPLACE methodology with greater confidence. (As discussed, there are many other reasons why this would be beneficial.) At present, there are admittedly problems in the underlying data and its relevance to consumption-based, per-capita, neighbourhood-scale modelling – problems that weaken the reliability of these results.

Nonetheless, these preliminary results do tend to suggest that WikiPLACE can give quite good predictions of reductions based on urban form, in line with empirical research. This is in spite of its simplicity and its “improper linear” attributes, as discussed previously. That is indeed the goal of this approach – a more comprehensive model, more able to account for larger behaviours of the system in question, and thus, more useful as a guide to urban design decision-making.

Of course, the essence of wiki methodology is evolutionary improvement, and post-doctoral research will provide a continuing opportunity for improvement. The next key step is likely to be an application of WikiPLACE on one or more actual projects involving a constituency of users, who can evaluate the user-friendly aspects of the tool.

The other key need is to redress the shortage of consumption-based GHG emissions data at neighbourhood scale. I may be able to help to accomplish that goal in part by bringing together existing data sets and combining them to create more comprehensive and comparative inventories. In part it could also be accomplished with local studies that develop the inventories according to a unified protocol. As noted earlier, it is my hope that WikiPLACE would be a useful stimulus for this research, and as such, a research tool in its own right.

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9 Conclusion: Goals achieved, further research needed – and the importance of urgent changes to business-as-usual policy and practice

Chapter summary

Summary of the research and its conclusions, with a discussion of background issues and opportunities for further development.

§ 9.1 Evaluation of Results of Objectives, Products and Thesis from the Research Framework

At the outset of this research, I identified the following general objective:

To develop the basis for a minimally accurate, effective and improvable decision support tool that will guide urban design best practice and policy in achieving potentially significant GHG reductions from feasible changes to urban morphology (including modifications for new construction, and retrofits of existing construction).

In the course of this research, I performed the following:

- Identified the various sources of emissions and their magnitudes (Chapter 2);
- Identified their interactions and the factors that modulate these interactions, including behavioural factors (Chapters 2, 3, 4);
- Evaluated and developed design and policy strategies to achieve meaningful and sustained reductions (Chapters 5, 7, 8).

The sub-objectives I completed were as follows:

- Identified the interacting influences of economic, socio-political, ecological and technological factors (Chapters 2, 3, 4);
- Developed the model to address more unified information systems, including web-based scenario models (Chapters 6, 7, 8);
- Developed the model to facilitate a more efficient design process (Chapters 7, 8;
- Worked to raise awareness of the problem (dissertation, symposia, publication of papers).

The final products were as follows:

- Clear research findings demonstrating the relation of factors of urban form on GHG emissions and the potential reductions from variations in urban form design (Chapters 2,3);
- A theoretical model of variable urban form and its effects on GHG emissions, reflecting and explaining the research findings (Chapters 6, 7);
- Prototype of a design decision support tool that incorporates (and can further refine) the above findings (Chapter 8);
- Publication of at least four journal papers documenting the above (at this writing, five have been published and one is in peer review).

Based on the research findings reported herein, I find that my thesis has been confirmed: that there is a major delta of global GHG reduction that is achievable by systemic changes in urban morphology, and that it may be on the order of one-third or more of all emissions – very likely much greater, particularly in relation to future emissions based on business-as-usual trends. In the process I have identified and minimally developed a new class of design technology.

My thesis that these reductions can be achieved through a methodology pursued with the assistance of new modelling and assessment resources to be developed in the course of the research has been given initial support by the success of this evaluation (reported in Chapter 8). The task remains to develop further implementation and evaluation of this methodology, and specifically, the new software technology embodied in WikiPLACE.

My thesis that this methodology is economically, socially and politically feasible, remains to be substantiated, although nothing in the findings has identified any significant barriers to such feasibility.

§ 9.1.1 Summary of Outcome of the Primary Goals

As further described in Chapter 1, this research project began with three primary goals. First, I wanted to identify the most salient factors of urban form that contribute to greenhouse gas emissions, with a focus on the underdeveloped area between the building scale and the scale of transportation systems. Second, I wanted to understand how those factors interact within actual neighbourhoods, as variables of urban form and urban design. Third, I wanted to ask how a new decision support tool could exploit these findings, and what methodologies would be required to support the effective use of such a tool. I conclude that, while further work is certainly needed, these three primary goals have been accomplished, as summarised below:

Goal 1. ***Produce findings on the salient factors of urban form that contribute to greenhouse gas emissions, with a focus on the underdeveloped area between the building scale and the scale of transportation systems.***

This goal was met early on, and the key results were published in the *International Journal of Architectural Research* as "Counting Urban Carbon" (Mehaffy, 2014). Additional results were included in *Urban Design International* as "Prospects for scenario-modelling urban design methodologies to achieve significant greenhouse gas emissions reductions" (Mehaffy, 2013).

Goal 2. ***Produce findings on how the factors interact within actual neighbourhoods, as variables of urban form and urban design.***

The findings from the second goal were published in the *Nordic Journal of Architectural Research* as "Unpacking Density" (Mehaffy, van den Dobbelsteen and Haas, 2014). Additional related results were published in the Journal of Urbanism as "The "neighbourhood unit" on trial: a case study in the impacts of urban morphology" (Mehaffy, Porta and Romice, 2014) and "Planning the 'Choice Architecture' of Neighbourhoods: Exploiting Urban-Scale Behavioural Economics to Manage Greenhouse Gas Emissions and Related Outcomes" (Mehaffy, 2015). (The latter paper is, at this writing, in peer review.)

Goal 3. Apply the findings to develop a new decision support tool, identifying and evaluating the methodologies (including new software methodologies) that are required to support its effective use and further development.

The findings from the third goal were published in *Urban Design International* as "Prospects for scenario-modelling urban design methodologies to achieve significant greenhouse gas emissions reductions" (Mehaffy, 2013). Additional findings relating to software methodology were published in the *Proceedings of the 20th Conference on Pattern Languages of Programs* as the paper "Wiki as Pattern Language: Exploiting evolutionary networks in software design" (Mehaffy and Cunningham, 2014).

The detailed evaluation of the model and its performance was presented in Chapter 8, "Evaluating WikiPLACE." As noted there, the results of the evaluation experiment are encouraging – although as I noted, the experiment suffers from a shortage of underlying data at the appropriate neighbourhood scale.

However, I believe the central contribution of the research is now well established. It is a new design decision support technology - embodied in the WikiPLACE prototype - built upon a synthesis of findings into a coherent and actionable conceptual model of the impact of urban form.

Here I aim to discuss these findings as part of a larger progression of research and development leading up to the present, and establishing the basis for future research. I will discuss the current status of the research, its context within policy and practice, other findings that may be ripe for further development, and the general basis for further development of the work herein.

§ 9.2 Context and Applicability of the Research

In the historical moment that this research is approaching its conclusion, the world is experiencing an unprecedented level of urbanisation. In part this phenomenon is fuelled by unprecedented population growth – at this writing 7.3 billion, and expected to reach 8 billion as early as 2020 – and unprecedented migration from rural areas to urban ones (UN DESA, 2014). The year 2007 marked the point at which the majority of the world's population now lives in urban areas, and this urbanisation trend is projected to continue and to accelerate with population growth (UNFPA, 2007). If present trends continue as expected, the world's urban population may well double by 2060, with an equal or greater doubling of developed urban area (UN DESA, 2014).

The implications for resource depletion, ecosystem degradation and environmental contamination – and most relevant to our interests here, for greenhouse gas emissions – are profound. In response, mature efforts are already under way to develop new low-carbon energy sources, and to develop low-emisison and even zero-emission technologies for buildings and transportation systems. But these narrower short-term goals are necessarily complementary to the long-term "dynamic systems" approach identified in this work. Indeed, precisely because of the long-term persistence of urban structures, small improvements in the structure of urban systems now, and in their dynamic behaviour, are likely to carry magnified long-term benefits.. The corollary is that continued urbanisation with "business as usual" models is likely to greatly magnify the negative trends already under way for many decades or even centuries into the future.

On this basis it seems apparent that that there is great urgency in the quest for new tools and methodologies that can improve the performance of urban systems – working together with new policies and practices that can effectively support them.

This research project also identified, as byproducts of its key findings, several important conclusions regarding the requirements for such an advancement. I will discuss them here because they set the context for a further research agenda, which I discuss at the end of this chapter.

§ 9.2.1 Supplemental Conclusion 1: *Urban dynamics are complex, and they require new and different methods to manage them successfully.*

This research has demonstrated that greenhouse gas emissions, like other outcomes of urban processes, are the product of a vastly complex set of dynamic interactions that cannot be simplified to a schema of independent quantities to be governed by targeted devices.

While technological changes can and should be used to make incremental improvements to efficiency, we also need to understand and exploit the inherent dynamics of urban systems. As we have seen, this is particularly so because targeted and "bolt-on" approaches have a tendency to erase gains with unanticipated consequences, including growth of consumption demand. I noted previously (i.e. in Chapters 2 and 6) the problem of "induced demand," "Jevon's Paradox" and other related phenomena of systems interactivity.

There is also a larger lesson about urban dynamics. Because urban systems are evolutionary and in part self-organising, they cannot be treated as simple aggregations of quantities in isolation. They must instead be treated as interactive networks, which can be managed most effectively with the new tools of system dynamics modelling and "whole systems" modelling – an example of which is scenario-modelling (as discussed in Chapter 6). This in turn requires a major shift in tools and in methodology.

There is evidence that such a shift is occurring, but old methods and approaches continue. There are two apparent reasons for this. One is that in certain limited contexts, the older approaches work reasonably well, and thus they persist. When they are confined to such limited contexts, this does not pose a barrier to progress.

The other apparent reason is that many of our incentives and standards – what can be thought of as the "operating system for urban growth" – are holdovers from a previous era, when many problems were thought of as reducible to simple schemas of independent quantities. This was a point made famously by Jane Jacobs in the last chapter of her landmark book on urban processes, *The Death and Life of Great American Cities* (Jacobs, 1961). It is a point that is no less valid over a half century later.

The implication is that much work remains to change this "operating system for growth" so that we can deal more effectively with looming urban challenges, and achieve a more durable, sustainable and resilient form of urban growth to meet them. The changes will require new insights into the dynamics of urban processes, and new tools and approaches based upon these insights. This work is a small step in that great work ahead, dealing with one particularly ominous challenge: the mitigation of urban factors contributing to climate change.

§ 9.2.2 Supplemental Conclusion 2: *We must pay more attention to urban processes – but at the same time, we cannot ignore urban forms.*

This research has reinforced the conclusion that urban processes play a profound role in the rates of resource consumption and greenhouse gas emissions -- notably transportation activities, exchanges of goods and building operations. But urban forms shape and limit those processes and the interactions that can result. While we cannot expect changes in urban form alone to produce desired outcomes, neither can we expect to produce the desired outcomes *without* changes to urban form.

An apt analogy might be drawn with computer systems. We need the hard wiring of circuits to house the software and its interactions, which can vary and change over time – and indeed, it can self-organise over time (especially through open-source development) in response to changing users and contexts. The form of the hardware does nothing by itself, but nonetheless it must be shaped optimally according to our understanding of the potential of the software and the user activities. Its form then facilitates – or greatly limits – what can happen.

In this sense, the characteristics of urban form can be thought of as conductors, facilitators and limiters of urban processes – that is, frameworks that tend to act as regulators and/or accelerators on the processes that can occur. Infrastructure networks such as public space networks, for example, can facilitate social and economic interactions, and also, through their geometric layout, limit the activities and exchanges that are possible by foot, car or public transit, respectively.

Continuing the computer analogy, it is possible for programmers and users to take the basic hardware and software – in our case the infrastructure of the city, including its public spaces – and shape and articulate those structures further in order to achieve greater adaptivity and complex function. This open-ended adaptation forms a continuous, dynamic evolution of the structure and its processes, with an open-ended result in terms of its economic and social creativity. We see this today on the Internet and in evolving information systems such as Wikipedia, and the pattern languages that are used to program computers using open-source Wiki exchanges. (This analogy to computers and open-source programming becomes a literal relationship when it comes to the software methodology used in this project, as discussed in more detail in the Appendix.)

This conclusion highlights the need for an end to the dualistic debate between urban form and process, replaced by a unified picture in which form and process are two aspects of the same phenomenon. In such a view, we can ask useful questions about form as a factor in phenomena like greenhouse gas emissions – so long as we keep in mind the strategic value of form in shaping and limiting the critical processes that produce the phenomenon.

§ 9.2.3 Supplemental Conclusion 3: *Older models of urbanization are still dominant, and we urgently need better-performing ones.*

The planning and design models developed in the 20th Century are still commonly employed in new projects today: relatively low-density and fragmented suburban development, automobile-dependent neighbourhoods, large-format users exploiting economies of scale, large physical and network separations between users, isolated "campus" models of planning featuring superblocks, isolated object-buildings, gated communities, private shopping malls, and related urban types. These models are further enshrined in legal standards, including segregated-use zoning, restrictive setbacks, and auto-centric street standards.

Indeed, there is disturbing evidence that these trends are accelerating in many parts of the world today. In China in the last ten years, average density has declined over 25%, reflecting the growth of low-density suburban sprawl (World Bank, 2014). Similar trends are occurring in other countries, and the trend is expected to grow under a "business as usual" scenario, resulting in a possible tripling of urban areas from 2000 to 2030 (Seto, Güneralp and Hutyra, 2012).

The consequences for energy demand, resource consumption and ultimately, greenhouse gas emissions, is profound. A recent study of worldwide cities projected that almost 60% of growth in energy consumption will be directly related to urban sprawl, significantly exceeding rates of growth in both GDP and population (Bourdic, Salat and Nowacki, 2012).

These models were developed in an era when depletion of resources and greenhouse gas emissions were not considered problematic, and when relatively cheap energy made such schemes especially attractive. That era was also relatively unaware of the behaviour of cities as complex adaptive systems, and unaware of the potential social and economic benefits of diversity, interaction and self-organisation, as well as their ability to promote more sustainable urban development.

Such models continue today because they are still profitable and functional in the short term, even though they carry long-term externality costs that so far have not been monetised. (However, a recent report by the Global Commission on the Economy and Climate (2014) projects that in the United States alone, the externality cost of sprawl is approximately $400 billion per year.) Part of the work of developing more effective replacement models of urbanisation will be to find compensating incentives in financial, regulatory and other systems, and to create implementation approaches that are feasible. Indeed, one key advantage of scenario-modelling is that it allows the comparison of feasibility parameters along with other variables.

There have been efforts towards a "new urban agenda" – a term used by the UN for its planning of Habitat III in 2016 – under various names and schools of thought. The Global Commission on the Economy and Climate, a panel of leading economists and policy experts, argued in its 2014 report, *The New Climate Economy*, that "countries at all income levels have the opportunity to build lasting economic growth and at the same time reduce the immense risk of climate change" – but that to do so, they must rein in sprawl, and change the incentives that drive it (Global Commission on the Economy and Climate, 2014).

However, this research has tended to show that – to the extent that such efforts do not recognise the complexity of urban dynamics, the need to unite form and process, and the need to incentivise better-performing models – they may be incomplete at best, and, perhaps, plagued by philosophical and tactical faults that must be addressed.

This research also suggests a strategy to actually implement such changes, by developing scenario modelling tools that can identify externalities such as emissions. This is the first step in monetizing these externalities – that is, setting prices that serve as economic incentives to drive change – and actually generating change from within the dynamics of complex urban and economic systems.

§ 9.2.4 Supplemental Conclusion 4: *Hopeful new tools and approaches are emerging.*

As this discussion has shown, instructive progress has been made on similar dynamic problems in other fields, notably computer science and modelling. These fields have begun to treat design problems as problems of complex adaptive systems, amenable to strategies that can manage such problems, with very positive results. The use of network design tools, object-oriented design approaches and system dynamics modelling, have all been productive. Examples include powerful open-source development software like Linux, Wiki collaboration systems including Wikipedia, object-oriented programming, design patterns and pattern languages, and network-based, self-organising models such as artificial neural networks.

The outcome of this research was shared periodically with the members of the Open Planning Tools Group, a partnership of several universities and NGOs in the USA as well as the federal Department of Housing and Urban Development. The OPTG is one of a number of initiatives that are beginning to apply these insights to urban design and planning, using a suite of new tools including scenario-modelling tools (see e.g. Envision Tomorrow, discussed in more detail in Chapter 7).

The work of the OPTG and other related initiatives point to a promising frontier of open-source development using a collaborative "research coordination network." This work has benefitted from a similar network of researchers dubbed the "Environmental Structure Research Group," including leaders in software, mathematics, complex systems research, and urban design fields (Mehaffy, 2015).

Such collaborative, evidence-based development has proven very effective – again, see the rapid developments within computer science, and also other fields – and it appears to hold promise for much greater development within urban design fields.

§ 9.2.5 Supplemental Conclusion 5: *The subject of urban dynamics and its network structures offers a very promising basis for further development.*

One of the most intriguing insights from this research – apparently presenting important opportunities for further development – is the identification of network properties within urban systems as important factors in emissions and other urban outcomes. As has been demonstrated by Bettencourt (2013) the network structure of cities plays a key a role in their non-linear behaviours. Indeed, cities can be thought of usefully as "social reactors," in Bettencourt's words, bringing their elements together into "mixing networks." It is this mixing that allows interaction, productivity and exchange. Moreover, this network mixing is analogous to metabolic processes in biological systems, with one important consequence being the efficient use of resources.

What has not been investigated to date is the particular pattern of network connections and their consequences. It has long been understood that metabolic networks have particular structures that enable feedback loops, re-use of resources and other patterns of interaction. The question whether there are direct correlations with urban spatial networks – with patterns of movement and exchange within the public realm, for example – seems ripe for exploration.

Regarding specific classes of network, a rich body of research has arisen around so-called "small-world networks," "rich club motifs" and other detailed patterns of networks (Xu et al., 2011). These have been explored within metabolic and biological processes, with promising results. It remains to be seen whether there is an important relation to patterns of urban connectivity, such as the networks of public and private places that form around streets, squares and other public infrastructures. In turn these patterns may play a role in social and economic interactions.

In urban economics, the notion of a "knowledge spillover" has been developed by Jacobs (1970, 1984), Glaeser (2009) and others. (It is also sometimes referred to as a "Jacobs spillover" in recognition of Jacobs' work.) The essential finding is that urban systems, by virtue of their public space networks, create the propinquity in which knowledge spillovers can occur, leading to creative collaboration and economic expansion. In essence, the city provides a synergy between individuals whose interaction of knowledge can create new knowledge and innovation. Once again, there seems to be an intriguing question what role is played by the patterns of spatial network connectivity.

There may also be a formal corollary to knowledge spillovers that we have tentatively dubbed a "resource spillover" – that is, a similar metabolic effect of urban networks, promoting a conservation of resources and a reduction of emissions of greenhouse gases as well as other benefits of greater efficiency (Mehaffy, 2011). Such a "catalytic" urban effect is implied in the research presented herein; but this is a topic that has not been developed, and it awaits further development in follow-up research.

An intriguing finding that supports this hypothesis is the clear association of compact cities with *more* economic expansion, combined precisely with *less* consumption and emissions per capita. I believe (thought this is still a hypothesis, but a plausible one on the evidence) that this apparent paradox can be explained by the dynamics of spillovers, and their "metabolic" ability to increase creative production of complex systems, at the same time that they increase the efficient use and re-use of resources. An analogy is with the metabolic functions of biological organisms, coupled with the ecological systems in which they grow, evolve, and efficiently consume resources within an ecological network.

But as I and my colleagues showed in our paper "Unpacking Density" (Mehaffy, van den Dobbelsteen and Haas, 2014) density alone does not explain this phenomenon. The detailed structure of the networks themselves, and their patterns of inter-connections (and also points that are not connected) is a crucial part of the story. What Jacobs shows that is relevant here is the role of urban public space networks, and this project certainly builds on that key insight.

§ 9.2.6 Supplemental Conclusion 6:
At a time of rapid urbanisation and rapid increases in emissions, the ability to exploit the benefits of urban dynamics – for multiple benefits including GHG reductions – takes on great urgency.

It is unfortunately true, as our research has confirmed, that rural residents who travel to cities tend to increase emissions per capita, often significantly. This is a consequence of their increasing wealth and consumption, and, to some extent, the high-emissions forms of urban environments to which they are attracted. However, our research has also shown that it is not true that, given constant levels of income, emissions are greater for city-dwellers than for rural residents, and in fact the reverse is true. We must surely agree that it is unacceptable to require residents to remain in impoverished rural settings, and not to pursue the opportunities for human development offered by cities. In fact, well-structured urban environments, in addition to their benefits for human development (including education, healthcare, population reduction, opportunities for women and more) do in fact offer the capacity for remarkable resource efficiency and emissions reductions, given the same levels of human development and opportunity. Furthermore, it is unlikely that the current wave of urbanisation can be stopped, even if that were considered acceptable. Therefore our goal ought to be to aggressively pursue advancements in the subject of urban dynamics, and the ways that urban design (working in concert with other fields and sectors) can exploit these benefits.

§ 9.2.7 Supplemental Conclusion 7:
The topic of economic dynamics, and in particular the influence of economic externalities, looms large as a set of factors that requires more accurate valuation.

The behaviour of urban systems cannot be understood apart from the influences of economic incentives and disincentives, and the complex way they interact with each other and with other factors. The *failure* of urban systems to meet human need over the long term is, in large measure, a failure of markets to account for externalities (such as greenhouse gas emissions, resource depletion, ecosystems degradation, and related impacts). But this class of failure cannot be resolved by simple policy and regulatory corrective alone. It must instead be dealt with as part of a complex interactive system, where externalities are more accurately represented, and their true impacts are reflected in costs and pricing signals (which is to say, the system of financial incentives and disincentives) of the economic feedback system itself.

This is an enormous topic that deserves urgent work as a priority. Its extent is far beyond the scope of this dissertation. However, I will note that the WikiPLACE scenario-modelling tool is one small step toward the necessary modelling capability for precisely these kinds of externalities. (As noted, the tool name is short for "Wiki-based, Pattern Language-based, Adaptive Calculator of *Externalities*.") It therefore proposes a methodology by which such externalities could be better accounted for, as the basis for an economic valuation. In that limited sense, this dissertation does contribute to the urgent work ahead on this topic.

§ 9.2.8 Supplemental Conclusion 8: *There appears to be an important question regarding the specific nature of urban public space patterns and their formation.*

Following on the insights discussed above, this work has not delved very far into the question of how these spatial networks are actually formed, or what are their geometric and topological configurations, and other characteristics. There is indeed a rich body of research on such questions, including the work of Hillier on Space Syntax (Hillier and Hanson, 1984, Hillier 2006) and Madanipour (2003), describing the network topology of public space and its intricate relation to private space through both form and process. In social psychology there is also a rich body of research on how people interact with one another as a network phenomenon, including the work on "Actor-Network Theory" of Latour and others (Latour, 2005).

My own work has identified a corollary, or perhaps it is better to say it is a synthesis, of the spatial network ideas of Hillier, Madanipour, Latour, Jacobs, Alexander and others, and developed it into a description of the form and process of public space, a synthesis view that I have termed "place network theory" (Mehaffy, 2014b). Such a picture can be helpful in understanding how public space is formed, activated, strengthened and eroded, and how its relation to private space and to the economy of the city can be safeguarded and enhanced. As my research has shown, these "place networks" also appear to play a key role in the patterns of activity, consumption and GHG emissions within the city.

This is a timely subject because, as mentioned previously, the United Nations is preparing its third bi-decennial conference on cities, Habitat III, to be held in Quito, Ecuador in February 2016. Its theme, "Towards a New Urban Agenda," will emphasise the declining quantity and quality of public space around the globe, and examine policies, tools and approaches that can mitigate this worrisome phenomenon. As part of my work in this area, I previously led a "consultation" to discuss with the conference secretary-general the research in this area and the opportunity to inform the "new urban agenda" that is proposed with some of the insights of this work. Place network theory could help to provide a useful schema for understanding the opportunities, tools and strategies that are available.

Place network theory could help to extend the work reported herein into a more fine-grained analysis of the factors contributing to GHG emissions as well as other parameters of consumption and interaction. Briefly – and recognising that this is a much larger subject that will need to be covered elsewhere – place network theory combines the following basic insights, which partially overlap with the findings reported herein:

1. *Cities and other settlements consist of individual actors interacting with one another, and with their resources, within a network structure that has a definable (though evolving) form.*
2. *This network is spatial, that is, it is anchored within the spatial structure of the settlement.*
3. *The spatial features can promote, or alternatively inhibit, connectivity along a range of parameters including sight, sound, contact, etc. That is, they are capable of modulating the connectivity.*
4. *The structures we think of as forming a settlement are in fact structures that modulate this connectivity: walls and roofs, doors, windows, blinds, curtains, gates, hedges, etc.*

5 *The range of connectivity exists along a continuum from the most private (bedrooms, bathrooms etc) to the most public (streets and other public spaces) but through a complex network of intermediate spaces and layers of control.*

6 *The range of connectivity also carries with it a range of sizes, from the largest public spaces to the smallest compartments for valuables, and many ranges in between. The patterns of these spaces and their connections are very important, as are their variations in different locales..*

7 *There is also an aesthetic dimension to this pattern of connections, such as the "biophilic" experiences of layering, filtering, partially enclosing, "prospect and refuge," and other aspects of environmental psychology. That is, place networks are not abstract patterns, but in fact very concrete elements of routine urban experience. (Hence the term "place" is used instead of the term "space", indicating the direct relation to human experience.)*

8 *These characteristics directly affect human experiences and satisfaction of human needs, such as the need for greater contact or, alternatively, greater privacy; greater variety and intensity, or, alternatively, greater calm and respite; exposure to natural forms, beauty, contrast, variety and harmony; and other factors contributing to physical, social and psychological well-being.*

It is interesting to note that many of the findings reported herein fit well with this picture of settlement. An environment with greater complexity of place networks is generally denser, more varied and mixed use, and more multi-modal and walkable. It may also be more appealing to potential residents or visitors, because it offers a greater range of choice to meet the varying needs for privacy or contact. There may be a key relationship to the liveability of denser urban environments, which could be key to the successful implementation of policies aimed at building more sustainable cities.

But these are preliminary hypotheses that await further development through additional investigation.

§ 9.3 Some Critical Reflections

I previously described a number of weaknesses in the model and in its evidence base. I will summarize them here.

1 ***The model relies upon what is at present a limited data source.*** The model requires per-capita, consumption-based inventories at neighbourhood scale, and these are uncommon. The data that has been used is inconsistent and must be used carefully and in combination to get a reliable prediction. Moreover, the data establishing a connection between urban form and rates of emissions is itself uneven and in need of further development (although that is a much larger goal far beyond the scope of this dissertation).

2 ***The relative importance of the four patterns, and the ways they interact, has not been fully demonstrated.*** The capability of modelling systemic interactions between the patterns, discussed in Chapters 6 and 8, remains undeveloped. This is an important goal for further research.

3 ***The model at present uses a limited number of patterns, and this research has not demonstrated its capabilities with larger numbers of patterns.*** Potential problems from the number of patterns or the ability of the software to manage them have not been explored.

4 ***The tool has not been tested with an actual project and actual users.*** A major goal of the project has been to develop a user-friendly scenario-modelling tool that is effective in project settings. This remains as a goal of post-doctoral research.

In spite of these weaknesses, my interpretation is that this "improper linear model" (Dawes 1979) is, in fact, "robust" by Dawes' definition. It employs Bayesian methodology to produce a reliable set of predictions that conform usefully with the observed reality – the essential task of any model. It does so in order to identify and guide design action on a topic that is certainly urgent, as this work helps to demonstrate. It thereby advances knowledge on a subject that has previously not been documented sufficiently.

Moreover, it offers an evolutionary methodology where the accuracy can improve incrementally over time, gradually becoming more reliable and useful within a community of users. As we discussed previously, it can also aid in the more detailed identification of problems in the data, and thereby serve as a research tool in its own right.

The line that is included in the dedication to this dissertation illustrates the point well. It is from physicist and poet Piet Hein's short poem, *The Road to Wisdom*: "Err and err and err again, but less and less and less." In a sense, Hein's short poem captures the essence of the scientific method itself. Its spirit has certainly guided the methodology used herein.

§ 9.4 Toward a further agenda of research and development

As I believe the evidence has shown, the model presented herein - or rather the two models, the WikiPLACE software tool, and also the conceptual model, together with the synthesis of findings on which it is based - make a material contribution to advancement of an evidence-based science of urbanism and urban design. However, this work requires more development to produce a robust tool that is ready for routine practice. It is in the nature of open-source development that the process is open-ended, and it will benefit most from early participation of many developers and many experiments in actual practice. Put simply, it is time for "beta-testing" of the model by actual users in actual settings.

Therefore the next phase of development would benefit from wider evaluations in actual case studies, with more participants who can use and modify (or suggest modifications to) the decision support tool.

In particular, there remains the question whether the decision support tool can function as a support for public involvement in urban planning and design. As projects are increasingly embedded in community involvement processes, there are many questions about how public involvement can be done meaningfully and productively. Currently such processes (which I conduct regularly as part of my own consulting work) tend to fail in several key ways: they become tokenistic "sales exercises" for a pre-established expert vision; they include immature ideas that lead to weak projects; or they fail to address key economic or technical requirements for success. In all cases, the real impacts of the projects under consideration (both positive and negative) are poorly understood.

The WikiPLACE tool can contribute to more meaningful development and evaluation of concepts and their impacts. It can, through open-source evolution over a number of projects, develop a robust capability to identify good solutions that are more feasible and more implementation-ready. This will be an important research opportunity to develop in subsequent work.

Most significantly, perhaps, the tool could help to identify impacts that are not well accounted for, and allow them to be quantified and monetized as part of the implementation process. For example, reductions in greenhouse gas emissions could in principle be identified, certified (through an agreed process) and then sold as carbon credits, helping to incentivise a lower-emissions project. Other impacts could also be identified and monetised and/or further incentivised, e.g. efficiencies in consumption of resources, damage to neighbouring ecosystems, and so on.

All of these factors point to the need for more transparent modelling, more evidence-based, and more able to evolve and self-correct. In this way, our own self-organising knowledge can be harnessed to guide the productive self-organising growth of the city, with the outcome of a much more efficient, productive and sustainable kind of settlement – at a time when there is a clear and urgent need.

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Appendix A Background on Software Methodology

Summary

A discussion of the methodology behind the WikiPLACE software, and its use of wiki and pattern language software technologies..

NOTE: This paper was originally published as "Wiki as Pattern Language" and presented at the Pattern Languages of Programming 2013 conference at the University of Illinois. It was co-authored with Ward Cunningham, software engineer. The reference is as follows:

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A.1 Introduction

Wiki is today widely established as a kind of website that allows users to quickly and easily share, modify and improve information collaboratively (Leuf and Cunningham, 2001). It is described on Wikipedia – perhaps its best known example – as "a website which allows its users to add, modify, or delete its content via a web browser usually using a simplified markup language or a rich-text editor" (Wikipedia, 2013). Wiki is so well established, in fact, that a Google search engine result for the term displays approximately 1.25 billion page "hits", or pages on the World Wide Web that include this term somewhere within their text (Google, 2013a).

Along with this growth, the definition of what constitutes a "wiki" has broadened since its introduction in 1995. Consider the example of WikiLeaks, where editable content would defeat the purpose of the site. We will exclude discussion of these other, broader uses of the term, and confine our discussion to the original wiki, and to the popular encyclopedia, both of which provide sufficient breadth to illustrate our points.

While the general concept of a wiki is thus extremely well known, somewhat less well known is the history of wiki development. Wikis were an outgrowth of the development of what is known as "pattern languages" in software, or as they are sometimes referred to, "design patterns." As we describe below, they were in fact developed as tools to facilitate efficient sharing and modifying of patterns. In part for this reason, the structure of wikis itself bears a relationship to the structure of patterns and pattern languages – a relationship that, as we will also discuss, offers intriguing new opportunities. This relationship, and the evolving opportunities it presents, will be a central focus of this paper.

Specifically, we will present a new approach to wiki that includes greater capacity to handle and process quantitative elements. This new approach makes greater use of the logic of pattern languages within the structure of wiki pages. It also exploits the power of "federated" open-source development, as we will explain below.

We will close by discussing the implications for wiki technology specifically, and for the collaborative growth of knowledge more broadly. We will draw attention to the need, in an age of explosive and potentially chaotic growth of information on the web, for new strategies of "curation" of knowledge toward effective future problem-solving.

We summarize the connection between pattern languages and wikis below, and then we proceed to discuss the details of that connection.

A.2 The shared logic of pattern languages and wikis – and their possible shared future

Many people who are familiar with both pattern languages and wikis are surprised to learn of the direct connection (discussed in more detail below). But in simplest terms, a pattern represents a structure in the world that has value in a particular context. At a fundamental level, a wiki does the same thing.

Both patterns and wikis are useful only in the context of a publication – that is, a web page, a book or other tangible form of dissemination. An example in paper form is the book, A Pattern Language, which publishes (literally) each pattern of the language on a page. Another example is the early wiki for patterns of programming created and published at the c2.com site. Yet another example, most familiar, is Wikipedia, which publishes a linked network of encyclopedic articles, each on its own web page. (Each article is "curated" by independent peers, and content is rejected if it is not deemed to be "notable" and of a "neutral point of view".)

In all three cases, the publication is not of a single discrete and static body of information, but of a hyperlinked network that can be linked in useful ways according to the user's needs. In the case of Wikipedia, the links are explored by a user conducting research into a subject, and focusing on links that are relevant to that exploration. In the case of c2.com, the links are between patterns of programming, reflecting the ways that they can be linked in the design of software. In the case of the book A Pattern Language, the links are intended to allow users to customize their own "project pattern language" that is relevant to a specific environmental design project.

But there is also a fundamental limitation for all three examples: the publication itself bounds the growth and evolution of the context. There is no way to transcend the original creator's intention, and there is no way to allow overlap between the communities that might subsequently create content. In the case of the printed book A Pattern Language, the volume itself "traps" the patterns. But the same is true of the other web-based examples, which are limited by the form of publication.

As we explore further below, a method that might transcend this limitation is the relatively recent emergence of "federated" publication methodologies. These methodologies allow "overlap" - duplication of work by parties who might have different needs, concepts and approaches – in the same way that a plural and democratic culture also allows overlap.

Indeed, so do biological systems, as has been noted by evolutionary biologists. As with these systems, the successful examples emerge from proliferation and variation, not through creation by a singular and exceptional agency (even a curation agency). The authored output incorporates measured and interpretive experience, i.e. quantitative and qualitative representations.

In this sense, entities of interest to us can be represented within a contextual modeling system taking the form of an open-ended network, and then it can be published and subsequently edited and refined. The next great advancement awaits: namely, the limitations of publication can be transcended through a plural, evolutionary system.

We discuss below the details of this advancement, and its background in the history of wiki and pattern language.

A.3 Early development of pattern languages

The general logic of pattern languages is closely related to the hierarchically compressed structure of object-oriented programming. A series of re-useable information packets can be manipulated as units, within a grammar-like set of rules for combining and exchanging their inputs and outputs. However, as we will discuss, pattern languages have particularly useful attributes that are more similar to those of natural language.

The formalized concept of a "pattern language" was developed by the architect Christopher Alexander, growing out of his work published in the book *Notes on the Synthesis of Form* (Alexander, 1964). Alexander was seeking to understand how forms arise as solutions adapted to specific configurations of problems, but then can be generalized for other similar uses. The problem had new relevance for a cybernetic age in which complex technological systems were becoming routine, and new design strategies were needed. As Alexander noted in the introduction, "Today functional problems are becoming less simple all the time. But designers rarely confess their inability to solve them." Instead, Alexander argued, designers fall back on an arbitrarily chosen formal order, with negative consequences.

This description had its counterpart in the work of Herbert A. Simon about the same time, in his classic paper "The Architecture of Complexity" (1962). Simon was searching for principles of structure among complex systems, and he noted the tendency of complexity to take the form of "nearly decomposable hierarchies." The elements of such complex systems often had strong interaction capacities as well as weak ones, and the strong interaction capacities tended to form hierarchical subsystems, allowing the system to be "nearly decomposed" within our models – that is, grouped into functional sub-units that could then interact in a more usefully comprehensible way.

Alexander also identified strong and weak relationships, with the strong relationships forming what he termed "diagrams" (later "patterns"). These subsystems could also then be treated as recombinable units within design models, following grammar-like rules. Alexander observed that something similar does happen in human language – and indeed, in the design processes of vernacular cultures, where "patterns" were identifiable elements of design. This formed the basis of a new design method that mimicked the features (and recaptured the usefulness) of previous vernacular methods.

"A pattern language has the structure of a network," wrote Alexander and his colleagues in the book A Pattern Language (Alexander et al., 1977). "Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice." In that book and its companion The Timeless Way of Building, Alexander and colleagues outlined the theory behind this language-like approach to design, drawing on structuralist influences like George A. Miller and Noam Chomsky (Alexander, 1979).

In essence, pattern languages are clusters of elements that form a solution to a problem, and that tend to recur in a pattern-like way. These elements are related to each other via "strong forces" – forming the requirements for relationship between the elements of a successful solution.

For example, the hinges and handles of a door must be in a particular configuration in relation to one another for the door to work successfully: generally, they must be on opposite sides of the door. (Figure One.) This is the resolution of the rotational forces of the door, which allows the user to operate the door with ease. (Imagine a door with the hinges and knob on the same side, and you can begin to see why this resolution of strong forces is critical in design!)

But in most cases, two separate doors are connected to one another with only weak forces – that is, in terms of their ease of use, there is little consequence to variations in their placement in relation to one another. Placing one door closer to another does not make that door easier or harder to operate. This relationship, then, is considered a "weak force."

These forces operate within a scale-free domain – that is, a weak force at one scale might be regarded as a strong force at another. (A placement of doors might not matter at the scale of the doors, but might matter a great deal at the scale of a room.) Thus a "pattern" is a cluster of stronger forces at one scale, which can be combined with other clusters, using grammar-like relationships.

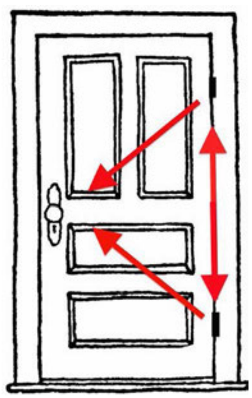

FIGURE APP.A.1 A simple pattern, "Door," resolving strong forces between the hinges and handle. (Illustration by the author.)

Indeed, most design problems – including software design problems – follow this kind of structural logic. Therefore it is possible to abstract the relationships within a recurrent problem, and treat them as objects within a generative design system. Such a system can in principle (and does in practice, as we will discuss) allow a much more efficient development of design solutions for a wide range of problems.

It is noteworthy, then, that "pattern languages" are less a new technological invention per se, than a kind of discovery, within the logic of problem-solving – and indeed, within the logic of nature itself, in a sense. Alexander himself made this point recently. (When asked by one of the authors "what was the most significant thing you've learned about pattern languages, looking back on them after all these years," Alexander answered, "I thought I was making an invention – but I was making a discovery. This is a structural aspect of nature that I was describing.")

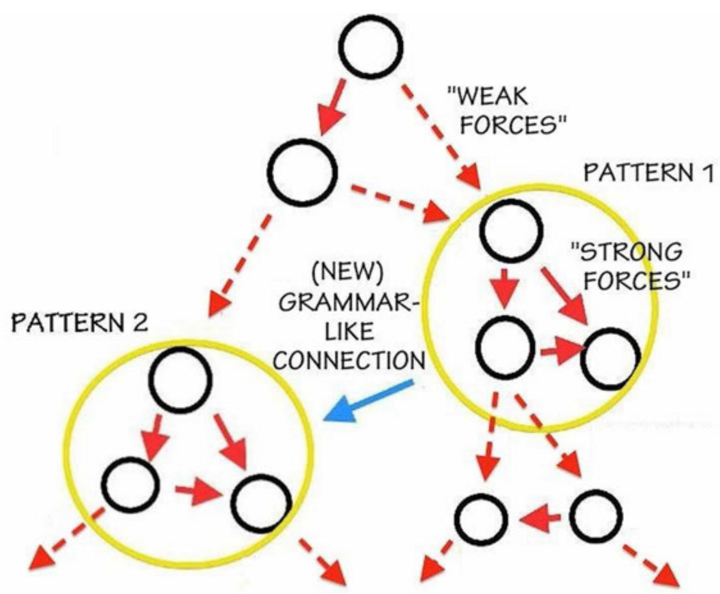

FIGURE APP.A.2 The structural logic of pattern languages.

In an even more fundamental sense, both Alexander and Simon were reconsidering the age-old philosophical topic of mereology, the nature of part-whole relations, but doing so from the perspective of a cybernetic age in which the elements of design were vastly more numerous. Both identified strong and weak classes of relationships, and the tendency of strong relationships to form "nearly decomposable" clusters within hierarchical groupings. But Alexander focused more than Simon on the inter-connected, not fully decomposable nature of the patterns – that is, the network aspects – and their crucial importance in creating the web-like structure of many languages – and many successful designs. Alexander used these insights to mount an incisive mathematical critique of modern planning, writing in a celebrated 1965 paper titled "A city is not a tree" (Alexander, 1965).

But the later book A Pattern Language – moving beyond the earlier critique and proposing an alternative, network-powered methodology – quickly overtook his earlier work to become Alexander's best-known publication, and it remains a perennial best-seller more than 35 years after its publication. At this writing (2013) it hovers at about the 7,000 total sales rank on Amazon-US, in spite of its expense ($65 retail, $40 through Amazon), and is also the highest ranking book in Amazon's category of architectural criticism (Amazon.com, 2013). Yet interestingly, William Saunders, former editor of Harvard Design Magazine, has pointed out the dilemma that "[A Pattern Language] could very well be the most read architectural treatise of all time, yet in the architecture schools I know, it is as if this book did not exist" (Saunders, 2002).

We will have more to say about why A Pattern Language may not be as influential in architecture – the very field for which it was created – as in other fields. First, we turn our attention to the field in which pattern languages have clearly had the most impact to date, software design.

A.4 Pattern languages in software

While many architects seem to have ignored Alexander's work – perhaps not so surprising, since he was unapologetically critical of their professional status quo – software engineers and others were following the work with considerably more interest. A number of influential programmers of the 1970s were already aware of and influenced by Notes on the Synthesis of Form, including Ed Yourdon, Tom DeMarco and Larry Constantine (Yourdon, 2009). But beginning in the 1980s, A Pattern Language formed the basis for what is now known as "pattern languages of programming," or "design patterns" – general reusable solutions to commonly occurring problems within given contexts (Beck and Cunningham, 1987).

As described by Erich Gamma, a pioneer of pattern languages in programming, "This approach to patterns differs from [Alexandrian] pattern languages: Rather than coming up with a set of interwoven patterns top-down, micro-architectures are more independent patterns that eventually relate to each other bottom-up. A pattern language guides you through the whole design, whereas we have these little pieces, bites of engineering knowledge. I confess that this is less ambitious, but still very important and useful..." (Gamma, 2005)

Nonetheless, the ability to manage complex systems through design strategy was a common goal. In software patterns, as in Alexandrian patterns, the value was precisely in their flexibility and language-like adaptability. They gave useful guidance to designers generally, and to programmers specifically, in the form of structured essays offering solutions to recurring problems in context. The total set of patterns available constituted a body that evolved through repeated application and evaluation. As we will see, that capability would prove to be a crucial goal – if one that remained only partly met (Kerth and Cunningham, 1997).

A.5 Pattern languages in other fields

Since the publication of the book A Pattern Language, the structure of pattern languages has been applied to a dizzying number of subjects. A Google search quickly reveals applications in human-computer interaction, management, service design, economics, communication, education, engineering, landscape design, and dozens of other fields (Google, 2013b). One can even find references to pattern languages for weddings, and for pattern writing!

Interestingly, the term "pattern language" draws some 477,000 Google search hits – yet the term "design pattern," the more common term used exclusively for software, draws some 5 million hits, a ten to one ratio (Google, 2013c). Clearly this ratio suggests a far greater impact of pattern languages in software than in architecture – which is only one of many fields affected by pattern languages, and only one of many using that term.

It is worth noting that the interest in pattern languages in other fields was fueled in large part by the rapid growth of interest in software. As software work was applied to many other fields, practitioners in those fields also took note of the use of pattern logic, and in many cases, extended its development to other topics.

A.6 Development of wiki

The influence of wiki is notably greater than that of design patterns – as one indicator, its Google hit score of 1.25 billion is over 250 times greater than that of "design pattern," and 2,500 times greater than "pattern language." What does this tell us? It may indicate that a method has been arrived at that combines ease of use with collaborative power.

The best-known example of wiki is surely Wikipedia, the on-line encyclopedia that is currently the most-used content site on the World Wide Web. (This definition excludes search engines like Google, which use content from other sources including Wikipedia.) But as a quick perusal of the web will readily demonstrate, there are many hundreds or thousands of other kinds of wikis, spanning many diverse fields. There are wikis for medical information, real estate, legal data, and national intelligence, to name a few. And of course, there are many wikis for software development, including sites created by Google, Microsoft and IBM. (S23.org, 2013.)

As these examples suggest, the power of wikis is in their very diversity, and their ease of handling many unique and specific features that are inter-linked, while also being able to provide universal approaches and organizing frameworks. In that sense, they combine the ability to identify useful generalities with the ability to identify new particulars. Moreover, they do so in a way that allows these capabilities to improve with time.

This is because, like patterns, wikis are bodies that evolve through repeated application, evaluation and refinement. The improvement of Wikipedia over time, for example, is legendary. In the early days of Wikipedia, it was common to hear comedians lampoon the many errors that were contained in its articles. But over time, errors were spotted and corrected, to the point that a recent study concluded that Wikipedia error rates are comparable to those of academic encyclopedias, although Wikipedia has far more entries on many more specialized subjects (Giles, 2005).

The evolutionary relationship between wikis and patterns languages is a simple one. Wikis were developed in 1995 as a tool to support the development of pattern languages in software (Cunningham, 2009). More specifically, it was developed as a tool to allow collaboration between many people as they evolve better collective solutions to shared problems. That means, among other things, that both the knowledge of the problem, and of the solutions that have worked so far, needs to be captured and refined, in a form that can be shared and further refined (Leuf and Cunningham, 2001).

A.7 Wikis as proto-pattern languages

We believe, in fact, that wikis and pattern languages share fundamental structural characteristics – and that it is not too much to claim that wikis (in their originally intended form) are, in fact, a form of elementary pattern language. They both share the following unique set of characteristics:

1. ***Both are open-ended sets of information, consisting of unitary subsets (pages or patterns) connected by hyperlinks.*** Each set of information is able to expand, while remaining within a linked network.
2. ***Both are topical essays with a characteristic structure: overview (with links), definition, discussion, evidence, conclusion, further links.*** This limited structure creates the capacity for extensibility and interoperability – the capacity of new pages to function smoothly with older ones, with the capacity for open-ended growth.
3. ***Both are structured to be easily creatable, shareable and editable by many people.*** This capacity facilitates the creation of user communities, who are crucial to the development of a large and useful body of shareable pages or patterns.
4. ***Both are (in principle) evolutionary, falsifiable and refinable.*** As structured essays, both make assertions about characteristics of the world they describe – assertions that can be falsified. Once falsified, they can be modified to correct discrepancies, and to refine accuracy. This evolutionary capacity translates into greater accuracy and usefulness over time.
5. ***Both aim to create useful ontological models of a portion of the world, as a more formalized subset of language.*** These are models of design specifically for pattern languages, and models of knowledge more generally for wikis.

A number of these elements are common to other information-sharing systems such as blogs and user-editable websites. They are also common to some other systems that are described as "wikis" only as a marketing device, or to emphasize some enhancement in convenience. But to our knowledge no other systems include all of the above elements. No others are intended to provide this capacity to an entire community of users, working in collaboration. In the case of wiki, we will refer to this complete capacity, implicit in the original conception, as "wiki nature."

It is worth noting here, as we discuss in more detail below, that pattern languages in architecture have not lived up to expectations as tools for communities of designers and builders. We believe this is precisely because, trapped within an alluring printed volume, the prototypical pattern language was unable to be shareable and editable by a wide community of users, and unable to be falsified and refined over time. These key requirements were included in the original wiki, and we believe, are key to its success. We also believe this fact indicates the basis of a promising revival of pattern languages in architecture, and other new developments as we discuss below.

A.8 New Technologies exploiting the natural capacities of language

In the case of both patterns and wikis, the goal was to exploit the power and flexibility of language to generate new knowledge, working from the best of existing structural knowledge. In both cases this required the collaborative identification and storage of this existing knowledge, in a way that it was available in a simple and ready form.

In both cases the development of the technology was informed by a philosophy of language that was informed by thinkers including John Searle (1965), Noam Chomsky (1980), George Lakoff (2008) and others. We can summarize this philosophy in the following points:

- Humans have the capacity to construct shared reality through a series of acts.
- When those acts are vocalizations we call them speech acts in natural language.
- Those acts and their consequence are heritable and thus subject to evolution.
- Pattern language, as developed by Christopher Alexander, mapped a useful subset of the heritable knowledge of building.
- Wiki, as developed by Ward Cunningham, maps a useful subset of heritable knowledge within the context of user websites, and their missions or "site charters".

As we will discuss in the next section, a new generation of wiki, called "federated wiki," enlarges this landscape in several ways: it allows shared ownership; it has the capacity to manage datasets; and it accommodates plugins to perform specialized applications.

A.9 Patterns and wikis as more "agile" forms of technology

Both design patterns and wikis were developed to address a fundamental problem in software: simply specifying new solutions to new problems in sequence leads to a cluttering of code, and an increased likelihood of malfunction from unforeseeable and unintended interactions. Cunningham and Beck, working at Tektronix Corporation near Portland, Oregon, were seeking new forms of software that would display what mathematicians often refer to as "elegance": the ability to do more with less. Cunningham embodied this principle in the question, "what is the simplest thing that could possibly work?" This encourages a process of exploration and learning, without assuming the need for particular structures in advance (Cunningham and Venners, 2004).

Cunningham was intrigued by the capacity of language, in its very ambiguity and economy, to serve more ably as a useful working model for problem-solving. A problem is, by definition, not pre-decomposed into simple functional units, but as Alexander noted, has many overlapping and ambiguous connections. Language mirrors this capacity, and therein lies its usefulness. Therefore the goal is, in a sense, to achieve the same robustness of language, by endowing the model with its own set of powerful (but limited in number) generative components, much as language does.

Thus, the goal is not simply a matter of economy, but one of greater context-adaptive problem-solving power. In fact it goes back to the heart of Alexander's concept of language-like networking: a simple grammatical system, functioning generatively, can be far more powerful than a complex set of specification-based processes. As Cunningham put it, when asked by programmer Tom Munnecke to explain how "the generativity of a pattern is a way of expressing complexity:"

> "That was an idea that excited me, and that seemed more powerful than most notion that I had seen. ...And that is, language is generative, I follow some rules, and I can't remember when I learned them, but I was probably pretty young. And that idea that I can have a set of rules that generates something that I could value is really important. So the question was, why don't we do everything that way? And the answer was, well we pretty much did, until we let professionals get involved. And they said, no, no, no, no, it's really much simpler, you know, and they made it complex by trying to make it simpler, because they didn't understand how some system of rules could generate behaviors instead of specifying behaviors." (Cunningham, 2011)

This generation refers to the capacity to reproduce the essence of a functioning structure without having to specify all of its characteristics. A simple example is the distinction between the way a genetic process generates the blue eyes, say, of a child, which recapitulates the blue eyes of the parent without having to specify them in minute detail (their intricate retinal pattern, round shape, etc). Instead, the genetic process is able to generate, and regenerate, an intricately complex structure from a relatively simple set of language-like instructions.

The result of this kind of work is, somewhat paradoxically, to reduce the complexity of the models we use for structuring our world – even as we increase their ability to handle real complexity more effectively. This is not so hard to understand, again, if we use an analogy to language. We do not need to draw little pictures to specify everything we see. Instead, we use a flexible language offering immense versatility, with just a small number of generative elements. With just 26 letters and a few other symbols, we can cover plate tectonics, or the plays of Shakespeare, or any of an infinite range of other subjects.

This is, in essence, the structure of natural complexity as well. That is, this is the kind of structure we usually confront as we seek to understand the complexity of a natural system, or a large-scale design problem. When confronted with such a complex phenomenon, we might choose to map all the aspects of its structure. This might, however, lead to an enormous and unwieldy map, posing many of the same structural challenges as the problem itself. But a more elegant solution, mathematically speaking, would be to identify the generative elements that produced the structure, recombine them in another generative process, and let the structure be re-generated. This is a far simpler, more elegant – more "agile" – approach to design.

Many of these principles were refined further within the Agile programming methodology to which Cunningham contributed, and which has also been widely influential (Cockburn, 2007). One of the principles of the "Agile Software Manifesto" is in fact to "maximize the work that isn't done" (Beck et al., 2001).

A.10 Wiki as "curation"

The issues raised by these topics take on special urgency, in an age in which information is exploding on the web – some would say cluttering the web – and the reliability of that information is increasingly problematic. Traditional forms of knowledge (such as print) are in decline, and the old methods are simply changing too rapidly to be reliable, while the incentives for those who claim knowledge is harder to verify. The web fills with rumor, promotion, distortion and simple misinformation.

Professionals, with their own parochial incentives, do not always fare better. Some fields seem increasingly to fill with self-serving pronouncements, pseudo-science, and simple hucksterism. A kind of low-grade corruption debases the integrity of honored professions, like journalism, law and even academia itself – a point that the great polymath Jane Jacobs made in her final, disquieting book Dark Age Ahead (Jacobs, 2004).

In this environment, wiki (and Wikipedia in particular) offers a usefully instructive model. The contrast with, say, almost any comment section of a blog, is striking. Aside from the strident and opinionated tone of most comment sections – in contrast to the "neutral tone" demanded of Wikipedia articles – it is very easy to see diametrically opposed accounts of the reliability of any given piece of information, often from what seem the most outlandish perspectives. By contrast, on Wikipedia there is remarkable reliability of information, which does tend to conform to the recognized conclusions of acknowledged research bodies, in stark contrast to many other web-based information sources.

How does this happen? In wiki knowledge-development tools like Wikipedia, there is a strong relationship to the way that reliable knowledge is acquired and improved in other fields – although wiki represents a faster and more efficient way of doing so. Again, the question goes to part-whole relations and to the mereology of knowledge – the ways that we can reconcile some portions of knowledge with others, and determine, to a large degree, an overall working reliability.

In the institutions of science, new knowledge can in principle come from any source, but it must be assessed for its accuracy and fit with what is already known. New knowledge must be able to explain not only the unknown but also, in the same terms, the already known. Generally this assessment is done through the peer-reviewed journal process, whereby a paper is submitted anonymously, and reviewed by reviewers who are unknown to the author, nor is the author known to them (a process known as "double-blind peer review").

In Wikipedia, for example, anyone can edit most articles, but the edits also go through a kind of peer review, by reviewers who can reject or flag content that does not appear to be up to standards. They are not necessarily experts in the field in question, but they are referees who are skilled at determining if the information given is consistent with what is known. Most importantly, they rely upon other contributors to judge, among the different contributions, which is more reliable.

Of course not all knowledge is as well-established or shareable as that of an encyclopedia. There are many spheres of life where differences of perspective, valuation and judgment are important, even essential. Culture is surely not a "tree" – in the same sense that a city is not a tree. On the other hand, it is not a murky thicket either, and we must not let our knowledge come to seem a murky thicket of misinformation, ignorance and self-serving hucksterism. There are surely many times when communities, of varying scales, must develop a working consensus to solve their problems together. Indeed, this is probably the very definition of "intelligence," defined as a species trait.

Therefore, we should recognize that only some knowledge has the characteristics of "encyclopedia knowledge." In important cases of policy and practice – such as climate change, for example – some knowledge of details and predictions will always remain uncertain, while there is a working consensus about a key portion. The uncertainty is not a liability, however – it is the very essence of the process of learning.

In this sense a 'federated" body of knowledge (along with the tool to share it) can function as a kind of "chorus" – a larger network of voices that are not stating exactly the same thing, but that contribute, through their very diversity, to a larger whole. From that larger whole, a working consensus can emerge. Out of that consensus comes what we would commonly recognize as "encyclopedia knowledge."

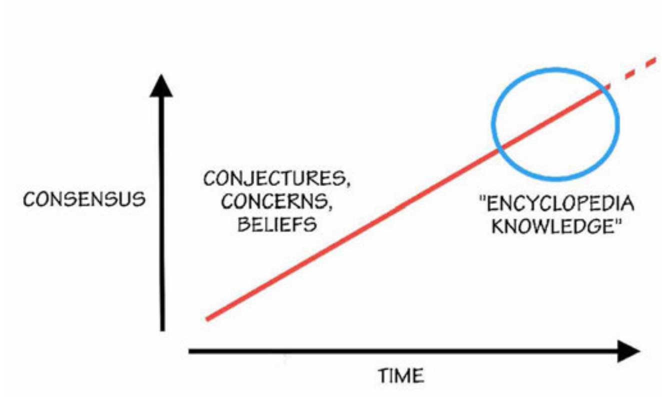

FIGURE APP.A.3 Conjectures, concerns and beliefs form a "chorus" of information from which evaluation and consensus can produce "encyclopedia knowledge" over time.

As in the Wikipedia example, the goal is that knowledge (conceived more broadly than "encyclopedia knowledge" would suggest) is able to grow more comprehensive, integrated and reliable, in spite of – or actually because of – the remaining differences in perspective. In effect, the resource becomes "smarter," and in principle, the people who use it are able to act in a way that is more beneficial, from a human point of view. Those who are seeking to solve a particular kind of problem will learn more readily about what is needed, and perhaps discover new and more effective ways to solve the problem. Knowledge about broader and more abstract human challenges (for example, geostrategic issues like climate change and sustainability) may also evolve and improve, offering further benefits.

We see in this the suggestion of a kind of "curation" of knowledge – identifying and refining the more important and relevant knowledge for the most urgent problems facing groups of people, and humanity as a whole. It builds on the processes already at work within the institution of science, as well as other similar cultural institutions that build progressive bodies of knowledge. In developing such a process that can effectively manage the flood of information on the web, wiki could well prove to be a useful and perhaps important model (Zaino, 2012).

There is also the possibility that such a strategy could improve the feedback cycles of research and learning. Whereas typical peer-reviewed journal publications can take up to two years between completion of research and actual publication, a wiki-like system could, in principle, greatly accelerate the cycle of research into publication. Wiki's collaborative, open-source and open-data model also suggests ways that knowledge could be shared and evaluated more widely by more investigators, potentially improving the results of research itself. But to achieve this capability, wiki systems would need to develop new capabilities. Although the specific capabilities are beyond the scope of this paper, the discussion below will serve to suggest the outlines.

A.11 Remaining problems with pattern languages in architecture

Alexander and his co-developers did in fact seek an evolutionary model for patterns, following Karl Popper's model of falsifiability. They proposed that each pattern is a kind of hypothesis, to be applied, tested, refined or even thrown out (Ishikawa et al., 2009). This methodology was comparatively easy to apply in the case of software design, where the feedback of success or failure tends to be immediate. It proved to be much harder in the field of urban design, where evaluation may require years or decades of use before conclusive evidence can be established and reported.

There was also a more fundamental limitation of pattern languages in architecture. The book The Timeless Way of Building makes it clear that there is an essential methodology of writing any number of patterns and pattern languages, and that the book A Pattern Language is only one such instance of a language. In fact the introductory section of A Pattern Language, "Using This Book," states, "In this book, we present one possible pattern language, of the kind called for in The Timeless Way." This suggests that many more patterns and pattern languages would be written, and that the existing patterns might well be re-used, modified, or even largely discarded.

But this is not what happened. In part because the book was such a successful complete piece of literature, the original 253 patterns in effect became frozen in time. Patterns and parts of patterns that even the original authors now repudiate have remained unchanged, and no published patterns have been added to this original corpus.

Also contrary to the initial intention (Ishikawa et al., 2009), the publisher has not released the content of the patterns into the public domain, and several websites that tried to reproduce the content have received warnings of copyright infringement. This represents a severe constraint on the further use, modification and addition to pattern languages in architecture.

Of course it is possible to write entirely new pattern languages in architecture that exclude all of the 253 patterns, and a number of architects have done this. But as Alexander and his authors noted, many of the patterns are archetypal, and very hard to exclude from common projects. A sampling of patterns indicates the magnitude of the challenge: Row Houses, Road Crossing, Circulation Realms, Small Parking Lots, Entrance Room, Dressing Room, Built-In Seats, Ornament.

Still another limitation of the dominant form of architectural pattern languages is in their basis on paper. Alexander has created a website that uses the hyperlink function, but it requires a subscription payment, and the patterns cannot be modified or added to.

All of these limitations are in contrast to pattern languages in other fields, notably software. Whereas architectural patterns are largely limited to the 253 original ones, plus those laboriously created in isolation by a few other architects, many thousands of patterns and pattern languages have been created for software. Whereas few people ever collaborate to make architectural patterns, many thousands of individuals have collaborated on software patterns. Whereas architectural patterns are limited to paper, software patterns begain life as shareable resources on the web, and were fueled by wikis to greatly expand their collaborative evolution and improvement.

These comparisons suggest important opportunities for pattern languages in architecture to greatly improve their efficacy and influence. While the time cycle of urban projects may not be shortened significantly, effective modeling approaches may be able to predict, with reasonable accuracy, the results of various patterns. We will have more to say about this below.

A.12 New horizons of wiki

From the previous assessments, we believe we can now describe several exciting opportunities for the future of wiki.

A Federated Development

First is the mode by which wikis are shared and improved. The original wiki technology functioned in a direct open-source mode, which allowed individuals to contribute small pieces to incrementally improve the whole. (Think of a Wikipedia article, for which contributors typically add only one small piece at a time.) But this posed a constraint for development of larger aspects of a wiki.

In the open-source software development community, a new approach developed known as federation. Typified by the "Git" methodology of Linus Torvalds, it allowed an entire copy of a system (of software or of other information) to be freely copied over in toto to a new site, and treated as though it were the original copy. (This is known as "forking" a copy.) Then, when beneficial changes are made to this copy, it may be kept as a separate improved version, or recombined with the original, or both. (A request to recombine with the original is called a "pull request.")

A new generation of wiki, called "Smallest Federated Wiki," is now based on this federated model. The wiki can be forked to new sites, and shared with other collaborators. Thus it can not only proliferate over many individual websites, but also evolve in unique ways in response to new and local conditions. On occasion these benefits prove valuable for older versions, in which case they can be recombined through a pull request.

B Data Manipulation Capability

Another fundamental innovation of the new generation of wikis is to be able to handle quantitative data. This gives wikis the power to handle processing tasks and modeling functions, wherein quantitative data can be taken through predicted transformations. (For example, in estimating costs, or calculating environmental metrics.)

We have used this capability in a prototype wiki developed for the apparel manufacturer Nike. In operation, a designer would select wiki pages or patterns, corresponding to the designer's choice of material or other design element. The designer will then select other wiki pages that can extract the metrics of performance on various sustainability criteria, such as water and energy use. The designer may select still other pages to display that information in ways that the outcome can be optimized, by adjusting the sequence or other specifications of the earlier pages. (Figure Five.)

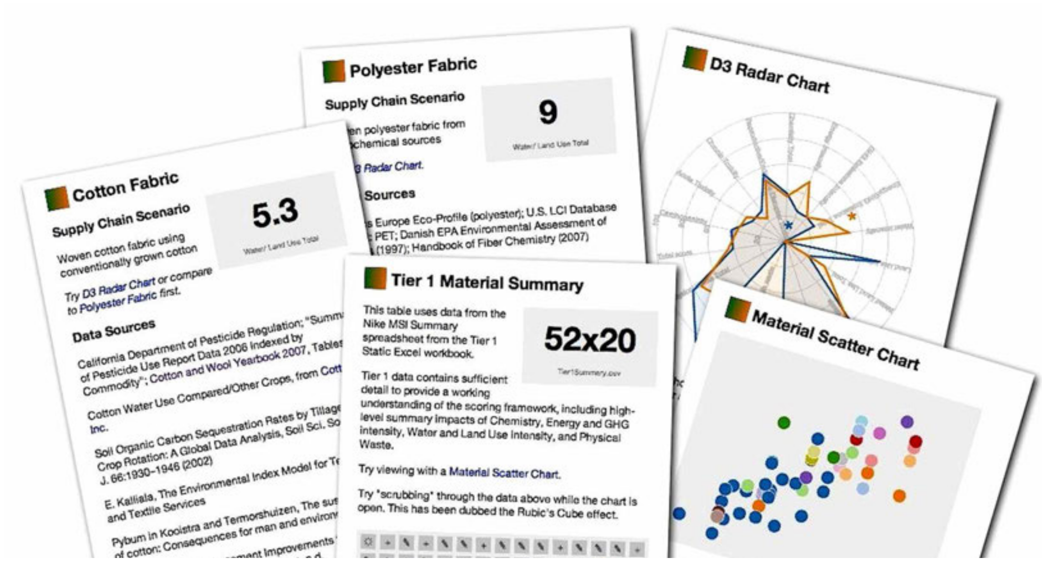

FIGURE APP.A.4 Sample pages from the Smallest Federated Wiki developed for Nike's Open Data Fellowship.

C Scenario-Modeling With Data Outputs

It is at this point that the power of such an approach, functioning as a pattern language-based modeling system, becomes apparent. In effect, each wiki page is now treated explicitly as a pattern, and the pages together form a working pattern language. Incorporated explicitly into the new wiki system, the patterns can guide the quantitative transformations, in such a way that each pattern governs the interaction occurring at that stage.

This is essentially what happened previously with narrative information in patterns – and to some extent in wikis – but now it is possible to do so for numeric and quantitative information. This represents an enormous leap forward for both pattern languages and wikis. The goal is, in effect, "to do for numbers, what wiki has done for words."

Moreover, the explicit combination of the two creates another level of capability for each. Specifically, by making more explicit the already pattern-like aspect of wiki, its capability to operate within extensive working networks is greatly expanded.

D Patterns of Elements, and Patterns of Process

Yet another powerful aspect of this approach, not yet evident in the older pattern language approaches in architecture, is the explicit combination of patterns of modeling process with patterns of physical structures. As in the example above, the pattern "Polyester Fabric" can be combined seamlessly with the pattern "Tier 1 Material Summary". This is analogous to the concept of von Neumann architecture (or stored-program architecture) in computing, in which a piece of data can represent both a value for an external element, and an instruction to the computer, depending on context. As in the case of von Neumann architecture, this represents a powerful new interactive capability.

We have begun to develop a first application of this Smallest Federated Wiki structure, incorporating process patterns, to the field of urban design. The goal is to allow urban designers to model alternative design scenarios, much as the Nike apparel designers would model alternative choices of fabric. Also as with the Nike example, some patterns are able to combine the results of other patterns, and display results in a format that facilitates optimization. The system is called "WikiPLACE," an acronym meaning "Wiki-based Pattern Language Adaptive Calculator of Externalities." The metrics that are calculated are so-called "externalities," that is, factors that are not usually calculated (nor even possible to calculate) in urban design, such as changes to greenhouse gas emissions per person. And they are able to be calculated in an "adaptive" way, that is, by adapting the configurations of the patterns to reach an optimum.

A further advantage is that, as with all wikis, a model developed by one party could be shared with others, and further adapted and refined. Through the federated structure, it is possible in principle that the model could grow much more accurate and useful. In addition, other variations could be developed for many other factors of interest, including other "externalities' such as infrastructure maintenance cost, future tax revenues and the like. These factors are extremely important in the long-term performance of an urban design – but because they are unable to be modeled accurately at present, they are generally very poorly considered.

An illustration may suggest the capabilities of such an approach. As shown in Figure Five, the designer might start with a basic unit of urban design, such as a residential neighborhood. They might then choose to specify a number of single-family detached (free-standing) homes. They might next decide to specify a number of attached homes, such as townhouses. Finally, they might decide to specify the density of these homes, expressed as the number per unit of land. At each of these steps, they would select the relevant pattern from a drop-down menu. At each step, the patterns would automatically recalculate, displaying metrics of interest (red arrows).

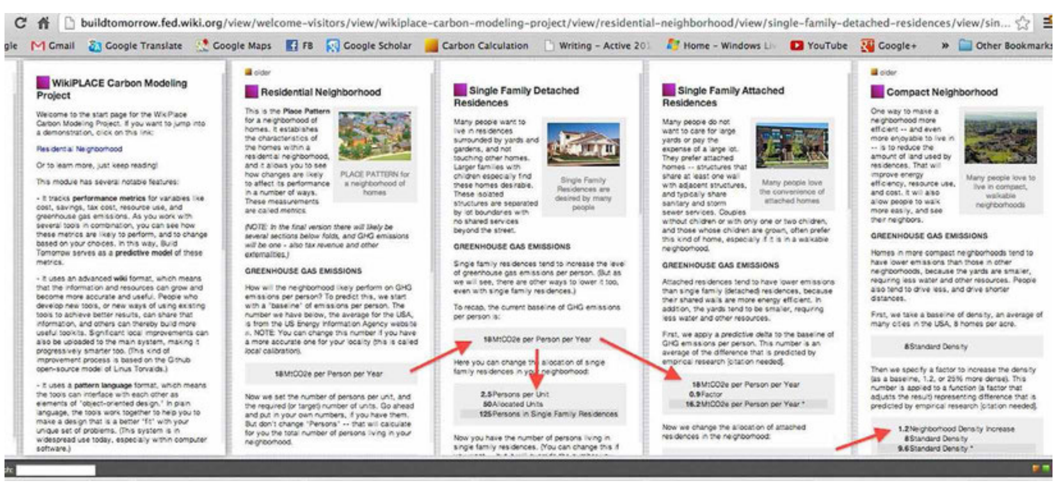

FIGURE APP.A.5 A screen shot of the new "Smallest Federated Wiki," showing an early experiment for an urban modeling software system called WikiPLACE.

Next, they might choose to perform a summary analysis of the metrics of interest – in this case, greenhouse gas emissions per capita. (The data manipulations between patterns are shown with the red arrows; in this case they are "predictive deltas" applied to the previous metrics.) If they do not feel this outcome is optimal, they can go back and adjust the previous patterns, or their sub-components..

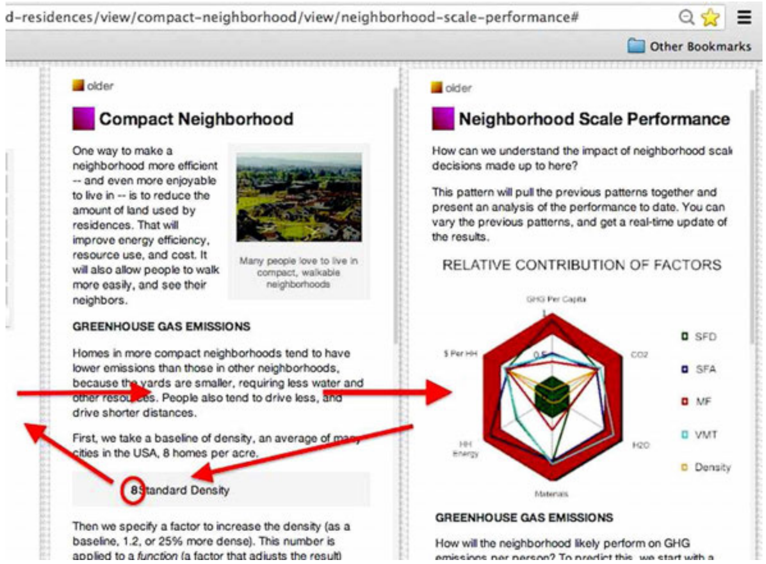

FIGURE APP.A.6 In addition to physical patterns, WikiPLACE can also incorporate analysis patterns, with visual displays of optimal results.

A.13 Conclusion

The previous work with both pattern languages and wikis demonstrates their extensive capabilities, and suggests even more capabilities that may yet be realized – particularly in combination, and with added capabilities as we suggest here. What we believe is most intriguing is that with the collaborative power of wiki, pattern languages can indicate desirable outcomes that are not yet explicitly identified, but nonetheless are suggested (and possibly confirmed) by the structure of the patterns. In this way, pattern languages could become effective research tools in their own right, hastening the development and application of useful scientific knowledge at a time that the world needs it more than ever.

As noted previously, this work also suggests a way of managing the explosion of information on the web, and in our lives – and more importantly, a way of assessing the reliability and importance of information and knowledge, in a way that seems most likely to enrich our lives, and our civilization.

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Index

Curriculum vitae

Michael West Mehaffy

1 Academic and Research Appointments

Member of the Faculty and Ph.D. Researcher, Delft University of Technology, Delft NL. Research in urban morphology and greenhouse gas emissions. February 2011-present.

Sir David Anderson Fellow, University of Strathclyde, Faculty of Architecture, Glasgow, UK. Researcher and lecturer in sustainable architecture, urban design and development, and walkable cities. Consultant on curriculum development for new graduate degree and distance learning programs. 1-year appointment. March 2011-March 2012.

Adjunct Faculty Instructor, University of Oregon, School of Architecture and Allied Arts, Portland OR USA. Instruction in architecture and urban design theory, history, design studio, Portland Urban Architecture Program. Research Associate, Portland Urban Architecture Research Laboratory. June 2008-present (intermittent).

Visiting Faculty Associate, Arizona State University, Phoenix AZ USA. Dual appointment to School of Geographical Sciences and Urban Planning, and School of Sustainability, Phoenix, AZ. Lecturer and researcher in urban planning and design, sustainable urban development, TOD, codes, development economics, and related topics. January 2011-January 2012.

Visiting Professor, University of Trento, Italy. Lecturer in philosophy of design, sustainable urban development, biophilia, evidence-based design, and related topics. Collaborator in the Center for Aesthetics in Practice. December 2010-February 2011.

Visiting Professor, Tecnologico de Monterrey, Department of Architecture, Queretaro, Mexico. Collaborator on creation and development of a new graduate degree program in sustainable urban development and new urbanism; develop curriculum materials, organize and conduct study tours, teach classes. March 2006-present (intermittent).

Research Associate, Centre for Environmental Structure, Berkeley CA USA and Arundel UK. Research center founded and directed by design pioneer Christopher Alexander in 1967, home of noted research and publications on pattern languages and other award-winning work. Research collaborations with Alexander and colleagues on sustainable design, generative codes and pattern languages. March 2006-present.

Guest Lecturer and/or Visiting Critic, Bartlett School, University College London, University of Greenwich, Politecnico de Bologna, Technical University Dortmund, Catholic University of Portugal, University of Miami, University of Notre Dame, et al.

Academic Chair, the European School of Urbanism and Architecture, Oslo, NO. Directed creation of a pilot curriculum in sustainable urban development funded by the European Union's Leonardo da Vinci Programme. Lectured, taught classes, wrote curricular materials. Website: www.esua.org. September 2007-December 2008.

Coordinator, EDUAC project (European Dissemination of Urbanism Architecture and Crafts), Oslo, NO. Directed development of a pilot curriculum in sustainable urban development, with an emphasis on the integration of traditional crafts skills. Partnered and worked closely with six universities, as well as NGOs and private practitioner consultants. Prepared and managed workshops, lectured, taught classes, prepared curricular materials. June 2008-April 2010.

Director of Education, The Prince's Foundation for the Built Environment, London UK. Partnered with UK national government, leading NGOs and six universities in development of new graduate degree educational programmes and curricula. Programme was the basis of a new Masters degree programme in sustainable urban development at the University of Oxford, UK. September 2003-November 2005

2 Research Grants and Program Contracts

Sir David Anderson Bequest, University of Strathclyde, Glasgow, UK. £18,000 research award for work in sustainable urbanism, urban codes, walkable cities, curriculum development and related work. (See additional listing below.)

The Prince's Foundation for the Built Environment. £40,000, grant for research with Dr. Christopher Alexander on new "generative codes" for sustainable urban development, 11/05-3/06. Christopher Alexander, PI; Michael Mehaffy, managing director.

Academy for Sustainable Communities (UK government funding body). £20,000, grant to develop new professional education program at The Prince's Foundation for the Built Environment, 5/2005. Michael Mehaffy, Director of Education and applicant.

Eva and Hans K. Rausing Trust. £750,000 (renewal), grant to develop new education curriculum at The Prince's Foundation for the Built Environment, 3/2004. Michael Mehaffy, Director of Education.

Leonardo Da Vinci Programme in Lifelong Learning (European Union). €250,000 for new inter-disciplinary curriculum in sustainable architecture and urbanism for continuing professional education. Michael Mehaffy, partner applicant (as Director of Education, the Prince's Foundation for the Built Environment) and chair, academic committee.

3 Professional Experience

President, Structura Naturalis Inc. Consultant to governments, NGOs and private developers in sustainable development strategies, urban and building designs, codes, standards and certifications. Projects have included noted urban development projects in the US, Canada, Mexico, South America and Europe. Work has pioneered new tools, certification programs and implementation strategies, reflecting the latest advanced research and evidence-based practice. September 1993-present.

Executive Director, Sustasis Foundation. 501(C)(3) NGO in Portland, Oregon. Research, publication and consulting in climate change and urban morphology, new coding approaches, strategic urban development, implementation strategies, economic toolkits, and related topics. Create partnerships and research for publication; organize or collaborate on conferences and symposia. Website: www.sustasis.net. September 2007-present.

Director of Education, The Prince's Foundation for the Built Environment. Directed creation of a new program in sustainable urban development, in partnership with the UK Office of the Deputy Prime Minister, Royal Institute of British Architects, Royal Town Planning Institute, other leading NGOs, and six universities. September 2003-November 2005

Project Manager, PacTrust. Project manager and owner representative for the master developer of Orenco Station, a landmark transit-oriented development in Portland, Oregon, described in a New York Times op-ed as "perhaps the most interesting experiment in New Urbanist planning anywhere in the country." The project used one of the earliest "form-based codes" in the country. Septeber 1997-January 2003.

Project Manager, developer, designer and builder, Green Gables Design and Restoration Inc., and/or Diaita Development Co. (as owner). Supervised projects to $2 million and staff up to 20, including self-financed projects. Architectural apprenticeships, design, documentation, finance, hands-on construction, development and business management. September 1982-September 1997.

4 Education

Delft University of Technology, Delft (NL) Faculty of Architecture. Doctoral research in sustainable urban design and greenhouse gas emissions. ABD status as of March 2012.

University of California at Berkeley (CA USA), Graduate School, College of Environmental Design, Masters Program in Architecture. Study areas: architecture, planning, urban design and sustainability. Credit toward Masters degree; GPA 3.8. (9/80-6/81)

University of Texas at Austin (TX USA) Graduate School, Masters Program in Philosophy. Study areas: philosophy of science, philosophy of design, public affairs and business management theory. Credit toward Masters degree. Graduate Record Exam: 720 Verbal, 700 Math. (9/79-6/80)

The Evergreen State College, Olympia (WA USA). Studies in architecture and liberal arts. Bachelor of Arts. (1/77-6/78)

The University of Texas at Austin (TX USA), Plan II Interdisciplinary Honors Program. Studies in liberal arts and sciences. (9/75-12/76)

California Institute of the Arts, Valencia (CA USA). Studies in 20th century music, art and design. (9/73-6/75)

5 Editorial and professional or NGO boards

Editorial Board Member, *Urban Design International* (6/08-present)

Editorial Board Member, *Journal of Urbanism* (3/07-present)

Editorial Board Member, *Cuadernos de Arquitectura y Nuevo Urbanismo* (3/08-9/13)

Founding Board Member and Chair, INTBAU-USA, US chapter of London-based NGO dedicated to sustainable urbanism and architecture (10/07-present)

Chair, INTBAU College of Chapters, international governing body of London-based NGO dedicated to sustainable urbanism and architecture (08/14-present).

Board Member, Council for European Urbanism (C.E.U.), Stockholm based professional association of urban planners, designers and architects (4/09-present)

Board Member and Executive Director, Sustasis Foundation, Portland, Oregon based research and development NGO founded as part of Hurricane Katrina community planning.

6 Publication History

Author or contributing author, twenty-two books on topics including urban morphology and morphogenesis, sustainable urbanism, New Urbanism, new "generative" codes, pattern languages, architectural theory, aesthetics, technology, economics, and sustainable development.

Regular contributing author to professional journals in architecture, urbanism and sustainable development, including *Urban Land, The Atlantic's CityLab, Metropolis, Planetizen, Building (UK)* and others.

Google Scholar Statistics: Citations 284, h-index = 7, i-10 index = 6 (as of September 2015).

7 Notable Projects

Presenter, UNFCC Conference of Parties 21 (COP21) climate change conference, December 2015 (invited).

Contributor, United Nations Sustainable Development Conference, Goal 11, as Academic Chair of the Future of Places Forum (a partnership of UN-Habitat, Project for Public Spaces, and Ax:son Johnson Foundation). September 2015.

Consultant, development of new urban streetscape codes for the City of Moscow, Russian Federation and Strelka KB. June -July 2015.

Consultant, planning for Habitat III (United Nations Conference on Housing and Sustainable Urban Development), to conference Secretary-General and staff. October 2014.

Consultant, Government of Ecuador, for Yachay City of Knowledge, new walkable mixed-use, resource-efficient city of 200,000 with university and technology development zone. October 2015-June 2014.

Project Manager, Vista Field, Kennewick, Washington, 100 acre (40-hectare) brownfield redevelopment of walkable mixed-use community of 1,400 residences and 100,000 square meters of commercial development. 2012-present.

Consultant, REACH Community Development, strategic planning for affordable housing NGO for transit-oriented development. 2011-12.

Consultant, Northwest Housing Alternatives, strategic planning for affordable housing NGO for transit-oriented development. 2010-12.

Consultant, City of Lake Oswego, Oregon, on strategic planning of urbanization strategy for urban growth boundary expansion. 2010.

Consultant, City of Milwaukie, Oregon, on stategic economic development of downtown area. 2010.

Consultant, Metro (Portland, Oregon regional planning authority), for strategic development of "centers and corridors" as transit-oriented mixed-use zones. 2009.

Consultant, Pringle Creek Community, Salem, Oregon, strategic planning consultant to owner, for 32 acre (13 hectare) brownfield redevelopment of walkable mixed-use community featuring advanced solar photovoltaic systems, geothermal heat, electric car share, "green mortgage" package of sustainable building features. 2007-2010.

Project Manager, Orenco Station, Oregon, for greyfield redevelopment of mixed-use transit-oriented community of 1,800 residences and 100,000 square metres of commercial development along the Portland, Oregon light rail line. (See listing above.) 1997-2003.

8 Research Interests

- Urban form and greenhouse gas emissions
- Walkable multi-modal neighbourhoods and their dynamic spatial networks
- New design technologies using scenario-modelling, pattern languages, and open-source computer tools and technologies
- Urbanisation, sprawl, resource efficiency, self-organisation, and complex adaptive systems
- Urban codes, types, standards, "generative" tools and toolkits
- Critical assessments of the work of Christopher Alexander, Jane Jacobs, "The New Urbanism" et al.
- Philosophy of design, aesthetics, semiotics; science, technology, culture, and nature