

Operationalising Urban Sustainability: defining, measuring and modelling.



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Abstract

Despite its ubiquity urban sustainability is a contested concept with no widely accepted definition of what it is, or what it should look like. This lack of consensus surrounding meaning presents barriers to coherent operationalisation to bring about positive change, leading to the dominance of undertheorised indicator based approaches. Such approaches present various issues including the marginalisation of less quantifiable aspects, and the erasure of holism and interaction between relevant phenomena. This thesis seeks to develop a deeper understanding of urban sustainability, and how it can be operationalised to explore coherent ways of improving upon it.

These issues are explored in three distinct research streams, centred around the descriptors of ‘define, measure, model’. Initially urban sustainability is decomposed into its two constituent terms which are reviewed in isolation, in reference to the ‘fractures’ within the bodies of literature. An integrative review utilising backward snowballing probes the origins of the three pillar paradigm of sustainability with reference to the early literature. A semi-systematic review then explores the disciplinary divide between urban studies and urban science drawing out common themes that emerge across the two.

This literature analysis is followed by an exploration, through physical analytical techniques, of thermodynamic entropy as a ‘physical basis’ for measuring unsustainability. Following this, a prototype urban integrated assessment model is developed through the adaptation of Meadows et al. (2005)’s World3 model. Here the paradigm of system dynamics is investigated as a useful frame for emphasising the interaction and feedback between relevant phenomena. Whilst starting from a post-positivist research frame attempting to ‘define, measure, and model’, an epistemological shift was made within this work to a more interpretivist approach using the language of ‘understanding’; this forms an underlying meta-narrative.

Through this work, the Urban1 model is forwarded as a prototype multi-scale system dynamics model presenting a novel method for both understanding and operationalising urban sustainability. This model is used to explore the relationship between the sustainability of the urban system relative to the wider global context. By emphasising feedback, cascading effects, and unintended consequences, such a modelling framework allows for deeper consideration of coupling mechanisms

between subsystems both within the urban system and across the broader global scale. By running several scenarios it is demonstrated that there is no place for urban sustainability in an unsustainable world, and therefore multi-scale models are key for assessing the wider context of policy measures taken across different hierarchical scales.

Thermodynamic entropy is outlined as a conceptual dead end for further exploration, and its continued popularity is shown to derive from conflation of a rigorously defined physical quantity with a metaphorical understanding. The analysis of the literature fractures underscore the political nature of urban sustainability, and it is argued that it should be viewed as a semantically open concept. A synthesis of these research streams outlines a future path for better practice in operationalisation in the future; emphasising the importance of boundaries, a choice that should be pragmatic but ensure interspatial equity; the need for clear theoretical framing rooted in the literature, stating its assumptions and understanding of terms; the importance of pluralism, both methodological and epistemological, alongside the involvement of marginalised stakeholders. These findings have implications for future endeavours attempting to operationalise urban sustainability, and offer significant considerations for future research in this area.

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Statement of Originality

I declare that the intellectual content of this work is my own and all assistance received in preparing it has been acknowledged. This thesis has not been submitted for any other degree or other purposes. Some of the content of this thesis has been previously published within the publications listed on the following page. Where text from these works has been reused in the body of this thesis, this has been appropriately attributed.

List of Publications

B Purvis, Y Mao, D Robinson. 2017. “Thermodynamic entropy as an indicator for sustainability?”, *Procedia Engineering* 198, 802-812

B Purvis, Y Mao, D Robinson. 2019. “Three pillars of sustainability: in search of conceptual origins”, *Sustainability Science* 14(3), 681-695[†]

B Purvis, Y Mao, D Robinson. 2019. “Entropy and its application to urban systems”, *Entropy* 21(1), 56

B Purvis, Y Mao, D Robinson. “A system dynamics model to support urban sustainability”, Sustainability Science (In preparation)

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List of Abbreviations

ABM	Agent-based model(ling).
CSD	Commission on Sustainable Development.
DSS	Decision support system.
EPSRC	Engineering and Physical Sciences Research Council.
GBP	Pound sterling.
GDP	Gross domestic product.
GIS	Geographic information system.
GNP	Gross national product.
GVA	Gross value added.
HEF	Human ecological footprint.
HWI	Human welfare index.
IAM	Integrated assessment model(ling).
IIED	International Institute for Environment and Development.
ILO	International Labour Organization.
IUCN	International Union for Conservation of Nature.
JPI	Joint programming initiative.
LtG	Limits to Growth.
LUCAS	Laboratory of Urban Complexity and Sustainability.
LUTI	Land-use transport interaction.
MFA	Material flow analysis.
NERC	Natural Environment Research Council.
OECD	Organisation for Economic Co-operation and Development.
ONS	Office for National Statistics.
SDGs	Sustainable development goals.
STEM	Science, technology, engineering, and mathematics.

TBL		Triple bottom line.
UNDESA	. . .	United Nations Department of Economic and Social Affairs.
UNEP		United Nations Environment Programme.
USD		United States dollar.
WCED		World Commission on Environment and Development.
WWF		World Wildlife Fund.

If solutions within the system are so impossible to find, then maybe we should change the system itself.

— Greta Thunberg, *You are stealing our future*

1

Introduction

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1.1 A Map of the Problematique

Urban sustainability is a prevalent concept, receiving the attention of both local and national governments around the world, corporations, academics, and non-governmental organisations, as well as holding the focus of Sustainable Development Goal 11 within the United Nations’ 2030 Agenda (UN 2015a). With increasing levels of urbanisation, the ‘urban challenge’ remains one of the pressing issues of the 21st century; urban areas dominate global resource use, with correspondingly

adverse environmental impacts, they exhibit concentrations of great wealth and poverty, and represent centres of innovation, community, activism, and change, but place great pressure on surrounding land and a globalised commons for their continued functioning. As presented by the UN's Habitat III 'New Urban Agenda', despite occupying approximately 2% of global land, cities represent 70% of global GDP, 60% of global energy consumption, and 70% of global waste (UN 2017). Urban areas thus can be seen as both a concentrated source, and a key focus for potential solutions to the challenges facing the world (Angelo and Wachsmuth 2020). It is here that a notion of 'urban sustainability' comes to the fore as an umbrella term for conceptualising the multifarious issues and needs relating to the futurity of urban areas. Despite much attention however, 'urban sustainability' remains a contested concept with no widely accepted definition of what it is or should look like (Hamman 2017).

Occupying the fuzzy realm of 'I know what it is when I see it', urban sustainability holds apparent consensus as benign necessity, and has thus been co-opted by a diverse range of actors with sometimes diverging objectives (White 2013; Tulloch and Neilson 2014). It exists as a label to be applied where a confluence of 'urban' and 'sustainability' arises, and is often only loosely defined, if at all, in work considering it (Lorr 2012). The blurriness of the term can be in part explained by the meaning of its two component words, 'sustainability', and 'urban', each being contested in their own right (Brenner and Schmid 2015; Ramsey 2015). Sustainability, often viewed in terms of social, economic, and environmental 'pillars', is perceived by Goodland and Daly (1996) as becoming a "landfill dump for everyone's environmental and social wishlists" (p1002), and it has frequently been described as a 'buzzword' (Glasser 2016; Ben-Eli 2018). The urban on the other hand has been subject to recent debates surrounding its nature; Brenner and Schmid (2014) suggest that the urban is better understood as a process rather than a universal form, and various authors from diverse backgrounds argue that due to the nature of urban boundaries it is difficult to separate what may be considered urban from what may not (see e.g. Batty 1994; Satterthwaite 2010; Merrifield 2013; Champion and Hugo 2016; Vis 2018). Coupled with this, the multidimensional complexity of the issue draws researchers from all manner of disciplinary backgrounds, creating additional barriers to communication (Dahm et al. 2019)

This contestation of meaning presents issues when it comes to operationalising¹ a notion of urban sustainability (Dao et al. 2017). It is widely recognised that

¹Mueller (2004) describes operationalisation as the process of moving from the abstract to the empirical level (p162).

‘sustainability’ must be translated into tangible outcomes, both within the urban context and more generally (Keirstead and Leach 2008; Turnheim et al. 2015). Such outcomes are usually considered in terms of policy actions (Fitzgerald et al. 2012; Vojnovic 2014; Patterson et al. 2017), but may also be realised in the form of behavioural changes (Barr et al. 2011), educational initiatives and knowledge transfer (Shephard 2008; Bond et al. 2010; Hacker et al. 2012), or changes in ‘best practice’ (Elkington 1997; Holmström et al. 2017). As a barrier for moving from theory to practice, the contestation surrounding an understanding of urban sustainability must be confronted. Whilst numerous authors call for a more integrated, holistic approach, and the need to build consensus (see e.g. Tanguay et al. 2010; Mori and Christodoulou 2012; Krueger and Buckingham 2012), there exists a growing school of thought promoting the benefits of pluralism² and ‘dissensus’³ based approaches (Isgren et al. 2017; Kaika 2017; Brenner 2018; Di Paola 2019; Barthold and Bloom 2020).

Work operationalising urban sustainability is primarily quantitative in nature, centring around the development of indicator sets⁴ and frameworks⁵ which seek to ‘define’ and ‘measure’ sustainability (Turcu 2013; Verma and Raghubanshi 2018). Other operational frameworks exist which conceptualise planetary limits (Rees and Wackernagel 1997), analysis of resource flows (Girardet 2004; Cui 2018), ‘assessment tools’ (Reyes Nieto et al. 2018), or the use of ‘integrated’ models (Lautso 2002; Li et al. 2016; Robinson 2019). There is great variety in how this work is approached, with varying levels of interaction with relevant stakeholders⁶ (Mielke et al. 2016).

With the proliferation of competing approaches, there remains a need to develop novel, critically reflexive ways of understanding and operationalising a notion of urban sustainability. In particular, there exist numerous theorisations upon sustainability and critical perspectives which are routinely overlooked in shallowly theorised indicator approaches. A novel approach should confront the fractured

²Defined by Schlosberg (1999) (p68) as the “recognition and acceptance of difference”.

³Associated with the work of Rancière (2010), dissensus approaches subvert the ‘sensible order’ which “identifies and defines who is qualified to speak and about what, who is heard and in what way” (Keshavarz and Maze 2013, p11). Dissensus may thereby be viewed as a “radically democratic” participatory process which reorders “existing organisational authority and power relations” (Barthold and Bloom 2020, p7).

⁴Dao et al. (2017) defines an indicator as “an indirect and/or a partial measure of a concept that is relevant for a given purpose” (p640).

⁵In this work, a ‘framework’ is understood as a formal organising structure which outlines the core concepts and theoretical principles of a study, aligned to Grant and Osanloo (2014)’s ‘conceptual framework’.

⁶Welp et al. (2006) describe stakeholder dialogue as the “structured communication processes linking scientists with societal actors such as representatives of companies, NGOs, governments and the wider public” (p170).

literature landscape, and plurality of different disciplinary understanding and conceptualisations.

1.1.1 Purpose statement

This thesis seeks to progress towards a better understanding of urban sustainability, and explore novel modes of its operationalisation informed by this theory development. This work started out from a post-positivist frame seeking to ‘define, measure, and model’ (Kondyli et al. 2017; Larson et al. 2018) urban sustainability, as the research progressed however an epistemological shift was deemed necessary to a more interpretivist frame and the new language of ‘understanding’. The resultant research design uses a mixed methods approach loosely based upon this ‘define, measure, model’ structure, the results of these individual parts are then analysed together through an emergent theoretical frame focusing on the strands of pluralism, boundaries, and theory.

1.1.2 Chapter overview

This chapter outlines the necessary literature for providing the motivation and context behind the research questions articulated in Section 1.4.1. Section 1.2 elaborates a brief history of urban sustainability as a distinct concept, and explores how it has been conceptualised and understood across the broad bodies of literature which consider it, ending with a working definition of urban sustainability which is used within this thesis. Section 1.3 covers the meaning of ‘operationalisation’ as understood within this thesis, and explores ways in which urban and planetary sustainability have been operationalised within the literature, painting a critical picture of indicator based approaches, as well as introducing modelling. Finally Section 1.4 outlines the research design of this work, presenting research questions, the contribution, and providing a roadmap of the subsequent thesis structure.

1.2 What is Urban Sustainability?

The notion of ‘urban sustainability’ can be attributed to any number of roots, such as the garden cities and ecological cities that peppered modernist planning endeavours of the 20th century (Howard 1902; Basiago 1996), urban ecology (Wu 2014), or indeed much of the corpus from which the wider sustainability literature draws (see Section 3.1 for an outline of the conceptual history of sustainability). Consideration of urban sustainability as a distinct concept only dates back to the

1990s, and is arguably precipitated and shaped by the UN’s 1992 Rio Declaration (UN 1992b; Vojnovic 2014). Prior to Rio, the urban had primarily only been thought of with regards to sustainability in relation to specific phenomena such as urban ecosystems (Meier 1984), economic development (Button and Pearce 1989), and agriculture (Smit and Nasr 1992).

1.2.1 Historical origins

The conceptual origins of sustainability proper are not much older (Caradonna 2014; Grober 2012). More in depth consideration of sustainability and sustainable development is given in Chapter 3, but it is helpful here to provide a brief overview for context. ‘Sustainable development’ was allegedly coined in the mid 1970s by Barbara Ward who complemented her work on international development with concern for the environment (Satterthwaite 2006). The publication of *Our Common Future* by the UN’s World Commission on Environment and Development (WCED) in 1987 is widely seen as a watershed moment in the evolution of the sustainability paradigm (Redclift 2005; Barkemeyer et al. 2014; Petrișor and Petrișor 2014). Commonly referred to as the *Brundtland Report* after the chair of the WCED, this work is responsible for producing the still widely cited ‘Brundtland definition’ of sustainable development:

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (UN 1987, p43)

From this point the literature on sustainability and sustainable development is closely intertwined with various major outputs from the UN, including the 1992 Rio declaration, and more recently the articulation of the 17 ‘Sustainable Development Goals’ (or SDGs) (UN 1992b; Tulloch and Neilson 2014; UN 2015a). Whilst the terms sustainability and sustainable development are still largely used interchangeably, an expansion beyond the development paradigm sees sustainability considered in all manner of domains (Sneddon 2000; Olawumi and Chan 2018). Nevertheless, through this conflation, economic growth-centred ‘development’ is reinforced as an implicit part of ‘sustainability’, sidestepping critique of what is being developed and for whom. Such strategic ambiguity allows this fuzzy concept to be utilised by any actor for their own means. In the earlier literature such as Caldwell (1984), and Barbier (1987), ‘sustainable development’ is understood as a necessity for developing nations, and is often decoupled from growth. But this distinction is lost when the UN equate development with growth, and the Organisation for

Economic Co-operation and Development (OECD) calls for sustainable development for their member countries, i.e. developed nations (OECD 2004b, p3).

This issue has been addressed by numerous authors who hold the term ‘sustainable development’, like that of ‘sustainable growth’, to be an oxymoron (Redclift 2005; Johnston et al. 2007; Brand 2012). Notably Redclift (1987) argues the notion of ‘development’, rooted in Western colonial capitalist narratives, presents numerous barriers to sustainability, and without interrogation and political change, sustainability itself is jeopardised. Sneddon (2000) proclaims that ‘sustainable development’ has “reached a conceptual dead-end”, and that for clarity it is necessary to decouple the notion of ‘sustainability’ from its counterpart. He problematises the recasting of ‘development’ as sustainable citing the numerous socioecological abuses enacted throughout its history, and its blindness to deep-set structural issues. Sustainability on the other hand, despite having a reputation as a buzzword, carries far less historical baggage.

Within the academic community sustainability research is largely seen as a multi- and interdisciplinary⁷ endeavour, and receives attention from researchers across the whole of the academy (Schoolman et al. 2012; Haider et al. 2018). The last 20 years have witnessed the emergence of ‘sustainability science’ as the infancy of a new broad field attempting to integrate theory, applied science, and policy (Kates et al. 2001; Komiyama and Takeuchi 2006; Bettencourt and Kaur 2011; Kates 2011; Spangenberg 2011; Fang et al. 2018). A conceptualisation which is often employed in grappling with the disciplinary spanning properties of sustainability involves thinking of it as three constituent ‘pillars’ representing economic, social, and environmental aspects, which are then either integrated or analysed separately (Barbier 1987; Carter and Moir 2012; Caradonna 2014). Such conceptualisation provides a useful tool for managing broad cross-disciplinary aspects, although has received criticism for its ‘siloeing’ of issues (Davidson et al. 2012; Nabavi et al. 2017), and there are questions to its conceptual roots (Thompson 2017).

⁷Understood in this work through Repko (2012)’s definitions: “Interdisciplinary studies is a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insights to construct a more comprehensive understanding” (p16). Multidisciplinary research on the other hand “involves more than a single discipline in which each discipline makes a *separate* contribution” (p17).

Origins of urban sustainability research

Chapter 6 of the *Brundtland Report*, entitled ‘*The Urban Challenge*’, starts with the declaration “by the turn of the century, almost half of humanity will live in cities” (UN 1987, p22), proceeding to present a bleak picture of rapid urbanisation in the developing world overtaking the ability of cities to provide adequately for the needs of these new inhabitants. These few paragraphs present an archetype for the prelude to any discussion of urban sustainability seen again and again in the literature, a statistic-heavy presentation of the growing urban population, an articulation of what this means in terms of capability to support these numbers, and hand-wringing about the challenge to support this growth ‘sustainably’ (see Satterthwaite (2010), as well as the opening paragraph to this chapter). ‘*Agenda 21*’, a global sustainable development ‘action plan’ developed at the 1992 *Rio summit*, follows a similar narrative to Brundtland, championing the need for action at the local level, and devolving decision-making responsibilities to sub-national levels (UN 1992a, Chapter 8; Haughton and Hunter 1994, p7).

The *Aalborg Charter* of 1994, committed over 3000 signatory municipalities from more than 40 countries to setting up ‘*Local Agendas 21*’ (Lafferty 2001). The *Charter* recognises urban areas as “responsible for many environmental problems humankind is facing” and therefore cities and towns as “key players in the process of changing lifestyles, production, consumption and spatial patterns” (Aalborg Charter 1994, p1). Seemingly based on a ‘three pillar’ foundation of “social justice, sustainable economies, and environmental sustainability”, this considered issues such as land-use, mobility, pollution, and local self-governance, and paved the way for the implementation of sustainable action plans in urban areas around the world (Evans and Theobald 2003). Various sustainability plans were consequently adopted by urban administrations in the 1990s, although not always using the language of sustainability, such as ‘*Sustainable Barcelona*’ in 1995, and Singapore’s ‘*Green Plan*’ in 1992 (Shen et al. 2011). Thus the urban is re-cast here into an arena in which the practices of sustainable development should be applied (Petts et al. 2008).

1.2.2 Defining and understanding urban sustainability

Whilst the early literature tends to coalesce around Rio, the *Local Agendas 21*, and the efforts of local and national governments, it seems there has always been a conceptual ambiguity and array of understandings to the meaning of urban sustainability. One of the earliest definitions is presented in Hanson (1989)’s consideration of transport use in urban centres:

“urban sustainability, by analogy [to *Brundtland*’s ‘global’ sustainability], can be defined as the capability to support concentrations of human population indefinitely, which includes an adequate water supply in quality and quantity, shelter, transportation and communication services, food, employment, and various types of institutional support provided by government or cultural entities” (p95).

Here, urban sustainability is understood as a contextual reapplication of a global notion of sustainability, with the urban area understood as the focus for action to be taken. Mitlin and Satterthwaite (1996) articulate a similar understanding in their discussion of the application of sustainable development to cities, this is distinguished from the notion of ‘sustainable cities’ which they understand as the reliance of a city on its immediate hinterland⁸ for the fulfilment of its citizens’ needs, a demand which they consider unrealistic (p35).

‘Footprints’ and reliance on ‘hinterland’

The insistence that to be sustainable an urban area must be self-sufficient on a local hinterland is arguably an issue of semantics, and ignores the complex reality of contemporary life and the globalised economy. It is through this understanding however that various authors claim that ‘urban sustainability’ remains a contradiction of terms (see e.g. Owens 1992; Blassingame 1998; Martínez-Alier 2003a; Berger 2014). To Berg et al. (1989), “cities aren’t sustainable because they have become dependent on distant, rapidly shrinking sources for the basic essential for food, water, energy and materials” (p104). Such a view also echoes Rees (1996)’s ‘*Why cities cannot be sustainable*’ which argues that the reliance on a hinterland that is spatially divorced from the city proper means that cities cannot be sustainable. From this, and earlier considerations of ‘carrying capacity’⁹, the notion of ‘urban ecological footprints’ is forwarded. This is defined as the area of land which is required to meet the carrying capacity of an urban area, and is argued to be an important operationalised measure of sustainability by the authors (Rees 1996). These ‘footprint’ methods remain well established, and the ‘*Global Footprint Network*’ regularly produces accounts or national, regional, and city level footprint calculations (Lin et al. 2018). Such conceptualisation confronts the implications of globalisation, where the hinterland can no longer be considered local, but transcends international boundaries. This is

⁸The concept of a loosely defined ‘urban hinterland’ is frequently invoked in discussion of urban sustainability. It is understood here as land typically considered outside the traditional urban boundary, but still functionally connected to it (Sukopp 1998, p4).

⁹The number of people that may be supported by an area of land (Rees 1992).

something which has been explored in various manners by authors in the field of urban studies such as Friedmann (1986), Sassen (1991), and Brenner (2018).

The contestation surrounding this issue may be interpreted as one relating to the definition of boundaries. The city or urban system is invariably delimited by one or multiple politically defined boundaries (Yang 2019). Such boundaries are usually instrumental in the application of policy (Shaw 2015), but largely arbitrary and irrelevant in delimiting the urban's functioning (Hidle et al. 2009). Thus the 'functional boundary' may be considered in relation to bounding the functioning of particular phenomena of interest. Such a concept is useful theoretically but may not easily translate to a spatial area, or may require a formal empirical definition (Klapka and Halás 2016; Berdegúe et al. 2019). Classically such functional boundaries have been used to capture economic phenomena such as flows of capital, or labour markets (Hartshorne 1950; Frey and Speare 1992; Jones 2017), however they may also be considered in relation to more diverse flows such as that of waste and pollution, knowledge, or social norms (Davoudi 2008). Thus it can be argued that the reliance on a globalised hinterland itself, is not a criterion for 'unsustainability' if functional boundaries are redefined in broader terms than the traditional spatial confines.

Exporting 'unsustainability'

Satterthwaite (1997) presents an early discussion of the lack of clear definition to the term 'sustainable cities'. He argues that this ambiguity allows agencies to claim they are leaders in promoting sustainability when in fact they are encouraging practices that are detrimental to such goals being met. To Satterthwaite, it is "not cities or urbanisation that sustainable development seeks to sustain, but to meet human needs in settlements" which necessitates institutional and regulatory frameworks for this to be realised without exporting costs (p1682). The issue of boundaries is discussed here in terms of exporting 'unsustainability' or 'negative externalities', not only to future generations, but to people in other, generally poorer, geographical locations. This pairs the 'intergenerational equity' which is commonly associated with sustainability discourse (see Vojnovic 1995) with what may be thought of as an 'interspatial equity'. Satterthwaite argues that the people who are affected by this transfer of costs often have no political influence to combat this. He articulates a framework of five important environmental aspects for cities: sanitation, chemical and physical hazards, urban environment quality, minimising transfer of costs to surroundings, and sustainable consumption; the first three issues for local authorities, but the latter two are argued to be more problematic and must be dealt with at broader scales. Local authorities often lack power to act, and regardless, some

aspects such as sustainable consumption need to be implemented at higher levels, requiring both national and international agreements and incentives which are often at odds with globalisation. This frames urban sustainability as a multi-scale issue, spanning different hierarchical governance levels (Bulkeley and Betsill 2005).

The issue of interspatial equity and the notion of exporting unsustainability once again highlights the importance of drawing appropriate functional boundaries. Such accountancy tricks that redraw boundaries to exclude unsustainable practices further down the supply chain without providing any tangible benefits to improving sustainability at the global level should not be deemed acceptable (Wood et al. 2015). Spangenberg (2010) states that in our globalised world there remains nowhere left to export local unsustainability, contrasting this to expansionist approaches taken with an imperialist view. He acknowledges that there remains work to be done to move towards a future world where “cultures collabor[ate] on equal footing, recognising their mutual complementarity” (p572). Martínez-Alier (2003a) discusses the exporting of unsustainability in reference to gentrified renewal of urban centres, and asks “who has the power to privilege one analytical point of view (the economic, the social, the environmental) at a chosen time-space scale?” (p49). This emphasis on a three pillars conception of sustainability underlines that such export should not be considered just in terms of environmental impacts, and recalls reports of local authorities ‘solving homelessness’ by bussing rough sleepers out of their administrative boundaries (Gee et al. 2017). Martínez-Alier (2003a) goes further linking an ‘environmental justice’, which connects environmental issues with racial and gender inequality and poverty, with the politics of scale; here several open-ended questions are asked “at which scale(s) should (un)sustainability be assessed?” (p50), “where are the actors of urban environmental conflicts actually located?” (p53). Whilst not necessarily easy to answer, these questions highlight key areas that any operationalisation of urban sustainability must consider when demarcating its boundaries of interest.

An interdisciplinary endeavour

Much like sustainability proper, urban sustainability has been presented as an interdisciplinary endeavour. The British research councils began actively funding such research in the early 1990s, with both the *Engineering and Physical Sciences Research Council* (EPSRC) and *Natural Environment Research Council* (NERC) launching funding programs following a 1992 review (Evans and Marvin 2004; Petts et al. 2008). Whilst initial ambitions foresaw strong interdisciplinary collaborations, the inherent siloed structure of the research councils, coupled with a desire for

‘application’ lead to a heavy bias towards science, technology, engineering and mathematics (STEM) (Evans and Marvin 2004). Thus the core of the EPSRC’s ‘*Sustainable Cities Programme*’ was purposed towards the development of “environmental modelling and monitoring techniques” (p17). Evans and Marvin (2004) criticises the reductive engineering derived systems approach taken to understanding the city developed by these funding programmes, where society is taken merely as a backdrop rather than a part of the solution (pp17-21). It is argued that the interdisciplinarity initially promised by the initial research council aims was ultimately outsourced to local authority users who were forced to fill the gaps themselves in applying research outputs (pp26-27). Petts et al. (2008) explore additional barriers to interdisciplinary work in this area too, including inherent epistemological differences, and unequal divisions of labour, arguing for a greater emphasis on the intellectual challenge of interdisciplinary work. More recently, the European Union’s ‘*JPI Urban Europe*’, which launched in 2010 unbounded by the specificity of disciplinary research councils, has positioned itself as fostering “ambitious, sustained and truly inter- and transdisciplinary research” for sustainable and liveable urban futures (JPI Urban Europe 2015, p4).

Various interpretations of urban sustainability exist throughout the literature, and these are often geared towards the specific disciplinary interests of the authors. This for example includes a focus on advancing sustainability through planning, by recognising the negotiations at different levels of policy implementation, and a tension between growth and conservation (Campbell 1996; Mazza and Rydin 1997; Campbell 2016). To Wu (2014) the competing methodological frames for understanding ‘urban sustainability’ appear to converge upon the concepts of ecosystem services, resilience, complex adaptive systems, and coupled human-environment systems (p218). The ‘three pillars’ are also commonly seen as a central framing device for understanding urban sustainability (Bithas and Christofakis 2006; Keivani 2010; Tanguay et al. 2010; Fu and Zhang 2017 etc.). Here issues such as pollution, meeting the needs of the urban poor, and economic growth are often discussed. This arguably endorses the hypothesis that many authors view ‘urban sustainability’ as a simple reapplication of ‘global sustainability’ at a local scale. Despite this, issues such as transport and energy which have received significant attention under the banner of ‘urban sustainability’, often do not fit neatly within these three silos, leading instead to cross cutting themes of consideration.

Hamman (2017), who is critical of an undemocratic, managerial, and economic centred sustainable development paradigm, reviews understandings in the literature of the ‘sustainable city’, performing lexical analysis to map related terms. The

analysis argues that the ‘sustainable city’ is “permanently in the making”, being both a transitional concept temporally, and a transactional concept socio-spatially where various actors, by their own agency or not, are involved in trade-offs and compromises for their co-existence (p20). Hamman argues that whilst some alternative approaches to the normative sustainable development paradigm, such as resilience, degrowth, and ‘transitions’ exist, the nature of ‘sustainable’ as a ‘catch-all’ term precludes these as true alternatives. Ultimately “no single meaning and model of urban sustainability” emerges from Hamman’s review. Remaining critical of the normative paradigm implicitly asserting the maintenance of the economic status quo, the author argues that alternative practices should be conceptualised and implemented locally, and a change in values should be encouraged.

1.2.3 The nature of urban sustainability

The nature of urban sustainability conceptually may be viewed through various lenses, whilst these are not mutually exclusive, they elaborate a range of perspectives that exist within the literature.

A reapplication

Urban sustainability can be viewed as a contextual reapplication of a global concept. This is seen in the *Local Agenda 21* initiative as a modification of the global *Agenda 21* (Selman 1998), and the arguments detailed above from Hanson (1989), and Mitlin and Satterthwaite (1996).

Here the context of the city is often taken as a given, and this can be seen by local actors and urban researchers reapplying the global notion of sustainability to their domain of interest, i.e. the urban. This is particularly prevalent in the earlier literature where sustainability research can be viewed as novel. Mazza and Rydin (1997) argue that there remains an intrinsic ambiguity here relating to how this reapplication should play out in an operational sense.

A wicked problem

Sustainability has frequently been referred to as a ‘wicked problem’ (Murphy 2012; Pryshlakivsky and Searcy 2013; Blok et al. 2016; Yearworth 2016). Defined by Rittel and Webber (1973) in opposition to ‘tame problems’ for which “the mission is clear [and] it is clear, in turn, whether or not the problems have been solved. Wicked problems... have neither of these clarifying traits” (p160). Conklin (2005) generalises wicked problems based upon 6 characteristics: You don’t understand the

problem until you have developed a solution; Wicked problems have no stopping rule; Solutions are not right or wrong; Every wicked problem is essentially unique and novel; Every solution to a wicked problem is a ‘one-shot operation’; Wicked problems have no given alternative solutions (pp7-8). Head (2008) characterises wicked problems in public policy by high levels of complexity in sub-systems and interdependencies; high levels of uncertainty in relation to risks, consequences of action, and changing patterns; and high levels of divergence and fragmentation in viewpoints, values, and strategic intentions (p103). Urban sustainability can be argued to meet all of these criteria due to its contested nature, the fragmentation of the ‘experts’ and actors interested in it, and the conflicting values underlying its ‘solution’ (Thorén 2015).

Furthermore, Murphy (2012) argues that the consequences of unsustainable practice are often distant in time and space, embedded in social structures which resist change, and exhibit a ‘scale impasse’ in that successful local endeavours are dwarfed by the mass scale required for global change (p18). Of course, by their very nature wicked problems remain a serious challenge to address, Frame and Brown (2008) argue the need for a ‘post-normal science’ which is “transdisciplinary, context-sensitive and committed to methodological pluralism and concepts of active stakeholder engagement” (p226). Conklin (2005) presents similar arguments, emphasising the need to develop coherence in the face of fragmentation. Roberts (2000) presents three strategies for tackling wicked problems, authoritative, which place the responsibility in the hands of a few people, eliminating many diverging viewpoints; competitive, which encourage confrontation between opposing views in the hope of a compromise solution; and collaborative, which aim to engage actors to find common ground.

A complex process

The wickedness of a problem is in part derived from its complexity, understood here as multidimensionality, being composed of numerous concepts and referring to a process rather than a fixed state (Dao et al. 2017). With sustainability being complex and multidimensional itself, the addition of the urban context necessitates an additional layer of complexity (McPhearson et al. 2016a). The multidimensional complexity of urban sustainability is widely accepted (Finco and Nijkamp 2001), and indeed is central to varied discussion on how this complexity should be grappled with on an operational level in prioritising the needs and wants of relevant actors (Turcu 2013; Mori et al. 2015; Gutiérrez et al. 2018).

Framing of urban sustainability as a process is often referred to in literature on ‘urban transitions’ (see e.g. Hodson and Marvin 2012). Traditionally this has been cast in terms of a path to ‘low-carbon’ urban areas with a focus on emissions, retrofitting, and ‘smart’ technologies (Haarstad 2016). More recently however a more critical narrative has arisen that gives greater focus to the social aspects of these processes, particularly regarding gentrification, and models of ownership (Luque-Ayala et al. 2018). This evokes parallels with the multidimensional nature of the ‘three pillars’ of sustainability.

A goal

To others urban sustainability is seen as an end point or goal that can be reached or should be strived towards, often framed as the ‘sustainable city’ (Wu 2010). This ‘goal’ status is present in wider discourses in sustainability, and leads to the question as to whether it is conceptually relative or absolute (Faber et al. 2009). Thompson (1992) is wary of characterisation as an absolute goal, arguing that this demands a definition of boundaries, a task which “quickly take[s] on ethical or political connotations” leading to a “normative judgement being smuggled into the analysis without argument” (p15). Rana (2009) argues too that the goal oriented sustainable city discourse is biased towards the Global North, and largely inappropriate for cities in the Global South which necessitate a greater emphasis on ‘just’ and ‘equitable’ transformation.

The articulation by the UN of an urban sustainable development ‘goal’, ‘*sustainable cities and communities*’, has arguably galvanised a new wave of research probing urban sustainability conceptually. Klopp and Petretta (2017) discusses the challenges surrounding the urban sustainable development goal, including defining indicators in the first place, the lack of standardised, comparable data, and the diversity of urban contexts around the world. Much of this reconceptualisation has surrounded the same approach to sustainability that precipitated much criticism of the *Brundtland report*. Due to the nature of the UN approach being embedded in politics, the subgoals of the SDGs have been argued to not be ‘entirely scientific’, with indicators which are inherently rigid and unable to confront urban complexity (Moreno Pires et al. 2014). Simon et al. (2016) test proposed indicators across 5 diverse cities, including Cape Town, Greater Manchester, and Bangalore, finding that all cases were constrained by data. Thus a tradeoff plays out between what is useful and practical for city administration and what meets the ‘scientific goal’ of understanding urban complexity. One further criticism of the goal framing is that it implicates a static rather than dynamic view of sustainability, the landscape is constantly evolving with new priorities and issues arising all the time (Faber et al. 2005).

A contested concept

Dao et al. (2017) define contested concepts as a subset of complex concepts with an “implicit normative value” where “all parties to the debate agree that the concept is positive/negative” but “internal complexity leads to a diverse descriptability” and “the meaning of the concept is open and subject to unpredictable revision through time and context” (p642). The examples given by Dao et al. (2017) are invariably political in nature such as democracy or social justice. Urban sustainability also meets the specifications of this definition (Winter 2016), as do sustainability and the urban individually (Connelly 2007; Barnett and Parnell 2016).

This conceptualisation underlines the political and value-laden nature of urban sustainability. Whilst it is normatively understood as implicitly positive and desirable, there is much diversity as to how it should be conceptualised and who it should benefit (Winter 2016).

A working definition?

Given the clear multidimensional complexity of urban sustainability even in terms of how it may be understood, it is not easy to provide a singular definition. Nevertheless it is necessary here to articulate how ‘urban sustainability’ is to be understood within this thesis:

Urban sustainability is a reapplication of ‘sustainability’, in a global sense, to the urban context. This brings sustainability as a semantically open concept of what it means ‘to keep something going’ (Ramsey 2015), together with the contestations surrounding the urban, typically understood as relating to agglomeration at the local scale, and the numerous contextual specificities this brings. The multidimensionality of urban sustainability necessitates consideration across traditional disciplinary boundaries including environmental, social, and economic factors. The emphasis on locality highlights interaction across boundaries and scales, as well as consideration of an ‘interspatial equity’ in parallel to the more typical focus on intergenerational equity.

Whilst urban sustainability may be cast as a goal or ‘ideal state’ that may be reached, the notion of an absolute urban sustainability is rejected here. The future is inherently uncertain and thus without specification of a time horizon it remains problematic to describe something as sustainable in the absolute. Sustainability is then held as a relative concept, where the transition to a more sustainable state can only be described to the best knowledge.

1.3 Operationalising Sustainability

Dao et al. (2017) conceptualise the operationalisation process as a sequential one from ‘definition, measurement, interpretation’, through ‘agreement’ to ‘use’. This implicates operationalisation as a participatory process. Such an approach can be viewed as good practice, and logically follows the necessity for the researcher to engage with third party stakeholders for tangible outcomes, yet the nature of this interaction is debated (Mathur et al. 2007). Turcu (2013) describes top-down (expert-led) versus bottom-up (citizen-led) approaches to operationalisation, and explores the tensions between them in developing indicators for urban sustainability. To confront this an integrated approach is forwarded which includes early involvement of citizens but stresses the role of expert-led methods in evaluation and dissemination.

Cohen (2017) presents a systematic review of methods for assessing urban sustainability. The findings presented suggest that indicator based approaches dominate the assessment literature, making up nearly 60% of the reviewed literature, while other approaches were found to be less common such as principle-based frameworks, metabolism studies, and eco-efficiency measures. As well as identifying areas of progress, indicator frameworks propose to highlight areas of weakness to policy makers where attention is required. There exist significant efforts to develop and promote indicator frameworks to measure sustainability in cities around the world, both in academic circles and institutionally, such as with the UN’s sustainable development goals (Simon et al. 2016; Winter 2018).

1.3.1 Measuring: indicator approaches

With the abundance of differing indicator frameworks a variety of contexts of application may be seen, with some studies being specific to particular locales (e.g. Braulio-Gonzalo et al. 2015; Lützkendorf and Balouktsi 2017; Pili et al. 2017), whilst others claim generality (e.g. Tanguay et al. 2010; Mori and Christodoulou 2012; Mori et al. 2015), or detail generalised frameworks that may be applied locally (Munier 2011; Tran 2016; Ali-Toudert and Ji 2017). Further, a systematic review of the academic literature by Verma and Raghubanshi (2018) reveals a diverse range of methodologies used for post-processing and weighting of indicators. Various statistical techniques such as principal component analysis (Mascarenhas et al. 2015), factor analysis (Huang et al. 2015), and Fourier analysis (Luan et al. 2017) are seen, both with and without stakeholder and/or expert engagement.

Top down and bottom up

There appears to be a growing school of thought, that to be useful in practice, indicator frameworks must engage with stakeholders including both policy makers and citizens (Shen et al. 2011; Turcu 2013; Mori et al. 2015). It is thus possible here to differentiate these studies and frameworks roughly into top-down (expert led), and bottom-up (citizen led) approaches (Reed et al. 2006). These latter approaches tend to embrace context specificity, and cast doubt on the search for a universally applicable framework. A detailed example of the attempted marriage of these approaches is presented by Turcu (2013) who develops a framework for measuring urban sustainability in the UK context through an iterative process of consultation between ‘experts’, and residents of three chosen communities. Turcu argues for citizen led approaches to better address the specificity of local issues, but concedes that a fully integrated set of indicators cannot be comprehensive at all levels, and the process is as much political as scientific. Further a reminder is given that community level priorities are not static but evolving in time in response to changing events and circumstances, this necessitates flexibility and precludes the existence of a definitive indicator set.

Choosing indicators

Various studies exist which aggregate and compare indices from a selection of frameworks. For example, Tanguay et al. (2010) conduct an analysis of 17 studies which apply sustainability indices to the urban context. The analysis reveals a stark lack of consensus in both the optimal number of indicators to use (ranging from 10 to 86), and the selection of the indicators themselves: from the 17 studies a total of 188 individual indicators were identified, of which 72% applied to only 1 or 2 studies. This lack of consensus can be attributed to the broad definition of sustainability, as discussed previously, as well as differing aims between the studies, and constraints imposed by the accessibility of data leading to indicators that are selected primarily for convenience rather than based on a rigorous theoretical framework (European Commission 2015). Tanguay et al conclude by compiling a list of 29 indicators, as a subset of the original 188; this list is obtained subject to the constraints of using (1) the most cited indices, (2) even coverage of the ‘three pillars’, and (3) simplicity to aid data collection, and understanding. Such an approach is useful for understanding what common issues and priorities exist across studies, however this is at the expense of understanding the specificity of the case in question. Generalised frameworks of course allow for comparison of different contexts, but the value of comparison for the local level is not necessarily clear.

Mori et al argue the need for an absolute evaluation with standards and thresholds, admitting the difficulty of its creation (Mori and Christodoulou 2012; Mori et al. 2015; Mori and Yamashita 2015). In a similar approach to Tanguay, Mori and Christodoulou (2012) conclude that such an index should consider the ‘three pillars’; capture leakage effects to the environment; be initially purposed for assessing cities; be applicable to both developing and developed locations. Mori et al. 2015 build on this previous work to develop an assessment system. They distinguish between what they call constraint and maximisation indicators, the former based on environmental sustainability and socio-economic justice, e.g. CO₂ emissions, and access to safe water; the latter measures socio-economic benefits, e.g. GDP per capita, housing costs, traffic congestion. Under this proposed framework, all constraint indicators must be satisfied for a city to be considered as sustainable. They argue the need for future work to address the methodology for calculation, criteria to determine clear thresholds, and a need for an assessment of the dynamic trajectory of sustainability.

Criticism

Verma and Raghubanshi (2018) identify both internal and external challenges to indicator based approaches, the former composed of issues relating to methodology, weighting, dealing with boundaries, and complexity, and the latter regarding barriers to implementation such as data constraints, a lack of political will, and failure to build consensus. Satterthwaite (1997) emphasises the difficulty of comparing factors across widely different urban contexts, as well as arguing that quantifiable indicators get more attention than they perhaps deserve, e.g. sulfur dioxide concentration over sanitation. One recurrent criticism, outlined by Cohen (2017), is that assessment often has no underlying theoretical framework, often only loosely conceptualised in terms of a three silo approach which overlooks interdependence as well as spatial and temporal aspects. Indeed it has been argued that this weak theoretical framing that contributes to indicators being picked based on data availability (Keirstead and Leach 2008). Cohen (2017) critiques the blind application of indicators without framework or underlying principles, leading to tradeoffs and uncritical acceptance of economic goals, but admits a lack of consensus on what guiding principles should be. He recommends the standardisation of terms and concepts across studies, although offers no clear route to this being realised, as well as the need for a concise and coherent theoretical framework which draws from diverse methods to generate robust assessment.

Whilst the problems associated with sustainability assessment are well elaborated, a clear approach to overcoming them is not, indicating that there is no easy way forward. There is no shortage of proposed solutions to technical issues (e.g. Huang et al. 2015), but one must also consider that there seems to exist as many critical papers attempting to integrate various disparate frameworks as there are frameworks themselves. Yet despite this, there remains little progress in this area. Kaika (2017) argues that this should give indicator advocates some caution to their view that complex factors such as socio-environment quality can be reduced to a series of indicators. To Kaika, these “old methodological tools” have failed, and new grassroots ‘dissensus’ approaches are required.

This chimes with the observed domination of positivist approaches with a lack of awareness to inherent biases, whereby sustainability issues are framed as technical and scientific problems rather than political and social challenges (Turcu 2013). This is presented too as a bias towards physical and environmental factors as observed by authors such as Braulio-Gonzalo et al. (2015) and Opp (2017). Turcu (2013) argues that the unity of a single ‘best practice’ approach must be renounced in favour of pursuing a ‘methodological pluralism’. Still, approaches should centre around a strong methodological framework rather than an ad hoc checklist of indicators chosen for expediency. Without agreement on what sustainability means, any methodological frame should clearly state the nature of its understanding and robustly justify its formulation.

1.3.2 Modelling

Schichl (2004) defines a ‘model’ generally as “a simplified version of something that is real” (p28). As the production of abstract representations of real life, modelling then may be understood in various forms, from the production of physical scale models of natural or engineered systems (Bruno 2005); ‘analogical models’ such as the billiard ball model of particle dynamics (Gutkin 2013), or gravitational models of migration (Karemera et al. 2000); to ‘toy models’, which are highly simplified and idealised representations (Reutlinger et al. 2018), such as Lotka–Volterra population models in ecology (Wangersky 1978). Authors such as Greca and Moreira (2000), Morgan (2017), and Frigg and Hartmann (2020) provide detailed overviews of taxonomies of various modelling approaches, but the general purposes of modelling may be understood as explanatory, predictive, communicative, or informative (for decision making) (Schichl 2004). In this thesis, modelling, unless otherwise specified refers to computational modelling.

Modelling for policy analysis

Walker (1982) traces the application of modelling in policy formation from the operations research which arose during the second world war (see Fortun and Schweber 1993). Models are recognised as an important tool for policy makers allowing for impact assessment, diagnosis, and forecasting, as well as acting as learning tools, providing a means to analyse potential consequences of proposed policy in a virtual environment (Walker and Van Daalen 2013). It is therefore clear that modelling has much to offer for operationalising a notion of urban sustainability (Lautso 2002; Robinson 2019).

The interface between policy and academic research has been conceptualised within the fields of Interpretative Policy Analysis and Science and Technology Studies (Wesselink et al. 2013). Rather than a linear model of mono-directional knowledge transfer from ‘science’ to ‘policy’, this interaction is better understood as two-way and ‘turbulent’ in its dynamics, with no clear boundary between science and politics (Hulme et al. 2011). Despite this the place of computer modelling within the policy process remains little understood or documented (Brugnach et al. 2007). Often policy modelling occurs behind closed doors, being outsourced to private consultancy firms, or models are developed ‘in house’ but are not openly available, either due to data sensitivity, a lack of resources, or just an unwillingness to share (Henrion 2007; Pfenninger et al. 2018). Urban sustainability modelling within the academy can therefore range from work which is co-produced with heavy involvement of both policy makers and ‘experts’ to work which involves no interaction across this boundary, but adds to the body of knowledge which may inform future work (Rizzoli and Young 1997; Voinov and Bousquet 2010).

Modelling urban sustainability

Modelling for urban sustainability may be categorised as either phenomena specific or integrated (Mulligan and Wainwright 2013, p16). Phenomena specific, or ‘single-domain’ models focus on a single issue such as land use, or energy systems, although many of these may be considered integrated to an extent due to the necessity to incorporate various exogenous phenomena¹⁰. Integrated models then seek to integrate multiple phenomena to present a more complete picture by centering interaction and feedback effects which may be missed by phenomena specific

¹⁰Endogenous phenomena may be considered those which are modelled directly, exogenous phenomena are not modelled directly but fed into the model via parameters which are generated externally (Richardson 2011)

models¹¹. The appropriateness of these two approaches is dependent on the questions they are intended to answer, as well as the spatial and temporal scales of interest (Robinson 2019). This work, in considering urban sustainability broadly is clearly best suited for an integrated approach.

Matthies et al. (2007) conceptualise such integrated models across a spectrum from integrated assessment models (IAM)¹² to decision support systems (DSS)¹³. Whilst much overlap exists between the two (Seidl and Le 2012), DSS tend to be focused towards stakeholders using them directly as the end user (McIntosh et al. 2011), whereas IAM are primarily used by scientists (Harfoot et al. 2014). Ravetz (1998) suggest that urban modelling could benefit by learning from global integrated assessment models. Argent (2004) suggests that the growth in integrated modelling which promotes deeper consideration of socioeconomic factors in environmental management can be seen as a response to the ‘triple bottom line’ concept adopted elsewhere.

Examples of integrated models for addressing urban sustainability include the *InSmart* project which integrates several tools and methods to produce future policy scenarios to aid municipal stakeholders in the development of sustainable action plans (Gargiulo et al. 2017). The *SUSTAIN* project integrates urban transportation and societal metabolism to develop a system dynamics ‘board game’ for use as a learning tool for students and policy makers (Armenia et al. 2020). Balocco et al. (2004) develop an integrated exergy based method which combines life cycle analysis with thermodynamic concepts to model and analyse the sustainability of an urban area.

Phenomena specific models which intend to operationalise urban sustainability are of course diverse, including flood modelling (Ellis and Viavattene 2014; Miguez et al. 2015), transport modelling (Jakimavičius and Burinskiene 2009), urban growth (Barredo and Demicheli 2003), waste management (Sufian and Bala 2007), etc. Here a wider range of simulation techniques and methods may be employed such as cellular automata (Li and Yeh 2000), computational fluid dynamics (Jun Chung and Choo 2011), system dynamics (Shepherd 2014), agent based modelling (van Duin et al. 2012; Bustos-Turu et al. 2016), as well as GIS and 3D modelling (Reinhart and Cerezo Davila 2016).

¹¹It is necessary to differentiate between ‘integrated models’ as the integration of diverse phenomena into a single model, and ‘model integration’ as the integration of pre-existing models, often built using diverse techniques, into a ‘modelling framework’ (Argent et al. 2006; Rizzoli et al. 2008). This work is concerned with the former.

¹²Defined by Nordhaus (2013) as “computerised dynamic models... that integrate knowledge from two or more domains into a single framework” (p1070), typically across what Pauliuk et al. (2017) refer to as the ‘global socio-ecological system’.

¹³Defined by Arnott and Pervan (2008) as “the area of the information systems (IS) discipline that is focused on supporting and improving managerial decision-making”.

Outputs to modelling methods for operationalising urban sustainability are often presented in the form of ‘scenarios’. As is perhaps fitting following the presentation of urban sustainability above, Bradfield et al. (2005) state that “there appears to be virtually no area in scenarios on which there is wide-spread consensus” (p796). Nevertheless, a scenario may be loosely understood as an “attempt to define a number of possible futures [...], which span the space of all futures” (Audsley et al. 2006, p149). Since the growth of computing in the 1960s, scenario modelling is now commonly used across the management sciences, as well as for policy analysis, notably in relation to climate change (Hulme and Dessai 2008; Greiner et al. 2014). Whilst scenario modelling has clear strengths for informing policy, the ambiguity surrounding its understanding can lead to confusion. In particular this can surround the scenario’s status as a forecast or prediction, a misunderstanding that led to much criticism of the 1972 *Limits to Growth* study (Meadows et al. 1972; Bardi 2011; Jackson and Webster 2016). Scenarios rarely come alone, and must be considered a set of plausible futures based upon varying assumptions and policy decisions (Eastin et al. 2011).

1.3.3 Other approaches

Outside of traditional indicator approaches and the use of simulation modelling, other common approaches to operationalising urban sustainability include rating systems and eco-efficiency assessment, footprint analysis, and urban metabolism methods.

Reyes Nieto et al. (2018) review a series of ‘urban sustainable assessment tools’, these are impact assessment tools for assessing the ‘sustainability’ of construction projects, above single building scale, such as *LEED* (USGB 2000) and *BREEAM Communities* (BRE 2012). Such approaches tend to be indicator based, yet are focused towards the built environment due to their intended use in planning and construction, thus limitations regarding their coverage of multiple dimensions of sustainability are routinely critiqued, particularly regarding the social dimension (Sharifi and Murayama 2013; Ameen et al. 2015).

Urban metabolism approaches regard the city as analogous to a biological organism, necessitating the continual flow of matter and energy through it to maintain operation and growth (Hoornweg et al. 2012). Developed by Wolman (1965), the field has seen a resurgence in recent decades following the emergence of urban sustainability as a fashionable research paradigm (Kennedy et al. 2011). Wolman’s 1965 article modelled a hypothetical US city drawing on per capita consumption and production data, to demonstrate the volume of input and output materials such as water, fuel, pollutants and sewage. The field primarily focuses

on ‘environmental’ issues related to resource throughput, such as waste generation, resource conservation, and waste generation. To some advocates, this provides a theoretical framework from which parameters may be generated that measure the environmental impact of urban areas, allowing for urban planners to work with indicators in a ‘scientifically valid’ way (Céspedes Restrepo and Morales-Pinzón 2018, p216).

A Physical Basis?

Some authors have looked towards the physical sciences in order to develop less interpretivist, and more ‘objective’ sustainability principles (Hueting and Reijnders 1998; Sciubba and Zullo 2011a; Csernai et al. 2016). These vary from conservation based rules grounded in systems science, such as Goodland and Daly (1996)’s basic input/output conditions for maintaining a circular resource economy, to approaches which employ fundamental laws of thermodynamics (Sciubba and Zullo 2011b). Amsler (2009) argues that the desire for a ‘mathematical description’ of sustainability, rather than a more loose understanding, coheres with fields considering urban sustainability from a positivist or post-positivist tradition. In many of these fields, the need to develop an objective framework of conceptualisation and measurement is perceived as necessary to bring ‘scientific rigour’ (Stirling 1999; Silka 2010).

1.4 Research Design

This introductory chapter has covered the various ways in which ‘urban sustainability’ has been conceptualised and operationalised within the literature. Urban sustainability has been shown to be contested across numerous fronts, both in terms of the interpretation of its constituent terms, but also due to its complexity and multidimensionality of the concepts which fall under it, and the multiple geographical scales across which it spans. As an interdisciplinary endeavour urban sustainability receives interests from a diverse spectrum of disciplinary backgrounds, each with their own methods and epistemological foundations.

A working definition for urban sustainability was proposed in Section 1.2.3 to take forward in this thesis. Following this, a variety of methods used for operationalising urban sustainability were reviewed with a particular focus given to dominant indicator based methods. These were discussed in reference to criticism of the limitations of this approach, and the nature of engagement with stakeholders and experts in co-creation of methods. Throughout this review the fractured landscape

of the relevant literature was frequently encountered, with divergent methods and approaches witnessed, and a multiplicity of invested understandings.

This section outlines the research questions this work intends to confront, the contribution this thesis makes, and a sketch of the thesis structure. These are loosely structured around the organising structure of ‘define, measure, model’ (Kondyli et al. 2017; Larson et al. 2018).

1.4.1 Research questions

1. How can urban sustainability be understood? (‘Define’ → ‘Understand’)
 - (a) In a globalised world where the notion of the urban as a singular physical location is contested, how does ‘urban sustainability’ differ from ‘sustainability’ proper, normatively conceived as a global project?
 - (b) What part should consensus building or pluralism play to confront the fractured literature relating to urban sustainability?
2. How can such an understanding be operationalised to explore coherent ways of improving upon it? (‘Measure’/‘Model’ → Operationalise)
 - (a) To what extent may thermodynamic concepts be employed to provide a ‘physical basis’ for sustainability?
 - (b) How should an integrated assessment model be designed to be useful for such a purpose?
 - (c) How can the issues of boundaries be confronted?
 - (d) What barriers exist moving from theory to practice, and how might these be overcome?

1.4.2 Contribution

The contribution of this thesis is primarily theoretical and methodological. Section 7.2 discusses how such a theoretical contribution might be built towards an operational contribution in the future. The main contributions should thus be viewed as the following:

- A prototype multi-scale urban system dynamics model which presents a novel method for operationalising urban sustainability.

- An examination and analysis of the fractures and contestation surrounding urban sustainability, and a reflection of how these might be confronted to allow for successful operationalisation.
- An affirmation of thermodynamic principles for quantifying ‘unsustainability’ generally as a conceptual dead end.

These contributions have primary significance for researchers across all disciplines engaged in research on urban sustainability, as well as the operationalisation of sustainability more broadly. Some of the high level messages elaborated in Chapter 7 are also of relevance to urban stakeholders including policy makers and other institutional actors. It is hoped that in making the system dynamics model and associated documentation publicly available further research may be undertaken by others in using and adapting it.

1.4.3 Thesis structure

This thesis follows a somewhat unconventional structure¹⁴. It loosely follows the approach described by Dunleavy (2015) (pp60-62) as the ‘compromise model’ of the thesis, whereby the thesis core, here Chapters 3-6, are sandwiched between a focused literature review centred around the central research questions and research design, this introductory chapter and subsequent methodology chapter, and an analysis, Chapter 7, which integrates the conclusions of the individual core chapters. This is illustrated in Figure 1.1. Thus despite Chapters 3 and 4 being literature heavy, they should be considered ‘core’ rather than a preliminary literature review.

Thesis conventions and norms differ across the humanities, social sciences, and natural sciences (Holtom and Fisher 1999; Eco 2015). Carter et al. (2012) suggest that an interdisciplinary thesis allows for flexibility in structure and style, but that the expectations of the reader should be anticipated (pp14-15), this is echoed by Murray (2017) who cautions that “even the words ‘theory’ and ‘method’... can have very different meanings in different academic disciplines” (p25). It is for this reason that key terms have been defined in text and through footnotes, to ensure consistent understanding.

The following chapter, Chapter 2, presents broadly the methodology and research design of this body of work. It starts with an account of my positionality in respect to this work, and the context in which it was produced. Following this, successive

¹⁴A conventional structure is understood as Introduction, Literature Review, Methods, Results, Discussion, Conclusions (Carter et al. 2012, p17).

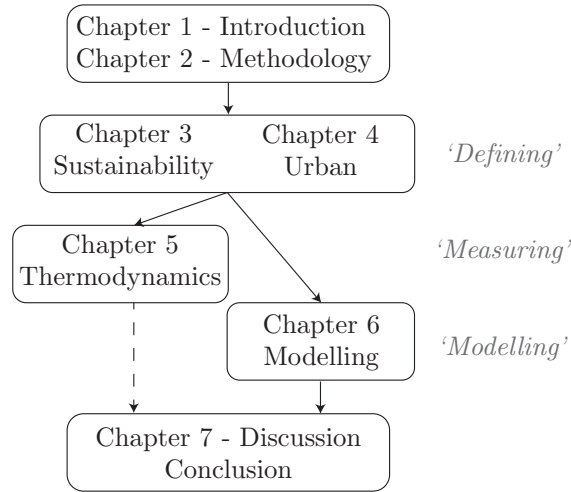


Figure 1.1: Overview of thesis structure.

sections break this thesis into four chunks, described as ‘defining, measuring, and modelling’, as well as a research synthesis. In each of these sections a part of my research questions are developed and elaborated in the context of related literature, and the proposed method outlined in how they will be addressed. The final research synthesis section describes how the findings of each of these sections will be synthesised into a coherent whole, and defines the scope of this work.

Chapter 3, in extending understanding of sustainability more broadly, focuses on the ‘three pillar conceptualisation’ of sustainability. This is outlined in terms of an integrative review of the early literature which conceptualises it both from academic and institutional sources. Through this it highlights further the key contestations associated with the concept of sustainability and suggests how these should be engaged with.

Chapter 4 addresses how the urban has been understood and conceptualised across the broad bodies of literature which consider it. This is done by focusing on the fracture in urban literature between the domains of ‘urban studies’ and ‘urban science’. Understandings of the urban in each of these areas are reviewed, and an outlook section outlines recurrent emergent themes spanning this divide. Ways of overcoming this barrier are discussed alongside how this can be confronted in this thesis and future work.

Chapter 5 looks at a particular physical view of operationalising urban sustainability, the use of thermodynamic entropy. The necessary thermodynamic basics are covered in relation to the work which has proposed the potential use of entropy here. Using physical analytical techniques, the merits of such an approach are explored. In light of the failure of this particular operationalisation to bear

fruit, reflections are given on why proposals relating to this remain prevalent, and what we can learn from its failure.

Chapter 6 then presents an alternative method of operationalising urban sustainability through the use of system dynamics simulation. The basics of system dynamics modelling are presented alongside a structural overview of the World3 model and its scenario outputs. The process of downscaling this to produce a coupled urban model is then described in full alongside the model equations and data sources used. After presenting scenarios and a discussion of what they reveal for understandings of sustainability in the urban context, an appraisal is provided of this approach and a discussion of how it could be adapted in future work.

Chapter 7 presents a final discussion which draws together the threads of the preceding chapters into a whole, in reference to the research questions proposed in Section 1.4.1. Emergent themes are analysed and discussed and reflections are given on the approaches taken within this thesis. A final Conclusion explicitly answers the research questions, summarises the contribution of this thesis, and details avenues for future work.

*The only thing that makes life possible is permanent,
intolerable uncertainty: not knowing what comes
next.*

— Ursula K. Le Guin, *The Left Hand of Darkness*

2

Methodology

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The term methodology is used here, in its general sense, to refer to the research design of this work in terms of both practical and theoretical issues (Oliver 2004, pp120-121). To Clough and Nutbrown (2012) the purpose of the methodology is to “persuade the reader of the unavoidably triangular connection between *these* research questions, *these* methods used to operationalise them, and *these* data so generated” (p46). This therefore necessitates a detailed description of the research

design including its theoretical orientation, justification, and methods.

This chapter begins by describing the research context, and my own position within this work, discussing the implications this has for the presentation of my thesis. Following this, the chapter is split into four sections, each describing the background and methods for each research streams, The first, Section 2.2, covers the epistemology of ‘defining’ and how this has been engaged with in work seeking to define urban sustainability and related terms. It outlines the motivation and methods taken for Chapters 3 and 4 in looking at two particular ‘fractures’ in the literature. Section 2.3 outlines literature related to the ‘measuring’ of sustainability, before justifying consideration of the thermodynamic literature seeking a ‘physical basis’ to sustainability and an approach to assessing it. Section 2.4 discusses the nature of modelling, and how integrated assessment models promise opportunity for operationalising urban sustainability. Several modelling methods are reviewed before an approach is outlined to be taken in Chapter 6. Finally Section 2.5 outlines how these individual research streams will be synthesised into a final discussion chapter which addresses the outlined research questions. A limit is placed on this work’s scope, and a discussion of ethics is given.

2.1 Positionality and Research Context

The metaphor of the PhD as a journey has been frequently invoked within the education literature (Batchelor and Di Napoli 2006; Carter et al. 2012; Lantsoght 2018). This PhD is no different in this respect, yet the context in which it has taken place has strongly influenced the evolution of this work and the divergence of the research trajectory from its initial design. It is for this reason that an approach of ‘reflexive transparency’ (Tuval-Mashiach 2017) is taken to illustrate the context of this work and contextualise decisions taken during the ‘messy process of research’ (Langmead 2018). This allows for greater critical reflection on the resultant methodology, and situates myself as a researcher within the social context of my research environment, rather than an independent observer carrying out controlled experiments (Finlay 2002).

2.1.1 Research background

I completed my undergraduate in theoretical physics in 2015, with my research dissertation focusing on mathematical models¹ of the expansion of the early universe.

¹Here the term ‘model’ is understood as a differential equation that represents the evolution of a scalar field over time.

This work used both computational and analytical techniques to compare expected model outcomes to empirical data (Purvis 2015). Following this I was recruited to the Laboratory of Urban Complexity and Sustainability (LUCAS) at Nottingham for an EPSRC funded PhD studentship with the working title ‘*physical modelling of sustainable urbanisation*’. In practice this was supplemental funding for the Leverhulme Trust funded project ‘*Sustaining urban habitats: an interdisciplinary approach*’ of which I was an active part, sharing office space with other students from the project, and attending seminars, ‘progress and integration meetings’, and stakeholder workshops.

This ambitious project drew together a broad range of researchers from across the social and natural sciences with the aim to “transform our understanding of how sustainable cities, and by extension our species, can be” (University of Nottingham 2015). Thus it was intended that I would utilise my ‘expertise’ as a physicist with an analytical modelling background, and a personal interest in environmentalism, within this interdisciplinary environment. Of course the PhD is a singular endeavour, so this meant carving out my own research project within the context of the wider group’s shared aims. Nevertheless my immersion in an interdisciplinary environment strongly influenced the evolution of my research, particularly regarding my own personal epistemology.

Thus my PhD journey represents a shift in my worldview from a primarily positivist tradition featuring textbooks full of foundational ‘facts’ to a constructivist realm where even the foundations of knowledge are contested. It captures an escape from a disciplinary silo into an area which is rich in interdisciplinary, post-disciplinary, or ‘undisciplined’ understandings (Haider et al. 2018).

2.1.2 An interdisciplinary study

Repko (2012) defines interdisciplinarity as the process of “addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insights to construct a more comprehensive understanding” (p17). The traditional academic disciplines themselves only date back to the 19th century but find themselves institutionalised with hegemonic status within the modern university (Moran 2002). Each discipline holds its own perspective of reality, composed of phenomena of interest, epistemology, assumptions, concepts, theory, and methods (Repko 2012, p101). Becher (1989) conceptualises these bounded disciplinary knowledge practices as ‘tribes and territories’, each with their own cultures and practices and often wary or hostile to explorers crossing into their research domain. Thompson Klein (1996)

uses the metaphor of ‘crossing boundaries’ to describe interdisciplinary work that engages with multiple knowledge practices, arguing that “the task of understanding is complicated by the ‘jungle of phenomena’ ” (p4).

Sustainability and the urban are both areas where interdisciplinarity is seen as a necessity in research addressing associated problems (Shmelev and Shmeleva 2009; Costa and Oliveira 2017; Fernandes and Philippi Jr. 2017). Interdisciplinarity is also a recurrent theme within the policy sciences and simulation modelling (Lenhard 2017; Vogel et al. 2017). It may be viewed as a possible remedy for grappling with complexity, multidimensionality, and addressing wicked problems (Pohl et al. 2017). It is therefore clear that understanding and operationalising urban sustainability cannot be done from the confines of a single disciplinary boundary.

As a singular endeavour, the ‘interdisciplinary PhD’ brings with it challenges, requiring versatility in research practices and conflicting methodologies, as well as navigating the complex ‘jungle’ of relevant literature (Golde and Gallagher 1999; Lindvig 2018). Various work has been produced regarding the interdisciplinary doctoral experience (see e.g. Manathunga et al. 2006; Calatrava Moreno and Danowitz 2016). Dooling et al. (2017) describe ‘dual loyalties’ of students to disciplinary and interdisciplinary intellectual communities (p576). Balaban (2018) conceptualises the experience of PhD researchers immersed in interdisciplinary research environments, within a university environment still very much grounded in traditional disciplinary structures, as one of ‘homelessness’. This is something which resonates with my experience, particular following the ‘dead end’ of the applicability of entropy and my redirection towards an area less obviously identifiable with my previous disciplinary background. Haider et al. (2018) talk about this path as ‘uncomfortable space’, where epistemological agility has been achieved but methodological grounding remains uncertain. Through the construction of this thesis however, I have managed to characterise my methodological grounding in simulation modelling, with further depth achieved in system dynamics as a means of exploring an understanding of sustainability for future scenarios.

2.1.3 Implications for this thesis

It is not controversial to state that research design is an iterative evolutionary process, particularly in the context of doctoral research. There remain questions however on how this research design should be presented. Langmead (2018) presents a non-linear thesis design, which reflexively accounts an ethnographic study focusing on worker cooperatives. As Langmead’s fieldwork progressed, her methodology evolved in response to perceived limitations of her original research design, described as “the

messy process of research”. She details how her identity as a practitioner engaged in participatory research was not conducive to the traditional thesis structure (p54).

In presentation of this thesis then, the decision was made to employ Tuval-Mashiach (2017)’s principle of ‘reflexive transparency’. The author recommends “significant events that took place during the course of the study and that caused the direction of the study to change” should be included in any final report (p10). Thus the temporal methodology is presented in this thesis rather than a ‘fictional’ methodology which attempts to integrate. The shifting goal posts of the methodology as presented is not then evidence of poor research design, but an honest representation of the research process, allowing for a richer and complimentary metanarrative reflecting on interdisciplinarity and pluralism (Burford 2017).

The work in this thesis started as a straightforward goal, from a positivist physical science perspective, to ‘define, measure, and model urban sustainability’. During the ‘messy process of research’ I began to believe that these former two prefactors were inadequate. Thus the ghost of this original organisation may be seen in this thesis: two literature chapters seeking to ‘understand’ sustainability, the investigation of a ‘measure’ for unsustainability in Chapter 5, and the modelling of Chapter 6. My methodology chapter then, having largely been written after the conclusion of the bulk of the work it describes, articulates a middle ground between the initial intentions and the final work that was carried out.

In symmetry, my theoretical framing is one centred on contentions and fractures; the disconnect and friction between ‘urban science’ and ‘urban studies’, the uncertain relation between the ‘three pillars’ of sustainability, and the lack of agreement on how the urban boundary should be defined. This is considered to be a natural result in a field which transcends traditional disciplinary boundaries. Such framing is first laid out in terms of the recurrent themes of theory, boundaries, and pluralism in Section 4.3, and further developed in Chapter 7.

2.2 Defining

This first research stream purposes itself towards the first research question, ‘how can urban sustainability be understood’. Section 1.2.3 articulated a working definition of urban sustainability as a semantically open reapplication of sustainability to the urban scale. The words urban and sustainability merit definition and understanding on their own terms however. This first research stream, described here as ‘defining’, is intended to explore sustainability and the urban separately in order to develop a more solid grounding in terms of background theory.

2.2.1 Definitions in the literature

The search for a ‘definition’ of sustainability is a recurrent theme within the literature (see eg. Brown et al. 1987; Allen and Hoekstra 1992; Basiago 1995; Johnston et al. 2007; White 2013; Farley and Smith 2013; Ramsey 2015). Yet despite over 30 years of literature in this area, there is no clear consensus on how sustainability should be defined, or even what specific concepts it should encompass. Both ‘sustainability’ and ‘sustainable development’ have held a reputation as something of a buzzword since as early as the 1980s (Cocklin 1989; Simon 1989; Palmer et al. 1997). The most widely cited definition remains the 1987 Brundtland definition of sustainable development quoted in Chapter 1. Despite perhaps being the closest thing to an accepted definition that exists, the myriad criticisms of it are summed up by Daly (1996) who describes the definition as “sufficiently vague”, ambiguous enough to allow for consensus building, but devoid of real substance (p2).

One widespread interpretation of sustainability is in terms of ‘three pillars’, or as the confluence of environmental, social, and economic aspects or goals. This understanding is implicitly accepted across most of the sustainability literature (Thompson 2017), though some authors compliment these three with other dimensions such as institutional (Spangenberg et al. 2002; Turcu 2013), or cultural (Gibson 2001; Soini and Birkeland 2014). Despite such widespread use of this conceptualisation however, it has no clear single origin.

Towards an understanding

For the purposes of this work’s endeavour to bring clarity to ‘urban sustainability’ it remains necessary to have a clearer understanding of what is meant by this term. Yet it seems apparent that an unambiguous, objective, and operationalisable consensus ‘definition’ is an impossibility. This quandary is addressed by Ramsey (2015), who argues that “we cannot define our way to clarity” (p1085). According to Ramsey, “meaningful definitions... presuppose a social context in which one can give a definition”, that is definitions depend upon a context which cannot be uniquely prescribed, and thus the pursuit of a universal definition is doomed to failure. Whilst Ramsey cautions the futility of a top-down explicit definition, he acknowledges the development of understanding by theory-led approaches which attempt to draw out meaning within “already existing normative structures of what it is to ‘keep something going’ ” (p1086).

This differentiation may seem subtle, but it opens a route to develop an understanding of sustainability within this thesis. The distinction therefore is

made from producing a top-down *definition* of urban sustainability, i.e. one that is prescribed, to developing a bottom-up *understanding* of urban sustainability, based upon understandings within the literature, which can then be refined based upon a theory-led approach.

2.2.2 Methods

To develop a better understanding of urban sustainability the decision was taken to split the phrase into its constituent parts and examine each individually. Whilst this remains somewhat reductive, its intention is to explore foundational concepts and literature which may be overlooked when merely considering ‘urban sustainability’ as a whole. The hypothesis here then is that this literature may provide deeper insight and transferable knowledge for better understanding urban sustainability itself. Thus, Chapters 3 and 4 are dedicated to developing deeper understandings of sustainability and the urban respectively. A broad literature review has already been presented in Chapter 1, these chapters then are intended to provide a narrower focus on two relevant examples of what are termed here as ‘fractures’.

Fractures

Urban sustainability research has already been presented as a highly interdisciplinary endeavour. The metaphor of ‘bridging’ is frequently used in work considering interdisciplinarity to describe the practice of overcoming a barrier, boundary, or divide between disciplines (Youngblood 2007). This represents not just a gap in knowledge bases and language conventions, but often more fundamental aspects such as basic models of how the world works, what knowledge is, and how it may be obtained (Parry 1998; Boon and Van Baalen 2019). This can be considered then as not just a gap but a fracture. The following two chapters focus on two examples of fractures. The first surrounds the three pillars of sustainability which have been criticised as disciplinary ‘silos’ where social and less quantifiable aspects often find themselves marginalised, and the interdependence of these dimensions ignored (Davidson et al. 2012; Opp 2017). The second considers scholarship of the urban and the fracture between academics addressing it from social science and natural science perspectives (Acuto et al. 2018).

These two ‘fractures’ were chosen in part as a reflection of similar divisions observed in my interdisciplinary ‘urban sustainability’ focused research group (see Section 2.1.1). The Leverhulme project itself was structured around the three pillar paradigm, following what may be considered a dominant approach in the

wider sustainability literature. This fracture thus seemed a natural organising structure for a chapter on understanding ‘sustainability’, necessitating delving into the conceptual history of the term, and holding up as a novel contribution itself (published as Purvis et al. 2019b).

The urban studies/urban science fracture is given relatively little explicit analysis within the literature. Its choice of examination was informed by the observation of a distinct divide between ‘modellers’ and ‘social scientists’ within my research group, as well as viewing departments elsewhere which seem to fall within one camp or the other, with little overlap (cf. the Centre for Advanced Spatial Analysis at University College London, and the Urban Flows Laboratory at the University of Sheffield with the numerous Urban Studies departments which exist across the UK). Cauvain (2018a) argues that the dominant research culture surrounding urban sustainability holds a heavy STEM bias which acts to marginalise scholars from an urban studies background, particularly those with more critical epistemologies. This mirrors a wider trend across the academy, as well as the marginalisation of the social pillar of sustainability as noted by a number of scholars (Dempsey et al. 2011; Davidson et al. 2012; Opp 2017). A bridging of this fracture, by focusing on how the urban has been conceptualised and understood across these ‘fields’, could thus yield a wealth of transferable knowledge for developing a deeper understanding of urban sustainability.

Of course there are numerous other ways in which these two chapters could have been organised, for example by deeper consideration of the ‘applied’ fields such as planning, architecture, and engineering, or through the UN’s SDGs. Other relevant ‘fractures’ also exist such as the weak/strong sustainability debate (Davies 2013), or ecocentric versus anthropocentric interpretations (Gagnon Thompson and Barton 1994). The chosen foci however both draw upon my personal experience and observations from my immersion in urban sustainability research, reflecting the barrier to interdisciplinary work surrounding the competition of quantitative and qualitative approaches, and the dominance of technoscientific methods in informing policy and research trajectories in this area.

Three pillars

Chapter 3 focuses on the three pillar conceptualisation of sustainability, seeking to develop a better understanding of sustainability by probing the origins of this dominant paradigm. By taking the form of a historical review it not only uncovers early theory which may inform future operationalisation of urban sustainability, but also sheds light on the origins of this ‘fracture’ to aid in bridging understanding.

This literature survey takes the form of an ‘integrative review’ (Snyder 2019), a methodology aimed to “assess, critique, and synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge” (p335). This approach is better suited for critical review and reconceptualisation of an existing knowledge base than other literature review methods such as the systematic or semi-systematic review (p336). To limit the body of literature for consideration, a cut off year of 2001 was selected, based upon Giddings et al. (2002)’s description, at this time, of the three circles diagram as a “common view”, so common-place it seems not to require a reference (p189). Since the language of sustainability is relatively new, there is no need for the selection of an initial date. The purpose of this literature survey is to probe the elusive origins of the three pillar paradigm.

The initial literature search employs the *Scopus* database (Elsevier 2017) to cover academic journal articles, with the search string "sustainab*" AND "soci*" AND "econom*" AND ("ecolo*" OR "environment*" OR "biolog*") in an abstract-title-keyword search. This string reflects the varying descriptions ascribed to the environmental pillar, and wildcard characters allow for the search to cover related terms. Since a single search string may overlook relevant work, or the database may be missing relevant items, particularly books, this search will be complimented with a ‘backward snowballing’ approach (Jalali and Wohlin 2012) which necessitates looking up material deemed relevant from the references of the items consulted in depth. Since the sustainability discourse has been greatly shaped by the work of several international institutions, the online document archives of the UN, World Bank, OECD, and International Union for Conservation of Nature (IUCN) were also consulted with similar search terms. This selection is based on the IUCN presenting the first widely cited conceptualisation of ‘sustainable development’ (Pezzey 1992; Sneddon 2000), and the UN, OECD, and World Bank being judged instrumental in the institutionalisation of sustainability (Tulloch 2013).

The sample size is narrowed by scanning each article’s abstract for relevance, resulting in a total of 182 documents. Analysis of these articles requires scanning them for relevant text regarding the conceptualisation of sustainability or sustainable development in terms of three pillars or related constructions. The most relevant articles are then reviewed in more detail and a synthesised analysis of these allows for construction of theory and narrative regarding the origins of the three pillar paradigm.

Urban studies vs urban science

Exploration of a second fracture surrounding scholarship on the urban and the disconnect between urban studies and urban science forms the basis for Chapter 4. The field of urban studies is commonly recognised as deriving from the social sciences tradition (Ramadier 2004), this domain excludes scholarship relating to the urban from the natural sciences (see e.g. Batty 2013). Whilst ‘urban science’ is a less mature and centralised area of research, it has experienced a recent boom following attention from global policy initiatives including the UN’s *New Urban Agenda* (Acuto et al. 2018). There appears to be very little specifically written on this disciplinary divide, whilst several authors purport to map urban research, this tends to be solely focused on urban studies and related domains such as planning (see e.g. Bowen et al. 2010; Harris and Smith 2011; van Meeteren et al. 2015).

It was therefore decided to explore this fracture implicitly by focusing on work in these two areas which purports to build understanding of what is meant by the urban. This derives from Paddison (2015), who maps urban research in terms of 12 key questions, one of which is “how do we define the city?” (p941). Due to the broad nature of this focus, this literature chapter takes a less systematic approach than the previous, instead relying on ‘briefsearch’ and ‘snowballing’ methods (Rowley and Slack 2004; Jalali and Wohlin 2012). The analysis focuses on common themes that emerge across these two bodies of literature.

2.3 Measuring

The second research stream focuses on measuring urban sustainability, this focuses in particular on the case of thermodynamic entropy as a ‘physical basis’ for unsustainability. As discussed in Section 2.1.3, this ultimately proved to be a dead end and it is implicit observations from this approach which are brought further in this thesis rather than any ‘results’. This work has been ‘preserved’, following Tuval-Mashiach (2017)’s principle of ‘reflexive transparency’, as it is deemed significant for the metanarrative of this work, and remains valuable in its own right in clarifying the scope of applicability of entropy.

The focus on entropy was again informed by my research context. I am a physicist by training with competency in numerical and analytical methods and an understanding of thermodynamic concepts. As Section 1.3.3 alluded to, there is a tradition within the literature, rooted in positivist epistemology, which seeks to conceptualise sustainability in terms of fundamental physical laws. One prominent instance of this considers entropy and other thermodynamic concepts as a measure

relating to sustainability or ‘unsustainability’ (Quental et al. 2011; Bristow and Kennedy 2015). Despite this there remains no emergent framework for its application to environmental problems (Filchakova et al. 2007). This conceptualisation was chosen for closer examination due to having historical roots in the early sustainability literature, with consideration of entropy being popular among ecological economists from the 1970s such as Georgescu-Roegen and Daly (see e.g. Georgescu-Roegen 1971, and Daly 1973).

Discussion of entropy is widespread, but often only mentioned in passing, for example it is discussed in relation to pollution emissions in Meadows et al. (1974)’s description of their ‘*Limits to Growth*’ model. The OECD (2004a) report on measuring sustainable development correlates it to increasing economic activity (p72), and Rees and Wackernagel (1997) dedicate a section of their work on urban ecological footprints to ‘*Cities and the Entropy Law*’ (pp547-548). Whilst peppered throughout the literature in various forms, discussion of entropy in relation to urban sustainability, has up until now received inadequate conceptualisation to develop a strong theoretical frame. It is often discussed, yet there exists no text developing theory and methods of how this entropy framing may be used in practice to understand and operationalise urban sustainability. This causes some pause for thought: despite decades of literature proposing the use of entropy in this way why has an operational framework not arisen? Some authors have suggested this could be due to the nature of work considering it being conducted by non-‘experts’ (see e.g. Martyushev 2013). Occam’s razor might suggest that this is not a fruitful avenue. Nevertheless, in the absence of any definitive literature sealing this area off as a dead end, there remains space for a novel contribution.

2.3.1 Measuring sustainability

Section 1.3.1 outlined the dominant indicator paradigm which is commonly employed to provide measures for sustainability in various contexts. The conceptualisation of urban sustainability as a goal, or desirable state or direction of travel implies the need to chart a trajectory to reach it. It follows that without some form of assessment method, it is difficult to identify progress, as Böhringer and Jochem (2007) state, “an issue that can not be clearly measured will be difficult to improve” (p1). In some epistemological stances too, measurement is an implicit part of ‘scientific rigour’ (Stirling 1999; Silka 2010).

Yet measurement is not without issues. In Section 1.3.1 common issues and criticisms of indicator approaches to measuring sustainability were outlined, relating to data constraints, bias towards more readily quantifiable aspects, universalism,

and the method of combination. Much of this is not unique to indicator based approaches. Liverman et al. (1988) problematise measurement in relation to the contested nature of sustainability as a concept, “the first step in measurement is to define clearly what is being measured” (p133). It is here that, if viewing sustainability as merely a ‘technical challenge’, the need for a “scientific, objective, and value free” measure arises (McCool and Stankey 2004, p301). Whilst at the time of writing I recognise this view as short-sighted and perhaps even dangerous, this is where my epistemological stance lay when I was planning this stream of work. This will be revisited with a more nuanced discussion in Section 7.3.3. The remainder of this section details the methods used in Chapter 5.

2.3.2 Methods

The intent of Chapter 5 is to probe claims that thermodynamics might provide a ‘physical basis’ for measuring sustainability, addressing Question 2a regarding a ‘physical basis’ for urban sustainability. Methodologically this will review and analyse claims relating to entropy here made in the literature, assess validity using analytical techniques, and conclude how future work can consider these claims in endeavours to operationalise urban sustainability.

Following a ‘textbook’ outline of the necessary thermodynamics background, an integrative review (Snyder 2019) is required to assess the literature considering thermodynamics in the context of urban sustainability. This follows methods employed in Chapter 3, utilising ‘snowballing’ and literature searches composed of combinations of terms related to ‘urban sustainability’, ‘thermodynamics’, and ‘entropy’. These articles are then reviewed for claims relating to the use of thermodynamics in relation to quantifying sustainability concepts. From this, two recurrent arguments are identified which were elaborated as hypotheses to test.

Each claim is investigated using physical analytical techniques. This means applying the quantitative thermodynamic theory outlined at the beginning of the chapter to claims which are primarily qualitative, in order to examine their applicability.

2.4 Modelling

Initially it was intended that an integrated assessment model would be designed incorporating the entropy ‘measure’ which would have been developed in the previous section of this thesis. This would perhaps have followed the exergy assessment work of e.g. Balocco et al. (2004), complimenting this with a more holistic set of indicators capturing the three pillars of sustainability. As work

progressed on the preparatory aspects of this (as detailed above) it transpired that not only was an entropic indicator, as previously suggested by the literature, inadequate, but the postpositivist epistemology adopted of ‘defining, measuring, modelling’ was brought into question itself.

A shift towards a more constructivist epistemology without a tie requiring strict definition and measurement allows for a more flexible modelling approach. Here system dynamics in particular presents itself as a modelling methodology which is able to accommodate a broad range of divergent epistemologies (Pruyt 2006). The modelling chapter then, as outlined in Figure 1.1 sits in parallel to the previous ‘measuring’ chapter, which informs it only indirectly through its reinforcement of the emergent themes of boundaries, pluralism, and theory. The observations imparted by the ‘defining’ chapters are also implicitly drawn upon, particularly regarding how sustainability might be understood within this modelling framework, as well as the highlighting of the fracture between urban studies and urban science.

This research stream is thus intended to address Question 2, as outlined in Section 1.4.1; in particular 2b, “How should an integrated assessment model be designed for operationalising an understanding of urban sustainability”, whilst also confronting 2c and 2d “How can the issues of boundaries be confronted?”, “What barriers exist moving from theory to practice?”. It should be emphasised that this exercise is conceived as an exploratory study and proof of concept, and primary focus lies in the process of developing the model itself.

2.4.1 Modelling approaches

Section 1.3.2 outlined modelling and why it is deemed useful for operationalising urban sustainability. IAM was identified as an appropriate modelling paradigm for operationalising urban sustainability, however within this there remain a variety of suitable approaches. Verburg et al. (2016) produce a set of five generalised categories for classing models relevant to anthropocene dynamics. Of these, “reduced-complexity social-ecological models” and “agent-based social-(ecological) and cellular (social) ecological models” sit at the appropriate level of complexity for developing an urban scale model, as well as the feasibility for constructing a working model as a singular researcher constrained by time available. Within these two categories Verburg et al. (2016) also identify two suitable model types, system dynamics in the former category, and agent-based modelling in the latter.

Agent-based modelling

Agent-based modelling (ABM) is a class of simulation methods which allow for the disaggregation of a system into individual classes of ‘agents’ which follow their own characteristic set of rules and behaviours (Crooks and Heppenstall 2011). It is a diverse area and has been applied widely in the life and ecological sciences, as well as the social sciences (Niazi and Hussain 2011). Agents may represent individuals, or collective entities such as households, firms, or even geographical regions (Bonabeau 2002; Valbuena et al. 2010). As such ABM lends itself well to modelling systems with “heterogeneous, autonomous and proactive actors” (Siebers et al. 2020, p3).

Verburg et al. (2016) suggests that this methodology is most suitable for IAM at the local to regional scale, over relatively short timescales. Applications at the urban scale typically centre around decisions made by agents for example housing choice and segregation (Fontaine and Rounsevell 2009; Jordan et al. 2011), and transportation and pedestrian movement (Kerridge et al. 2001; Wise et al. 2017).

ABM has clear benefits when the actions and decisions of individuals or agents is important for the model scope. This would be suitable for an urban sustainability model focused around behavioural change or the response of individuals and firms to progressive policy implementation. As a decentralised modelling method where the system behaviour emerges from individual agent behaviour it is less suited to a more aggregate consideration of urban processes and economic activity (Crooks et al. 2008).

System dynamics

System dynamics is a modelling paradigm purposed towards understanding the behaviour of complex non-linear systems over time. The approach emphasises the importance of feedback loops, and holistic thinking of the whole system as more than the sum of its parts. Sterman (2000) defines it thus:

“System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems. System dynamics is also a rigorous modelling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations” (pviii).

The paradigm is based on a series of feedback loops interacting with stocks and flows within a closed structure system. A basic example of this is presented in Figure 2.1 which illustrates an exponential population growth model, presenting a stock (**Population**), flows (**Births** and **Deaths**), and causal relationships (arrows relating

the population, and birth and death rates, to births and deaths respectively). Specialised simulation software enable modellers to construct graphical models as shown in Figure 2.1, with the underlying differential equations automatically constructed by the software based upon this diagram structure. This allows for accessibility and ease of understanding, enabling users to develop and implement models in an intuitive manner which does not require explicit formulation of equations or coding experience.

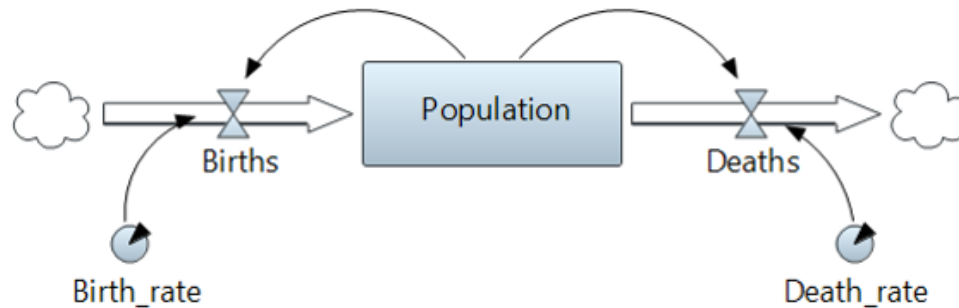


Figure 2.1: System dynamics simulation diagram for a basic exponential population growth model. This diagram was constructed within the *AnyLogic* simulation software, however the symbols tend to be used universally, and differ only superficially between different modelling environments.

The basic model presented in Figure 2.1 has its dynamics described by a few simple equations. Both ‘Birth_rate’ and ‘Death_rate’ are constants, and are given the values of 0.035 and 0.01 per year respectively for this example. The equations for births and deaths are then $\text{Births} = \text{Population} \times \text{Birth_rate}$, and $\text{Deaths} = \text{Population} \times \text{Death_rate}$, and the change in the ‘Population’ stock, given an initial value of 1×10^6 , is then $d(\text{Population})/dt = \text{Birth_rate} - \text{Death_rate}$. The simulation is then run, computing the value of the ‘Population’ stock at each time step, the results of which have been plotted in Figure 2.2. This simple example does not exhibit particularly interesting behaviour, but gives a hint as to what more complex models involving multiple stocks and variables may look like, giving rise to interesting and unexpected dynamics. One of the main advantages of the system dynamics approach is that it allows for the inclusion of complex interactions to model the evolutionary behaviour of phenomena that are not otherwise easy to predict due to non-linearities.

System dynamics has been used to model various applications of interest to operationalising urban sustainability. The *SUSTAIN* project focuses upon the issues of urban transportation and societal metabolism to develop a system dynamics

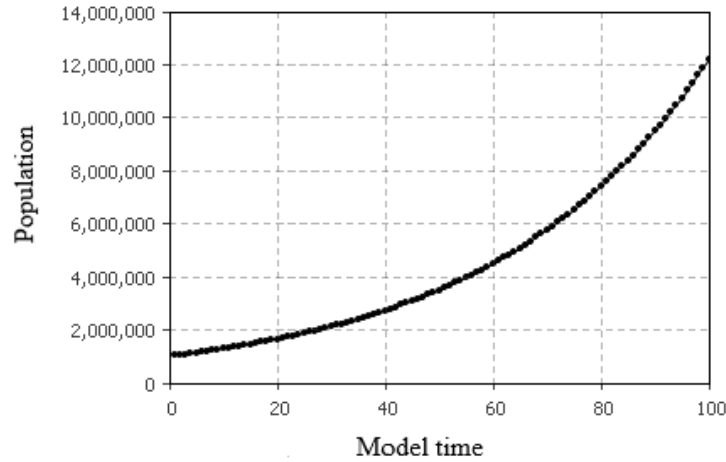


Figure 2.2: Output over 100 model time steps (years) of the ‘Population’ stock for the basic exponential population growth model presented in Figure 2.1.

‘board game’ for use as a learning tool for students and policy makers (Armenia et al. 2019a). Armenia et al. (2019b) review a selection of open access system dynamics models tangentially relating to urban sustainability, all of those listed are purposed towards a specific sector such as waste management, transport, and services. The *Steer Urban Dynamic Model* simulates the interaction of transport, land-use, population and employment over several years to aid in the formation of transport policy using a zonal system dynamics model (Swanson and Gleave 2008).

In contrast to ABM, system dynamics is an aggregate modelling technique which tends to impose a centralised system structure. This means it is less suited to capturing human aspects of social systems with the use of averages tending to hide variation and inequalities. Verburg et al. (2016) suggests system dynamics is well suited to the regional to global scale with decadal and sub-decadal timescales.

Hybrid Models

Increasingly system dynamics and ABM have been realised as complimentary methods which may be used together to draw on the benefits of each (Lättilä et al. 2010; Siebers et al. 2020). Many simulation software packages now allow for hybrid approaches (Ding et al. 2018). Examples of relevant applications include Siebers et al. (2020) who develop a hybrid global IAM as a proof of concept for expanding the functionality of an existing system dynamics model.

2.4.2 Hypothesis

Due to the nature of the PhD and the amount of time and resources available for this research stream it was judged not reasonable to develop an urban integrated assessment model from nothing. Therefore, it was decided to select an already existing global integrated assessment model to adapt and downscale as a proof of principle for application to an urban system. This follows Ravetz (1998)'s suggestion that urban modelling could learn much from global IAM. This approach employs the initial hypothesis that the urban system may be thought of as a downscaled version of the world system. This is of course a simplistic abstraction which erases hierarchical scales of governance, and the interdependence with other urban systems, yet it provides a simple base from which more detailed aspects may be added later.

There remain some theoretical issues of modelling the urban system as just a smaller sized world system. The primary issue concerns system bounds: the world system is bounded both physically and functionally, i.e. it is effectively closed with little interaction with its surroundings other than the exchange of energy. The urban system on the other hand is very much not closed, with constant flows across the boundary. This not only consists of people and materials, but also the wider interactions of the urban economic system situated within a wider global economic system.

Selection of such a model to provide a starting point may be based upon the satisfaction of some key criteria. Firstly, the model must be open access and well documented so that it may be easily obtained and understood, a black box model would be inappropriate here. Secondly, it should hold some validity, with results which have been independently reviewed and stand up to scrutiny. Finally, it should attempt to capture a holistic representation of the global system without being focused towards a specific phenomenon of interest. It should be noted that selection was made in early 2017, so most literature published after 2016 was not considered.

Candidates

The open access criteria dramatically shrink the pool of suitable models. Notable omissions here include 'GUMBO', presented by Boumans et al. (2002), purposed towards demonstrating the value of ecosystem services. The model primarily focuses on the aggregated flow and transformation of natural capital and 'human-made capital', between the biological and earth systems, and the anthroposphere. This was later succeeded by 'MIMES' (Boumans et al. 2015) which builds upon the 'GUMBO' model structure but introduces spatially explicit dynamics.

IMAGE 3.0 developed under the mandate of the Dutch government, focuses on the environmental consequences of human activities, it has a detailed modular structure developed over a number of years (Netherlands Environmental Assessment Agency 2006). Whilst a hosted website provides detailed documentation on the modelling framework and scenario outputs, the model itself is unavailable for download.

World3 was developed by a team in the 1970s funded by the Club of Rome as the basis for the publication of *'Limits to Growth'* (LtG) (Meadows et al. 1972). It uses system dynamics to simulate the interaction of population, economic, agricultural, resource, and pollution subsystems. Whilst the initial model was developed in the 1970s, it has received a couple of updates by the authors (Meadows et al. 1992; Meadows et al. 2005), and there are numerous recent studies which maintain the validity of the model and build on its structure (see e.g. Morecroft 2012; Bardi 2013; Turner 2014; Heath et al. 2019). Various copies of it exist freely online.

Nordhaus's DICE model first appeared in the 1990s as an integrated climate-economy model (Nordhaus 1992). The first iteration of the model was developed in the GAMS software package based on differential equations, although a system dynamics version has been constructed by Fiddaman (1997). As a relatively simple and accessible model, various independent authors have published work that builds on it (see e.g. Wouter Botzen and van den Bergh 2012; Traeger 2014; Siebers et al. 2020).

Whilst other less widely cited options no doubt exist, DICE and World3 give two suitable options which meet the selection criteria detailed above. Due to DICE's focus on climate change, something which is less tangible at the urban scale, the decision was taken to select Meadows et al. (1972)'s World3 model for adaptation.

2.4.3 Methods

The purpose of the model to be developed is to represent the sustainability, broadly understood, of an urban system in relation to the global system's sustainability. In its initial form as a proof of concept or prototype it is intended to allow for exploratory modelling and use as a learning tool for better understanding urban sustainability. It is also intended to demonstrate the potential of integrated urban system dynamics modelling to inform policy.

With the hypothesis that the urban system may be represented abstractly as a downscaled global system with opened boundaries, it is necessary for the model sub-systems to interact across scales. The urban layer of the model is based upon a downscaling of Meadows et al's World3-2003. The model contains two hierarchical scales relating to the urban, and global scales. The coupling between these scales

is initially modelled as mono-directional, meaning the behaviour at the urban scale does not inform the behaviour at the global scale. Given that Nottingham only accounts for a tiny fraction of the global population and associated resource demands, this is considered a reasonable assumption.

Nottingham was selected as the basis for sourcing model data inputs. This was decided partly due to the Leverhulme project (see Section 2.1.1) performing work related to urban sustainability that considered Nottingham as a case study. This meant that much data was readily available, as well as access to expertise in numerous considerations of Nottingham from a sustainability perspective, including modelling of sustainability issues using different techniques. For the case where sufficient Nottingham data is not available, various statistical techniques may be employed in order to transform national level data (see e.g. Snyder 2001 for discussion).

Software choice

There exist several options available for software with system dynamics modelling capabilities. The original World3 model was built using the *DYNAMO* software package, this is no longer commercially available, and the 20 year update rebuilt World3 using *Stella* (Meadows et al. 1992). Unfortunately there seems to exist no systematic comparison of software packages within the literature. There exists a Wikipedia article ², but it is limited in information, detailing only licensing, the implementation language used, last update year, and a brief description (Elsawah et al. 2017). Elsworth et al. (2017) state that researchers should carefully consider the trade-off between flexibility in allowing for model revision, and the ability to incorporate more complexity within the model (p140). The software choice is important as it creates a ‘lock-in’ effect, with the ability to easily export models to different software packages in the future being limited.

As there is no budget available for purchasing software, several popular packages which offer no free license are ruled out of consideration, including *iThink*, *Simile* and *GoldSim*. Additionally, whilst both *Stella* and *PowerSim* provide free ‘limited versions’, limits to 2 stocks and 50 variables respectively render them inadequate for intended use (ISEE Systems 2019; Powersim Software 2020). Table 2.1 thus lists a number of potential software packages sourced from the System Dynamics Society’s website³ (System Dynamics Society 2020). Additionally, *Simulink* and *Insight maker* were considered due to frequent consideration on lists available on *Researchgate* and

²https://en.wikipedia.org/wiki/Comparison_of_system_dynamics_software

³Also listed here was *Ventury*, but at the time of decision making this remained in its beta stage and was thus not considered.

Quora forums (see e.g. Researchgate 2014; Quora 2014). A crude estimate of each package’s popularity within the academy was determined from a *Web of Science* database query of “System Dynamics” AND “[software name]”. This was intended to provide a rough proxy as to the relative availability of online tutorials and support, as well as the likely audience if the subsequent model were to be published. These results, as well as apparent simplicity and limited functionality allowed *Insight maker* to be ruled out. Additionally aside from its website, *TRUE*, appears to have relatively little documentation or support tools, so was also discounted.

	License	Limitations	Notes	WoS hits
AnyLogic	Commercial; Free PLE	Limited analysis		21
Insight Maker	Free	Basic functionality	Browser based	1
PowerSim	Commercial; Free limited version	Max 50 variables		49
Simulink	Commercial; License available			153
Stella	Commercial; Free limited version	Max 2 stocks		117
TRUE	Free			N/A
Vensim	Commercial; Free PLE	Limited analysis		249

Table 2.1: Comparison of system dynamics software.

Of the remaining packages, *AnyLogic* is a ‘multi-method’ tool allowing for hybrid models which incorporate ABM or discrete event simulation (Grigoryev 2016). *Vensim* is primarily focused upon system dynamics although has some ability to allow for hybrid modelling (Ventana Systems 2015), and *Simulink* is a design environment which integrates with *MATLAB* offering varied functionality. *Simulink* whilst being the most versatile of the three exhibits a steep learning curve, and employs diagrammatic methods which differ from those used in mainstream applications (Lane 2008). It appears better suited to mechanical rather than social systems (see e.g. Palm 2010). Being relatively popular, with numerous learning resources freely available, as well as offering similar functionality, both *Vensim* and *AnyLogic* were downloaded to allow for experience of their modelling environment. After building basic models in both software packages and experimenting with features, it was decided that AnyLogic⁴ would be used for this study, being the most user friendly and intuitive in its interface and modelling environment, as well as its strong ABM capabilities allowing for the potential of hybrid modelling to be employed in the future.

⁴Specifically *AnyLogic 8.2.3 PLE*, obtained from The AnyLogic Company (2017)

Two step adaptation

To arrive at a successfully coupled urban assessment model it is necessary to develop a ‘working’ uncoupled urban model of World3 in isolation first. This simplifies the processes of verification and validation, as the isolated urban model may be verified before added complexity is introduced from the coupling (Verification and Validation are addressed in respective Subsections below). Further each adapted urban subsystem should be verified in isolation before coupling to each other (as was done in the original development of World3, see Meadows et al. 1974). Thus the proposed adaptation process is illustrated in Figure 2.3.

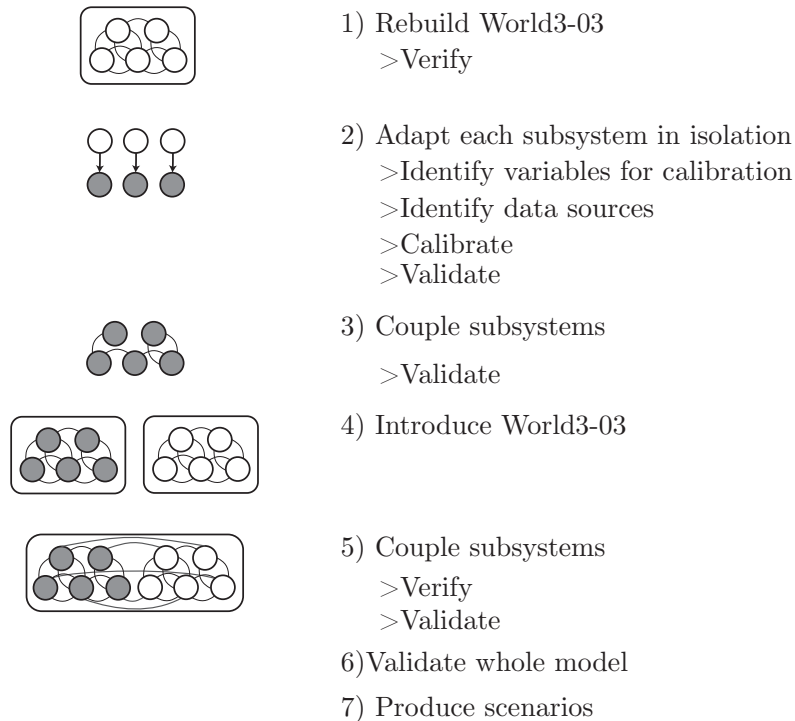


Figure 2.3: Outline of the modelling steps to be taken in Chapter 6 for creating an urban system dynamics model.

Since a detailed description of World3 is outlined in Meadows et al. 1974, it remains relatively easy to rebuild the model within contemporary system dynamics software. Whilst freely available copies of the model exist online (e.g. a copy of World3-92 in *Insight maker* (Fortmann-Roe 2014), and a port of World3-03 from the Meadows et al. 2005 CD in *Vensim* (Fiddaman 2010)), the decision was made to rebuild the model in its entirety using Meadows et al. 1974 as a guide. Whilst time consuming, this allows for a far greater familiarity with the intricacies of the model than would otherwise be granted by just implementing a model built elsewhere.

Since there remains relatively little scholarship which utilises or adapts the system dynamics models developed by Meadows et al's team, spatial deconstruction of the World3 model is a novel endeavour. Despite this, the global averaging inherent in the World3 model presents both an unrealistic abstraction of the 'real' global system, and a barrier to understanding the more complex interaction of regionalised decision making. Mesarovic (1974) recognised some of these limitations, and in '*The Second Report to The Club of Rome*', presented as something of a successor to *Limits to Growth*, developed a 'multilevel' model of the world system. Their approach splits the world into ten 'regions' aimed at overcoming the unrealistic homogeneity of World3. Despite confronting several issues regarding this homogeneity, the model itself relies explicitly on none of the preceding system dynamics formulations, instead starting from scratch and employing distinct methods (Saavedra-Rivano 1979). This study is thus of limited use here. There therefore remains little precedent for the approach proposed in this thesis, and it should therefore be considered as a tentative first exploration. Nevertheless, the results provide ways of understanding and further exploring the relation between urban and global sustainability within this system dynamics framework, and perhaps a first step to a new approach for examining the coupling of local and global parameters, in order to develop a better understanding in confronting 'sustainability'.

Aside from the approach outlined in Figure 2.3, it is important that the process is well documented to allow for easy replication. This necessitates keeping a detailed 'lab diary', which should be published or shared in some form along with the resultant model itself (Martinez-Moyano and Richardson 2013).

Verification

According to Findeisen et al. (1978) "a model is said to be verified if it behaves in the way the model builder wanted it to behave". Jørgensen and Fath (2011) recommend the following questions be answered in the step to verifying a simulation model: is the model stable in the long term; does the model react as expected; do all of the equations maintain consistency of units; are the statistical properties of the noise in the model reasonable? (pp31-33).

For the first criterion, the simulation period (200 years for the original LtG scenarios) should be sufficient to allow the model to demonstrate potential instability. For the second criterion, the results of the original World3 simulations provide, qualitatively, a guide for what some expected behaviour might be, this may be assessed by running various scenarios and closely examining the software package which flags up an error message where mismatched units occur. The final criterion is

difficult to assess without specialised statistical packages, however crude sensitivity analysis may be undertaken on key parameters to ensure stable behaviour.

In line with Meadows et al. (1974), an important step in verifying the model regards building each subsystem individually and running it independently of the other subsystems to test its behaviour.

Calibration

Mulligan and Wainwright (2013) describe calibration as the tuning of parameters that define the order of magnitude of processes within the model structure (p15). According to Jørgensen and Fath (2011), “the goal of calibration is to improve the parameter estimation”. The World3 model has already been calibrated, as detailed in Meadows et al. (1974), nevertheless there are parameters and table functions that must be redefined in order to reproduce the urban context for the urban system model. Here Meadows et al. (1974) may be used as a guide.

Calibration may be automated or done by ‘hand’, the latter relying on the modeller identifying discrepancies and adjusting parameters accordingly in an iterative process (Oliva 2003). Whilst ‘by hand’ calibration has been criticised for its lack of replicability (Lyneis and Pugh 1996), it allows the modeller greater control and insight into this process relative to the ‘black box’ nature of automated calibration.

Steps to be taken to calibrate the model are therefore: Identify parameters that require calibration (i.e. the value used by World3-03 is insufficient, or not appropriate for the urban context); obtain data relevant for parameter estimation; if this is not available, then assess whether the value used in World3 is sufficient, or on a case by case basis determine with reference to literature how a value of the parameter may be best determined (parameter estimation methods are detailed in e.g. Aster et al. 2018); iterate this process ‘by hand’ ensuring that ‘reasonable’ results, cohering to the expected order of magnitude, are obtained.

Meadows et al. (1974) suggest that due to the complex feedback structures, the qualitative behaviour of the model is generally not sensitive to small numerical changes to parameter values (p22). This seems to be confirmed by Heath et al. (2019), who perform sensitivity analysis of various World3 parameters, demonstrating qualitatively stable behaviour. Nevertheless a level of quantitative accuracy is desirable, both for validating the model against observed data, and for model acceptability in a dominant paradigm where quantitative outputs are valued.

Validation

Sargent (2013) defines model validation as “substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model” (p12). Greenberger et al. (1976) describe it as “a check on [the model’s] operational agreement with the reference system” (p70). Thus, to be valid here, the developed model should produce projections which are consistent with a real world urban system.

Meadows et al. (1974) argue that their model is “not constructed for quantitative accuracy” and thus the reproduction of past time-series data is not appropriate for establishing confidence (p24). This remains true for the model developed here, although it is suggested that the framing given by Meadows et al is problematic as it seems to dismiss important concerns regarding the model’s validity. First, reproduction of time-series data should not be interpreted as ‘proof’ of model validity, but it is the macro trends, rather than the micro time-series detail that is important in this type of modelling endeavour. Due to the aggregate and abstract nature of the model in question, it is not expected to reproduce every historical fluctuation, but to be judged useful its outputted trends should reflect historical reality.

Ford (2010) argues that a more pragmatic question than “is the model valid?” is “is the model useful?” (p163). This is a common argument made by modellers, Levins (1966) argues “all models leave out a lot and are in that sense false, incomplete, inadequate; the validation of a model is not that it is ‘true’ but that it generates testable hypotheses relevant to important problems” (p430).

Meadows et al. (1974) produce criteria for “judging usefulness” of their model: “1. Each assumption in the model should be consistent with direct measurements or observations of the real-world system” “2. When the total model is used to simulate historical time periods, the behaviour of each variable should resemble the historical behaviour modes of corresponding elements in the real world. When the system is simulated into the future, each variable should follow an understandable path within a reasonable range of values.” “3. The model should be sufficiently simple so that the reasons for its behaviour can be comprehended and abstracted as generally applicable principles for dealing with the real-world system” (pp24-25). Ford (2010) also produces five ‘tests to build confidence’: historical behaviour reproduced; verification; ‘face validity’ described as a “common sense test” to “ask if the model structure and parameters make sense”; sensitivity testing; testing results against other available models.

Steps for ‘validation’ or building confidence in the model are therefore intended as follows: 1, ‘Face validation’ to analyse the outputted trends from each scenario and

assess whether they seem reasonable. 2, Identify key outputted trends and compare their behaviour (both quantitative and qualitative) with available appropriate historical data. 3, Compare projected behaviour with World3 outputs, divergence is expected due to the calibration process, but some similar qualitative behaviour should be expected. 4, Compare projected behaviour with any projected data trends (if available), e.g. population growth trends.

Scenarios

In *Limits to Growth*, Meadows et al. (1972) produced a series of ‘scenarios’ represented by graphical outputs displaying the evolution of several key model parameters over time. Their first scenario represents ‘business as usual’, intended to represent the evolution of these variables if no policy action or measures are taken to address. Subsequent scenarios then build upon each other implementing policy measures which seek to address the previous scenario’s limiting factor. Two scenarios as illustrated in Meadows et al. (2005) have been reproduced in Figure 2.4. Each scenario in this figure is illustrated by two graphs, one detailing headline parameters, and the other using indicators of welfare and footprint to give a more intuitive visualisation of planetary sustainability within the scenario. The lack of y axes labels is intended to emphasise the qualitative aspect of these parameter curves rather than specific timings and values (p153).

This provides a basic methodology for producing scenario outputs for the proposed urban model. The format of figures used in Figure 2.4 is employed using a headline parameters chart, and a sustainability indicators chart. Additionally these are complemented with a third chart displaying several other important parameters such as life expectancy, food per person, and consumer goods per person as displayed in the Meadows et al. (1992) scenarios. Similarly, no y axes labels are displayed to emphasise the qualitative nature of the outputs, and as per the World3 scenarios a time window showing evolution up until 2100 is used.

Following validation and calibration of the model to an acceptable standard an initial set of scenarios is output. These follow the approach of Meadows et al of pushing back the limiting factor, and are intended both as further validation, and to examine the effect of the multiscalar coupling between the global and urban models. As such it is necessary to also display the accompanying World3 scenarios alongside the counterpart urban model.

Following these initial scenarios, the model is used to address the research questions outlined in Section 1.4.1. Specifically focusing on Question 1a regarding the relation between understandings of global and urban sustainability. To do so,

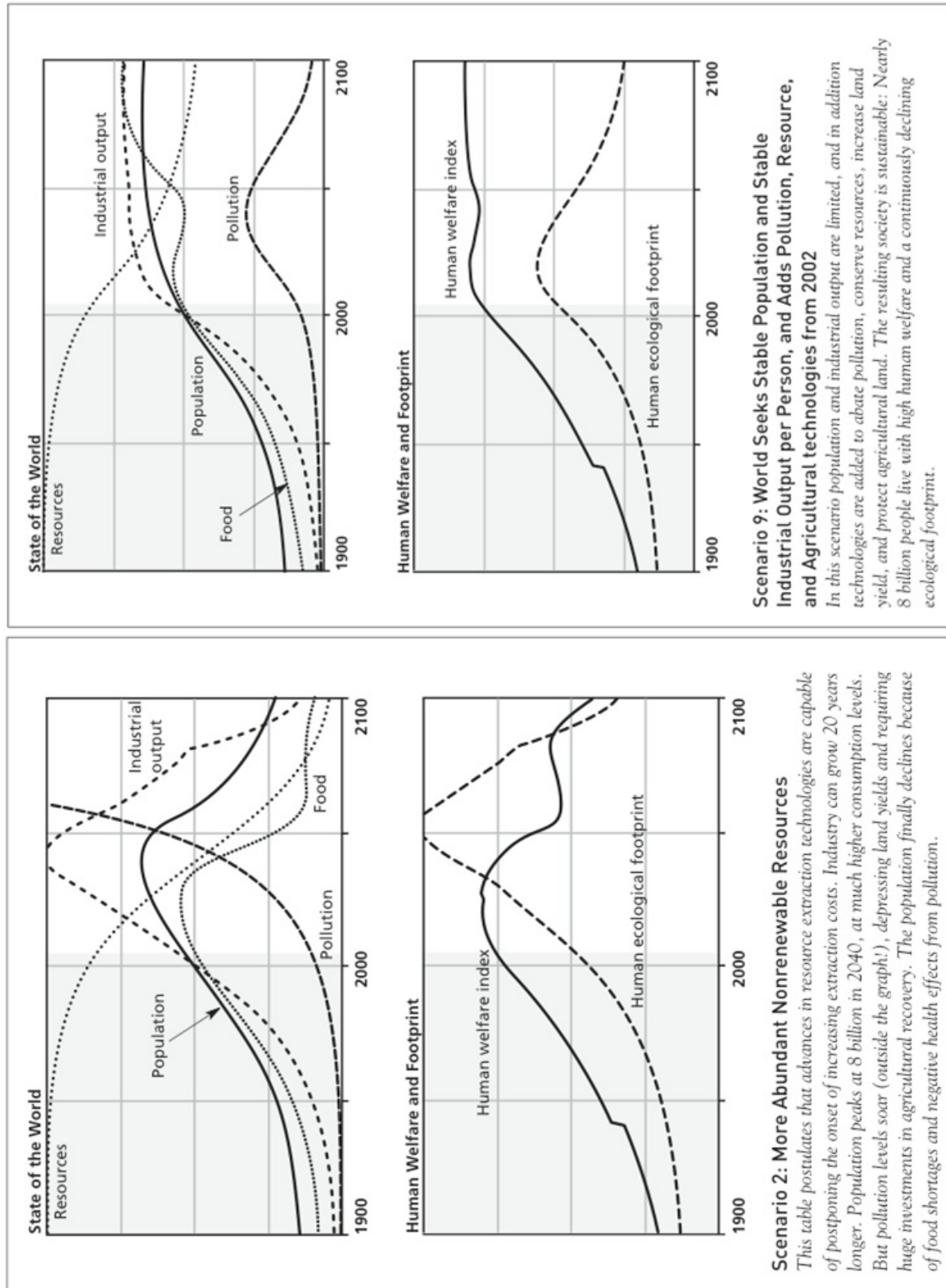


Figure 2.4: Reproduction of Scenarios 2 and 9 from the '30 year update' showing overshoot and a stabilised world respectively (Meadows et al. 2005)

these scenarios investigate the effect of coupling on the sustainability of an urban system in both an unsustainable world which undergoes collapse, and a stable world system where collapse is avoided. This is intended to question under this paradigm or ‘in-model universe’ how independent the urban system’s sustainability may be from the global system’s.

2.5 Research Synthesis

The research streams previously described form distinct chapters. A discussion chapter is required following these to integrate the findings of these prior chapters and address the research questions which were proposed in Section 1.4.1. This section briefly discusses how this ‘research synthesis’ is to be undertaken, highlighting major cross-cutting themes and placing a limitation on scope. Due to the non-linear nature of the research process, these themes largely ‘emerged’ or developed during the research process itself.

2.5.1 Analysis and aims

Whilst Chapters 3-6 confront multiple research questions, it is in Chapter 7 that they will be explicitly addressed in full. The structure of the research questions in two consecutive parts provides a logical framework for organising the research synthesis. This follows an inductive approach whereby a cross-cutting frame of analysis is used which centres around the three themes of pluralism, boundaries and theory which emerged during the course of the research. These are first outlined in depth in Section 4.3.

This analysis also should represent a space for reflection on the stumbling blocks and dead ends that were encountered during the progress of this work. These should not be thought of as failures, but as learning points (Burford 2017), it is necessary to consider how the process of encountering these issues has informed this current work, and can go on to inform future work.

Where this work has fallen short in realising its proposed aims, assessment needs to be made of why this was the case. A necessary part of a research project is to come full circle and critique the initial proposal, was it too ambitious or unrealistic? Was it based upon incomplete information? Reflecting upon what could have been done differently provides not only avenues of future work, but can inform future research design.

2.5.2 Scope

As a single authored monograph conducted and written in a finite time period, there are necessary limitations that cannot be engaged with. Firstly, a broad abstract view is taken in reference to ‘urban sustainability’ conceptually. This comes at the expense of considering relevant phenomena in particular detail. An attempt has been made to ground the abstract level work of Chapters 5 and 6 within the urban reality, yet they remain relatively abstract.

Further, this work sits upon the boundaries of several bodies of literature and disciplinary spanning fields. This has already been acknowledged in Section 2.1.1 in regards to an evolving epistemology, and the nature of disciplinary conventions in Section 2.1.2. Whilst this work endeavours to engage across these disciplines and silos of literature, there are limits to the breadth of literature than can be engaged with in a meaningful way.

One final limit to this work’s scope is that it does not benefit from any engagement with relevant stakeholders. This is an issue that became more apparent as this work progressed and my epistemology evolved, but due to the research design and a lack of contacts or funds it was not something that could be changed. The necessity of stakeholder engagement is discussed in depth in Section 7.3.2.

2.5.3 Ethical considerations

Since this research involves no direct interaction with people it requires no formal ethical approval. Nevertheless, the endeavour to produce future scenarios which are intended to have a tangible outcome upon policy, consideration should be given to the ethical impact of this. Whilst it is not expected that this work will directly influence any policy decisions, as its intended purpose is to be a first step towards real world operationalisation, ethical considerations must be engaged with in the discussion of results and analysis of the method.

Becker (2012) argues that in dealing with the moral relationship between humans, their contemporaries, future generations, and nature, sustainability holds an inherent ethical dimension (pp17-19). It is argued that this limits the ability of the traditional sciences, primarily restricted to “factual analysis” to address issues of sustainability, and that this ethical consideration must be integrated into sustainability research (p4). Relevant articles here include Cafaro (2012)’s review of the ethical issues of population policy in response to climate change, Kamminga (2008) who forwards a generalised framework for consideration of climate ethics, and Buchholz (1998)’s consideration of the ethics of overconsumption. These works

are mostly philosophical in nature, and a full ethical appraisal of the approach forwarded by this thesis remain out of scope.

The fact that very few system dynamics modellers discuss or even consider ethics has been problematised by Pruyt and Kwakkel (2007). They recommend basic steps such as the transparency of value laden technical choices, and communicating uncertainty. Since system dynamics models aggregate causal assumptions they are uncertain by nature, regardless of any validation process (Palmer 2017). Kunsch et al. (2007) discuss ethics in Operational Research in terms of ‘good’ and ‘bad’ decision making. It is argued that system dynamics presents itself as a potential tool for identifying ‘good’ or ethical decisions, by modelling overshoot and collapse and tragedy of the commons scenarios. Palmer (2017) explores consequentialist moral philosophy and its application to the modelling process and communication between modellers and decision makers. Palmer argues there is a much needed debate regarding the ethics of system dynamics, where modelling will have a direct effect on society through use in policy. It is held that this debate should go beyond mere questions of validation (i.e. how does one know whether the model reflects reality well enough to be used in influencing policy) to questions of transparency (to what extent is the uncertainty of the model communicated). Rabins and Harris (1997) suggest that the modeller must adopt some humility in the limits of their own abilities to model complex phenomena outside their expertise. This should either be addressed or reflected in discussion of modelling uncertainty or validation. Chapter 7 then should also provide a discussion of ethical considerations of system dynamics, focusing particularly on model transparency, and uncertainty.

*We are living in a material world;
and I am a material girl.*

— Madonna, *Material Girl*

3

Three Pillars of Sustainability

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This chapter progresses towards a deeper understanding of urban sustainability by focusing on a ‘fracture’ in the literature surrounding the ‘three pillars of sustainability’. As outlined in Section 2.2, by focusing on particular discourses considering sustainability and the urban separately, existing knowledge and theory may be uncovered for developing a deeper understanding of urban sustainability. The following chapter then focuses on the three pillar conceptualisation of sustainability, seeking, through an integrative review (Snyder 2019), to explore the origins of this formulation.

This foray, as well as providing detail on early conceptualisation of sustainability to develop a deeper understanding, also encounters several issues which will recur throughout this thesis surrounding pluralism and theoretical frames. It confronts the first research question, “how can urban sustainability be understood”, by

probing the early sustainability literature and outlining the fractures that underlie the three pillar conceptualisation.

Parts of this chapter are based upon the work *‘Three pillars of sustainability: in search of conceptual origins’* (Purvis et al. 2019b), and portions of text have been copied verbatim. First the historical origins of sustainability are outlined, from the emergence of ‘sustainable development’ as a twin critique of economic development which was then institutionalised by the UN. An integrative review is then performed which analyses both academic and institutional literature to shed light on the origins of the three pillar paradigm. The analysis of this in Section 3.3 argues that rather than having a grounding in theory, the three pillar paradigm is a historical artefact that emerges due to the nature of the literature’s evolution. Finally, an outlook is given regarding on the status of sustainability, and how this chapter’s findings may be brought forward.

3.1 Historical Origins of ‘Sustainability’

Despite the relative dearth of literature probing ‘sustainability’ and ‘sustainable development’ conceptually, one conceptualisation, that of ‘three pillars’, environmental, economic, and social, has gained widespread traction. This description, around which much of the early conceptualisation within the literature occurred, employs three interconnected ‘pillars’ (Basiago 1999; Pope et al. 2004; Gibson 2006; Waas et al. 2011; Moldan et al. 2012; Schoolman et al. 2012; Boyer et al. 2016), ‘dimensions’ (Stirling 1999; Lehtonen 2004; Carter and Moir 2012; Mori and Christodoulou 2012), ‘components’ (Du Pisani 2006; Zijp et al. 2015), ‘stool legs’ (Dawe and Ryan 2003; Vos 2007), ‘aspects’ (Goodland 1995; Lozano 2008; Tanguay et al. 2010), ‘perspectives’ (Brown et al. 1987; Arushanyan et al. 2017), etc. encompassing economic, social, and environmental (or ecological) factors or ‘goals’. These competing terms are primarily used interchangeably, and the preference for ‘pillars’ here is largely arbitrary. This tripartite description is often, but not always, presented in the form of three intersecting circles of society, environment, and economy, with sustainability being placed at the intersection, as shown in Figure 3.1.

This graphic is found in various forms as a descriptor of ‘sustainability’ within academic literature, policy documentation, business literature, and online, and whilst often described as a ‘Venn diagram’, commonly lacks the strict logical properties associated with such a construction. Alternative manifestations include the three depicted visually as nested concentric circles, or literal ‘pillars’, or independent of visual aids as distinct categories for sustainability goals or indicators.

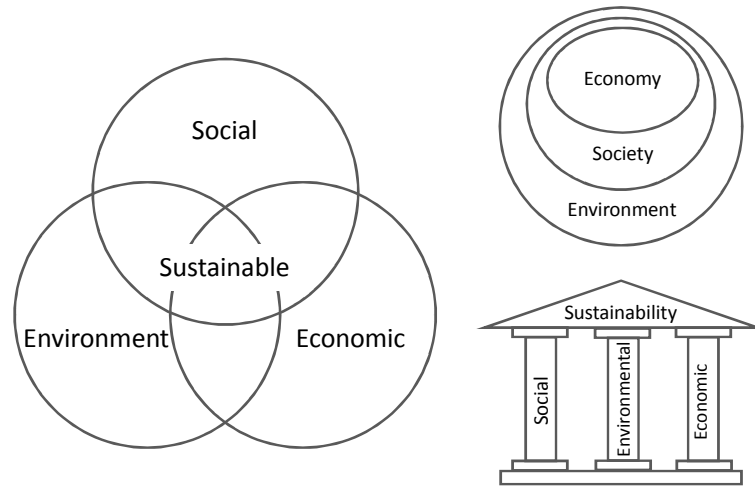


Figure 3.1: Left, typical representation of sustainability as three intersecting circles. Right, alternative depictions: literal ‘pillars’ and a concentric circles approach (Purvis et al. 2019b)

Whilst attractive for their simplicity, the meaning conveyed by these diagrams and the wider ‘pillar’ conception itself is often unclear, hampering its ability to be coherently operationalised. If one is prepared to overlook the lack of semantic clarity and confusion of competing terms, it can be argued that the ‘three-pillar’ conception of sustainability (or sustainable development) is a dominant interpretation within the literature. Yet the conceptual origins of this description, and the point at which it emerged into the mainstream, are far from clear, and its exact meaning is a matter of contention. As Thompson puts it, “much of the... discourse around sustainability... is organized around... the three-circle rubric without much disciplined thought about how it does and does not translate into a more comprehensive understanding of sustainability” (Thompson 2017, “Social Sustainability”). Whilst much contemporary sustainability literature may centre around the UN’s more diverse set of SDGs, the three pillars themselves were explicitly embedded in their formulation (UN 2012a).

3.1.1 Early history

To understand the emergence of ‘sustainability’ into the mainstream in the 1980s it is necessary to examine the broad roots from which the concept emerged. This is confounded by the fact that much of the work whose concepts feed into the narrative pre-date the language of ‘sustainability’.

Authors such as Grober (2012), Caradonna (2014), and Du Pisani (2006) have contributed much to shedding light on a wide range of early roots. Of particular

note are the forestry experts of the 17th and 18th centuries such as Evelyn, and Carlowitz, who introduced the concept of sustainable yield in response to dwindling forest resources across Europe (Warde 2011; Grober 2012). Of relevance too are the early political economists such as Smith, Mill, Ricardo, and Malthus who, in the shadow of the industrial revolution, questioned the limits of both economic and demographic growth, and recognised the inherent tradeoffs between wealth generation and social justice (Lumley and Armstrong 2004; Caradonna 2014). The natural scientists and ecologists of the 19th century and early 20th century too help precipitate the schism between the anthropocentric conservationists on one hand, prescribing conservation of natural resources for sustainable consumption, and the biocentric preservationists, who call for preservation of nature due to its inherent worth (Callicott and Mumford 1997).

The contemporary concept, along with the language of sustainability in a global sense didn't emerge however until the late 20th century. The Club of Rome's *'Limits to Growth'* argues for a "world system... that is sustainable" (Meadows et al. 1972, p158); this, claims Grober (2012), marks the first modern appearance of the term in its broad global context (pp155). The same year, in *'A Blueprint for Survival'*, which draws on the unpublished manuscript for *'Limits to Growth'*, the editors of *The Ecologist* present their proposals for the creation of a 'sustainable society' (The Ecologist 1972). Whatever the exact origins of the language, it is from the early 1970s that the concept snowballs; the World Council of Churches' commission on *'The Future of Man and Society'* in 1974 deems the notion of a 'sustainable society' more palatable than the language of limits (Grober 2012, p167). The Ecology Party (later to become the Green Party of England and Wales) adopt their *'Manifesto for a Sustainable Society'* in 1975 (The Ecology Party 1975), and a series of books are published prominently featuring the language of sustainability (Stivers 1976; Meadows 1977; Pirages 1977; Cleveland 1979; Coomer 1979).

In the interests of brevity, much of this earlier discussion is left to authors already mentioned. Instead the narrative is picked up at the cusp of the 1960s environmental movements, focusing on the strand of 'development' and how its critique contributed to the rise of 'sustainable development' in the 1980s.

3.1.2 A twin critique of 'economic development'

Soon after the Second World War, there emerged a consensus in the Western world that there was an urgent need for international efforts to aid the 'development' of 'less advanced countries' (Arndt 1989, p49). It was during this time that the notion of 'economic development', outside of Marxist discourse, evolved from

specifically denoting the exploitation of natural resources in a colonial context, to refer to a rise in material wellbeing indicated by an increase in the flow of goods and services, and growth in per capita income (Arndt 1981). Thus from the 1950s, ‘economic development’ became almost synonymous with ‘economic growth’, which in turn had become a major goal of Western economic policy, although the application of the former term was primarily reserved for poorer countries (Arndt 1989, p51). Truman’s 1949 ‘Point Four’ marked the first large-scale technical assistance development programme, notions of building up capital would follow, and by 1961 the United Nations would declare “International Trade as the primary instrument for economic development” (p72).

The late 1960s and early 1970s witnessed the rise of the modern environmental movement in the West (Rome 2003; Du Pisani 2006; Tulloch 2013). Popular publications such as Carson (1962)’s *‘Silent Spring’*, Ehrlich (1968)’s *‘The Population Bomb’*, and The Ecologist (1972)’s *‘A Blueprint for Survival’*, coupled with widespread media coverage of environmental disasters, such as the Santa Barbara oil spill in 1969, acted to increase awareness of the magnitude of the widespread environmental destruction caused by humans. It has also been argued that the environment, and quality of life issues came to the fore in the West at this point because ‘basic economic needs’ had been largely met following the economic growth of the post-war period (Dunlap and Mertig 1991; Martínez-Alier 1995).

The questioning of economic growth began to re-emerge, with the prominent works of Meadows et al. (1972)’s *‘Limits to Growth’*, and Schumacher (1973)’s *‘Small is Beautiful’*, both arguing that the modern growth-based economy was unsustainable on a finite planet. The 1973 oil crisis, and the worldwide recession that followed, helped to crystallise the idea of the limitations of growth into both the mainstream, and the academic discourse (Du Pisani 2006). This early discourse was radical, and argued that the capitalist economic growth of the Western world was fundamentally incompatible with ecological and social sustainability, and called for structural reform (Van Der Heijden 1999; Tulloch 2013; Tulloch and Neilson 2014).

Coupled with an environmental critique of the economic growth paradigm in the West, was a broad criticism of economic development programmes being implemented in the developing world for their lack of environmental considerations. Caldwell (1984) details several of numerous cases of failed development projects presented at the 1968 Airlie House Conference on Ecological Aspects of International Development. The recurring theme of these projects was a tendency to prioritise short term gains over serious considerations of ecological impacts, either to biodiversity, or ecosystem services. This forms part of a broader critique of the

seeming hubristic belief inherent in the mainstream development discourse of man's ability to dominate and control natural ecological processes (Woodhouse 1972).

At the same time, it was becoming apparent to many that the 'progress' that had been promised by the early economic growth based development programmes was in many ways failing to materialise. Whilst the post-war economic boom had seen a broad rise in living standards in the West, the focus began to shift to the gross inequalities and poverties that still existed in many of these societies (Hicks and Streeten 1979). This led to a second prominent counter discourse in the development literature, critiquing the focus on economic growth, with calls for a shift from a focus of means to ends, to better consider social problems, and a 'basic needs' approach. Arndt (1989) suggests that the first prominent example of this was Seers (1969)'s *'The Meaning of Development'* which argued that economic growth not only failed as a solution to social difficulties, but often was the cause of them. Seers argued that indicators of poverty, unemployment, and inequality provided a truer depiction of the state of 'development' or 'progress' (p91). Notable too is Hirsch (1976)'s *'Social Limits to Growth'*, which probes the pursuit of growth and its fetishisation at the societal level, arguing that it acts to perpetuate inequalities, and that in fact the social limits to e.g. productivity gains are more prescient than distant physical limits. This broad social critique of growth focused development received attention from both the International Labour Office (ILO), and the World Bank (see e.g. Hicks and Streeten 1979; ILO 1976; Streeten and Burki 1978), to the extent that it was considered by some to be the "current consensus" (Arndt 1989, p92).

The 1972 UN *Conference on the Human Environment* in Stockholm marked the first global summit to consider human impacts on the environment, and the first major attempt to reconcile economic development with environmental integrity which were commonly regarded as incompatible (Caldwell 1984). Emergent from the conference was the concept of 'environmentally sound development', which by 1973 had been coined as 'eco-development' (Clinton 1977; Mebratu 1998). 'Eco-development' was defined by Ignacy Sachs in 1978 as "an approach to development aimed at harmonising social and economic objectives with ecologically sound management, in a spirit of solidarity with future generations", further calling for "another kind of qualitative growth" (Glaeser 1984, p25). Credited as one of the earliest ecological economists, Sachs, as an adviser to the United Nations Environmental Programme (UNEP), was influential in promoting this growth-sceptic concept in policy circles during the 1970s (Gómez-Baggethun and Naredo 2015; Martínez-Alier 2015).

The core elements of ‘eco-development’ were described as the meeting of ‘essential human needs’, participation, environmental considerations, and the unifying principle of ‘self-reliance’, understood as not just freedom from the structural dependence on other nations, but freedom for the individual from the pressures of political powers or transnational corporations (Glaeser 1984, pp25-28). Important was the discussion of both local and international power structures and how eco-development faced an uphill battle in challenging them. In this body of literature, economic growth plays something of a neutral role. Sachs downplays the notion of ‘trade-offs’ between environmental management and economic growth, instead arguing for “a different, environmentally prudent, sustainable, and socially responsible growth”, bearing remarkable similarities with later United Nations rhetoric (Glaeser 1984, p216; Berr 2015). This approach seems to differ to that of other early ecological economists such as Daly (1973) and Mishan (1977) who suggested no-growth, and slow-growth economies respectively.

Whilst the environment was being reconciled with economic development, the ‘basic needs’ approach was being rejected by governments in the developing world; following the global economic slump of the late 1970s, there arose a tendency to see the aspirations of ‘modernisation’, and the creation of a ‘new international economic order’, as more important than, and incompatible with, a basic needs approach (Arndt 1989, pp104-111). Coupled with this, Sachs claims the basic needs focused ‘eco-development’ was vetoed as a term in international policy forums by the US administration (Gómez-Baggethun and Naredo 2015). With social critique somewhat pushed aside, McNamara, president of the World Bank, called for the need to “recapture the momentum of economic growth” (Arndt 1989).

By the 1980s the early environmental movements had lost momentum, as the wave of the radical social movements broke and rolled back (Van Der Heijden 1999). Having been somewhat subdued, throughout the 1980s, the twin ecological and social critiques of economic development began to interweave with economic development under what was to be termed ‘sustainable development’ (O’Riordan 1985; Barbier 1987; Brown et al. 1987). Thus, in 1987 when the UN World Commission on Environment and Development published its report *‘Our Common Future’* (the Brundtland Report), calling for “a new era of economic growth - growth that is forceful and at the same time socially and environmentally sustainable”, the debate had come full circle, economic growth was no longer the problem, it was the solution (UN 1987). Co-opting the eco-development argument of a ‘different quality’ of economic growth, a new ‘win-win’ scenario emerged by recasting the same old economic growth in “socially and environmentally sustainable” colours.

3.1.3 The institutionalisation of ‘sustainable development’

Although the term had been in use for some time (e.g. IUCN et al. 1980), the Brundtland commission is widely credited with popularising the concept of ‘sustainable development’ by introducing it into international policy discourse (Basiago 1999; Castro 2004; Johnston et al. 2007; Pope et al. 2004; Redclift 2005; etc.). It define sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In the years following the publication of the Brundtland Report, sustainable development became the dominant paradigm of the environmental movement, and the literature considering it grew exponentially.

The institutionalising of sustainable development would continue with the ‘Rio Process’, initiated at the 1992 Earth Summit in Rio, where the world’s political leaders pledged their support to the principle of sustainable development (Jordan and Voisey 1998). Central to this was the publication of the ‘Rio Declaration’ consisting of 27 principles intending to guide future ‘sustainable development’, and ‘Agenda 21’ which articulates a plan for putting these principles into practice. Agenda 21 built upon the Brundtland Report, emphasising the problems of the North-South development divide, championing economic growth and free trade, and the need to link social and economic development with environmental protection (UN 1992a). Subsequent summits occurred in 1997, 2002, and 2012.

Despite the importance of global efforts such as the Rio Declaration and Brundtland Report in bringing ‘sustainability’ into the mainstream policy discourse, the consensus building through compromise approach taken has been criticised. Tulloch (2013) argues these documents were responsible for transforming what was a “marginal counter-hegemonic radical movement” into a platform for legitimising and obscuring globalised neoliberal policy (p108). Indeed, the approach taken by the UN follows the assumptions that poverty causes environmental degradation; this environmental degradation can be reduced by reducing poverty; to reduce poverty, developing countries need economic growth, which requires freer markets (Castro 2004). This logic is at best simplistic (Lélé 1991), and at worst smuggling an inherently ideological agenda under the guise of benign necessity (Tulloch 2013), clearly running in direct opposition to the earlier growth-critical works. Indeed Dryzek (2005), in his categorisation of environmental discourses, describes sustainability as ‘reformist’, in opposition to the ‘radical’ discourses advocating systemic change, such as the limits discourse (pp13-16).

Criticism of the almost ‘business-as-usual’ approach of sustainable development, which has been promoted to the mainstream by bodies such as the UN, has

led to a heterogeneous counter-discourse. A common critique is typified by Daly (1996)'s dismissal of the "sufficiently vague" definition promoted by the international mainstream. By the mid-1990s, the concept of 'sustainable development' and the notion of 'sustainability' were in vogue (Gatto 1995), finding their way into academic literature and policy agendas around the globe.

3.2 Environment, Economics, and Society

The popular 'three pillar' conception of sustainability or sustainable development is typically realised as the balancing of trade-offs between seemingly equally desirable goals within categories of environment, economics, and society. One problematic facet of this conceptualisation, however, is its lack of theoretical development; there appears to be no original urtext from which it derives, seemingly just appearing in the literature and commonly taken at face value. As early as 2001, this approach has been presented as a "common view" of sustainable development (Giddings et al. 2002).

Although the three pillars have become commonplace throughout the literature, they are not universal. Some work considers additional pillars such as institutional (Spangenberg 2002; Turcu 2013), cultural (Soini and Birkeland 2014), and technical (Hill and Bowen 1997). Other frameworks bypass the compartmentalisation of sustainability completely, Milbrath (1989) for example presents a vision of a 'sustainable society' based on a set of defined values, the '*Natural Step*' framework is based upon four guiding criteria (Upham 2000), and Giddings et al. 2002's conceptualisation involves principles of equity.

The origins of the three-pillar paradigm have been variously attributed to the Brundtland Report, Agenda 21, and the 2002 World Summit on Sustainable Development (Moldan et al. 2012), yet in none of these documents is a clear framework or theoretical background made explicit. The following sections present an analysis of a series of academic and institutional documents as described in Section 2.2.2.

3.2.1 The IUCN

The first prominent occurrence of the phrase 'sustainable development' in published literature appeared in 1980 when the IUCN, in collaboration with the UNEP and the World Wildlife Fund (WWF), published their '*World Conservation Strategy*', subtitled '*Living Resource Conservation for Sustainable Development*' (IUCN et al. 1980). This early conception of sustainable development is motivated by the need for economic development, with its social and economic objectives, to take

conservation into account by considering resource limitations and ecosystem carrying capacity. Whilst there is no explicit mention of the three pillars, their roots can clearly be seen, and sustainable development is briefly defined as that which “must take account of social and ecological factors, as well as economic ones” (pI). It should be emphasised that these three aspects are not held up as a framework, and no judgement is made upon them. The implication appears to be that current development policy primarily focuses on economic objectives when it is an imperative to integrate conservation objectives into policy. There is no discussion of ‘trade-offs’, or the relative importance of the three objectives.

The *IUCN Conference on Conservation and Development* in Ottawa 1986 was convened to evaluate progress in implementing the World Conservation Strategy. It would conclude with a definition: “The emerging paradigm of sustainable development... seeks ... to respond to five broad requirements: integration of conservation and development; satisfaction of basic human needs; achievement of equity & social justice; provision for social self-determination and cultural diversity; and maintenance of ecological integrity” (Jacobs et al. 1987). These requirements cohere well with social and environmental aspects, but there is nothing to suggest a predecessor of anything approaching an economic pillar.

This appears to be a consistent narrative throughout the work of the IUCN. The successor to the World Conservation Strategy, *‘Caring for the Earth’*, calls for development that is “both people-centered ... and conservation-based” (IUCN et al. 1991). The strategy is based upon nine “interrelated and mutually supporting” principles of a “sustainable society”, including changing attitudes, conservation of Earth’s vitality and diversity, and a global alliance for attaining sustainability (pp8-12), and indicators for sustainability are presented under just two themes, “quality of life”, and “ecological sustainability” (p198). In 1996, an “increased emphasis given to people” was seen as an emerging issue, as well as the need to expand use of “legal and economic tools for conservation” (IUCN 1997, pp43-45). At the same time, the models of sustainability being considered by the IUCN included the ‘Egg of Sustainability’ and the ‘Barometer of Sustainability’ both of which considered the dual goals of improving ecosystem wellbeing and human wellbeing as the essence of sustainability (IUCN 1996).

Apart from a short-lived consideration in the early 2000s, when intersecting circles are presented as the “conventional model of sustainable development” (IUCN 2004, pp9–11), the IUCN thus largely avoids the use of the three pillars, preferring instead a model of sustainability that focuses on the goals of improving the ecosystem and human well-being. Discussion of the economy is generally focused on mitigating the negative impacts on the planet’s ecosystems of current practices and the need for a ‘greener’ economy.

The UN

The articulation of distinct social, economic, and environmental aspects of ‘sustainable development’ can be seen in Agenda 21 (1992), and are arguably implicit in the Brundtland Report (1987), although cultural and political/institutional aspects are also present. Indeed Agenda 21 mentions “economic, social and environmental dimensions” of sustainable development (8.4.1), but there is no conceptual justification or framework presented (UN 1992a).

Following the 1992 Rio Summit, the UN established the Commission on Sustainable Development (CSD) for the provision of guidance and monitoring of progress in the implementation of Agenda 21 and the Rio Declaration. In 1995, a workshop involving policy makers, members of international organisations, and scientists, was held with the intention of reviewing indicators of the “three principal aspects of sustainability” (environmental, social and economic) (UN 1995, p3). The conclusions were that the CSD should work towards a core set of indicators which equally emphasise the “economic, social, environmental and institutional aspects of sustainable development”, with the extra inclusion of the institutional aspect being left unelaborated (p5). It has been argued that this inclusion was due to the institutional aspect being integral to addressing the problems of unsustainable development practice (Spangenberg 2002).

The following year, the CSD published a testbed selection of 130 indicators, with the aim of having a “good set of indicators” by 2000. These indicators were categorised under the four aspects presented in the 1995 workshop, economic, social, environmental, and institutional (UN 1996). Despite this, the CSD do not use these 4 dimensions universally. A 1997 report on progress achieved since Rio is structured on the basis of three “mutually reinforcing components” of sustainable development, “economic growth, social development and environmental sustainability” with the aim of achieving “balanced achievement of sustained economic development, improved social equity and environmental sustainability” (UN 1997, pp4-5); but with no discussion of the tensions between these objectives. The existence of “three components – economic and social development and environmental protection” is again emphasised in the sixth session report of the CSD (UN 1998, p3).

In 2001 the CSD published the second edition of their indicator framework which maintains the categorisation of economic, social, institutional and environmental ‘dimensions’ of sustainable development (UN 2001). Goals of “advancement of social and institutional development, to maintain ecological integrity, and to ensure economic prosperity” are also mentioned (p21). By the third edition however,

the four dimensions are no longer elaborated explicitly in order to emphasise the “multi-dimensional nature” of sustainable development (UN 2007).

In parallel to the work of the CSD, the UN launched 8 millennium development goals (MDGs), to be achieved by the global community by 2015 (UN 2001). Interestingly, Goal 7 was to “ensure environmental sustainability”, although the concepts of social or economic sustainability are not explicitly explored. The report of the 2002 Earth Summit prescribes the need to “promote the integration of the three components of sustainable development-economic development, social development and environmental protection-as interdependent and mutually reinforcing pillars” (UN 2002, p8). The need for “integration” of these pillars and a “balanced and holistic approach” is emphasised (p128)

The narrative of “integrating economic, social and environmental aspects” of sustainable development continues throughout the report of the next World Summit 10 years later (UN 2012a). Following the 2012 summit, an ‘Open Working Group’ was established to develop the SDGs for the UN’s ‘post 2015 process’, part of the brief being to “incorporate in a balanced way all three dimensions of sustainable development and their linkages” (p47). Indeed, when the General Assembly adopted the finalised SDGs in 2015, it is stated how the goals are “integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental” (UN 2015a, p1). However, these three dimensions do not explicitly form any part of the framework of the 17 goals.

The OECD

The OECD start to take an active interest in sustainable development as late as 1997, seemingly as a response to the UN General Assembly’s call for national sustainable development strategies the same year (OECD 2006). The need for an “integrated approach to economic, environmental, social, and development co-operation issues” is referenced to Agenda 21 (OECD 1997). These ‘three dimensions’ are heavily emphasised in a 2000 report on indicators for sustainable development (OECD 2000), where the need to better understand the “complex synergies and trade-offs” between the three is recognised (p19).

The proceedings of the OECD conference on sustainable development in 2000 explicitly distinguish between economic sustainability, “the requirements for strong and durable economic growth”, environmental sustainability, “maintaining the integrity, productivity and resilience of biological and physical systems”, and social sustainability, “the importance of high employment, safety nets... equity, and democratic participation” (OECD 2001). The agenda of the OECD’s work

on sustainable development is explicitly stated to be “driven by the desire to advance member countries along a balanced path of economic, environmental and social development” (OECD 2004b, p3). Since the OECD member states are usually regarded as developed countries, this is symptomatic of a shift in the focus of development as a more universal necessity. Economic growth is presented unquestionably as the answer: “Sustainable development... depends on achieving long-term economic growth that is consistent with environmental and social needs” (OECD 2008, p3). The growth imperative is further emphasized in a 2011 publication where the primary aim of sustainable development appears to be to find “sustainable solutions of growth” (OECD 2011, p4), further the need to think holistically about the ‘three pillars’, and carefully consider ‘trade-offs’ is emphasised.

The narrative of ‘Green Growth’ seems to have taken the place of sustainable development within the OECD in recent years, marginalising somewhat the traditional social pillar (OECD 2011). It should perhaps not be surprising that the Organisation for Economic Co-operation and Development prioritises economic growth above all other considerations. Whilst the three pillars and ‘holistic’ thinking are promoted throughout the documentation, the primacy of economic growth is clear, and the social and environmental concerns are mere window-dressing unless they are seen to provide ‘economic opportunities’.

The World Bank

The World Development Reports produced by the World Bank in 1981, 1984, 1986, and 1987 discuss sustaining growth, but nothing on or approaching ‘sustainable development’. The 1990 report however focuses on poverty, emphasising that as well as the need for economic growth, social services such as improvements in education, health, and nutrition are “an essential part of any long-term strategy for reducing poverty” (World Bank 1990, p74). The 1991 report calls for a “look beyond growth in per capita incomes to the reduction of poverty and greater equity, to progress in education, health, and nutrition, and to the protection of the environment” (World Bank 1991, p4), and the phrase ‘sustainable development’ is used for the first time sparingly throughout. The following year’s subtitle is “Development and the Environment” and emphasises the “need to integrate environmental considerations into development policymaking”, arguing for careful assessments of costs and benefits where tradeoffs exist between income growth and environmental quality (World Bank 1992, piii). Published the same year as the Rio summit, this document can be seen as the first attempt of the World Bank to holistically consider what may be identified as sustainable development.

Despite a response to Agenda 21 in 1997 (World Bank 1997), by the 1998/1999 report, the Bank had not really embraced the language of ‘sustainable development’ in the same way as the UN, with little use of the term, and a heavy focus on economic development. This is continued into the 1999/2000 report, although the phrase ‘sustainable development’ is more widespread, and the concepts of intergenerational equity, intragenerational equity. The focus however, remains primarily on addressing the implications of increasing globalisation and localisation for development strategies, and whilst environmental and social issues are discussed, a fully conceptualised presence of ‘three pillars’ is hardly implicit (World Bank 1999). A consistent theoretical framework defining ‘sustainable development’ doesn’t seem to have gained much traction within the Bank; the 2004 report detailing ‘World Development Indicators’ does have categories of ‘people’, ‘environment’, and ‘society’, but also ‘states and market’, and ‘global links’ (World Bank 2004).

In a scathing attack in 2004, Annisette argues that the World Bank has never taken “poverty reduction and sustainable development seriously”. With these themes merely a “part of the Bank’s self-serving rhetoric designed to legitimise its existence and mask its unswerving commitment to private capital interests” (Annisette 2004, p304). This view seems to be shared by Robert Goodland, who spent 23 years working for the Bank, and is described in his 2014 obituary as the Bank’s ‘conscience’ (Goodland 2014). In a 2007 article, he laments that in the late 1990s “most social and environmental policies were gutted, and those that remain are no longer being rigorously followed”. He describes numerous unsustainable practices backed by the Bank, stimulating cattle ranching in the Amazon, encouraging investment in coal and nuclear in India, and the focus on “globalisation, helping multinationals extract oil, gas and other resources from developing countries” (Goodland 2007).

3.2.2 The academic literature

Whilst the IUCN introduced the term ‘sustainable development’ into the mainstream in 1980, it receives little conceptualisation in the academic literature prior to the 1987 publication of the Brundtland Report. Within this period there exists notably Caldwell (1984)’s consideration of the history of ‘ecologically sustainable development’ as the “uneasy union” of ecological and economic values, in the absence of three explicit pillars, the need for holistic thinking is emphasised, as well as “social, legal, religious, and demographic” factors. O’Riordan (1985) too proposes “two main kinds of sustainable utilization: ecological and sociocultural [later ‘socioeconomic’]” (p1443).

Brown et al. (1987) identify three “perspectives, or contexts, in which the term [sustainability] is used” emerging from their review of the literature. The ‘social’ perspective concerns itself with the “continued satisfaction of basic human needs” of individuals, the ‘ecological’ focuses on the “continued productivity and functioning of ecosystems” as well as the “protection of genetic resources and the conservation of biological diversity”, and the “elusive” ‘economic’ definition entails resolving “the limitations that a sustainable society must place on economic growth” (pp716-717). To Brown et al. these are different perspectives on the same concept which have emerged from the literature, closer to observation than anything approaching a conceptual framework.

The same year, Barbier (1987) articulates the development process as “an interaction among three systems: the biological (and other resource) system, the economic system, and the social system”, presenting an early antecedent of the intersecting circles diagram. Each system is ascribed goals: “genetic diversity, resilience, biological productivity”; “satisfying basic needs (reducing poverty), equity-enhancing, increasing useful goods and services”; and “cultural diversity, institutional sustainability, social justice, participation” respectively. The objective of sustainable development then is to “maximise the goals across all these systems through an adaptive process of trade-offs” (p104). This work marks what seems to be the first explicit conceptualisation of the pillars, complete with diagram, and discussion of inherent ‘trade-offs’. Indeed, it is claimed that Barbier first presented this as a result of a 1986 meeting within the International Institute for Environment and Development (IIED), where he was working as an economist, proposing a more analytical approach to understanding sustainable development (Holmberg 1992, p23). Barbier too identifies himself as the progenitor of the ‘Venn diagram’ in later work (Barbier and Burgess 2017), at one point referring to it as “infamous” (Barbier 2011).

Cocklin (1989) draws on Barbier (1987), conceptualising ‘sustainability’ in terms of a set of goals relating to social, economic, and environmental sub-systems. The relation of sustainability to other management goals such as resilience and economic efficiency is considered to be ultimately ideological in nature, and thus trade-offs occur both internally and externally.

Dixon and Fallon (1989) differentiate between purely ‘biological/physical’, and ‘socioeconomic’ definitions of sustainability which revolve around “social and economic wellbeing” hinting at necessary structural changes to current economic activity. Lélé (1991) distinguishes between two competing understandings of sustainable development: sustained growth, which he deems a contradiction; and ecologically sound development with implicit social objectives. He holds that

the concept of sustainable development requires strong clarification, arguing for the need to reject attempts to focus on economic growth, and to recognise the inadequacies of neoclassical economics.

Hancock (1993) approaches a three pillar model in efforts to consider issues of ‘health’ alongside sustainable communities. He argues for a shift in focus from economic development to a “system of economic activity that enhances human development while being environmentally and socially sustainable” (p43). A ‘Venn diagram’ model is presented of health, or ‘human development’, being the confluence of three systems which meet several requirements: a ‘community’ which is ‘convivial’, an ‘environment’ which is ‘viable’, and ‘liveable’ with respect to the community, and an economy which is ‘adequately prosperous’, ‘equitable’ with respect to the community, and ‘sustainable’ with respect to the environment. Superficially, this model is remarkably similar to contemporary models of the three pillars, but it presents the economy as ‘subservient’ to the community and environment, rather than as an entity with which trade-offs must be made.

Munasinghe (1993) claims ‘sustainable development’ encompasses “three major points of view: economic, social, and ecological”, whereby progress is best made via integration of their competing “non-comparable” objectives. Further, three differing approaches to ‘sustainability’ or ‘sustainable development’ are articulated; the economic which maximises income whilst maintaining capital stock, the ecological which seeks to preserve biological and physical systems, and the socio-cultural which encompasses equity and participation.

Yunlong and Smit (1994) develop the three general definitions of Brown et al. (1987) in reference to ‘sustainable agriculture’. They stress the need for integration but do not elaborate on how this might be achieved. Altieri (1995) presents a version of the ‘Venn diagram’ in his discussion of sustainable agriculture; here specific economic, social, and environmental goals are detailed, with the confluence representing ‘agroecology’ (p376). It has been suggested by Thompson (2017) that Altieri draws on Douglass (1984) in his articulation of these three domains, however it should be noted that this diagram is absent from the first edition of Altieri’s book (Altieri 1987). Derived from a 1982 conference on “Agricultural Sustainability in a Changing World Order”, Douglass divides his contributors’ perspectives along “economic, biological, and cultural” lines of thinking, later reiterated with the subtitles “Food Sufficiency: Resources, Technology, and Economics”, “Stewardship: Biology, Ecology, and Population”, and “Community: Justice, Participation, and Development”. Despite the focus on agriculture, these categorisations bear many similarities with perspectives drawn in the wider sustainability literature; however

like Brown et al. (1987) these are separate perspectives as observed in the literature rather than having theoretical basis. Altieri's (1995) work is placed here within the 'stewardship' camp, yet his concluding chapter emphasises the inherent linkages between the biological and socioeconomic problems of agricultural systems. He concludes, "the requirements to develop sustainable agriculture clearly are not just biological or technical, but also social, economic, and political, and illustrate the requirements needed to create a sustainable society" (Altieri 1987, p199; Altieri 1995, p379).

Basiago (1995) describes sustainability as a "methodology designed to maximize the vitality of social and environmental systems" (p119). Economic methods of defining sustainability are described (along with biological, sociological, planning, and ethical methods), although Basiago argues that "a major restructuring of the economy is implied by economic methods" (p114).

The work of Goodland and Daly seeks to distinguish the concept of 'environmental sustainability' from social and economic sustainability (Goodland 1995; Goodland and Daly 1996). They take a largely systems based approach to the environmental pillar, defining it in terms of input-output laws. They are critical of what they perceive as the term 'sustainability' becoming a "landfill dump for everyone's environmental and social wishlists" (Goodland and Daly 1996, p1002). Contrasting to a holistic integrated approach, they argue that the three 'types' of sustainability are "clearest when kept separate", and that "the disciplines best able to analyse each type of sustainability are different" (p1002).

In contrast, Milne (1996) suggests that it is "generally accepted that 'sustainability' is about integrating social, economic, and ecological values", but cautions a lack of agreement in interpretation, distinguishing between authors who call for 'balancing', and those who prioritise the biological aspect (p137). Milne leans towards the latter, concluding that "sustainability requires the subordination of traditional economic criteria to criteria based on social and ecological values" (p155). The World Resources Institute, in Hammond et al. (1995), attempting to produce environmental indicators for 'sustainable development' argue that "sustainability involves-at a minimum-interacting economic, social, and environmental factors" arguing that inadequate attention has been given to the latter (pp2-3). They too argue that sustainable development is that which attempts to "reconcile or establish a balance" between these factors (p31).

Macnaghten and Jacobs (1997) argue that the 'general model' of sustainable development, which emerges from the literature, emphasises trade-offs between economic growth, deteriorating environmental conditions, and a decline in the quality

of life. The authors argue for a model whereby ‘economic welfare’ is a component of the quality of life, which in turn is ultimately constrained by ‘environmental limits’. Such a nested model, as presented to the right of Figure 3.1, has been viewed as preferable to a ‘Venn diagram’ of trade-offs by numerous authors for its emphasis that the three systems represented by the pillars cannot be separated and are in fact subsystems of each other (Mebratu 1998; Giddings et al. 2002). Striking similarities can be seen between this nested model and a much earlier one by René Passet, a contemporary of Ignacy Sachs (Passet 1979). Passet’s systems approach emphasises that the sphere of economy is situated within the sphere of human activities, where social welfare is not reduced to the mere accumulation of goods and services, which in turn is situated within the biosphere. The diffusion of this model into the sustainability literature is uncertain, Passet’s work was likely familiar to Sachs¹, yet the model appears to receive little attention as a primary source in the English language until much later.

Custance and Hillier (1998) detail their work in developing a set of sustainable development indicators for the UK government. Here sustainable development is again understood as the “balance between three broad objectives – maintenance of economic growth, protection of the environment . . . and social progress” (p281). They build upon a set of indicators developed in 1996 which focused primarily on the economic-environmental interaction, acknowledge the importance of including a social dimension, but question whose role it is to define sustainable development. This work reflects a broader body of literature considering ‘indicators’ of sustainable development utilising the three pillars which appears to arise around this time (Bradley Guy and Kibert 1998; Fricker 1998; Stirling 1999; Azapagic and Perdan 2000; Valentin and Spangenberg 2000).

Parallels to the three pillars can be seen in the ‘planning triangle’ developed by Campbell (1996). Campbell produced a model of what he perceived as three major goals or priorities of urban planning: social justice, economic growth, and environmental protection, arguing that these goals introduce three fundamental conflicts, yet at the elusive centre of the three lies ‘sustainable development’, the balance of these goals. Campbell acknowledges the difficulty of finding this balance, emphasises the need to think holistically and move towards shared language, and urges collaboration between development planners and environmental planners. Campbell’s discussion explicitly highlights the notion of conflict or competition

¹The two were contemporaries in France in the 1970s working on closely related topics (Martínez-Alier 2003b, p21).

between these goals and of the need for interdisciplinary approaches in elaborating upon them towards a more comprehensive and rigorous conceptual framework.

Of final note is the treatment of sustainability within the business literature. From the late 1990s, Elkington's 'triple bottom line' (TBL) accounting method gained traction with the publication of his popular book *'Cannibals With Forks'* (Elkington 1997). Drawing strong parallels with three pillars, the traditional financial 'bottom line' of a corporation is complimented by bottom lines for social and environmental performance, termed 'people, planet, profit', encouraging firms to consider longer-term perspectives in their decision making. Corporate usage of the TBL has been met with scepticism in academic circles, however, with little evidence of effective use among the bodies that claim to advocate it. It has been argued that the TBL jargon is inherently empty, vague, and misleading (Norman and Macdonald 2004), paradoxically perpetuating business-as-usual approaches (Milne and Gray 2013). Whilst 'corporate sustainability' may trace its roots to 'corporate social responsibility' which arose in the 1950s, it was not until the 1990s that larger companies started publishing reports emphasising environmental issues, and later certain health issues, although the language of sustainability was rarely used (Milne and Gray 2013). Numerous 'sustainability accounting' methods predate the TBL, yet Elkington's work appears to mark the first use of a three-pillar conceptualisation here (Lamberton 2005). Whilst this body of literature does not appear to be the origin of the three-pillar framework, it seems that the TBL, which is presented in many cases as synonymous with sustainability, may have been influential in cementing its position in the mainstream into the 21st century

3.3 Analysis

Having reviewed much of the early literature, with the motivation of probing the genesis of the 'three-pillar' paradigm, it is of some concern to find no clear answers. Whilst Barbier (1987) appears to provide the origin of the widespread circles diagram and provides a framework to encourage maximisation of the goals of three systems, subject to implied trade-offs, it differs from later uses, most notably in its treatment of the economic system. The three-pillar formulation itself, however, predates Barbier, at least implicitly, appearing in the IUCN's 1980 'World Conservation Strategy', O'Riordan (1985), the contemporaneous Brown et al. (1987), as well as in works preceding the language of sustainability, such as the discussions of 'eco-development' by Sachs and Passet (1979)'s work.

Of the various works discussed here it is possible to broadly distinguish between two ways in which the pillars have been conceptualised. The first approach follows that of Barbier (1987) in presenting the individual dimensions as distinct, yet interacting systems, as taken by e.g. Cocklin (1989) and Hancock (1993) and Basiago (1995). On the other hand, there are those who follow from Brown et al. (1987) in seeing three distinct, yet interrelated perspectives or schools thought such as Lélé (1991) and Munasinghe (1993) and Goodland and Daly (1996).

3.3.1 Competing realities

The systems approach had been used earlier by Passet (1979), who may have indirectly contributed to its use. This approach typically presents three distinct systems with their own ‘goals’, and the interactions of these systems must be managed to meet these goals and the emergent goal of sustainability or sustainable development. The clearest example of this is given by Barbier (1987) and Cocklin (1989) who both emphasise integration of the systems and management of trade-offs between them. Hancock (1993) and Basiago (1995) also take a systems approach, but the implication is that the individual systems strengthen and enhance each other. Campbell (1996) also emphasises reconciliation. Here may also be placed the approaches taken by the UN and IUCN who whilst generally avoiding the language of systems talk about these individual dimensions having specific goals. In a similar vein then too, Munasinghe (1993), Altieri (1995), Milne (1996), and Custance and Hillier (1998) all discuss the integration and balancing of goals, whereas Macnaghten and Jacobs (1997) use the language of trade-offs. The language involved here frequently invokes the need to “integrate”, “balance”, and “reconcile” the pillars without necessarily articulating what this means in practice; whether this requires uncomfortable ‘trade-offs’ or not appears to depend on the level of optimism the work in question is pitching for. This missing link between theory and application is problematised by Barbier and others in later work (Barbier and Markandya 2013, p38; Barbier and Burgess 2017); it is difficult to make decisions about trade-offs without knowing the implications of such choices, and whilst they offer a utility maximisation approach, it remains value-laden. There thus appears an uncomfortable gap between undertheorisation on the one hand and making necessary political value judgements to allow for application on the other.

Alternative to a systems interpretation are the authors who talk about the three pillars as distinct perspectives of sustainability. These discussions range from calls for clarity of competing definitions, Brown et al. (1987), Dixon and Fallon (1989), Lélé (1991); further undertheorised calls for integration of these

perspectives, Douglass (1984), Yunlong and Smit (1994); and Goodland and Daly (1996)'s argument to retain disciplinary distinctions: "social scientists are best able to define social sustainability" (p1002). Blurring the lines of systems/perspectives distinctions come later descriptions such as the '3Ps' of Elkington (1997), or the '3Es' (environment, economy, equity) (Caradonna 2014), which embody broad values further removed from explicit conceptualisation.

Further to these distinctions, the meaning of the economic pillar remains a central point from which much of the early literature diverges. A prominent strand is heavily critical of the dominant global economic paradigm, and sees the economic pillar as a means of producing systemic change, both by erring away from the growth narrative, and thinking of the 'economy' as subordinate to social wellbeing and environmental health. This can be seen in Brown et al. (1987)'s considerations of placing limitations on growth, Basiago (1996)'s call for economic 'restructuring', Milne (1996)'s call for "subordination of traditional economic criteria". Barbier (1987) and Altieri (1987) both reject economic growth as their economic goals, and the IUCN too remains wary of the economic system throughout their literature, instead focusing on the balancing of environmental and social goals.

This contrasts heavily with the understanding pushed by the UN, World Bank, and OECD, where growth is the imperative. Rather than being met with scepticism, a growth focused economic pillar is central to their sustainable development narrative; here growth is key to meeting the social and environmental goals through trickle-down effects. The presentation of an economic pillar centred on growth, equal in importance to social and environmental pillars of sustainability, as an unquestioned, unprobed necessity cements this framing of the pillars as common sense. A lack of a clear conceptual basis acts further to hide this framing from critique, allowing for broad consensus from institutional actors that would otherwise have conflicting priorities. This highlights the problems of undertheorised calls for 'integration' and 'balancing' of the pillars without the acknowledgement that any attempt to do so in practice is value driven.

Historical emergence?

It can be argued that many of the conflicting conceptualisations of the three pillars, and sustainability itself, can be attributed to the historical origins of this body of literature. As has been suggested above, the historical roots and emergence of 'sustainability' is far from a straightforward narrative; indeed Kidd (1992) identifies six distinct but related strains of thought feeding in, as illustrated in Figure 3.2, and there are arguably more. It is through this that one begins to see the origins of why

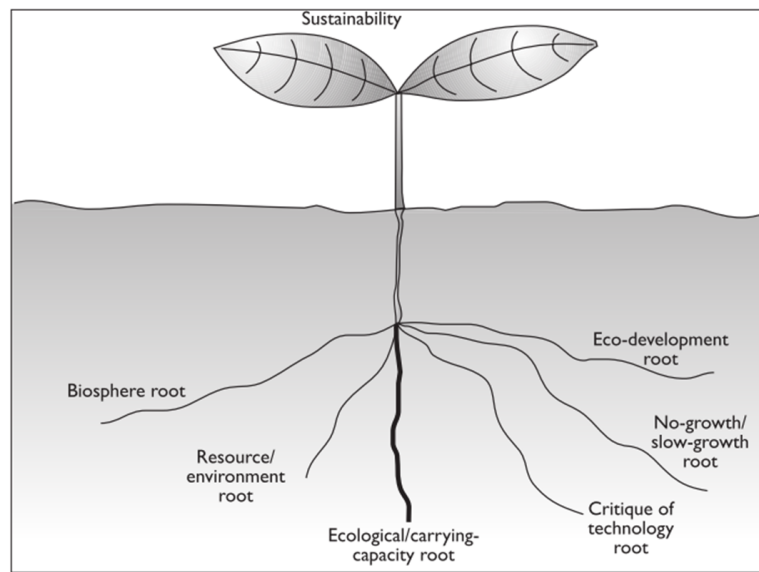


Figure 3.2: Bell and Morse (2008)’s visual depiction of Kidd (1992)’s argument, the roots of sustainability.

the sustainability literature is so broad and confusing: as Kidd argues, it is deeply embedded in fundamentally different concepts. From the development specialists, to the ecological economists, and systems ecologists, various broadly distinct schools co-opt the language of ‘sustainability’ around the same time, leading to what has become such a heterogeneous discourse. As Dryzek has argued, we then see a wide range of actors who see the emergence of ‘sustainability’ as a dominant discourse and recognise it as ripe for shaping in terms that are favourable to them (Dryzek 2005, p146). What arguably unites these disparate roots is criticism of the economic status quo, be that realised by blind pursuit of economic growth, short-sighted profit driven agriculture, or industrialism with little regard to the fragility of complex ecosystems.

Thus, focusing on the economic development strand as explored above, ‘sustainable development’ can be seen to have arisen from a twin critique of the previously popular notion of ‘economic development’, from both a ‘quality of life’ or social perspective, and an ecological perspective. Caldwell (1984) goes into some depth discussing the ecological critique, arguing that the 1972 Stockholm Conference succeeded in placing the need to reconcile economic development and environmental protection on the global agenda, and precipitated the notion of ‘eco-development’. The early social critique is explored by Arndt (Arndt 1989), and is picked up by the Brundtland report which holds that poverty and environmental problems are inherently linked, and that “meeting essential needs” is a key requirement of development (UN 1987, p16).

Thus, the three pillars are seen to be fundamentally rooted here in ‘sustainable development’ from its conception. Further, it is argued that this narrative of environmental and social critiques of the economic status quo is replayed over various other strands that adopt the language of sustainability. This can be seen in the work of the IUCN, who approach ‘sustainable development’ from the concept of conservation, in the limits discourse, considerations of sustainable agriculture as articulated by Douglass (1984), as well as in Elkington (1997)’s TBL. This demonstrates why the economic pillar is so fundamental - what unites these disparate discourses is the perceived inadequacy of the ‘economic’ be it from environmental or social perspectives. The confusion of competing conceptualisations, and different interpretations of the economic pillar within this early literature, can then be understood if sustainability is viewed not as a coherent singular concept, but as a common language of broad schools of thought with the commonality of this ‘economic’ critique.

The depiction of the economic pillar in terms of an economic growth goal, placed on equal footing with social and environmental factors, despite the wealth of critical literature, can be seen as an embodiment the ideological win-win scenario of ‘sustainable growth’ pushed in the 1987 Brundtland report. This was further reinforced by the 1992 Rio summit and publication Agenda 21 which brought this particular interpretation of ‘sustainable development’ to global attention, and further institutionalised by the OECD and World Bank. It has been argued by some that this neutralisation of the radical economic critique via institutionalisation was an inevitable consequence of the UN’s consensus building approach to addressing ‘sustainability’ (Huckle 1991; Carruthers 2001).

This ‘emergence’ of the three pillar model thus leads to it being in many cases presented, with little to no theoretical foundation or justification, as the norm, or a ‘common sense’ understanding of sustainability. This is mirrored in the documents of the UN, and may be seen too within organisations such as the OECD and World Bank. This problematic history puts into question how useful the three pillar conception may be for further consideration in this work, yet also sheds light on the contestations surrounding the understanding of sustainability conceptually.

3.3.2 Towards an understanding of sustainability

This chapter centred on the conceptual origins of the three-pillar paradigm of sustainability as a means for developing a better understanding of urban sustainability rooted in early literature and theory. By exploring the origins of this ‘fracture’, it has been shown that despite being widespread across the literature, there is no

underlying theory or justification behind this paradigm. Whilst a diagram with explicit economic, social, and biological system goals is presented as a model of sustainable development by Barbier (1987), the goals elaborated differ from those of the UN and the meaning is limited to developing nations. Further, an implicit notion of these three pillars predates this, appearing in work by the IUCN and in consideration of ‘eco-development’.

This highlights, as discussed in Chapter 1 the contested nature of ‘sustainability’ and its sister ‘sustainable development’. From an ideological perspective a major source of this contention surrounds the role of economics, and more specifically the status of the dominant global economic system centred on economic growth. This, it has been argued was crystallised into the sustainability discourse through the nature of its early history.

The early literature considering the pillars may be split broadly between those who view the three as distinct perspectives, and those who take a systems approach. Within these formulations, there lacks a commonality in how interactions are treated, whether trade-offs occur, or mutual reinforcements are made. The implications of ‘integration’ here are often undertheorised leading to the value judgements necessary for application often slipping by unnoticed and depoliticised.

By drawing on Kidd (1992)’s argument that the discourse is fundamentally rooted in different schools of thought which all adopted the common language of ‘sustainability’, it is suggested that this presents itself as the source of much confusion and competing conceptualisation. Central to these distinct schools however can be seen a broad critique of the economic status quo, both from ecological and social perspectives. Focusing on the development literature presents the example of twin ecological and ‘basic needs’ critiques of ‘economic development’ from the 1960s crystallising into three pillars of ‘sustainable development’ in the 1980s. It is then argued this narrative is replayed across various other schools of thought under the language of ‘sustainability’, such as those considering agriculture or conservation.

As these conflicts played out, ‘sustainable development’ was institutionalised by the United Nations in the 1987 Brundtland report, and during the subsequent Rio process, which pushes an understanding placing economic growth as the solution to ecological and social problems. This ‘win-win’ approach was later pushed by other major international bodies such as the World Bank and OECD, and reflects the biases inspired by their intergovernmental consensus building remit. This effectively neutralises much radical critique by depoliticising sustainability, and presenting three sets of equally important economic, social, and environmental goals as benign necessity. This notion is further entrenched by the blurring of the language of

‘sustainability’, and ‘sustainable development’ such that economic development remained an implicit, but inadequately formulated, part of sustainability.

A consequence of this lack of rigour is the difficulty in producing operational frameworks for the characterisation of sustainability which remain rooted in theory. Such applications should therefore be context-specific, requiring careful consideration of both spatial and functional boundaries. Although the targets and indicators associated with the UN SDGs are encouraging, a lack of detail is given to a transparent rigorous theoretical foundation in which to ground them and the value judgements that have been made along the way.

Outlook

In exploring the conceptual origins of the three pillar paradigm of sustainability, this chapter has confronted this thesis’s first research question, *How can urban sustainability be understood?* To some, sustainability means maintaining the macroeconomic status quo, whilst paying lip service to issues of environmental stewardship and social equity. To others it represents a radical restructuring of society involving social and ecological liberation. Elsewhere it is just the latest buzzword which must be indulged to receive academic funding or implement desired policies.

Here the observations made in Sections 1.2 and 2.2 have been built upon by revealing more fully the fractures surrounding conceptual understandings of sustainability. It has been shown that various actors, institutional or academic, often hold incompatible worldviews here, casting doubt on the role of consensus building for bridging this discipline spanning divide. The working definition of urban sustainability elaborated in Section 1.2.3, whereby sustainability is understood as ‘semantically open’ coheres well with the emergent understanding of sustainability within this chapter as a common language and an umbrella concept. The three pillars have been shown to be without any strong theoretical foundations, and therefore despite their widespread usage in the literature, this work will remain cautious to engage in an economic pillar centred around growth.

Moving forward this chapter has begun to highlight several of the emergent themes detailed in Section 2.5.1, which will be fully elaborated in Section 4.3. In terms of *theory*, the conceptual emptiness of the three pillar paradigm has emphasised the need to critically examine models employed for understanding. The inherently political nature of sustainability can often be forgotten, and care should be taken to avoid reproducing models without carefully considering their theoretical basis and the embedded ideology within them. This critical approach is taken forward in

future chapters, in terms of proposed thermodynamic measures in Chapter 5, and the critique of the economic growth paradigm which informs Chapter 6.

The view of the three pillars as competing perspectives of the same thing, as well as different approaches to the economic pillar highlights the theme of *pluralism*. The argument of Goodland and Daly (1996) that these perspectives are best kept separate, is rejected in this work as inward looking and not conducive to moving towards an operationalisation of sustainability. Nevertheless scepticism is also held regarding the language of ‘integration’ and its implication of building consensus and erasing difference in perspective.

There is no logic that can be superimposed on the city; people make it, and it is to them, not buildings, that we must fit our plans.

— Jane Jacobs, *Downtown is for people*

4

Urban Studies and Urban Science

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With the UN declaring an estimated 50% urban population in 2008 and further rapid urbanisation occurring, the so called ‘urban age’ is receiving increasing attention in the global research agenda (UN 2008; Brenner and Schmid 2014). ‘Urban sustainability’ has risen to prominence both in academic and policy circles, with “Goal 11: Sustainable cities and communities” elaborated as a crucial element of the UN Sustainable Development Goals Program (UN 2015a). With the rapid growth of available data at fine-grained scales (Rathore et al. 2018; Boeing 2019), it is now commonplace to regurgitate statistics on the impact of rapid urbanisation occurring in the 21st century, from population statistics to greenhouse gas emissions, justifying the importance of the need to focus heavily on urban areas. Regardless

of the reliability of such figures (Satterthwaite 2010), it is clear that the urban occupies a significant position within the global research agenda.

Statistics on the urban obscure the fact that across the planet the urban context holds incredible diversity, not only physically, but functionally, spatially, socially, and so on. It is therefore no surprise to find that the notion of what constitutes ‘urban’ is contested. Such debates go back decades in the urban literature, even if little of this is referenced in work on urban sustainability (Paddison 2001). Indeed it has been variously argued that the hegemonic status of STEM subjects has led to the pursuit of ‘urban sustainability’ being a largely technoscientific endeavour, at the expense of critical social and political urban literature (Petts et al. 2008; Opp 2017; Cauvain 2018a). Much like the wider sustainability literature, as discussed in Chapters 1 and 3, this technoscientific approach has been reinforced by the primacy of neoliberal economic approaches within the global institutional mainstream (Davidson et al. 2012; Martin et al. 2018). To Davidson et al. (2012) sustainability assessment is hampered by its “lack [of] conceptual frameworks that provide an epistemological link between a definition of sustainability and the indicators that measure it”. It is contended here then that urban sustainability assessment is hampered by both this and the conceptual frameworks surrounding a definition of the urban. The notion of ‘urban sustainability’ is thus contested across two separate broad bodies of literature.

As outlined in Section 2.2, urban research remains a fragmented area of study, hampering the imperative to understand the city as a holistic entity. Historically, study of the urban took root in 20th century scholarship, following the urban growth precipitated by the industrialisation of the 19th and 20th centuries which greatly outstripped anything witnessed previously. Whereby previous authors in the 19th century and prior, such as Engels (1845)’s analysis of the industrial growth of Manchester in *‘The Condition of the Working Class in England’* and Stow (1603)’s *‘Survey of London’*, primarily concerned themselves with *observing* the city, it was in the 20th century that scholars sought to *understand* the city (Paddison 2001).

Numerous authors have attempted to map an outline of urban research. A graphical representation of this landscape from the article classification process of the journal *‘Cities’* is reproduced in Figure 4.1 (Kirby 2012). These mappings, in contrast to what has been noted in Section 2.2.2 regarding the dominance of STEM approaches, tend to underrepresent the presence of the natural sciences. Rather than the marginalisation of STEM however, this reveals a distinct lack of interaction and cross pollination between these fields engaged in urban research.

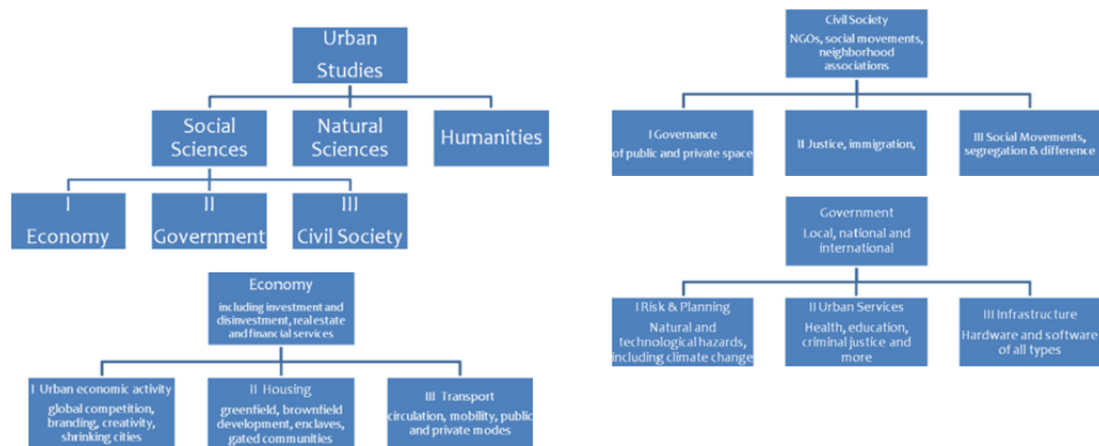


Figure 4.1: Schematic illustrating the themes used for the categorisation of article submissions for the journal ‘*Cities*’ (Kirby 2012).

It appears there is little dialogue between the critical social science literature seeking to understand what the urban means in our current age, and the largely technoscientific enquiry into operationalising a notion of ‘urban sustainability’. This chapter examines the fracture between these siloed schools of research and how the urban has been understood and conceptualised within them. In doing so, this addresses the first research question in Section 1.4.1, moving towards a pluralistic understanding of urban sustainability.

Section 4.1 briefly reviews the development of urban studies as a field, before considering how research within has answered the question ‘what is a city’. A review outlines the defining conceptualisations of the ‘urban-rural dichotomy’, and the question of ‘planetary urbanisation’. Following this, a review of how the urban has been understood in policy is given consisting of the multiplicity of ways urban areas are defined across the globe, before focusing on how the city is defined in the UK context. Section 4.2 considers authors who have talked about a field of ‘urban science’, this is considered from both biological and physical science perspectives. Outlines are given of how the urban has been understood and conceptualised in terms of urban ecology, metabolism, mathematics, and modelling, and within the complexity and system sciences. Finally, Section 4.3 articulates emergent themes which have been encountered across the urban studies/science fracture, and links them to observations that were also made in Chapter 3.

4.1 Urban Studies

Through the evolution of urban studies there has emerged an epistemological struggle between positivist ‘universalising theories’ searching for the ‘paradigmatic

city’, and more postmodern approaches rejecting objectivity and embracing the diversity of urban landscapes (Clarke 2015; Paddison 2015). Much of the twentieth century in urban studies was dominated by the work of the *Chicago School of Urban Sociology*, of key importance were Burgess (1925)’s concentric zones theory of the urban, and Wirth (1938)’s conceptualisation of the city as a function of size, density, and heterogeneity of population (Chen et al. 2013, pp38-45; Gottdiener et al. 2016, pp1-5). By the 1960s and 70s this work was under attack by a new generation of Marxist scholars such as Castells who argued the re-evaluation of the urban under the lens of an all-encompassing modern capitalism (Chen et al. 2013, p51). Harvey too argued that the city displays uneven growth and spatial development due to the profit motive of capitalist enterprises, recasting the city as a “theater of class struggle, centered on land markets as machines for distributing wealth upward” (pp51-53; Scott and Storper 2015). From the 1980s, Scott and Storper (2015) identify three major branches of urban theory, the issues of social diversity, including gender, ethnicity, race, and class e.g. Massey (1991), Waldinger and Bozorgmehr (1996); the effects of globalisation on the internal structure of cities, e.g. Friedmann and Wolff (1982), Sassen (1991); and the reconceptualisation of urban politics and governance in relation to the nature of scale e.g. Brenner (1999), and Cochrane (2006).

Since the literature considering the urban is incredibly broad, spanning numerous disparate disciplines and methodological frames, it cannot be done justice here. Paddison (2015), reviewing the state of the art of urban studies, presents a field whose boundaries are in constant flux, with “a lack of consensus around its ontological core, what defines the city, and how it should be conceptualised” (p940). Like sustainability studies, urban studies is broadly interdisciplinary in nature, and thus suffers from many of the same challenges this broad scope engenders. This section this focuses solely on Paddison (2015)’s question of how the city should be defined.

4.1.1 What is a city?

What at first seems like a simple, innocent question poses numerous difficulties on further consideration. Oxford Dictionaries (2019) yield rather unhelpfully “a large town”, but goes on to define a town as “a built-up area with a name, defined boundaries, and local government, that is larger than a village and generally smaller than a city”. The city is more than its physical form. Robson (1975) argues that whilst one “can say with some confidence what we mean by ‘urban’ in physical terms, it is much more difficult to spell out its social significance” (p184). Mumford (1937) describes the city as “a geographic plexus, an economic organization, an institutional process, a theater of social action, and an aesthetic symbol of collective

unity” (p185). These points are developed by Pile (1999) who, in his chapter ‘*What is a city?*’, argues that it is the “intangible qualities of city life” that set it apart; a series of contradictions, luxury and poverty, tradition and innovation, order and disorder, freedom and dependency (p6). To Pile, whilst distinguished by its scale and intensity, it is the social significance of the city that makes it tick, the association between individuals and institutions, be they social, economic, cultural, or political; the proximity of their interactions, aided by the geographic plexus of the city which acts as a focus for all kinds of exchanges.

An urban-rural dichotomy

One way in which the urban has been defined is by what it is not, often encapsulated in terms of an urban-rural dichotomy. From the 19th century this has evoked both anti and pro urban discourses, lamenting loss of rural pastoral life to the dark satanic mills of industry, or alternatively viewing the urban as an engine for progress and innovation (Davoudi and Stead 2002). In popular discourse, this is a clear distinction, delimited by the spatiality, both in terms of density and level of homogeneity, as well as the perception of separate modes of social life. However, the boundary between the two is rarely clear, not only functionally, but spatially too. Indeed, in contemporary times, increasingly only the remotest areas lie largely outside of the city’s sphere of influence. Thus, a large body of work exists critiquing the usefulness of such distinctions.

It has been argued that this urban-rural distinction is artificially buoyed by statistical measures of urbanisation trends employing this categorisation (Stewart 1958). Employed by the UN since the 1940s, differences between ‘urban’ and ‘rural’ populations continue to be used in statistics tracking urbanisation trends (Champion and Hugo 2016). It is from here that various indicators are measured across this urban-rural differential, particularly relating to health (Hartley 2004; Singh and Siahpush 2014). Further, the distinction is enforced by a frequent lack of linkage in policy, with governance tending to treat urban and rural issues as separate policy areas (Davoudi and Stead 2002). Regardless, the blurring between urban-rural distinctions and the difficulty of where to draw the boundary has led to a plethora of competing approaches and terms such as urban areas, metropolitan areas, the urban fringe, suburban, and the urban region, all giving rise to different understandings of what constitutes urban and rural (Schaeffer et al. 2012).

The nature of this urban-rural distinction has also been thoroughly debated in socio-cultural terms, with the question of whether one can demarcate separate modes of living. Critique of the posing of this distinction as a dichotomy has led to proposals

of a less rigidly defined ‘urban-rural continuum’ (Stewart 1958). Dewey (2002) dismisses an uncritical characterisation of urban or rural specific aspects, and goes on to argue five aspects from which a continuum may be loosely defined: anonymity, division of labour, heterogeneity, impersonal relationships, and symbols of status. Dewey argues that these aspects are an inevitable consequence of population size rather than cultural artefacts. The correlation of spatial relationships to cultural differences is similarly explored and critiqued by Uzzell (1979) who evidences this as largely a myth, arguing such reductive thinking ignores historical social injustices and wider events which hold far more sway on cultural differences than any spatial factors. Regardless of this theoretical debate however, various empirical works reveal that a distinction between urban and rural life still holds significance in formation of identity (Bell 1992; Vanderbeck and Cheryl 2003; Guang 2003).

The conflation of rural with agriculture roughly reflected reality, at least in the US, until the mid 20th century (Schaeffer et al. 2012), however now with globalisation, the decline of small scale farming across large parts of the world, and the advent of urban agriculture, such notions have been exploded (Tacoli 1998). This corresponds to claims that the terms urban and rural are too broad brush as categories purposed towards uncritically grouping locales that differ vastly globally (Stewart 1958; Hoggart 1990). Further comparisons across the urban-rural divide tend to ignore the complexities and causality of social, cultural, and structural contexts (Pahl 1966). A natural conclusion is that the classification of areas as either urban or rural lacks theoretical rigour and is generally of limited value (Hoggart 1990; Murdoch and Pratt 1993). Whilst this extended debate seems to have diminished the importance of the ‘rural’ within the academy, it is difficult to claim the same can be said of the ‘urban’. This debate thus continues into consideration of how it is difficult to disentangle most areas of the planet from the influence and indeed label of the ‘urban’.

Post-city? Planetary urbanisation

In recent years, critical urban scholars have argued that to understand contemporary urbanisation, inherited understandings of the urban must be revised and interrogated (Schmid 2018). Brenner and Schmid (2015), argue that a consensus equating the urban with a “specific spatial unit or settlement type – the city, or an upscaled territorial variant”, despite dissent from e.g. Castells, remained largely uninterrogated throughout the 20th century (p54). They offer up an epistemological framework intending to clarify the foundations of critical urban theory which they argue have become disjointed in opposition to dominant neo-positivist ideologies.

Central to their framework is a deconstruction of the urban and urbanisation, arguing that these should be seen as theoretical categories, not empirical objects. The urban is thus conceptualised as a multiscalar process of evolution rather than a bounded unit or settlement type, and urbanisation becomes the interplay of three ‘moments’. These entail spatial clustering and agglomeration, persistent ‘implosion-explosion’ of sociospatial organisation, and the transformation of places outside the traditional ‘city’ in response to the “everyday operations and growth imperatives of often-distant agglomerations” (p167). This latter moment evokes the approach to a global hinterland, a so called ‘planetary urbanisation’ where globalised neoliberalism has exploded the traditional urban/rural opposition.

The idea of planetary urbanisation is anticipated by Lefebvre (1968)’s *‘The Urban Revolution’* which describes the rise of an urban ‘fabric’, and the ‘complete urbanisation of society’ by a relentlessly expanding urban capitalism (Merrifield 2013; Wilson and Jonas 2018). The concept has generated fierce debate in the last decade, prompting various responses to criticisms from its most notable defenders Neil Brenner and Christian Schmid (Storper and Scott 2016; Brenner 2018; Schmid 2018). Defending against the accusation from numerous voices that planetary urbanisation is a universalising theory, taking a broad brush to the variegated processes and forms of urbanisation around the world, Brenner (2018) argues that this is a misunderstanding and that the unevenness and contextually specific nature of urbanisation has always featured in the theory. Indeed, he positions this work as critiquing the “overgeneralized, acontextual concepts of ‘the’ city” (p2).

The thesis has gained support in its preference of a notion of the urban as an abstract process, over the more restrictive language of ‘the city’ as an object. Again, this argument draws on Lefebvre (1968) who dismisses the city as a ‘pseudo-concept’ arguing that it ‘no longer corresponds to a social object’, and that urban society ‘constitutes itself on the ruins of the city’ (Lefebvre 2003, p57; Merrifield 2013). Under this understanding, every place is somehow integrated into the processes of production, consumption, and distribution, stemming from the dynamics of the urban system (Barnett and Parnell 2016). While perhaps important theoretically for reconceptualising understandings, it has been argued that this postmodern critique overlooks ongoing practical and political significance of e.g. civil society groups laying claim to the ‘right to the city’ (Barnett and Parnell 2016). The value of planetary urbanisation arguably lies in its questioning of the obsession with demarcating a neat boundary between city and non-city (Brenner 2018).

4.1.2 Understandings in policy

The UN Population Division's '*World Urbanisation Prospects*' published every few years since 1988 remains the primary source for global data on urbanisation statistics (Satterthwaite 2010). Since there exists no common global definition on what may be considered an urban settlement, these reports draw on self reported data from national statistical offices, and detail each nation's definition. These vary widely, from Denmark's "localities with 200 inhabitants or more", to the Netherlands' "municipalities with 20,000 inhabitants or more", and the more complex such as Germany's "communes with population density equal or greater than 150 inhabitants per square kilometre", and Nepal's "since 1999, a complex set of rules varying by ecological zones and based on annual revenue, population size and infrastructure is used" (UN 2015b). A breakdown of the different criteria used by countries to identify urban areas is displayed in Figure 4.2. What this shows is that whilst institutional definitions of urban areas are crucial for policy and governance, these definitions vary greatly both internationally and over time as terms are updated.

	<i>Number and type of criteria</i>	<i>Sole use</i>	<i>Used in conjunction with other criteria</i>	<i>Percentage according to sole use</i>	<i>Percentage according to use in conjunction with other criteria</i>
1 criterion	Administrative	65	60	27.9	25.8
	Economic	—	32	—	13.7
	Population size/density	49	87	21.0	37.3
	Urban characteristics	10	44	4.3	18.9
2 criteria	Administrative and population size/density	26	—	11.2	—
	Administrative and economic	—	—	—	—
	Administrative and urban characteristics	12	—	5.2	—
	Economic and population size/density	14	—	6.0	—
	Economic and urban characteristics	—	—	—	—
	Population size/density and urban characteristics	15	—	6.4	—
3 criteria	Administrative, economic and population size/density	5	—	2.1	—
	Administrative, economic and urban characteristics	—	—	—	—
	Administrative, urban characteristics and population size/density	4	—	1.7	—
	Economic, urban characteristics and population size/density	—	—	—	—
4 criteria	Administrative, economic, population size/density and urban characteristics	13	—	5.6	—
	Entire population size	10	10	4.3	4.3
	Unclear definition	3	3	0.9	0.9
	No definition	7	7	3.0	3.0
	Total number of countries or areas	233	—	100.0	—

Figure 4.2: Breakdown by country of criteria used to classify urban areas - '*World Urbanisation Prospects, 2014 Revision*' (UN 2015b).

This variable data has implications for both comparison of datasets from different nations, as well as the accuracy of aggregate global statistics of urbanisation. Indeed Satterthwaite (2010) suggests that the much quoted 50% urban population is better understood as the centre of a loose band rather than as a precise figure.

City boundaries

Shaw (2015), in a discussion of Brenner and Schmid (2015)'s post-city epistemology argues that whilst the urban boundary may be an arbitrary social construction in theoretical terms, that does not preclude the fact that administrative boundaries exist and have real consequences. Such consequences are readily apparent in examples where the physical 'urban area' is considerably larger than the area within tightly defined administrative boundaries. The city of Nottingham remains a notable case here. Whilst mid-2017 estimates place the population within the City's administrative boundary at 329,200, that of the wider 'Greater Nottingham' urban area (including neighbouring districts of Broxtowe, Ashfield, and Rushcliffe) is placed at 675,000 (Nottingham City Council 2018b). It has been argued that these tight administrative boundaries have a large impact on statistics associated with the city (Parr 2007; Cauvain 2018b). Nottingham City performs poorly in indices of deprivation relating to poverty, education, and other social aspects. Comparison of statistics across the Greater Nottingham area reveals a stark spatial inequality across the tight City boundary, negatively impacting 'performance' relative to other cities. Whilst the socioeconomic deprivation has been partly precipitated through historical reasons, such as the large social housing stock, the tightness of the administrative boundary acts to reinforce many of these issues (Cauvain 2018b). Particularly in the contemporary climate of national austerity related cuts to local government budgets, the confined boundaries place limits on the revenue that the local authority may raise from other sources such as taxation; indeed this has proved such an issue that calls are being made to expand the city's boundaries (Nottingham City Council 2018a).

Status of an urban settlement as a 'city' is often largely arbitrary, usually granted to settlements administratively based upon the fulfilment of certain criteria. Up until the 19th century in the UK this was associated with the presence of a cathedral, leading to anomalies such as St David's in Wales holding City status, despite a population of less than 2000 (Office for National Statistics 2019). Although informal rules were established for the conferral of city status in the UK in the early 20th century based upon population, good governance, and a 'local metropolitan character', exceptions were regularly made seemingly at the whim of the home

office or monarch (Beckett 2005). In the UK, ‘City status’, whilst prestigious offers the settlement no special rights other than being able to refer to itself as a city (Beckett 2005). The arbitrary status of the ‘city’ in the UK is demonstrated well by the example of the ‘City of London’, which constitutes the historical centre whose population is less than 10,000 (Office for National Statistics 2019); the wider ‘Urban Area’ of ‘Greater London’ on the other hand, which would better fit the popular understanding of London as a city, does not hold city status.

Parr (2007) details four interrelated definitions of the city, on top of standard administrative legal definitions. The first, the ‘built city’, is based upon the physical extent of the built up area which whilst argued to be intuitive to visualise, suffers from boundaries which are porous to labour and housing markets, as well as service provision structures. As has been argued by numerous authors, spatial boundaries often don’t reflect the reality of social system boundaries (Uzzell 1979; Dewey 2002; Vis 2018). Thus Parr defines the ‘consumption city’ as the area which is primarily reliant on the built city for its consumption, and the ‘employment city’ as the area whose workforce is primarily composed of those working within the built city. Alternately the ‘workforce city’ is the area from which the majority of the built city’s labour supply is drawn based on workforce dependence rather than employment dependence. Parr argues that each of these definitions have strengths and weaknesses dependent on the context in question, such as infrastructure planning in the built case, retail and marketing for the consumption, public transport and regional development for the employment, and housing for the workforce city. These definitions are largely concerned with what may be termed socio-functional boundaries of the city based upon the regular movement of people in and out of a central zone (Vis 2018, p14). Whilst Parr’s specific definitions do not seem to have been picked up significantly, ‘travel to work areas’ have been defined by the UK government which are used for e.g. transport planning purposes (Office for National Statistics 2016b), corresponding roughly to Parr’s ‘employment city’.

4.2 Urban Science

Whilst the divide between the ‘natural’ and the ‘social’ sciences may be somewhat arbitrary, particularly within Geography, from as early as the 1960s coupled with the advent of more advanced computer modelling techniques, practitioners from fields such as mathematics, physics, and ecology have developed an interest in the urban (Alberti 2017). This has seemingly evolved from mere applications within cities to applications attempting to understand cities themselves. In more recent years, the

increasingly available access to large datasets has allowed for the expansion of the simulation and modelling of various urban phenomena at ever finer scales.

Batty argues that in the 21st century a new paradigm is emerging “developing formal ideas about how cities are ordered and structured”, a ‘science of cities’ centred on temporal dynamics, flows, and size and scale (Batty 2013, p15). To Batty, this is solidly founded within the complexity sciences, viewing cities not as a physical locations but “constellations of interactions, communications, relations, flows, and networks” (p15). Whilst Batty forwards a physics based mathematical foundation of a science of cities, a more biological version has been proposed by McPhearson et al. (2016b) centred around urban ecology, seeking a “holistic, integrated science of urban systems” (p198). These two approaches share a common regard of complexity science, but the authors come from quite different backgrounds with differing perspectives of what such a unified science may look like. Samet (2013) too attempts to unify ecological, biological, and physical conceptions into a a science of cities based upon complexity theory, which is argued to provide a ‘unifying framework’ for diverse aspects of the urban system.

This section presents a brief tour of what has been here labelled ‘urban science’, typically realised as research attempting to understand the urban from a primarily positivist natural science tradition. This ranges from initial biological and ecological perspectives, through physics and mathematical sciences, to complexity and systems theory. This literature selected, in focusing on conceptualisation of the urban as a whole, thus neglects several applied fields, particularly from engineering disciplines which tend to focus on individual issues such as research centering on urban climate, transport, and energy.

4.2.1 Biological perspectives

Arguably the first foray into an analysis of the urban from a natural science perspective arises from the field of ecology. This extends from simply applying standard ecological techniques within the city to recasting the city as an ecological system, moving from ecology *in* cities, to ecology *of* cities (Marzluff et al. 2008, pviii). This casting of the urban as an ecosystem also runs parallel to conceptualisation of the urban as a biological system through metabolism studies.

Urban ecology

Urban ecology arose in the 1920s from the Chicago School who viewed it in sociological terms as the interaction of humans with the urban environment, applying ecological concepts to human interactions (Wu 2014). Whilst bio-ecologists bordered on usage of the term throughout the 20th century, including various studies of the distribution of organisms within cities, there remained a strong preference to research nature outside of human influence. From the early 1990s however, the field bloomed, and Wu (2014) identifies three additional strands of urban ecology: the treatment of the city as an ecosystem consisting of both natural and socioeconomic components; an urban landscape ecology approach; and finally the emergence of an ‘urban sustainability’ emphasising the relationship between ecosystem services and human wellbeing (pp211-212).

McIntyre et al. (2000) systematically review a selection of ecology publications with respect to their understandings of ‘urban’. Notable within this is the ‘urban-natural’ dichotomy (cf. the urban-rural dichotomy presented above) as “undeveloped areas... outside human influence” (p51). Most papers reviewed generally treated the urban as a loosely defined biome. The authors argue that it would be mutually beneficial for the natural scientist and social scientist to draw on each other’s work to develop richer understandings of what the urban is; whilst admitting the inherent problems with seeking to define, they suggest at least a working definition of urban for each study be put forward. This view is largely shared by Marzluff et al. (2008) who argue that it is “highly counterproductive - to separate human and natural components in urban ecological studies” (px). They argue that the field must evolve towards a view of cities as emergent phenomena where human and natural processes form a complex interacting web, impossible to disentangle and analyse individually. An evolution towards a more integrated perspective towards social and ecological issues is observed by Pickett et al. (2008), although they state that it is still lacking in theory. By reviewing various approaches, they move towards a conceptual framework for an integrative urban ecology identifying social, biophysical, and integrative factors. Similarly, Young (2009) argues that integrative urban ecology across the nature-society divide has been inadequately theorised, and that a rich history of alternative viewpoints remain relatively unexplored.

Wu (2014) argues that the transdisciplinary landscape of an integrative urban sustainability seems to have been broached, with the field moving to a position where the emergent goal of ‘urban sustainability’ is sought in both theory and practice (p218). Whilst perhaps this is an idealised observation of urban ecology as a field coalescing around a single goal, other authors also argue that greater

emphasis on human wellbeing and its relation to ecosystem services provides a fruitful link between the natural and social sciences (Standish et al. 2013; Swaffield 2013). Nevertheless siloed approaches still exist, particularly in the realm of the biological sciences (Pickett and Cadenasso 2017).

In the 21st century urban ecology has also increasingly bordered on the complexity sciences. Marzluff et al. (2008) argues that perspectives have evolved from traditional ecosystem perspectives of viewing the urban as largely deterministic, to an acceptance that the level of complexity leads to emergent behaviour that is largely unpredictable (pviii). Whilst ecology has arguably always bordered the complexity sciences and thinking in terms of systems, Marzluff et al position this as a potential for integrating with wider considerations of the urban within the complexity sciences.

Urban metabolism: the city as an organism

As detailed in Section 1.3.3, the metaphor of the city as a human body has existed since at least the seventeenth century, following medical advances revealing the circulatory and respiratory systems (Sennett 1994). Early urban sociologists such as Mumford (1937) and Schnore (1966) have also made similar comparisons, stressing the interdependence of internal processes and the phenomena of adaptation and growth. This leads to the urban functioning being cast in terms of that of a living organism which maintains itself through metabolic flows of material and energy (Hoornweg et al. 2012). The foundations of this conceptualisation were laid by Wolman (1965) who used it to model a hypothetical US city.

In subsequent decades, the complexity of this type of analysis was recognised, and two main schools emerged, the Emergy analysis of HT Odum, and that of material flow analysis (MFA) spearheaded by authors such as Paul Brunner (Baccini and Brunner 2012; Kennedy et al. 2011; Cui 2018). Emergy measures the amount of embodied solar energy required to produce one Joule of energy of a certain form, for example it is claimed that there are 40,000 units of solar energy embodied in every unit of coal energy (Odum 1996). The analysis involves producing a system diagram identifying all flows between subsystems, which are quantified and then transformed into solar energy units (Odum 1983; Hau and Bakshi 2004). MFA produces detailed accounts for stocks and flows of resources in terms of mass, and is argued to be the mainstream approach to urban metabolism by Kennedy et al. (2011) due to its use of recognisable units. Urban metabolism studies have varied from general considerations, to analysis of specific nutrient cycles, with the general suggestion that throughput is increasing over time, and that certain substances seem to be accumulating in cities (Kennedy et al. 2011). Whilst numerous urban metabolism

studies exist for real cities, there remains no commonly established framework for carrying out data collection and analysis (Hoornweg et al. 2012).

A notion of ‘urban sustainability’ is realised in this context through the gradual move from linear urban metabolisms to circular ones, and it is through this that links are seen to the wider ecological economics literature and industrial ecology (e.g. Goodland and Daly 1996, Erkmann 1997). Here the sustainability of the city is maintained by minimising non-renewable resource consumption, and encouraging the maintenance and growth of local stocks through recycling and the reduction of waste production, whilst retaining livability (Newman 1999). This brings into question the nature of boundaries, as it has been argued by some authors that a true circular metabolism is not possible without the dependence of land outside the traditional urban boundary (Acsehrad 1999). This has also been discussed in the context of entropy by various authors (Newman 1999; Céspedes Restrepo and Morales-Pinzón 2018), linking to the work of Georgescu-Roegen who argued that complete closure is impossible due to the necessity of entropy production (Georgescu-Roegen 1971). This argument forms the basis of exploration in the next chapter. Further the existence of a near circular economy is seen as limiting the ability of any sort of growth of the system, as this would require additional tangible input. Céspedes Restrepo and Morales-Pinzón (2018) argue that these limitations are not often considered in the urban metabolism literature, and would benefit from becoming integrated into any future frameworks.

To Céspedes Restrepo and Morales-Pinzón (2018), the ‘tangible’ aspect of metabolism concerning material is becoming increasingly coupled with an ‘intangible’ dimension composed of socio-economic aspects such as perceptions, laws, politics, and social structures, leading to the transition to a ‘*social-ecological system*’. This mirrors the evolution of the urban ecology literature described above. The ‘intangible’ aspect is arguably integral to a more holistic representation of urban metabolism, but presents a less rigorous theoretical framework, as exemplified by Newman (1999)’s ‘extended metabolism model’ which includes less rigorously justified indicators for livability and internal urban dynamics. Broto et al. (2012) recognises the need for developing interdisciplinary approaches to urban metabolism, detailing the diversity of perspectives, and heralding its potential as a link between urban complexity, governance, and socio-economic change.

4.2.2 Urban physics

Away from the biological sciences, cities have also found themselves under the lens of analysis of physical scientists in a broad area often referred to as ‘urban physics’ (Pollock 2016). These approaches are generally heavily embodied in mathematical foundations as well as the complexity sciences.

Mathematics: scaling laws and fractals

A significant area of interest in recent years, in the niche of applied mathematics to urban theory surrounds the proposition of ‘scaling laws’ for urban systems. These ‘laws’ follow from Kleiber (1947)’s observation that the metabolic rate of various animals, Y , seems to scale with their body mass, M with an exponent of $3/4$, that is, $Y \sim M^{3/4}$. A log-log plot of the two parameters produces a straight line with gradient $3/4$. With parallels drawn between urban systems and living organisms, it was perhaps natural that urban theory literature should arise considering the scaling of city size with various urban attributes. A key example of this is presented by Bettencourt et al. (2007), with examples of a diverse range of parameters such as new patents, GDP, serious crimes, and length of electrical cables argued to scale with city size. Since this work there has been a flurry of interest in correlating all sorts of attributes with urban size (Bettencourt 2013; Louf and Barthelemy 2014; Arcaute et al. 2014; Tachet et al. 2017)

Despite a wealth of interest, particularly with the ready availability of large datasets in recent years, these so called scaling laws remain controversial in some circles. A natural consequence of these proposed laws surrounds the question of how one defines the bounds of the urban system. Cottineau et al. (2017) investigate how changing the bounds of the system in question based upon criteria surrounding density, commuting flows, and population cut-offs, affects the exponent of various scaling laws. They show that merely changing the population cut-off dramatically affects the observed scaling exponent, i.e. the scaling is relative to the city definition chosen. Whilst they claim that these deviations are neither random errors or systematic biases, the findings cast doubt on whether conclusions or theory can or should be derived from single observations with arbitrarily chosen urban boundaries.

Leitão et al. (2016) argue that least-square fitting is insufficient to conclude the existence of non-linear scaling, presenting a methodology to better investigate data fluctuations. Louf and Barthelemy (2014) argue too that it is unclear what insights the existence of such laws reveal anyway. They cite an example of investigating how the size of the city affects per capita carbon dioxide production, with two

different measures of the city bounds producing contradictory results. They argue that in the absence of a theoretical model that attempts to explain what is observed, no conclusions may be drawn.

This contention around the existence of scaling laws seems to lead to more fundamental epistemological questions. Foremost whether universal ‘laws’ that govern the properties of such complex systems as cities exist to be discovered, and whether the pursuit of some sort of ‘unified urban theory’ is misguided. Further there can often be conflation between understanding a system and being able to make predictions, the latter does not necessarily follow the former. Another epistemological conflict arises surrounding ‘measuring of the immeasurable’ and the differences between the quantitative approaches that tend to be taken by physical scientists and the more qualitative interpretative approaches taken within the social sciences. Regardless of the importance of mechanistic insight, data analysis without a strong grounding in theory is an oversimplification of complex reality. Further, it remains problematic to average over huge datasets over many diverse regions and historic time periods.

Urban modelling

The advent of computing in the mid 20th century launched an experimental arena for which various aspects of quantitative urban theory could be simulated and tested. This field was buoyed by the need to test the impact of various policy and infrastructural decisions prior to implementation, particularly those involving traffic simulation (Wilson 2016). With the increasing availability of abundant data sources, often with finely resolved geographic data from e.g. mobile phones, the field of urban modelling is currently experiencing a boom. Historically these models tend to be phenomena specific, with much attention given to transport and retail, although the need for more complex integrated models has been recognised with a renaissance in land-use transport interaction (LUTI) from the 1990s (Wegener 2014), to the extent that this paradigm largely dominates the umbrella term of ‘urban modelling’.

Wegener (2014) draws distinctions between both static equilibrium and dynamic modelling approaches, and aggregate macro models and microscale models. This first distinction separates between models which generate a static future scenario based on the assertion that the urban system moves towards equilibrium states, and those which attempt to explore time dependence and evolution often integrating recursive adaptation and feedback loops into model design. The second distinction concerns the level of abstraction to which the model is taken, both spatially and functionally. Early modelling approaches tended to take a macro zonal approach to

spatial disaggregation, modelling cities as a small number of spatial entities. The advance in computing power and spatially disaggregated data has allowed for more widespread micro scale approaches. Here techniques such as cellular automata (see e.g. Santé et al. 2010; White and Engelen 1997), and agent based modelling (e.g. Matthews et al. 2007; Castle and Crooks 2006) have been employed, particularly in the modelling of urban growth and land use patterns. This has led to a trend towards more disaggregation, and the modelling of individual actors and their decision making (Wegener 2014). Such individualised modelling however presents problems in terms of solution stability, as often stochastic noise, inherent in creating randomised populations, can dominate over the difference between alternative policy scenarios (ibid. p753). This suggests the need to identify the appropriate level of aggregation relevant for the modelling task in question.

Whilst the integration of land use and transport phenomena have existed for decades, there is still a dearth of models integrating a more diverse range of phenomena collectively. In part this is due to the continued dominance of spatial interaction and structural dynamics within the urban modelling paradigm, and whilst efforts have been made to integrate more diverse phenomena wider traction must still be gained (Wilson 2018). Often it seems that the need to develop comprehensive integrated models is presented as an imperative, without much thought given to their intended purpose. This may reflect an epistemic worldview in this research paradigm of the urban as a deterministic playground that may be replicated in simulated form if the right theories and data may be found to accurately represent it. Indeed whilst this may represent an extreme, it does also to an extent resemble the desire of policy makers for validity with generality, and the output of concrete quantitative answers to the outcome that are often sought from such models to aid in decision making (Shackley and Darier 1998; Jager and Edmonds 2015; Metcalf et al. 2015). Such models necessitate a well-defined system of interest however, which a city is largely not. This means that the city or urban must be ‘defined’ for the purposes of the modelling endeavour as an abstract simplified entity with rigid physical and functional boundaries.

The dominance of LUTI within the urban modelling paradigm is demonstrated by Wegener (1994) whose review on the state of the art of urban models limits its consideration to those which “integrate the most essential processes of urban development” referring here to “at least urban land use and transportation” (p18). This narrow conception of ‘urban modelling’, which is seen too in e.g. Wilson (2018)’s *“The Future of Urban Modelling”*, whilst perhaps reflective of the priorities of urban planning, overlooks alternative approaches to modelling the urban. Such

approaches hold incredible diversity, and are often only united by their claim to ‘integrative urban modelling’. The INSMART project for example models city energy systems in order to test the suitability of competing scenarios to aid in climate change mitigation (Simoes et al. 2018; Gargiulo et al. 2017). An integrative model focusing on urban economics is developed by Bertuglia et al. 1990, articulating subsystems for housing, land, and labour markets, services, and transport. Even earlier models include Forrester’s much maligned ‘urban dynamics’ model (Forrester 1969), which whilst pioneering a system dynamics approach lacked attention to theory and an empirical foundation, and the Lowry model (Lowry 1964), whose coupling of spatial interaction with an economic model presaged the rise in LUTI models. The approach to building complex integrated models has been criticised by some authors, Lee (1973, 1994) criticises both practice advancing models for their lack of rigorous operationalisation, and theory advancing models which he sees as consuming rather than producing theory. He remains skeptical of the data hungriness of such models, and the desire for ever finer scale micro modelling without clear justification. It is put forward that to be useful such models must be transparent, replicable, and pragmatically useful.

4.2.3 The urban system

With such disparate interpretations of the city and urban across a wide range of fields and epistemic understandings, the urban is seen to be a patchwork global process under planetary urbanisation, a tightly bounded political entity, an organism, an ecosystem, and a semi-deterministic sprawling fractal of evolving land use types. To an extent this pluralism of understanding may be united under the banner of systems thinking, by viewing the city and urban through the lens of the ‘urban system’.

Cities are indisputably complex, and have often been explicitly viewed through the lens of systems in an attempt to better understand the numerous complex processes and structures that form a greater whole (Alexander 1965; LaPatra 1973; Ayeni 1976; Knox and Taylor 1995; Salingaros 2000; Batty 2008, etc.). Significant attention is given to a plethora of interrelated urban issues such as segregation, pollution, and access to infrastructure and services, spanning all levels of complexity. Understanding these numerous cross-cutting issues demands a holistic approach considering the whole as more than the sum of its parts; focusing on individual processes can often lead to emergent interactions and feedback with the wider urban functioning being overlooked. “A city is not a tree” argues Alexander (1965), it is better viewed as a messy, multi-layered lattice, rather than with processes and activities neatly compartmentalised and separated into

branches which can be isolated individually. Numerous authors have argued that complexity science unifies a vast range of urban phenomena that have been previously dealt with from different disciplinary and theoretical perspectives (Portugali 2000; Samet 2013). The complexity sciences are viewed as a subset of systems thinking within this thesis, largely invoking a post-positivist mechanistic epistemology in search of generative rules (Morcol 2001; Phelan 2001); ‘systems thinking’ thus holds wider appeal allowing for a theoretical pluralism of otherwise incompatible epistemologies (Midgley 1992, 2004, 2011; Miller et al. 2008). This allows for the range of understandings and worldviews regarding the urban articulated above to be united under a single conceptual banner.

Consideration of the urban system in the natural sciences has arguably evolved from thinking of the city as a ‘machine’ to be thinking of it as an ‘organism’ (Berry 1964). Indeed, Batty (2013) argues that cities are more like biological rather than mechanical systems, with the latter being an overly simplistic analogy whose assumptions of closure, equilibrium, and top down order are found wanting (p14). This thinking unites the urban metabolists and ecologists with the urban physicists and mathematicians, even if they generally focus on different phenomena. Batty argues that such a systems approach was briefly fashionable in planning spheres in the 1970s when planning moved to more systematic social science approach (p22). This is evidenced by the work of McLoughlin (1969) and Chadwick (1971), who both draw on von Bertalanffy’s general systems theory, offering radical new approaches seeking a ‘general theory’ to planning which applies the scientific method. Such approaches have been criticised for their depoliticisation through the creation of a neutral ‘science of planning’, but nevertheless pave the way for thinking of the urban in terms of systems (Faludi 1973; McDougall 1973).

Urban ecology as has been shown relies on a strong systems tradition. Marzluff et al. (2008) in their introduction to the field state that it is “useful to consider the city as a set of strongly interacting systems or spheres” from the perspective of a new reader (vii). Although these editors acknowledge that the authors of each manuscript within their collected edition each hold their own different biases and perspectives on the structure and importance of each element within the system. Figure 4.3 illustrates their conception of the urban system from this urban ecology perspective, showing a bounded urban ecosystem comprised of the interaction of various subsystems, and open to the flow of inputs and outputs from the wider global system.

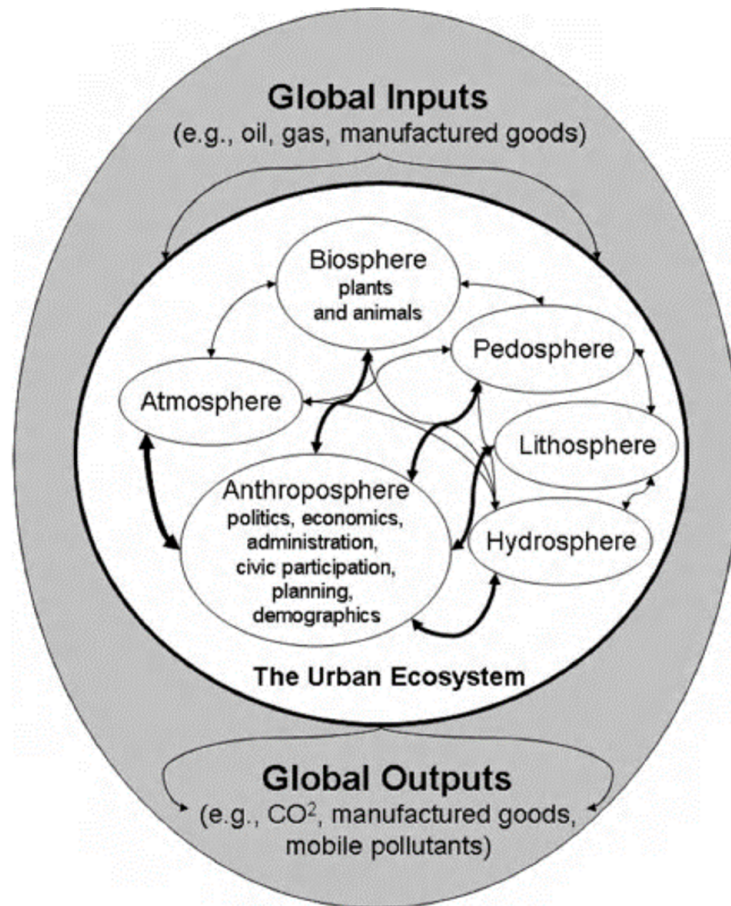


Figure 4.3: View of the urban system from an urban ecology perspective. Reproduced from Marzluff et al. 2008.

Links to urban studies?

Within the social sciences, consideration of an ‘urban system’ may be seen within Friedmann (1986)’s ‘World City’ hypothesis, which draws on critical urban scholars such as Sassen, Harvey, and Castells. This hypothesis situates the city within wider processes of globalisation, emphasising the financial connectedness of cities located around the globe. Marking a shift from international economies where closely regulated trade occurs across national boundaries, to a global economy with a loosely regulated web of corporate networks whose operations span across nation states (Knox and Taylor 1995). From this emerges a picture of a hierarchical world-system of cities, themselves foci of transnational enterprises and the control centres for various financial and cultural flows, ordered by the extent of their integration within this global capitalist system (Timberlake et al. 2012). To some extent this work overlaps with the planetary urbanisation of Brenner et al, although here the global urban is better understood as a networked set of central urban areas and

financial districts, described by Bassens and van Meeteren (2014) as an archipelago (Beaverstock et al. 2000). Indeed the notion of the city as a central foci is key to the hypothesis (Friedmann 1995). Nevertheless the two hypotheses both emphasise the interconnectedness of urban areas at the level of the global system, and the difficulty of delineating them from processes happening at the global scale.

From a systems perspective the issue of urban boundaries becomes one of closure. The urban system is not a closed one in any sense, whilst boundaries may be defined, these are open to the flow of people, resources, goods, capital etc. This must be taken into account in any consideration of urban systems, and holds heavy implications for any attempts to decouple the urban system from other urban systems, or indeed a wider multi-scale or global system.

4.3 Emergent Themes

This chapter has explored a wide range of literature theorising on the urban. It is clear that this literature is epistemologically broad, ranging from the postmodern ‘planetary urbanisation’ which critiques contemporary understanding of the urban as a fixed place, to the positivist ‘science of cities’ which in some incarnations seeks universal laws to describe the growth of cities. Despite such diversity in theorisations of the urban, and a noted lack of dialogue between the urban studies and urban science, several common themes arise that are recurrent across these multivariate schools of thought. These concern the construction of the urban boundary, the benefits of pluralism and interdisciplinarity as a route to better work, and the need to construct coherent theoretical frames.

4.3.1 Boundaries

The issue of boundaries, and delimiting the ‘city’ from the ‘not-city’, appears to permeate all work on the urban. This is unsurprising, as any field of study needs to delimit its area of interest, however it turns out this activity is far from straightforward. Not only is there the definitional problem resulting from an unclear understanding of what is meant by the ‘city’ or ‘urban’ that is to be bounded, but there exist many notions of what a boundary may be, whether physical, functional, institutional etc. The physical boundary is arguably the most straightforward to pin down, if ‘the city’ is thought of as a finite spatial entity, then geospatial techniques may be used to trace a one dimensional or even fractal boundary around this entity. This approach still requires largely arbitrary value judgements as to what constitutes ‘city’ and ‘not-city’ however, and a set of rules must be applied such as density

cut-offs and classification of land type. Further this technique falls down when the contiguous urban area corresponds to a conurbation containing multiple entities ascribed 'city' status, for example the Yangtze River Delta region in China which contains the cities of Shanghai, Nanjing, and Hangzhou forms one of the largest conurbations in the world. Thus, this physical boundary is perhaps better thought of in terms of delimiting the 'urban' from 'non-urban' rather than the 'city'.

The institutional boundary, is seen to be largely arbitrary, and often urban areas find themselves within multiple institutional boundaries, defined across different levels of government. Often institutional boundaries are historical, and whilst at one time they may have borne some correspondence to functional or physical boundaries, this congruence has been lost with growing urbanisation and sprawl. The arbitrariness of these boundaries does not preclude their very real effect on urban function however, as discussed by e.g. Shaw (2015) who forwards the reminder that institutional actors are largely limited to institutional boundaries in terms of their areas of influence. Here again, it is necessary to differentiate between 'the city' and the 'urban', the latter of which receives numerous definitions internationally that were detailed above, usually defined by the relevant country's statistical office, and not always in possession of a single governance body.

The 'functional' boundary can have numerous definitions depending on the phenomena of interest. It may, for example, be defined based upon economic considerations, e.g. the urban area as a functional 'economic unit', such as a travel to work or commuting area, often defined statistically as a percentage of residents travelling to central urban zones for work. Other examples include, its ecological footprint, defined by Rees (1992) as the area of land required to support the given urban population. Such examples are often not clear geographically however, and are perhaps better thought in terms of phenomena of interest and accounting methods rather than a strict spatial boundary. Depending on the function considered, there is a continuum of what spatial extent may be considered urban, with some notion of 'planetary urbanisation' on one end whereby it becomes impossible to delimit any global space as outside the functioning of the urban.

Thus, with these three understandings, some common space must be found depending on the purpose of study. Planetary urbanisation at the more postmodern end of the spectrum, whilst interesting theoretically, becomes impractical for most applications. Not only does this depend upon the actual functioning being considered, but in terms of who the work is for. Often some form of institutional boundary becomes the natural choice due to it being well defined, and offering (usually) a clear boundary of influence for effecting change at a government level.

4.3.2 Pluralism

The second recurrent theme regards interdisciplinarity, and the endorsement of leaving the comfort zone of traditional disciplinary silos to evolve towards some form of ‘engaged pluralism’, both methodologically and epistemologically. This mirrors an observation from the wider sustainability literature seen in Chapter 3, whereby calls for integration of expertise are frequently employed. The complexity of the urban realm is clear, and there exists an incredible diversity of approaches to understanding it. These approaches are not always in competition though, and it may be argued that engagement across wide approaches can enrich understanding.

This imperative for integrating heterogeneous approaches and knowledges often extends to engaging stakeholder perspectives, be they citizens or governance actors (e.g. Turcu 2013). This is often a high priority in research that is intended to have ‘tangible’ outcomes, at the confluence of science, policy, and practice, where informed policy making requires the input of knowledge from social and natural sciences, as well as local stakeholders (Klenk and Meehan 2015). This push for integration has been criticised in quarters though for ignoring the balance of power, whereby the social sciences, as well as voices from marginalised citizens are often undervalued in dominant methods of creating knowledge. Transdisciplinary knowledge production does not always have to involve having to seek a unified methodology or theory however; Klenk and Meehan (2015) offer up alternative approaches, including ‘triangulation’ whereby the suitability of different knowledge systems are assessed through experimentation, the framing of conflict and diversity as productive and leading to new insights, and the process of ‘unlearning’ by becoming reflexive about one’s assumptions and belief systems. Thus, whilst seeking common subjects across different knowledge disciplines provides a clear way forward, the focus should be less upon integrating, but highlighting and valuing ontological conflict. Thus, it is held here that approaches seeking to find ‘universal laws’, the ‘archetypal city’, or a unified understanding or approach to measuring ‘urban sustainability’ are misguided.

4.3.3 Theoretical framing

Cauvain (2018a) emphasises a need for considerations of urban sustainability to develop further theoretical grounding within the critical literature. This chapter has revealed a wealth of literature, surrounding conceptualisation of the urban, as well as emphasised the fracture between cross consideration of the urban from urban studies and urban sciences perspectives. Section 4.2.3 emphasises that similar theoretical

considerations exist across this divide. By grounding theoretical frameworks in work across this literature, operational work can build on these perspectives.

Related to this comes a critique of an abundance of approaches which make seemingly arbitrary decisions without an underlying logic or theoretical frame, as noted in in Section 1.3.1 regarding indicators, and the origins of the three pillar paradigm outlined in Chapter 3. The necessity of a strong theoretical frame which engages with ‘urban sustainability’ conceptually is deemed crucial to developing an understanding to allow for successful operationalisation. Such an approach requires a full declaration of its scope, a clear articulation of the problem being addressed, grounding in a replicable logic, and a frank assessment of any shortcomings. Without this, it is unclear whether the approach answers the problem it has set out to answer.

4.3.4 Onwards

These three observations provide a route for taking urban sustainability forward conceptually. Whilst the more postmodern understandings such as ‘planetary urbanisation’ hold weight in theory, Shaw (2015)’s grounding in reality acts as a reminder that administrative boundaries, whilst largely arbitrary, and often unhelpful, exist. Thus, if theory is to make gains into practical change, it must engage with the realities of these artificial boundaries. A thin line is therefore traversed, whilst the theories of planetary urbanisation and the breakdown of any bound to the urban are tentatively endorsed in this work, an effort is made to engage with urban boundaries as a messy reality that must be confronted to engender change.

The integrative imperative is limited due to this work being an individual PhD thesis which by its very nature impedes truly collaborative work. Nevertheless, the discussion of a broad range of literature so far has charted a messy academic landscape where despite the talking up of integration and pluralism, knowledge is often still isolated within separate disciplinary pools. It is beyond the scope of this work to unify this vast array of literature, but an attempt is made to engage with the breadth of this literature where it intersects, particularly around the problem of boundaries, and a critical epistemological openness is employed throughout.

McIntyre et al. (2000) highlight the difference between work that simply uses the urban as a backdrop to experimentation, such as classical urban ecology, and that which critically engages with it conceptually. This is something that this thesis will take forward, grounding itself within the literature that attempts to conceptualise and understand the urban itself, rather than taking it at face value as a commonly understood description or phenomena. Central to this shall be

the narrative of boundaries and the careful consideration of where they should be drawn and why, whether physical or functional.

Returning to the research question ‘how can urban sustainability be understood’, the analysis of the fractured literature landscape illustrated in this and the preceding chapter, has helped to build on this understanding. The working definition of urban sustainability illustrated in Section 1.2.3 has been fleshed out with more depth relating to the various ways that the urban has been understood, as well as its engagement with boundaries. Chapter 3 also provided depth to the semantic openness of sustainability, and its contestation across environmental, social, and economic domains. The following chapters take on this broad understanding of urban sustainability towards operationalisation by considering approaches for measuring and modelling.

Few physical concepts have caused as much confusion and misunderstanding as has that of entropy.

— James Lovelock, *Gaia: A New Look at Life on Earth*

5

Thermodynamic Entropy as a Physical Measure of ‘Unsustainability’?

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The notion of a ‘physical basis’ for sustainability measurement has generated interest in the literature particularly in relation to the thermodynamic concepts of entropy, and the second law (Rees and Wackernagel 1997; Fistola and Rocca 2014; Filchakova et al. 2007; Purvis et al. 2017; Bristow and Kennedy 2015; Pulselli et al. 2006; Balocco et al. 2004). This approach has its roots with both the work on non-equilibrium thermodynamics of Ilya Prigogine, and that of the economist Nicolas Georgescu-Roegen, who considered entropy in relation to the economic

process (Georgescu-Roegen 1971; Nicolis and Prigogine 1977). This characterisation also draws upon the description of the city as an organism, with strong links to the rich literature on ecosystem theory (see Section 4.2.1).

Consideration of entropy in relation to a notion of ‘sustainability’ derives from scholars such as Lovelock (1979) and Rifkin and Howard (1980), and notably Georgescu-Roegen (1971) who was instrumental in bringing considerations of ‘entropy’ and the second law of thermodynamics into view of the social sciences. This work focuses on the limits supposedly imposed by the laws of physics on economic activity, itself deriving from e.g. Boulding (1966)’s considerations of the Earth as a system closed or open to the circulation of resources. As one of the earliest ‘ecological economists’, Georgescu-Roegen’s ideas on entropy fed into the work of Herman Daly, forming one of the early schools of thought under the umbrella of ‘sustainability’, as discussed in Section 3.3.1.

In Purvis et al. (2019a), from which parts of this chapter are derived, the distinction is drawn between three interrelated definitions of entropy, the *thermodynamic*, the *figurative*, and the *information statistical*: 1) “a thermodynamic quantity representing the unavailability of a system’s thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system”; 2) “lack of order or predictability; gradual decline into disorder”; 3) “a logarithmic measure of the rate of transfer of information in a particular message or language” (Oxford Dictionaries 2019). The first definition comes from thermodynamics, and it may be argued to be equivalent to a special case of the third statistical definition, applied at the microscopic level (Jaynes 1957b; Curado and Tsallis 1992; Weilenmann et al. 2016). The second definition proves to be a source of much confusion, as this figurative sense is often conflated with the more strictly defined physical and statistical senses. This chapter primarily deals with the theory behind the first physical thermodynamics description, and an attempt to apply it to urban sustainability whilst avoiding the trap of the second figurative definition.

Section 3.1 begins by exploring the relevant thermodynamic theory necessary to understand the notion of ‘entropy’, and the casting of the city as a ‘thermodynamic system’. The merits of this conceptualisation as postulated in the literature are presented, before it is explored in detail with reference to the thermodynamic theory. A wider perspective is then presented considering the wider literature regarding the second law of thermodynamics and sustainability in order to examine the potential merits that this consideration could hold. Finally, reflections are made upon this thermodynamic system conceptualisation, and lessons drawn in regards to broader systems frameworks.

5.1 Entropy and the Thermodynamic System

Thermodynamics is the branch of physics associated with temperature, heat, and the transformation of energy. It is founded upon four fundamental ‘laws of thermodynamics’ which impose restrictions on the behaviour of what may be deemed ‘thermodynamic systems’. As the universe can be characterised as such a system, these laws are therefore universally applicable. Classical thermodynamics, was developed primarily in the 19th century following work on mechanical heat engines and extension towards understanding energy exchange in chemical reactions. This was complimented by a statistical interpretation of thermodynamics concerned with statistical properties of ensembles of particles, derived from their microscopic behaviour. Modern thermodynamics, whose formulation began in the 20th century extends this theory to the time-variance of irreversible processes (Kondepudi 2008).

5.1.1 Classical thermodynamics

Classical thermodynamics is concerned solely with idealised equilibrium states which are assumed invariant to the passing of time. It has its roots in the work of Carnot’s 1824 work *‘Reflection on the Motive Power of Fire’*, a thesis on heat, power, energy, and the efficiency of engines (Cropper 2001). Over the next two generations, the work of Kelvin, Clausius, Gibbs, Boltzmann, and many others helped to formalise classical thermodynamics and the key tenets of entropy and the first and second laws (Goodstein 2015).

The Thermodynamic System and the Laws

One of the central ideas of thermodynamics is the idea of the ‘thermodynamic system’. Here, the system is understood as the volume of space that the observer is interested in, it is defined by its boundary, and the type of exchanges that can occur between the system and its surroundings. As illustrated in Figure 5.1, a system whose boundaries allow no exchange to occur is called an ‘isolated system’, a system in which exchange of energy, but not matter is allowed with the surroundings is a ‘closed system’, and a system whose boundary allows both exchange of energy and matter with the surroundings is called an ‘open system’.

The ‘thermodynamic state’ of the system of interest is described by an ensemble of macroscopic quantities, known as ‘state variables’ whose knowledge gives a complete description of the system. State variables can be either ‘extensive’ where they depend on the size of the system, such as volume or mass, or ‘intensive’ where they are independent of the system size, such as temperature and volume.

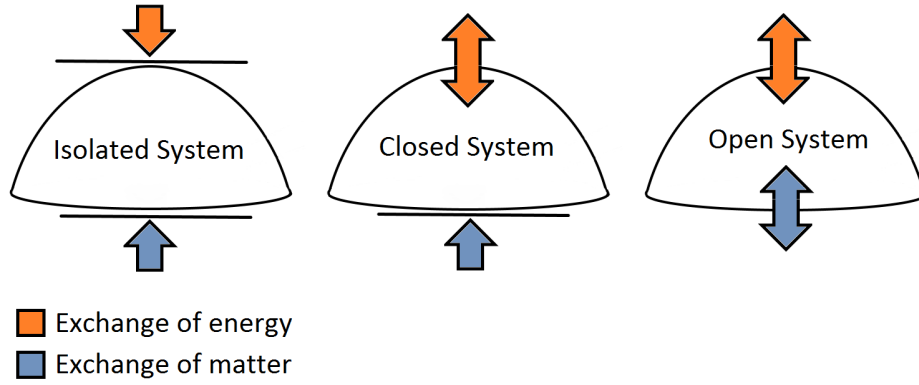


Figure 5.1: Energy and matter exchanges for open, closed, and isolated systems.

The ‘equilibrium state’ is time independent, and usually spatially homogeneous; it is associated with the absence of fluxes of matter and energy, as well as a maximisation of entropy (Lebon et al. 2008). Classical thermodynamics models thermodynamic processes as ‘quasi-static’, i.e. they are assumed to progress through a continuous series of equilibrium states. Such processes are either reversible, in which the transformation can occur in reverse without any external energy input, or irreversible in which this is not possible.

The thermodynamic system is defined based upon its adherence to the four fundamental laws of thermodynamics, which may be stated as follows (Lebon et al. 2008; Kittel and Kroemer 1980; Schroeder 2000):

The Zeroth Law: *If two systems are in thermal equilibrium with a third, they are also in thermal equilibrium with each other.* This allows for a formal definition of temperature as a state variable that is equal across systems that are in thermal equilibrium with each other.

The First Law: *The increase of internal energy of a closed system is equal to the heat supplied to the system minus the work done by it,*

$$\Delta U = Q - W. \quad (5.1)$$

The first law encapsulates the law of conservation of energy: energy can neither be created nor destroyed.

The Second Law: *Heat cannot spontaneously flow from a colder location to a hotter location (Clausius’ Statement).* This is an observation of the fact that over time inhomogeneities in isolated systems tend to even out. The concept of entropy is used to quantify the progression of this process. The second law is thus also

expressed as the law of increase of entropy: *The entropy, S , of an isolated system tends to a maximum over time,*

$$dS \geq 0. \quad (5.2)$$

The Third Law: *The entropy change in any isothermal process approaches zero as the temperature at which the process occurs approaches zero.* This is a statistical law which provides an absolute reference point for the determination of entropy.

Entropy

Entropy first entered the corpus of thermodynamics in the 1850s, with Clausius’s formulation of the second law, as a measure of the quality of heat energy in relation to temperature, and a characterisation of irreversibility. Clausius was seeking to generalise the work of Carnot on heat cycles (Kondepudi 2008). For a reversible process, the quantity of heat exchanged $\int_A^B dQ_{\text{rev}}$ depends on the path the process takes from the initial state A to the final state B. Experimental observations reveal that dividing dQ by the absolute temperature T produces an integral which is independent of path, depending only on the initial and final states of the reversible process, and thus corresponding to a function of state. Clausius named this state variable ‘entropy’, S , defined through its differential $dS = dQ_{\text{rev}}/T$, and:

$$\Delta S = S_B - S_A = \int_A^B \frac{dQ_{\text{rev}}}{T}. \quad (5.3)$$

Note that this definition rests on the assumption that the two states can be connected by a reversible transformation, something which in reality no real process satisfies (p116).

In an isolated system, the second law dictates that entropy continuously increases whenever an irreversible process takes place, until it reaches a maximum value at the equilibrium state. For a system that is not isolated, the entropy change consists of $d_e S$, due to the exchange of energy and matter with the surroundings, and $d_i S$ due to internal processes $dS = d_e S + d_i S$ (Svirezhev 2000). The second law means that the internal entropy production can only be greater than or equal to zero, $d_i S \geq 0$. This means that a system which undergoes irreversible processes may only return to its initial state at the expense of increasing the entropy of its external environment. The second law thereby establishes the ‘arrow of time’, since there is no real process in nature that can progress through a series of transformations and return to its initial state without entropy production occurring (Prigogine 1989).

The statistical mechanics formulation of entropy was hypothesised by Boltzmann through his famous equation $S = k_B \log W$, where k_B is the Boltzmann constant

and W is the number of ‘microstates’ accessible to the system. Here the microstate describes the quantum state of the whole system, specifying all relevant information relating to each individual particle. For physical systems consisting typically of 10^{23} particles, W is of the order 2 to the power of 10^{23} , an unimaginably large number. Hence it is generally not possible to analyse each of those microstates, without the assumption of ‘ergodicity’ (all accessible states are accessed) and the ‘principle of equal a priori probability’ (all accessible states are equivalent) (Haglund et al. 2010).

A generalisation of this formulation leads to the third information-statistical definition of entropy outlined above. This statistical definition has seen widespread application to urban systems, for example Wilson (1970)’s employment of the technique of entropy maximisation in the modelling of transport routing networks, and Batty (2013) on a ‘science of cities’. A review of this literature was presented in Purvis et al. (2019a), however since it remains distinct from conceptualisation of the city as a thermodynamic system, it is not covered in any depth here.

5.1.2 Modern thermodynamics: the dissipative system

The vast majority of systems observed in nature are not in equilibrium, undergo irreversible processes, and have time dependence. Classical thermodynamics, which is concerned only with the initial and final states of the systems in thermodynamic equilibrium, fails to include a theory of irreversible processes. A thermodynamic study of real systems requires a more general approach, something developed from the beginnings of the 20th century by theorists such as Onsager and Prigogine (Kondepudi 2008, pxii). Unlike its equilibrium counterpart, this area of thermodynamics is still an active work in progress lacking an established corpus.

Prigogine, in his study of the phenomena of self-organisation, forwards the notion of ‘dissipative systems’ to refer to complex open structures that maintain their functioning through the constant dissipation of thermodynamic entropy (Nicolis and Prigogine 1977). This usually involves consideration of the entropy balance representing the total entropy change of the system as the respective sum of its internal entropy production, due to irreversible processes, and entropy exchange, due to fluxes of matter and energy across the system’s boundary:

$$\frac{dS}{dt} = \frac{d_e S}{dt} + \frac{d_i S}{dt}. \quad (5.4)$$

In accordance to the second law, the internal entropy production $d_i S/dt \geq 0$, but the total entropy change of the system is permitted to be positive or negative, as $\frac{d_e S}{dt} = \frac{d_e S(in)}{dt} - \frac{d_e S(out)}{dt}$ may take on either sign.

One of the major facets that modern thermodynamics presents is a lens for understanding self-organisation, bridging the gap to the complexity sciences. Here the maintenance of ‘ordered’ structures is permitted through the production of entropy. Such ‘dissipative structures’ have fascinated researchers outside the traditional physics silo, and applications to life, biological, and social systems receive much attention within the literature.

Local thermodynamic equilibrium

As detailed above, classical thermodynamics is reliant on the assumption of thermodynamic equilibrium, and entropy classically is strictly only defined for quasi-static processes. Much of formal modern thermodynamics adopts an assumption of ‘local thermodynamic equilibrium’, which allows the system to be divided spatially into infinitesimal cells in which equilibrium thermodynamics applies to a good approximation. Matter and energy is allowed to pass between cells slowly enough to leave them in equilibrium. Under this assumption, thermodynamic variables such as entropy which were previously only defined for equilibrium systems become functions of position $\mathbf{x}$ and time t , $s(\mathbf{x}, t)$. This framework whilst useful for describing simple systems quickly becomes unwieldy for providing a complete description of complex systems.

Under the local equilibrium assumption, nonequilibrium systems are treated as near-equilibrium, where the relation between the thermodynamic forces and flows is treated as linear. Far from equilibrium however, the ‘non-linear regime’ is encountered, where this is not the case, it is here that spontaneous self-organisation and the existence of dissipative structures is observed (Lebon et al. 2008).

Dissipative systems

Prigogine found the framework of linear non-equilibrium thermodynamics restrictive, launching investigation into far from equilibrium systems that may still be described in terms of macroscopic thermodynamic variables (Nicolis and Prigogine 1977, p3). Of key interest to their early work was the phenomena of Bènard instability, the observation of regular convective cells appearing in a pan of liquid subjected to a sufficient temperature gradient. The term ‘dissipative structures’ was coined to refer to such ‘ordered’ phenomena occurring far from thermodynamic equilibrium.

Such phenomena seemingly violate traditional approaches which view entropy as a proxy for ‘disorder’, and the second law as tendency for thermodynamic systems to become ‘less ordered’ over time. This new molecular order is described by Priogine as the study of ‘self-organisation’ in nonequilibrium systems, and

‘order through fluctuations’ which is argued to have applications to chemistry, biology, and population dynamics (Nicolis and Prigogine 1977, p5). The bulk of this work is presented in a series of books which formalise the mathematics and present basic examples within microscopic systems (Prigogine 1955; Glansdorff and Prigogine 1971; Nicolis and Prigogine 1977). Strong links are drawn with the complexity sciences particularly regarding stability and bifurcations. Throughout later publications, the applications explored become more broad, with Nicolis and Prigogine (1977) dedicating several chapters to cellular processes, evolution, ecosystems, and the origins of life.

The postulate that all biological order may be understood with reference to the laws of physics is taken forward by Nicolis and Prigogine (1977) (p21). By reframing biology in terms of nonequilibrium thermodynamics one can bypass the apparent contradiction of the improbability of the origins of ordered life. This is something that was previously discussed in Schrödinger (1944)’s *‘What is life?’* regarding the maintenance of highly ordered far from equilibrium life. The central issue is one of boundaries, and Schrödinger argued that organisms are open systems which take energy from their surroundings, maintaining their state at the expense of the global entropy budget which is dominated by incoming solar radiation.

Schneider and Kay (1994a) argue that Prigogine’s description of a dissipative system is limited, since it relies on an expansion about the equilibrium state. They instead emphasise the importance of ‘gradient destruction’, offering a restatement of the second law: *“The thermodynamic principle which governs the behaviour of systems is that, as they are moved away from equilibrium, they will utilise all avenues available to counter the applied gradients. As the applied gradients increase, so does the system’s ability to oppose further movement from equilibrium”* (p29). The authors apply this principle to the study of life and ecosystems, proposing that life itself, as a means of dissipating the solar energy gradient is a consequence of this restated second law. This formulation has been widely cited in work bringing thermodynamics into the field of ecosystem theory (e.g. Svirezhev 2000; Schneider and Kay 1994b; Ho 2008; Jørgensen and Svirezhev 2004), as well as subsequent work considering urban systems (Filchakova et al. 2007; Rees 2012a; Bristow and Kennedy 2015; Samet 2013)

5.2 The City as a Dissipative System

The analogy of the city as a living organism is not a new one, and has already been discussed in Section 4.2.1. Such considerations bear similarities with Lovelock (1979)’s *‘Gaia Hypothesis’*, that Earth itself and the complex biological, geological, and atmospheric processes that occur on it may be viewed as a single self-regulating ecosystem. It is therefore not an unnatural leap from here to characterise the city as a thermodynamic dissipative system which maintains its structure through the constant dissipation of entropy.

5.2.1 Urban ecology: a new perspective?

Consideration of the city as a dissipative system in relation to a notion of sustainability appears to begin with Rees and Wackernagel (1997), who draw on earlier scholars such as Ayres (1994), and Goodland (1991). They describe cities as “entropic black holes” which draw in large amounts of entropy and matter, and “export the resultant entropy (waste and disorder)” to maintain their “highly-ordered dissipative structure” (pp547-548). It is argued that the ordered dissipative structure of the city is maintained at the expense of “increasing entropy or disorder in the environment”, citing trends of natural capital depletion, pollution emissions, and other adverse anthropogenic ecological consequences. Similar descriptions in the urban context may be found in e.g. Marchettini et al. (2006), who extend this thread of work, but caution against an “entropic euthanasia” where the urban system has fully degraded all potentials through unprecedented growth in energy and matter inflows, leading to “maximum disorder and maximum entropy” analogous to an ‘urban heat death’. Similar arguments are also explored in Rees (2012b).

Filchakova et al. (2007) consider such arguments in their wider review of thermodynamic concepts applied to the city, exploring its casting as an open system, and the analogy of the city as a living organism. Following the arguments put forward by Marchettini et al. (2006), they appear to strive toward a more quantitative thermodynamic representation to “represent urban metabolism in an operational way”. A suggestion of coupling ecosystem theory literature with that on urban metabolism is suggested, but no concrete steps are taken.

Fistola (2011) explicitly draws on Lovelock (1979) and Rifkin and Howard (1980), who both link entropy and the second law to notions of sustainability and humanity’s impact on global resources and ecosystems. A qualitative description of excessive levels of pollution is presented as a manifestation of “high entropy” and a loss of social capital due to increasing individualisation, which is linked to

an entropic trend of “structural decay” (Fistola 2011; Fistola 2012). A strategy is articulated, which includes the assessment of “urban entropy”. This is developed in Fistola and Rocca (2014) where a list of “entropy indicators” is produced including air quality, unemployment rate, waste production, and flooding risk, which are then mapped spatially. A similar approach using ‘entropy indicators’ is also taken by Pelorosso et al. (2017). These studies, while touching on a thermodynamic definition of entropy, in fact employ a more figurative definition of entropy as a broader metaphorical gauge for a lack of ‘order’.

Pulselli et al. (2005) present in depth the analogy of cities as dissipative ecosystems, going on to assess local consumption geographies via analysis of energy and matter flows, and a spatial analysis of urban activity through cell phone data. The analyses are argued to present how urban systems are presupposed to self-organisation in response to local perturbations, however the direct link to dissipative systems seems tenuous.

5.2.2 Analysis of claims

The above review reveals two broad arguments. First, the claim that to maintain ‘order’, $dS/dt \leq 0$ holds, and the urban system must export entropy to its surroundings, which, in turn, acts to degrade this external environment as suggested by Rees and Wackernagel (1997), Marchettini et al. (2006), and Svirezhev (2000). The second, which is not necessarily incompatible with the first, argues that, in some cases, the entropy of the urban system itself grows, $dS/dt > 0$, which threatens its functional integrity (Marchettini et al. 2006; Fistola 2011; Rees 2012b; Pelorosso et al. 2017). What is missing from all these considerations however is any broad analysis going beyond a mere superficial discussion of entropy and dissipative systems. Despite Filchakova et al. (2007)’s call for more quantitative conceptualisations of these representations, this remains largely absent from the literature. Where indicators have been presented, their link to ‘entropy’ remains qualitative, containing none of the thermodynamic theory either outlined above or in more classical considerations despite continued interest within the literature.

The first step in casting the city as a thermodynamic system is to define its boundaries. In practice this is a non-trivial task, as discussed in Chapter 4. From a theoretical sandbox perspective however, something like a dome may be pictured covering a hypothetical area containing an urban site. This follows approaches taken in engineering and thermodynamic textbooks to reduce a complex real life system into an abstraction that can be more readily analysed (see e.g. Thoma and Bouamama 2000). Since there is no impediment to the flow of energy and matter

across the urban boundary, the system must be open thermodynamically. This is depicted in Figure 5.2. For the purposes of thought experiment however, it is also possible to consider this system to be closed to the flow of matter.

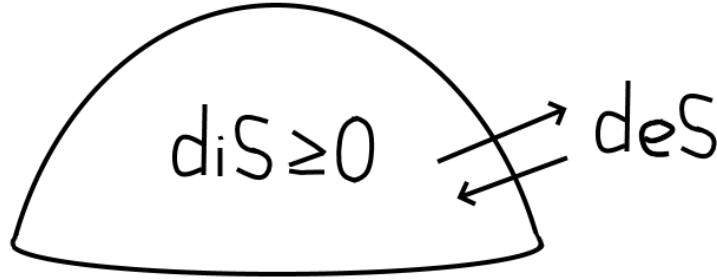


Figure 5.2: City as a system, showing entropy production and flux terms

Heat death in an urban system?

First examined is the claim that equates ‘high entropy’ of the urban system with some semblance of ‘unsustainability’. To the extreme this is suggested to lead to a state of maximum entropy whereby the system has degraded all potentials available to it (Marchettini et al. 2006; Fistola 2011; Rees 2012b; Pelorosso et al. 2017). In practice this could relate to the system’s hinterland being depleted of all ‘useful’ flows of material or energy. Of course, considering the globalised nature of contemporary hinterlands,, whilst being a less pressing concern than an immediate local hinterland, such an outcome would mark a global catastrophe. Initially this claim will be conceptualised for a thermodynamically open urban system which relies on a finite spatially bounded hinterland for its maintenance.

An entropy balance equation may be constructed for this open urban system, following Equation 5.4, the change in entropy of the system may be constructed as the sum of the flow of entropy due exchanges with the system’s surroundings $d_e S$, and $d_i S$ the internal entropy production within the system. This means the time averaged entropy change associated with all material flows across the boundary, such as people, imported goods, exported waste etc, energy flows, i.e. solar radiation, incoming/outgoing electricity lines, and internal entropy production associated with all urban processes involving energy transformations from the consumption of fuel, to individuals moving and breathing, and the photosynthesis of trees (Knox and Parson 2007). The second law states that this internal entropy production is always

positive, $d_i S/dt = \sigma \geq 0$. The entropy flux, $d_e S/dt = J$, may be described by a mass flow component and a heat flow component¹,

$$J = \frac{d_e S}{dt} = \frac{\dot{Q}_s}{T_\odot} + \frac{\dot{Q}_{L,in}}{T_{atm}} - \sum_{i=1}^n \frac{\dot{Q}_i}{T_i} + \sum_{in} \dot{m}s - \sum_{out} \dot{m}s. \quad (5.5)$$

These terms represent, respectively, incident solar radiation, longwave radiation, the summation of additional energy flows (typically, as per Brunsell et al. 2011, outgoing longwave radiation, latent heat, sensible heat, and ground conduction, as well as any additional terms associated with human activity), and incoming and outgoing mass flows. Thus, the total entropy change of the system is described by:

$$\frac{dS}{dt} = \frac{\dot{Q}_s}{T_\odot} + \frac{\dot{Q}_{L,in}}{T_{atm}} - \sum_{i=1}^n \frac{\dot{Q}_i}{T_i} + \sum_{tot} \dot{m}s + \sigma. \quad (5.6)$$

To better understand the internal entropy production σ , an in depth understanding of the processes undertaken within the system is required. Whilst there is an unimaginable spectrum of thermodynamic processes that can and do occur in a real urban system, for the purposes of thought experiment, permitted processes are limited here to the rearrangement of material (e.g. a construction process), and the combustion of material.

The construction process may be represented by the transformation of incident solar radiation to work which acts to reorganise a system of particles, as displayed in Figure 5.3. The thermodynamic characterisation of structural change has received significant attention in the literature, to varying degrees of rigour (O’Connor 1991). Confusingly the ‘degree of organisation’ has been linked to both ‘low entropy’ (e.g. Jørgensen and Svirezhev 2004) and higher rates of entropy production (e.g. Proops 1987). This thesis follows O’Connor (1991)’s view of a fundamental “inadequacy of any scalar concept of ‘organisation’ for describing or parametrising complex system structure” (p105). There is an implicit assumption of something approximating ‘quality’ related to more ‘organised’ structures, yet this notion is subjective, and cannot be quantified. Thus it is necessary to be more precise in the language of what this process entails.

Vagueness allows Process 1 to cover such varied processes from resource extraction, to construction of buildings, and at a stretch the creation of life. Yet these individual processes are qualitatively different and involve different thermodynamic descriptions and realities. Particularly where chemical reactions occur, the resultant entropy change would be dependent on the properties of the materials in question

¹Derived from Bejan (2016), and Brunsell et al. (2011). It is important to be careful with signs here, a positive sign is associated with an inflow, and a negative with an outflow.

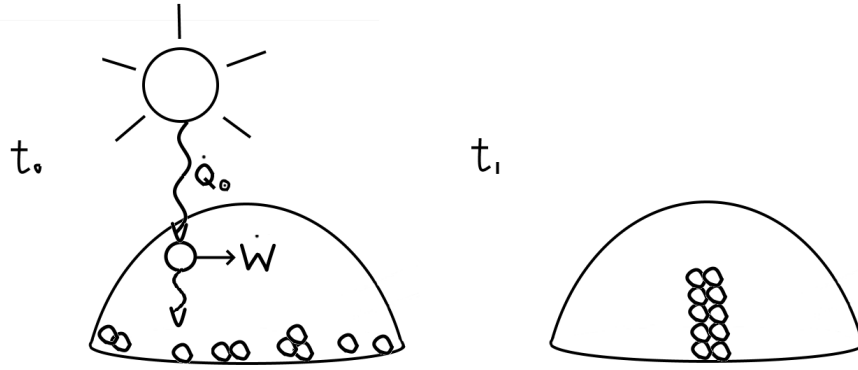


Figure 5.3: Process 1: the ‘ordering’ of material in the system using work, W , derived from incident solar radiation, $Q_{\odot}$. The initial state of the system at time, t_0 evolves to the final state at time, t_1

and the reaction itself. Instead the simple physical process of using a heat engine to move physical objects in order to create a structure, in the absence of any chemical reaction, is considered (e.g. a person building a dry stone wall). This rather simplistic example has more generalised applicability. Some authors have argued that such a process should be measured using concentration entropies analogous to the mixing of ideal gases (e.g. Gößling-Reisemann 2008; Gaggioli and Reini 2014), this is rejected here as a misapplication of microscopic theory to macroscopic analogy (see e.g. Kovalev 2016, and the discussion in Section 5.3.1).

Instead it is argued that to an approximation, this process may be reduced solely to a heat engine producing work. This work is then subsequently transformed into potential energy (e.g. from raising a brick to a height). The entropy change associated with this process can therefore be represented by:

$$\frac{dS}{dt} = \frac{\dot{Q}_0}{T_0} - \frac{\dot{Q}_{\odot}}{T_{\odot}}, \quad (5.7)$$

where $\dot{Q}_{\odot}$ represents the incident heat powering the engine, T_0 and $T_{\odot}$ are the temperatures of the urban system and sun respectively, and $\dot{Q}_0$ is the excess heat produced by the engine. Riemer and Shapiro (2011) estimates a second law efficiency of $\eta \approx 0.12$ for the modelling of a human body performing work as a heat engine. Using $\eta = (Q_h - Q_l)/Q_h$ gives $Q_0 = 0.88Q_{\odot}$, thus by using $T_0 = 293K$ and $T_{\odot} = 5800K$, it may be deduced that for process 1:

$$\frac{dS}{dt} = 2.83 \times 10^{-3} \dot{Q}_{\odot} W K^{-1}. \quad (5.8)$$

This entropy change obviously is dependent on the incident solar radiation $\dot{Q}_{\odot}$ utilised for work, but what is clear is that it is greater than zero. Thus, whilst this

process is converting incident solar radiation through work into potential energy stored in a structure, it nonetheless causes a net positive change in entropy.

Despite this observation, it must be remembered that this incident solar radiation occurs regardless of whether it is utilised for anthropogenic processes. If it is assumed that over a sufficient time period, all incident solar radiation is subsequently re-emitted from the system as longwave radiation, the entropy production of this process should be roughly equal to

$$dS/dt = \dot{Q}_{\odot}(1/T_0 - 1/T_{\odot}) = 3.24 \times 10^{-3} \dot{Q}_{\odot} WK^{-1}. \quad (5.9)$$

Thus, it is revealed that despite leading to a positive entropy production, this process, when considered against the wider natural processes within the system, in storing energy, actually acts to reduce the overall entropy budget.

The second process of consideration is modelled through a simple combustion. Any extraction required to obtain the combustible material can be modelled as process 1, so process 2 involves the transformation of the fuel into waste material and excess heat, as displayed in Figure 5.4. This may be demonstrated by using the example of the combustion of propane (Pittam and Pilcher 1972):



Here, ΔH , the enthalpy change of the reaction, describes the amount of energy that is released as heat. This release of energy results in an entropy change of the total system given by

$$\Delta S = (H_r - H_p)/T_0 - (S_r - S_p), \quad (5.10)$$

with H_r , H_p , S_r , and S_p representing the standard molar enthalpies and entropies of combustion of the reactants and products respectively. Assuming standard conditions ($T_0 = 273.15K$), and using the associated data tables (Haynes 2014) reveals a global increase in entropy of

$$\Delta S = (7446 - 101) JK^{-1}mol^{-1}. \quad (5.11)$$

This entropy change contains two contributions, the first from the heat released through the breaking and reforming of the chemical bonds, and a smaller negative contribution to account for the change in standard molar entropy of the new molecular configurations.

Thus, process 2 leads to a clear immediate positive change in entropy of the system. The effect of this over time to the overall entropy balance is less straight

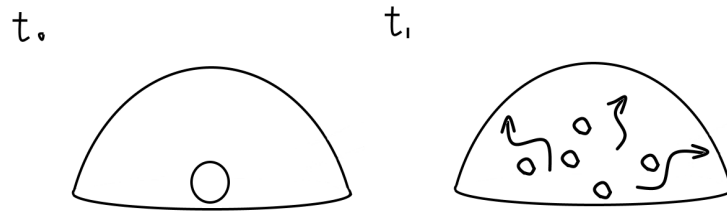


Figure 5.4: Process 2: the combustion of stored fuel producing waste material and heat.

forward. Since the system is closed, not isolated, there is no restriction on the resultant heat diffusing and leaving the system. Whilst it cannot be assumed that the urban system is in thermodynamic equilibrium with its surroundings, the boundary is not physical, and thus a continuous temperature across the boundary may be observed. This means that heat does not and cannot accumulate in the system, and a state of maximum entropy is denied. Of course, it is not unreasonable to assume that the inhabitants of the urban system may wish to maintain a higher temperature than that of the surroundings through the continual combustion of this fuel (or even may unintentionally create this through urban heat island effects). Yet this excess heat tends to dissipate. Far from leading to an urban heat death, it is the second law which denies the entropy of the urban system tending to a maximum, instead pushing it towards thermal equilibrium with its surroundings and $dS/dt = 0$ through the dissipation of excess heat. This is an important consequence of the system’s boundaries being open to the unimpeded flow of energy.

Returning to the entropy balance elaborated in Equation 5.6, the internal entropy production σ may be related to the sum of processes a la process 1, which acts to store incident energy, and the sum of processes equivalent to process 2, which release stored energy. Thus, the sign of σ is permitted to be both negative and positive. Despite this, it remains impossible to evaluate Equation 5.6 as the outward heat components are dependent on σ . Regardless, since the system is open and excess heat leaves the boundaries unimpeded, the tendency to a maximum entropy is denied, and a ‘heat death’ remains an impossibility.

Heat death in a closed urban system?

Suspending disbelief for a moment, one can imagine the thus far fictitious open boundary becoming a physical one, leading to a closed system. The urban system now becomes a ‘domed city’, a fixture of science fiction writing such as King’s ‘*Under the Dome*’, or an iteration of *Biosphere 2* (Avisé 1994). It is important to emphasise here that in this case, the system is thermodynamically *closed*, but not

thermodynamically *isolated*, the transmission of energy continues unimpeded across the boundary. This boundary thus can be assumed to deny the transmission of all matter across its boundary, but allow for the transmission of heat unimpeded. What effect would such a boundary have on the system?

For process 1 this has no effect, excess heat produced by the engine producing work is simply emitted from the system as before. For process 2 the emission of excess heat too experiences no change relative to the open system, this is not the case for the material combustion products however. These products will remain confined within the system as e.g. latent air pollution or deposits, clearly this can have negative environmental/health impacts if no action is taken, but what does it mean, if anything, thermodynamically? Superficially it can be deduced that at the least this will increase the pressure within the urban system, with solid material converted to gaseous matter which takes up more space. The effect of changing pressure on entropy may be approximated by:

$$\Delta S \propto \frac{5}{2} \ln\left(\frac{T_2}{T_1}\right) - \ln\left(\frac{P_2}{P_1}\right). \quad (5.12)$$

It can thus be seen that an increase in pressure, unaccompanied by a change in temperature (a reasonable assumption since the boundary still maintains a continuous temperature gradient), leads to not the entropic heat death of the domed city, but a decrease in entropy of the system. The magnitude of this change is likely very small however, due to the size of the system relative to the amount of solid fuel likely available.

Degradation of the environment?

The second argument present within the literature outlined above is that the production of entropy within the urban system yields negative consequences for the surrounding environment. For Rees (2012a), to maintain its structure, the system “exports degraded energy and material wastes (entropy) back into its host” (citing Schneider and Kay 1994b, 1995), which he argues has negative consequences for global ecosystems. Similar arguments have been made by e.g. Svirezhev (2000) who introduces an ‘entropy pump’ model to argue that only a ‘natural ecosystem’ can be in steady state without degradation to the environment, since no mechanism exists to remove excess anthropogenic entropy². It was shown above that the city, as an open system exports large quantities of entropy to the environment,

²This argument rests on the erroneous assumption that entropy somehow ‘accumulates’.

primarily in the form of waste heat. It is less clear what consequences this has for the surrounding environment.

The examples above showed that entropy production in the urban system is almost solely related to flows of energy, and the categorisation of ‘material wastes’ in terms of entropy is erroneous (this is discussed in more depth in Section 5.3.1). Pollution, greenhouse gas emissions, and other ill material effects posed to the environment by the urban system can therefore not be considered in terms of entropy. As Earth itself is a thermodynamically open dissipative system, like the urban system already considered, any anthropogenic entropy production is ultimately radiated into the wider environment as waste heat, in this case into space. The intermediate scenario is however of interest. The urban heat island is a well documented phenomena that presents ill-effects for both human and ecosystem health, water quality, and the local climate (Rizwan et al. 2008). Yet this is better understood in terms of heat rather than the less tangible concept of entropy.

The entropy production of human civilisation has been estimated previously by Weiss (1994) who shows that it is but a small fraction of the total entropy production of the Earth system. As a dissipative system capable of supporting life, the Earth balances a huge net influx of solar radiation with an equally large outflow of long wave radiation. It is this balance which contributes to a massive entropy production, since the solar energy is emitted at temperature $T_{\odot} \approx 5740K$ and re-emitted at a much lower temperature $T_E \approx 255K$ ³, this is equivalent to an entropy production very crudely estimated by $S = Q(1/T_E - 1/T_{\odot})$, where Q is the incident solar energy flux. Estimations of this figure, time and location averaged, vary depending on the method of calculation but are of the order $1Wm^{-2}K^{-1}$ (Kleidon 2009; Peixoto et al. 1991; Aoki 1983). Assuming a total anthropogenic energy consumption being emitted as waste heat, Weiss calculates the anthropogenic entropy production to be roughly of order $10^{-4}Wm^{-2}K^{-1}$, less than 1/10,000 of the total global production.

Peixoto et al. (1991), who calculate the entropy budget of the atmosphere using similar techniques assume steady state conditions over a “sufficiently long interval of time (e.g., a year)” (p10984). Here the net entropy flux into space equals the internal entropy production, i.e. $J = -\sigma$, and $dS/dt = 0$, at the expense of a 22 fold increase in the outgoing entropy exported to space. The assumption of steady state does heavy lifting in these considerations; however it is not unreasonable to assume that it should largely average out over an extended time period. Consider the discussion on the sign of σ above where it was shown that it may be negative if

³Note that this radiative temperature is less than that of the Earth’s surface by about 30K due to the greenhouse effect of the Earth’s atmosphere. See Weiss (1994), p42.

associated with storing incident radiation. A variation around steady state over time thus seems a reasonable approximation.

Despite this, the Earth’s energy balance is delicate so small variations cannot be dismissed offhand, furthermore whilst small globally anthropogenic contributions are generally localised in areas of intensive human activity (such as urban areas). Zhang and Caldeira (2015) argues that whilst thermal emissions from fossil fuel combustion are not negligible locally, their effect on the global climate system through radiative forcing dwarfs in comparison to the resultant CO_2 emitted. Furthermore, the lifetime of the CO_2 within the atmosphere greatly exceeds that of the anthropogenic heat, so that it’s contribution to radiative forcing is dwarfed by a factor of approximately 100,000 (Zhang and Caldeira 2015). Thus on a global scale negative effects of anthropogenic entropy production appear to be negligible.

Locally the anthropogenic heat flux can have negative environmental consequences, such as the urban heat island, but framing this in terms of thermodynamic systems and entropy seems an unnecessary and obfuscating complication. Whilst the entropy production can indeed provide a measure of anthropogenic heat waste, it is difficult to see what additional insight such framing provides at the expense of additional complexity and confusion. Furthermore the formulation of entropy as the division of the heat flux by temperature means hotter cities produce less entropy per Joule of heat than cooler cities, but the physical implications of this, if any, are unclear.

Rather than focusing on the entropy produced by urban systems, it remains far more insightful to focus on individual inputs and outputs, whether material or energetic and focus upon their implications for ‘sustainability’ at face value. The usefulness of entropy and thermodynamic system framing, on close examination seems to be the solution of an ever diminishing set of problems. Before dismissing such conceptualisation entirely, a final examination of the literature advocating its merits towards conceptualising ‘sustainability’ is made, and a discussion is presented as to why it is still viewed by many as a fruitful approach, despite yielding little useful analysis to date.

5.3 A Wider Perspective: The Second Law and Sustainability

The literature considering entropy from the perspective of sustainability is wide ranging, and the urban literature is but a special case. Whilst disappointing results have been yielded from an examination of the stated potential to urban

applications, it is worth briefly considering the wider literature for any further avenues of exploration.

5.3.1 Georgescu-Roegen and material entropy

The ecological economist Nicholas Georgescu-Roegen receives credit for introducing consideration of entropy to a wider audience outside of its prior mathematical/physical science background. His influential *‘The Entropy Law and The Economic Process’* (1973) proposed a link between the degradation of resources and the second law, arguing that human economic activity acts to irreversibly transform and systematically degrade ‘low entropy’ resources into ‘high entropy’ wastes, hastening a planetary ‘heat death’ (p129). After some refinement, he later posited a ‘fourth law of thermodynamics’ which states that the complete recycling of matter is theoretically impossible due to the irreversible degradation of resources and an increase of ‘material entropy’ (Georgescu-roegen 1986). He would later reflect on how delving into the field as an interdisciplinary pioneer, he was inspired by the writings of Max Planck on entropy and ‘matter dissipation’, leading to this proposed ‘fourth law’ (Georgescu-Roegen 1992).

Since publication, the concept of ‘material entropy’ and the proposed ‘fourth law’ has provoked much controversy in the literature, from the social and physical sciences alike (see e.g. Young 1992; Cleveland and Ruth 1997; Schwartzman 2008; Cojanu 2009; Hammond and Winnett 2009; Kovalev 2016 for engaging discussions), and its status is now widely regarded as overreaching in its application of thermodynamics. Ultimately the suggested ‘law’ has no basis in physics, and the interpretation that thermodynamic entropy production may be observed in relation to macroscopic material flows is erroneous. Despite this, Georgescu-Roegen’s challenge to the economic orthodoxy from an environmental standpoint is seen as a defining moment in terms of the founding of the field of ecological economics (Røpke 2004; Levallois 2010; Martínez-Alier 2015).

This confusion surrounding the application of entropy to macroscopic material flows has persisted in subsequent literature, as noted in the previous section. At first the analogy seems obvious, the human system ‘consumes’ material input, ultimately transforming and degrading it to unusable waste products, this is apparent for e.g. fuels, even if entropy is not considered a property of the material inputs. For other material flows where the utility of the material is unrelated to its energy content or suitability as a fuel, the problems become more visible. Whilst it can be argued that the utility of the material flow is degraded in the human system, the link to thermodynamic entropy is merely an analogy. Thermodynamic entropy

cannot account for the loosely defined human concept of ‘utility’, it can only hope to measure the potential for use as a fuel. Furthermore numerous counter examples may be displayed which demonstrate that entropy categorically fails to account for qualitative aspects (Ayres 1999; Kåberger and Månsson 2001). For example the entropy change associated with releasing hydrogen cyanide into the environment is roughly the same as releasing the equivalent mass of carbon dioxide.

A conflation of thermodynamic entropy with an ill-defined conception of ‘disorder’ can be argued to blame for the mistaken belief that thermodynamic entropy production can be observed in relation to macroscopic material flows (Lambert 2002). A bottle smashed into a thousand pieces for example represents a negligible increase in entropy, simply because on a molecular level, the number of chemical bonds that have been destroyed is insignificant. This presents a good example of wider confusion that pervades applications of thermodynamic entropy, and how the distinction between its figurative use as an analogy and proposed operationalisation as a well-defined physical quantity is not always clear.

5.3.2 The second law and efficiency

As the thermodynamic system conceptualisation is probed for everything that may be of use, there remains one further concept worth probing, that of efficiency. Entropy production can also be thought of as a measure of how ‘efficiently’ energy is utilised. This was touched upon briefly in section 5.2.2 where the entropy production of ‘process 1’ was related to a heat engine efficiency. In engineering thermodynamics, the concept of exergy is defined as the maximum amount of work that may be obtained from a system by bringing it into equilibrium with its environment, and is frequently used for quantifying efficiency (Dincer and Cengel 2001; Szargut et al.). Historically, exergy analysis has been used to improve the thermodynamic efficiency of various industrial processes, by identifying and attempting to minimise irreversibilities. This has led to applications to larger, societal systems assessing energy efficiency at national, regional, and urban scales (Hammond et al. 2001; Balocco et al. 2004; Balocco and Grazzini 2000; Nielsen and Jørgensen 2015; Kalinci et al. 2017). For example Nielsen and Jørgensen 2015 develop an exergy accounting framework, mapping the locations of large exergy consumption across six societal sectors for a small region, allowing for the identification of key areas of attention for a proposed ‘sustainable energy’ transition plan.

It can be shown that the exergy destruction of a process, Ψ_D , is related to its entropy production, S_G , through the environmental reference temperature, T_0 , $\Psi_D = T_0 S_G$ (Pal 2017). Thus, similar approaches considering entropy as a geographically

applied indicator for targeting and improving upon energy inefficiencies are presented in Bejan (1996), and Bejan (2013). These methods remain superior to traditional energy accounting methods, as they capture the ‘quality’ of energy, that is its capacity to perform work (Sciubba and Wall 2007; Kotas 1985). For example 1kJ of electricity has a higher quality, or potential for performing work, than 1kJ of heat at ambient temperature (Ayres 1999).

Thermodynamic efficiencies

It is important to highlight that the use of the term ‘efficiency’ within thermodynamics has a very specific definition, applying only to processes which use or result in the production of heat. There are several types of efficiency defined within thermodynamics, the most common is defined by:

$$\eta_I \equiv \frac{\text{useful energy output}}{\text{energy input}}. \quad (5.13)$$

This is known as the *first law efficiency* since the conservation of energy upholds its limits in the range of 0 and 1 (Vijayaraghavan and Goswami 2002). The second law however places a fundamental limit on the efficiency of the conversion of heat to work. The *second law efficiency* is thus defined by:

$$\eta_{II} \equiv \frac{\eta_I}{\eta_{\text{reversible}}}, \quad (5.14)$$

giving the ratio between the actual first law efficiency and the first law efficiency that would be obtained from an ‘ideal’ perfectly reversible process (Patterson 1996). It is this efficiency that the exergy destruction and entropy production describe, as each of these equate to lost work themselves.

Such methods are generally better suited to analysing the inefficiencies of industrial processes where the internal details are known and data exists to make accurate calculations. Wider application at e.g. urban and regional scales whilst existing within the literature, is generally restricted by a lack of detailed data, and is therefore limited in scope, i.e. being better suited to theoretical considerations of specific actions relating to energy efficiency. For example, analysing competing large scale scenarios where the exact details are known, at least in theory, such as the installation of district heating systems or rollouts of solar PV. Such applications were reviewed in Purvis et al. (2017).

Efficiency and sustainability

The link between efficiency and sustainability is often taken for granted and passes unquestioned. More efficient energy use implies a reduction in consumption and therefore a reduction of any ill effects associated with this consumption such as greenhouse gas emissions, social issues associated with the supply chain etc, leading to a more ‘sustainable’ future.

Of course, in practice this is not so straightforward. The infamous Jevons’ Paradox, first observed in the 19th century in relation to the efficiency of coal use, disputes this conventional wisdom. Jevons argued that an increase in the efficiency of resource use leads to a price reduction which in turn can act to increase demand, leading to a rebound effect that exceeds the efficiency savings made (Sorrell 2010). The existence of this effect has been debated heavily, leading to much criticism of sustainability through efficiency approaches, with authors from the ecological economics tradition arguing that policy changes to cut consumption must be utilised to counter any rebound effects (Alcott 2005; Wackernagel and Rees 1997).

Furthermore efficiency analysis used retrospectively, whilst informative is often not useful in practice, being much better suited to the design phase. Walsh and Thornley (2012) through consultation with both academic and industrial stakeholders, identify key barriers to improving thermodynamic efficiency. The most significant barriers were found to be related to cost, location, and the availability of infrastructure, with additional risks such as halt in production and the use of untested technology perceived to outweigh any benefits saved. Thus, it seems efficiency analysis, especially applied retroactively, presents little of use in helping to understand and apply the principles of ‘urban sustainability’.

5.4 Reflections on a ‘Physical Basis’ for Urban Sustainability

The recurrent failure for entropy to live up to expectations leads to the question as to whether there is any hope for applications of entropy and the second law to be of use outside their strict thermodynamic backgrounds. The considerations reviewed from the literature are almost entirely qualitative in their analysis, talking around the potential value of entropy without attempting to measure in practice. It can be argued, as was done in Purvis et al. 2019a, that this derives primarily from conflation between the first two definitions of entropy detailed in this chapter’s introduction, the thermodynamic sense and the figurative sense. This can be seen in the language that tends to be used, centred on a notion of ‘disorder’ and ‘degradation’, beyond a simple thermodynamic context.

5.4.1 The pervasiveness of (mis)applied thermodynamics

Despite a failure of thermodynamic entropy, and applying ‘thermodynamic system’ analysis to urban and wider sustainability issues, such conceptualisation remains an active area of interest within the literature. This is despite a plethora of papers casting serious doubt on many of the more fundamental claims, and the lack of emergence of any widely accepted application or theory after nearly 50 years of research. It is not controversial to state that entropy is a confusing concept, indeed trained physicists struggle with it. Yet, the popularity of thermodynamic conceptualisation outside the traditional bounds of thermodynamics persists, and is arguably amplified by a lack of understanding, and conflation among separate definitions of entropy. This persistence can be seen in part due to a desire of some scholars to incorporate interdisciplinarity and pluralism into their work, and the ambition to synthesise knowledge and methods well established in other fields, in order to invigorate and enrich their own fields in new directions. Further, there is something of a more metaphysical draw to the second law thermodynamics, and it has seen interest beyond academia into popular culture perhaps far more than any other minutiae of physical science.

Thermodynamics is a difficult subject area within physics (Mulop et al. 2012; Bain et al. 2014; Sokrat et al. 2014). This is evidenced by a lack of an established corpus outside of steady state, equilibrium systems (i.e. most real world systems). One only has to look at the vast range of approaches taken to understanding the subject area in undergraduate introduction to thermodynamics texts (Dreyfus et al. 2015). Entropy perhaps takes pride of place here as one of the more difficult fundamental concepts (Kesidou and Duit 1993; Sozbilir 2003; Bennett and Sözbilir 2007; Haglund et al. 2010). Introductions to it vary widely, and it is a common joke that few understand it, even within the field itself⁴. Arguably this is due to its abstract nature, it cannot be measured directly or observed, and is not a conserved quantity unlike its counterpart energy. Whilst energy is also an abstract concept, its nature as a conserved quantity, allows for intuitive understanding through the metaphor of a fluid for example. Entropy offers no such luxury, and this is a major reason why it remains a difficult concept to grasp, let alone put into practice, leading to more difficult metaphors for understanding. It is here

⁴Notable examples include von Neumann’s supposed suggestion to Shannon to name his quantity entropy as “no one understands entropy very well, so in any discussion you will be in a position of advantage” (Lesne 2014). Or in Sears’ textbook, “There is no concept in the whole field of physics which is more difficult to understand than is the concept of entropy, nor is there one which is more fundamental” (Sears 1950, p459)

that the metaphor of order and disorder arises, first put forward by Boltzmann and Helmholtz in the 19th century (Lambert 2002).

Georgescu-Roegen (1993) documents “struggling with the divergent and vacillating literature” (p187). This is a reflection that in certain subfields, the theory is far from settled and many conflicting statements and lack of agreement may be seen, even among scholars well versed in thermodynamic theory (see Popović 2014). Numerous examples exist in the literature, such as argument surrounding the existence of a minimum entropy principal (Landauer 1975; Jaynes 1980; Bertola and Cafaro 2008), and a recent debate surrounding a paper by Jennings et al. (2005) which claims a proof that photosynthesis violates the second law (Lavergne 2006; Jennings et al. 2006; Knox and Parson 2007; Mauzerall 2013). This is confounded by numerous scholars adopting thermodynamic concepts without a strong theoretical grounding, and making numerous mistakes which perpetuate this. On top of this, due to links between thermodynamics and the origins of life, the area receives input (even within reputable journals) from proponents of intelligent design (e.g. Sewell 2013), politicising a field which at its fundamentals should be lacking in ideology.

Order, disorder, and complexity

The terminology of disorder is something that has received criticism as a misleading analogy, and can arguably be seen as a source of much of the confusion both within physics itself and beyond (Lambert 2002). Primarily it shifts thinking away from energy towards the arrangement of matter in the system, which itself is only tangentially related to entropy. The analogy is often put forth with examples of a deck of cards becoming less ordered when shuffled, or a child’s bedroom becoming messier over time, this offers an intuitive understanding of the abstract entropy that is appealing, but also demonstrably misleading. A full review of the merits and problems of the disorder metaphor is presented in Haglund (2017), in short though it is seen that over-reliance on this metaphor leads to qualitative perceptions of ‘disorder’ being presented as evidence of entropy. This figurative use is widespread, but becomes problematic when one attempts to ‘operationalise’ it. It is for this reason perhaps that actual implementations of measuring thermodynamic entropy in this way, as noted by Filchakova et al. (2007), appear almost absent from the literature. As has been pointed out both above, and by authors in the past, anything seen as a source of ‘disorder’, such as pollution, cannot be simply coded as ‘entropic’ or acting to increase entropy in the thermodynamic sense (Kovalev 2016; Gillett 2006). Entropy, at least in its thermodynamic sense, is not a sufficient measure

of the negative externalities caused by human activity, and the association of the sign of dS/dt to these is problematic.

Conflation of strictly defined thermodynamic entropy with a loosely defined figurative sense is something that has arguably been persistent since these definitions were first popularised. It is for this reason that Purvis et al. (2019a) emphasises three separate definitions of entropy as the thermodynamic, the figurative (disorder), and the information statistical. The figurative definition should be avoided at all costs in any serious analytical approach, but the third definition has a rich body of literature associated with the urban, and tangentially with sustainability issues that may also pose a source of confusion. The informational definition of entropy was described by its progenitor Claude Shannon in probabilistic terms as a “measure of how much ‘choice’ is involved in the selection of the event or of how uncertain we are of the outcome”⁵ (Shannon 1948, p392), and can be variously interpreted as the unpredictability of the observed state, or the expected amount of information obtained from a single observation. Because the state with the largest informational entropy is also the most probable one, this has led to various techniques of ‘entropy maximisation’ which provide a method for making inferences based upon the possession of partial information (Jaynes 1957b, 1957a; Lesne 2014). From here various statistically grounded methods derive for the application of informational entropy for both a measure for geographic dispersion of phenomena such as ethnic diversity (Allen and Turner 1989), urban sprawl (Yeh and Li 2001; Cabral et al. 2013), and biodiversity (Phillips et al. 2006), as well as for its use in entropy maximisation techniques for inference of e.g. transport networks (Wilson 1970; Wilson 2010).

These techniques mark a rapid departure from the thermodynamic definition of entropy, although thankfully remain largely separate in the literature. Whilst thermodynamic entropy may be seen as a special case of informational entropy, the thermodynamic interpretation is concerned with quantum mechanical microstates, where the laws of thermodynamics may be derived from the statistics of the incredibly large number of microstates (of the order of 2 to the power of 10^{23}), with energy and temperature playing central roles. In contrast, information statistical applications generally deal with macroscopic configurations (such as transport routing), whose combinations are significantly fewer in numbers. Despite a clear distinction in scale, some authors have attempted to erroneously combine entropy maximisation with the

⁵In probabilistic terms this ‘event’ can refer to e.g. ascertaining the value of each dice from the sum of two dice rolls, X . A low probability sum of $X = 2$ gives more information about the state of the system, i.e. two rolls of one, than $X = 7$ which represents a more ambiguous or uncertain state, and thus a higher entropy one.

language of dissipative systems (e.g. Zhang et al. 2006; Feng et al. 2014). Further link between informational content and ‘complexity’ has led to further qualitative conflations, where thermodynamic entropy is used as a measure of complexity, this again borders on the ‘order/disorder’ conflation, and should be resisted.

Pluralism?

Much of the literature considering entropy and thermodynamic systems analysis derives from authors outside a physical science background, such as ecologists and economists. There is evidence that this foray into exploring physical concepts is caused by a desire to bring ‘physical rigor’ to soft science approaches (Proops 1987; Young 1992). For example, the following extract from Schneider and Kay (1994b) reveal their underlying epistemology, “one of the major obstacles that ecology faces as a science is that it does not currently have an accepted theoretical framework that can be derived from first principles, as do physics and chemistry. Due to the lack of ecological theory, it has proved difficult to predict the future states of perturbed ecosystems beyond simple limited resource models” (p628). A similar view appears to be held by some of those seeking a general ‘science of cities’, such as Wilson (2009), “what is needed is a coming together of skills, the building of new interdisciplinary teams: urban modellers, statistical physicists and the mathematicians who have been generalizing the thermodynamic and statistical mechanics formalisms” (p30). McKinney (2012) argues that “entropy is an essential aspect of environmental degradation commonly overlooked by sociologists, which is consequential for theoretical and empirical advance in the field” (p297). Such stances reveal the structural hierarchy within the academy, and a belief by some that qualitative methods and frameworks are somehow less valid than those with a basis in ‘physical laws’. This is evidenced both by social scientists attempting to import physical methods and frameworks (e.g. Georgescu-Roegen 1971, and Rifkin and Howard 1980), as well as physical scientists venturing into the social sciences (e.g. Wilson 2010).

Despite ambitions for pluralism, a lack of ‘epistemological agility’ (Haider et al. 2018), is witnessed in many of these cases. Where methods and frameworks are adopted beyond their traditional disciplinary bounds, this appears to often not be accompanied by a recognition or confrontation of underlying epistemology or worldview of the other field. This can be demonstrated by the body of work produced by Georgescu-Roegen, who despite numerous revisions and reclarifications insisted that his concept of material entropy was consistent with the underlying

thermodynamic laws. Clearly Georgescu-Roegen was well versed in the thermodynamic theory of physicists⁶, yet there seems to be an omission of the positivist frame that thermodynamics occupies as a field of study, and the ‘fundamentality’ of the laws of thermodynamics. This critique cuts both ways however, and there is much to be said about the preoccupation of many physical scientists with seeking to quantitatively measure and model phenomena that to many social scientists transcends measurement (Porter 1996; Böhringer and Jochem 2007).

Of course, such work should not be disparaged, and arguably holds great merit, however critical reflection and examination of conflicting epistemologies would go a long way to enriching understanding across disciplines. Indeed, some authors have presented explicitly analogous mathematical constructs to thermodynamic and statistical mechanics principles, in the hope of bringing insights into other fields, including within ecology and urban analysis (Jørgensen and Svirezhev 2004; Wilson 2009; Hernando and Plastino 2012). This has the potential to provide novel modelling techniques and insights. Caution should be taken however, in the limits to which such analogies can apply, since fundamental thermodynamic concepts like energy and the second law are not well defined here. And there is a need to be sceptical of attempts to seek underlying ‘laws’ that govern social interactions, as such modelling techniques provide broad statistical insight only.

Whilst the cross-pollination of frameworks and methods across traditional boundaries has clear benefits (as discussed in Section 4.3), it is clear that there are many obstacles too. As has been evidenced, in translation across disciplines, it becomes common to misplace much of the thermodynamic theory in favour of more figurative understandings of entropy. This leads to many applications where the use of analogy is not apparent to the authors let alone the reader. Such work appears to slip through the net of peer review, since it seems reviewers themselves are not always well versed in the specifics of thermodynamic theory. Paradoxically a situation has arisen where the misapplication of thermodynamic system analysis and entropy to societal systems is an established field, despite being largely based on incorrect assumptions.

⁶Perhaps not aided by prominent scholars making unhelpful or erroneous claims, such as Boltzmann’s metaphor of disorder, or similar arguments by Planck, or Schrodinger (Schrödinger 1944; Haglund 2017)

Boundaries

It was shown above that inconsistencies also derived from understandings of the open or closedness of the thermodynamic system boundaries. It is often overlooked that the second law only applies to isolated systems, which are rarely found in nature, not closed systems, which allow the exchange of energy across their boundaries. This may be in part due to approaches in system science, such as von Bertalanffy (1950)’s general systems theory, which conceptualise only open and closed systems, without capturing energy flows. Regardless of this, the urban system, and the earth itself are open systems, meaning the second law does not apply to them in isolation; the entropy of each is permitted to reduce so long as the total entropy of the *universe* increases.

5.4.2 Implications for operationalising urban sustainability

This chapter has shown that thermodynamic system framing and calculation of entropy in this context is complex, and not something well understood across the literature. This is both due to widespread misinterpretation and mistranslation of concepts across disciplinary boundaries, but also because the more complex thermodynamic theory is contested and seen as difficult within a physical science context regardless. Concepts such as entropy which are rigorously defined in the context of thermodynamics do not translate easily to application outside their traditional bounds, and a thermodynamic system analysis is confounded by this. Thermodynamics is blind to subjective notions of ‘utility’, ‘quality’, ‘complexity’, or ‘order’ as they are understood in their everyday context, and is thus ill-equipped in application to quantifying these terms.

Section 4.3 articulated three recurrent themes within the urban sustainability (and wider) literature, boundaries, pluralism or interdisciplinarity, and theoretical framing. The work in this chapter has implicitly or explicitly confronted each of these three themes. A discussion was given to urban boundaries in Section 5.2.2 where a basic model was articulated of the thermodynamic urban system as being placed under a dome. Whilst this description and the choices made were somewhat facile, it suited the task of what was but a thought experiment where the physical extent of boundaries were largely arbitrary and irrelevant. Where deeper analysis was developed was in the nature of boundaries as described in thermodynamic theory, whether open, closed, or isolated. These descriptions all have clearly articulated meanings in this context with no room for interpretation. Whilst it was seen that some previous authors had misunderstood or not considered these articulations, such

description adds a second layer to the nature of boundaries. Being largely ‘invisible’ or abstract, physical urban boundaries are nearly always open, this presents extra room for consideration of implications of what it means for these to be closed, or at least limited, e.g. for the flow of people, or certain types of goods or pollutants. Further what does closure or openness mean for ‘functional boundaries’? This is perhaps something that has different implications depending on the context, although it is more likely that such boundaries should be drawn where they have the property of closure, so as to contain the phenomena of interest. Thus whilst, open or closed boundaries have a specific meaning for thermodynamic systems, they provide a perspective that may be adapted for more general consideration.

Pluralism was discussed in the dedicated subsection above. It is clear that the thermodynamic system consideration of the urban stems from the desire to develop an interdisciplinary perspective. As articulated however, this has sometimes neglected epistemological agility. This is a clear example of the barriers to realising pluralism in practice, and how it differs from simply using methods and frameworks from a different discipline. A successful approach would do best to consider and confront the specific worldviews held not only by those whose work is being used to inform such an approach, but that of the scholar undertaking the approach themselves.

Thermodynamics on the surface articulates a clear framework for describing a thermodynamic system. It has been seen however that this framework is less clear than it should be, and many aspects of thermodynamic theory remain poorly understood or contested by scholars well versed in fundamental theory. This contestation diffuses into reapplication of these ideas to urban systems or sustainability where further incomplete understanding widens the holes in an underlying framework. Whilst in general such a framework does not have to be quantitative in nature, thermodynamics is fundamentally a quantitative field relying on measurements and calculation. A framework reapplying it thus must be quantitative in nature or else it fails at being more than just analogy. This is something that several authors, such as Filchakova et al. (2007) have argued for, but has so far failed to materialise in the literature. Thermodynamic entropy is measurable, at least in theory, whereas its figurative definition is not. To be of any use as an indicator of sustainability, a framework must be provided that can measure thermodynamic entropy, in thermodynamic units of JK^{-1} . Without a concrete method to do this such an approach ceases to provide any real insight, remaining no more than a metaphor, and one which further sows confusion rather than bringing clarity.

This chapter has only tangentially dealt with the notion of distinguishing ‘urban sustainability’ from the normative global understanding of sustainability. In part this is due to little distinction made in the literature, as most of the thermodynamic applications discussed are equally applicable to both urban and global systems. This is evidenced by Rees et al’s articulation of urban and global footprints in terms of entropy, which differ little other than in the system they have been applied to (Rees 1992; Rees and Wackernagel 1997). Similarly, descriptions of entropy relating to negative externalities and internalities differs little in its consideration of either the urban or the global systems. This lack of distinction may be due to the abstract nature of the thermodynamic system conceptualisation, where the details of the urban are generally not considered in much detail.

Section 2.3 reviewed some of the issues surrounding ‘measurement’ of urban sustainability. Notably the issues surrounding data constraints and quantification have been encountered within this chapter. An urban wide exergy/entropy analysis as detailed in Section 5.3.2, whilst possible in theory would require data on every thermodynamic process occurring within the urban boundary, something which is not feasible. The approaches reviewed in Section 5.2 generally seek to develop a rigorous quantifiable basis to sustainability grounded in thermodynamic theory. In part this appears to be motivated by the desire for a “scientific, objective, and value free” measure (McCool and Stankey 2004). The irony is not then lost when the failure of entropy here is largely due to sustainability by its nature *not* being an objective concept. The imperative to measure for the sake of measuring is then viewed as somewhat defeatist, and opportunity remains to explore approaches which do not focus on explicit measurement.

Whilst there may be some merits to a thermodynamic approach to operationalising urban sustainability, the opinion expressed here is that heavy caveats severely constrict purported benefits. Entropy could, for example, supplement and enhance traditional energy/exergy analysis, e.g. in diagnosing energy efficiency within the urban system. It could also offer analogous use of thermodynamic identities for modelling urban phenomena as proposed by Wilson and Dearden (2011), albeit with much caution taken to emphasise the limits of *analogy*. These approaches however are particularly niche, and do little to move towards a better understanding of urban sustainability. The analysis made in this chapter however has not been in vain and the process of exploration has yielded important considerations. Firstly, the need for a clearly defined framework is re-emphasised, both in terms of the conceptualisation being made, all assumptions made in developing a model, and a detailed explanation of the methods being used. Such a framework should

have quantitative aspects if taking into account measurable phenomena based on fundamental laws and equations. Secondly a need to articulate and reflect upon epistemological assumptions is emphasised as the key to realising pluralism. Borrowing methods from other disciplines without seeking to understand their broader context and foundations is not sufficient. Finally there is something to be said about simplicity and complexity. The urban system is complex and methods and frameworks that are difficult to grasp act to confound and further entrench this complexity. For successful operation, it could be argued that methods need to be accessible to lay stakeholders, as well as attempting to bridge academic fractures through clear communication. The proposed entropy approach, even if it had more promise, concentrates operational knowledge in the hands of a minority elite of academics who are able to understand and engage ‘rigourously’ with thermodynamic concepts.

*All models are wrong.
Some models are useful.*

— aphorism

6

Towards an Urban Integrated Assessment Model

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The publication of ‘*The Limits to Growth*’ report (LtG) (Meadows et al. 1972) under support from the Club of Rome was arguably integral to the growth of the sustainability movement, drawing attention to planetary boundaries in a new way (Lumley and Armstrong 2004; Gómez-Baggethun and Naredo 2015). Central to

this report was a system dynamics model, ‘World3’, which represented the global system as a complex web of interaction between five subsystems. By simulating the feedback between population, economic, agricultural, resource, and pollution subsystems, from 1900 to the end of the 21st century, the model produced a series of future scenarios with variations of ‘business as usual’, technological advancement, and social policy responses to an unravelling future. These scenarios were then presented as graphical outputs showing the time evolution of various parameters such as industrial output, food per capita, and population across the scenario time window. Ultimately the report used these scenarios to demonstrate and argue the unsustainability of a societal system founded upon exponential economic and population growth on a finite planet. The publication of the modelling report spurred much debate and criticism following its conclusion that without significant efforts to enact change, ‘business as usual’ would lead to “sudden and uncontrollable decline in both population and industrial capacity” (Meadows et al. 1972, p23). Despite heavy criticism from numerous quarters since its conception, the model has arguably withstood the test of time, with several recent studies still maintaining the validity of its outputs (Turner 2008; Bardi 2011; Turner 2012, 2014; Randers 2012a; Pasqualino et al. 2015).

Regardless of claims to ‘validity’ or otherwise, the model presents a clear theoretical framework of what it means for the world system to be sustainable, subject to the constraints of the modelling scope. An ‘unsustainable’ system here is represented by a sudden collapse in population within the projected time window, and a ‘sustainable’ one by the maintenance and often equilibration of this population, with, in later revisions of the work, a sufficient level of ‘human welfare’ (Meadows et al. 2005). Despite the clear limitations of this as a comprehensive definition of sustainability applicable more generally, it articulates a well-defined conceptual frame within the model universe which does not require strict measurement or quantification.

This chapter outlines the theory and method of adapting World3 to produce an urban system dynamics model. Initially an overview of the modelling technique of system dynamics is given including its history, application, and underlying philosophy. Following this the World3 model is described in detail, the results from LtG presented, and a selection of literature surrounding its critique to the present day is discussed in context. The approach of adapting World3 to an urban model, Urban1, is described in detail, and the boundary issues this process evokes are addressed. Following this, several scenarios are then run from this urban model detailing the system’s evolution under varying criteria. Finally, a brief prelude to Chapter 7 discusses the developed urban model and its merits and limitations.

6.1 Background

6.1.1 System dynamics

System dynamics was developed in the 1950s by Jay Forrester, an electrical engineer, working at the MIT Sloan School of Management (Forrester 2007a). Forrester began to develop the method as a means for better understanding the instability in business cycles for several General Electric household appliance plants, by simulating the impact of various feedbacks caused by decision-making. By the 1960s, Forrester had moved from the consideration of corporate systems to broader, more complex, societal systems, and in collaboration with the former mayor of Boston, John F. Collins, a crude economic model simulating population, housing, and business activity of a central urban area was produced (Forrester 1969). The results of this model were controversial. One key outcome from the simulation suggested that the construction of low-cost housing was, contrary to established thought, a major cause of poverty, using up space for job-creation whilst acting as an attractor for the unemployed. This conclusion is something that has been heavily criticised, and belies that such a methodology can lead to unexpected and unwanted results (Alfeld 1995). It is for this reason that it is important for all modelling assumptions and equations to be detailed in full.

In 1970 Forrester was approached by the Club of Rome, a think-tank purposed towards confronting the “predicament of mankind”, which lead to the development of ‘*World Dynamics*’ (1971) and the World1 and World2 system dynamics models (Forrester 1971). World Dynamics caught the imagination of the press worldwide, as did its successor ‘*Limits to Growth*’ (1972), based on a refined version of Forrester’s original World models. The results produced by LtG’s World model were contentious, and the initial response to the report was mixed. After sustained criticism into the 1980s however, the debate, as well as subsequent work building on the initial model, went largely out of fashion having failed to make any tangible impact in the policy domain (Bardi 2011; Jackson and Webster 2016).

System dynamics today

Forrester has suggested that the field of system dynamics has stagnated somewhat outside of business management dynamics in the early 21st century (Forrester 2007b). Forrester’s 2007 reflections on the future of the field do not make for optimistic reading, revealing a dissipation of much of the momentum launched by LtG 35 years previously. This has been linked to structural issues within academia whereby, outside use in management sciences and computer science, scholars rehearsed in the

methodology often find themselves lone experts in their departments (Richardson 2011). Richardson and Forrester also note a lack of ‘heavyweights’ established in the field, and an only superficial treatment of the subject delivered in undergraduate courses (Forrester 2007a; Homer and Richardson 2017).

Despite this, the System Dynamics Society still holds an annual conference, with a collection of eclectic work presented and disseminated each year, as well as their *System Dynamics Review* journal which publishes 4 issues a year. System dynamics has been applied too to various phenomena loosely surrounding issues of the urban, and sustainability. For example Macmillan and Woodcock (2017) use participatory system dynamics to model factors influencing cycling uptake in cities, and Liu et al. (2015) develop a model to investigate transport emissions scenarios in Beijing. These models typically focus upon a single well defined phenomena, although examples exist which cast a wider scope such as Hennessy et al. (2011)’s development of a system dynamics ‘tool’ for use by policy makers in looking at a broad city economy, or Kidwai and Saraph (2016)’s recommendation of the system dynamics process as a novel solution for policy makers for a variety of phenomena. Forrester’s ‘*Urban Dynamics*’ similarly, whilst providing an early conceptualisation of the urban economy through housing and labour markets, lacks a broader view that would make it useful for considerations of sustainability. Nabavi et al. (2017) review the potential for system dynamics as a tool to contribute new pathways to sustainable development, they argue that the success of techniques is highly dependent on ‘boundary judgements’ made around “sustainability principles, problem scope, and methodological choices” (p321). They further argue that the modelling process itself should ideally be participatory with strong stakeholder interaction, and an openness to reflection, laying out all assumptions, and responding to critique. These examples show that the field retains relevance in the area of urban sustainability, despite a lack of any particular model that may be used to explore the broad concept of ‘urban sustainability’ and the urban system holistically.

6.1.2 Modelling with system dynamics

An illustration of the basic steps in implementing and computing system dynamics models is outlined by Bossel (2007), (pp2-3):

1. Enter the simulation time parameters
2. Place system variables and parameters on screen
3. Connect the different quantities by influence arrows to complete the simulation diagram

4. Quantify system quantities through inputting model equations
5. Start the simulation

The software then evaluates the modelled quantities every time step using numerical integration methods to solve differential equations, this is typically done using the Euler or Runge-Kutta (RK4) methods (Zauner et al. 2007; Bossel 2007).

For simple systems, such as the population model presented in Section 2.4.1, behaviour is unremarkable. But for more complex systems, with numerous coupled equations and feedbacks, the method offers an elegant way of simulating non-linearities, allowing for understanding and exploration of the often unexpected consequences of feedback. As Sterman (2000) states, it is generally from such feedback interactions that complex behaviours emerge rather than a necessary complexity of the components themselves (p12). Feedback loops may be self-reinforcing (positive) or self-correcting (negative). Both loops in Figure 2.1 are positive, the larger the population, the larger the number of births and deaths. Negative feedback loops seek equilibrium, for example price mechanisms, a high price can lower demand leading to excess inventory, and a subsequent lowering of prices to shift stock.

Meadows et al. (1974) suggest that system dynamics models have use to policy makers due to their ability to make statements about the future through the modelling of complex phenomena. Specifically, these are described as “conditional, imprecise projections of dynamic behaviour modes (If corn prices are stabilized, will hog prices tend to fluctuate more or less strongly?)” (pp7-8). It is argued that social systems are unpredictable, since any predictions are likely to influence the outcome of the system’s behaviour through e.g. social policy changes. Further, the inadequacy of available data impedes any precise long-term prediction.

The World3 model as a complex system dynamics model contains just five basic elements which comprise its workings: stocks, flows, static parameters, dynamic parameters, and table functions. The first three of these were all present in the basic exponential growth representation presented in Section 2.4.1. Dynamic parameters, as their name suggests, have dependence on the model time described by time variable equations often dependent upon other dynamic parameters or stocks and flows. Table functions are used to provide non-linear functions relating two variables, mapping inputs as described by the function. Such relations are thus described by corresponding values of a table which are then interpolated to create a (usually) continuous function. Where inputted values fall outside the range of the table function, system dynamics software usually provides options for extrapolating,

using the nearest defined value, or producing an error. Figure 6.1 illustrates a table function within the AnyLogic software. Further, additional functions may be built into equations which involve time delays, these vary from exponential smoothing functions, to step delays, acting to dampen or delay variable effects over a specified time period.

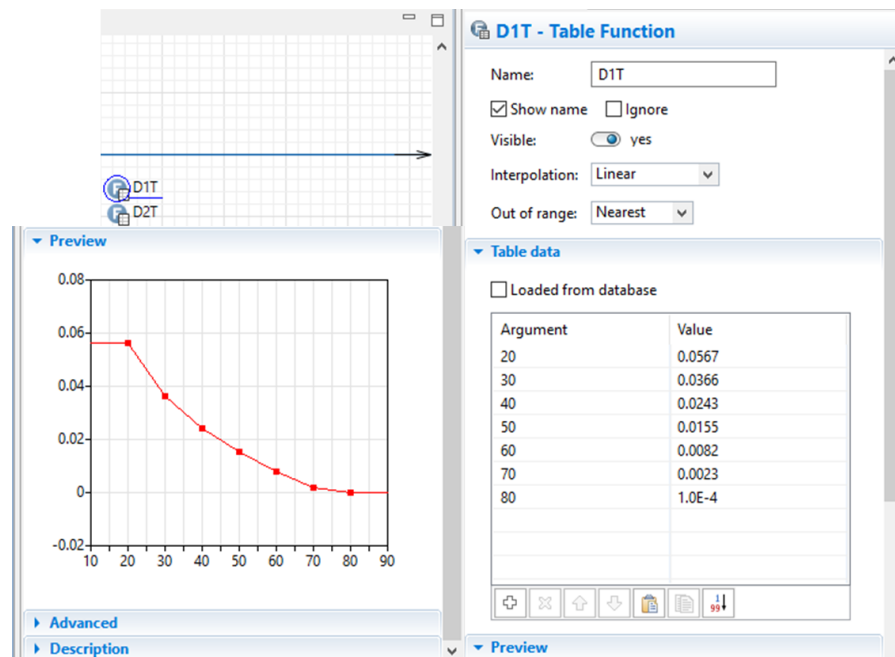


Figure 6.1: Overview of a table function from the system dynamics software ‘AnyLogic’. Note the drop down list of options for interpolation between data points, and the response of the simulation when an argument lies out of range. The function is inputted numerically in the ‘table data’ view, and displayed graphically under ‘preview’.

System dynamics in AnyLogic

A screenshot of the software’s modelling window is displayed in Figure 6.2 showing the basic population model illustrated in Section 2.4.1, as well as the properties panel of the **Births** flow, and the system dynamics modelling palette. Figure 6.3 shows a screenshot of the simulation window, which shows the model running over a predefined time frame. Simulation occurs in ‘real time’, and the software automatically keeps track of each variable over time allowing for visual output, this aids in keeping track of any model errors allowing to see which variables are ‘misbehaving’.

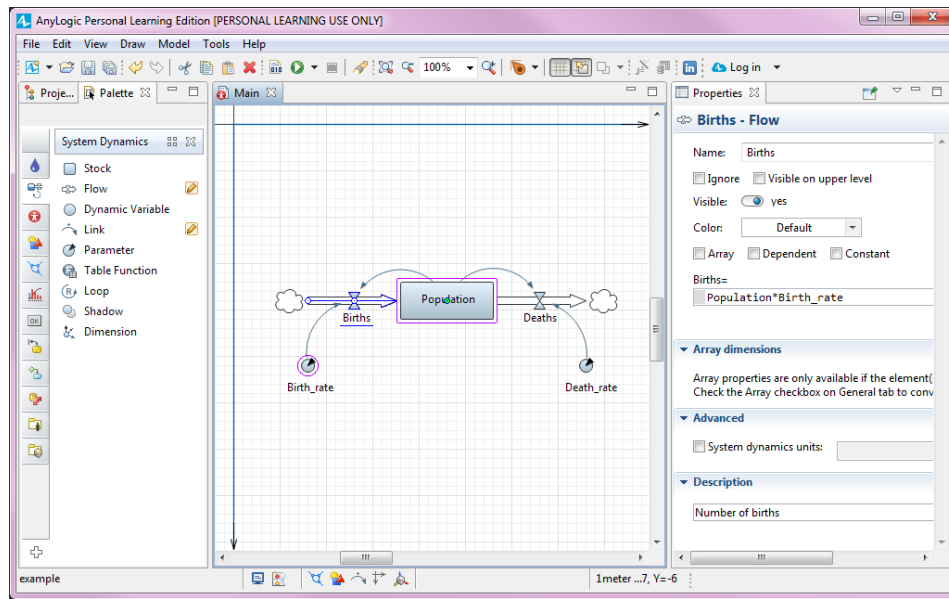


Figure 6.2: AnyLogic modelling window displaying the example population model. The palette panel, left, shows the different types of function that may be employed for a system dynamics model. The centre panel displays the pictorial representation of the model, and it is here where it is built. The right-hand panel displays the properties of selected parameters, here the **Births** flow, displaying its equations, as well as several options and the space for a description. The green arrow button on the top panel is used to run the model and open the simulation window.

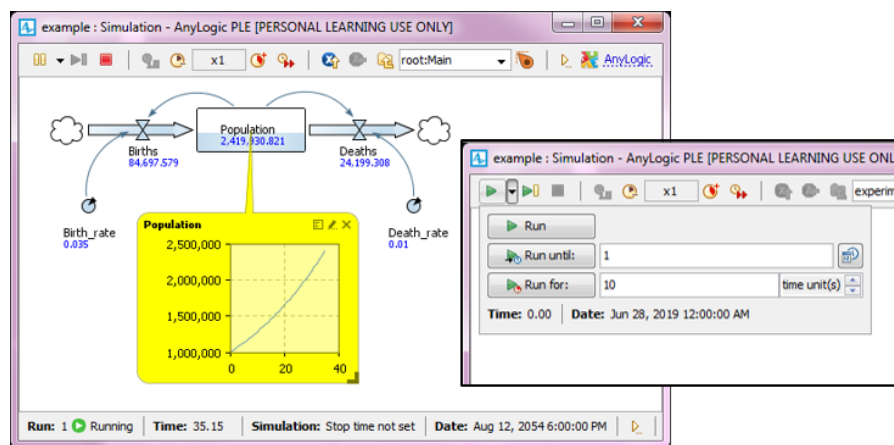


Figure 6.3: The AnyLogic simulation window. The right hand clipping shows the run options, allowing to run until a given in model time, or run for a given number of time steps. The 'date' given is when the simulation starts, and may be predefined in the modelling window. The left-hand clip shows the graphical depiction of the model running, this is animated in real time, with the numbers given updating constantly. Each parameter may be selected to produce a real time graph showing how its value changes over the course of the simulation run. The model may be paused, sped up, or reset at any time using the controls in the window toolbar.

6.1.3 Limits to Growth: modelling the world system

Adapted from Forrester's World models by an interdisciplinary team of 17 researchers based at MIT, who expanded and refined Forrester's initial models with new data and theory, the World3 model and its outputs were first presented in LtG (Meadows et al. 1972). Two years later the lead authors of the report published '*Dynamics of Growth in a Finite World*' which detailed the structure of the World3 model, outlining each equation, and every assumption made in full (Meadows et al. 1974). This was accompanied by all working of assigning values to parameters and table functions complete with the data sources used. In short Meadows et al. (1974) allows anyone with access to system dynamics software to rebuild the World3 model in its full original form, and understand how and why its dynamics lead to the scenarios articulated in LtG.

Two official updates to the initial LtG report were produced, '*Beyond the Limits*' in 1992, and '*The 30-Year Update*' in 2005. The first of these uses updated data to argue that the conclusions from 20 years previously remain valid, but emphasises that the 'choice' of a stable trajectory remains possible (Meadows et al. 1992). The 30 year update argues that much of this choice is being constrained by a failure to take adequate action regarding limits, and for the first time a CD was included which provided users with the updated World3 model to analyse and run scenarios themselves (Meadows et al. 2005). Aside from these updates, relevant publications from the original authors include, Jorgen Randers' '*2052*' which attempts to provide a 40 year forecast based upon the latest data, arguing that the trajectory remains close to the initial report's 'Scenario 3', a 'pollution crisis' (Randers 2012b, p304).

The World3 model was updated for '*Beyond the Limits*', which included conversion of the language from DYNAMO to STELLA resulting in a new version World3-91. This update also contained seven changes to the constants and table functions reflecting an extra 20 years of global data (Meadows et al. 1992, pp239-249). An official World3-03 update was further presented in '*The 30 Year Update*'. As well as updating one table and one parameter, this model added two new variables: a human welfare index, and a human ecological footprint. These variables were used to better understand wellbeing and environmental impact which were previously not readily observable from the existing model structures.

World3 is structured around five interdependent subsystems, representing population, capital, agriculture, pollution, and resources. The interactions of these five sectors is displayed below in Figure 6.4, reproduced from Meadows et al. (1974). As well as five subsystems, World3 comprises of seven groups of stocks, population, industrial capital, service capital, non-renewable resources,

pollution, land, and land fertility. Figure 6.5 presents a visual representation of the whole model as articulated initially within the Dynamo software (pp490-491). At first glance this model is substantially more complex than the basic exponential population model. Whilst containing over 150 defined equations and functions, the underlying feedback loops are relatively simple, and are subsequently detailed here. Meadows et al. (1974) should be consulted for full details of the causal structure, data, assumptions, and equations underlying the model.

World3: demographic subsystem

The basic structure of the population subsystem is shown in Figure 6.6. Similar to the basic example of Section 2.4.1, this population is mediated by parameters for ‘fertility’ and ‘mortality’, although in World3 these parameters are dynamic and dependent on an array of biological, social, and economic factors captured within the model. More specifically, fertility is moderated by limitations on health services and food supply, social response to perceived life expectancy, and a desired family size norm. This latter parameter is influenced, via time delays, by wider macroeconomic performance, as well as individual responses to economic status. Average mortality is also dependent on similar involuntary, voluntary, and means based factors, including health services, and food production as well as adverse phenomena such as pollution and crowding. As can be seen in Figure 6.5, the population is delimited by age structure, this step is taken to correspond these groups roughly to working age (the middle two stocks), and childbearing age (the second stock).

World3: capital subsystem

The capital sector in World3 is based upon an allocation mechanism which diverts industrial output to investment in industry, services, agriculture, and consumption. Industrial capital produces industrial output comprising of various products, including those relevant for other sectors as allocated e.g. fertilisers, farm machinery, and pesticides for the agricultural sector, medical equipment, offices, schools etc. for the service sector, consumable goods for consumption, with the remaining allocated to producing new industrial capital such as factories and machines. The actual composition of the capital stock in terms of what it represents, beyond its sectoral allocation, is irrelevant to the general functioning of the feedback cycle, and is thus not captured within the model. As stocks, the industrial and service capital depreciate over time, representing e.g. material degradation, and the need to replace machinery etc., thus constant investment is required to maintain this capital. Market demand is tangentially captured through mechanisms which maintain

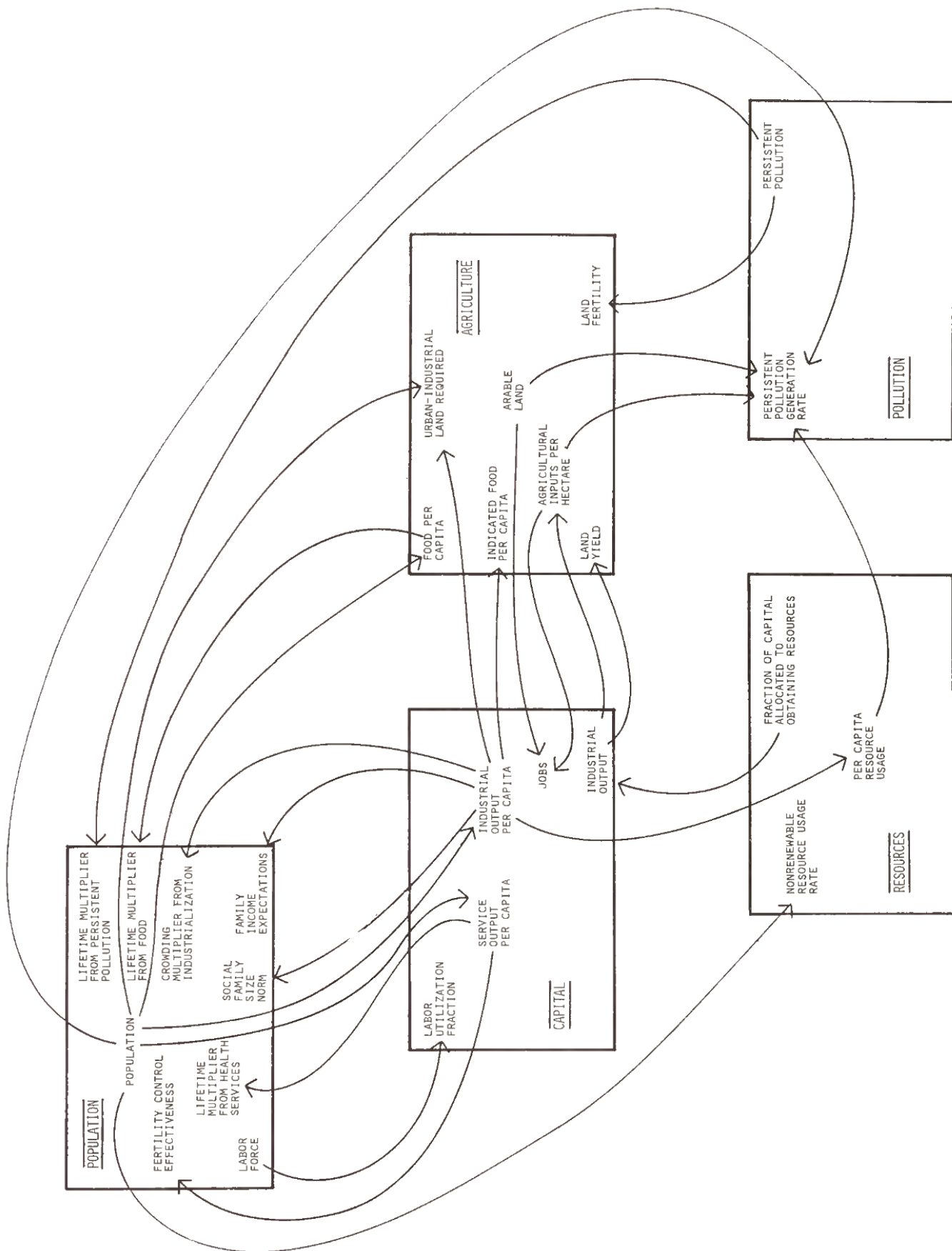
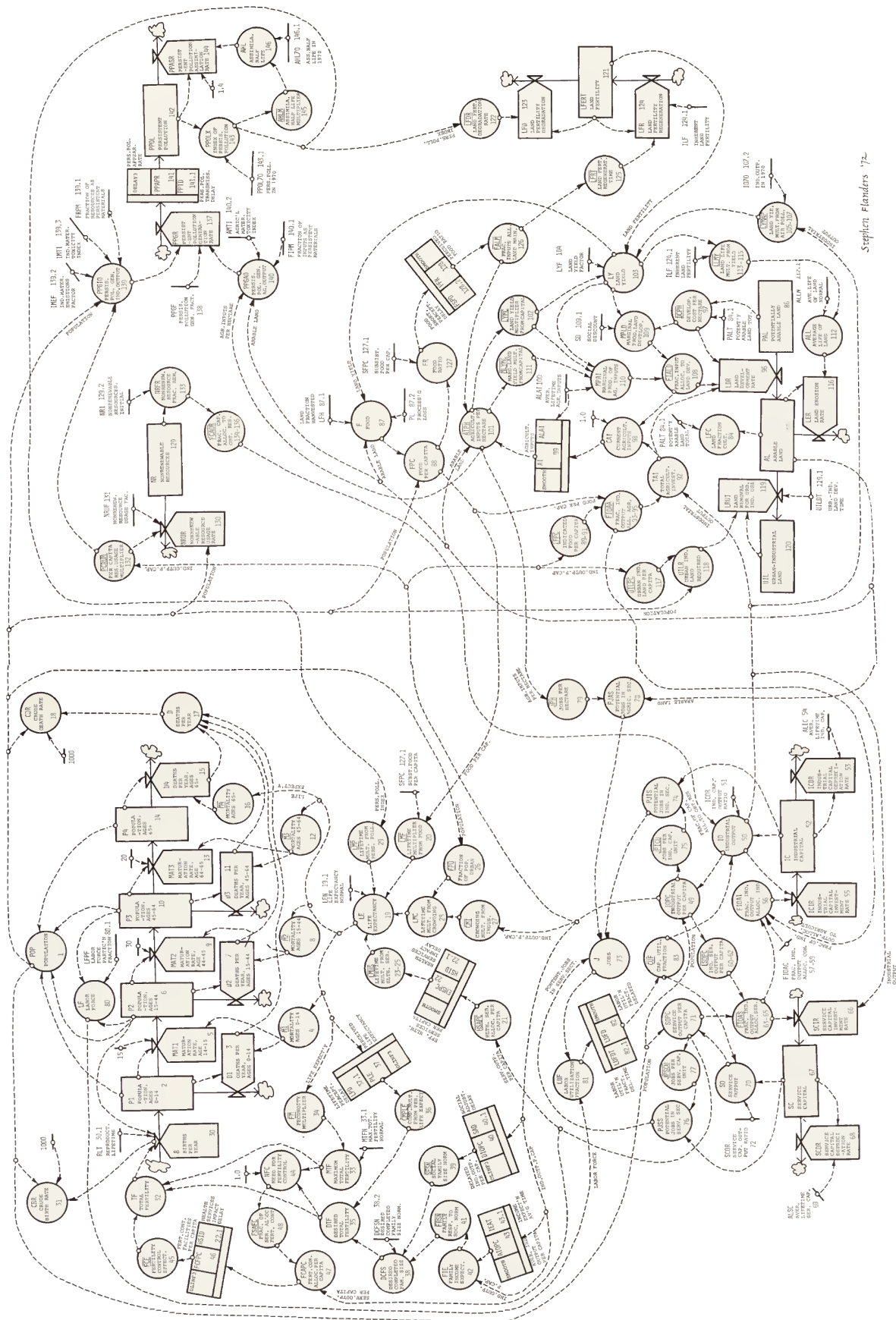


Figure 6.4: An outline of the five subsystems which comprise the World3 model, showing the interaction of variables across subsystems. Reproduced from Meadows et al. (1974), p11.



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Figure 6.5: Dynamo model diagram presenting the World3 structure for illustrative purposes (Meadows et al. 1974, pp490-491). Dynamic variables are represented by a large circle, static parameters a thick line, modulated table functions by a large box, and stocks by rectangles attached via solid arrows to the flows (with sources and sinks represented by a 'cloud'). The subsystems are grouped together, with the population subsystem in the top left, capital bottom left, agriculture bottom right, pollution top right, and resources centre top.

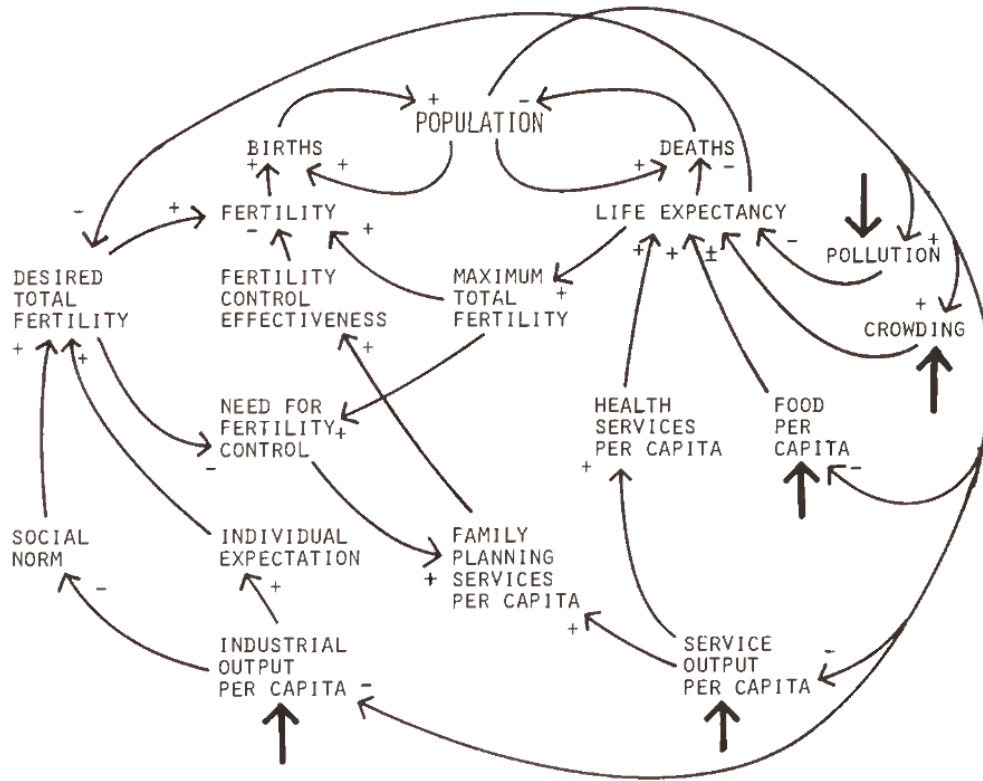


Figure 6.6: Causal loop diagram of the population subsystem structure. Reproduced from Meadows et al. (1974), p51.

various levels of certain parameters, for example if food per capita drops below a certain level the model will seek to allocate an increased fraction of industrial output towards increasing this parameter. This mechanism is represented through aggregate demand functions such as ‘indicated’ service and food outputs. The fraction of output allocated to services or agriculture then depends on the ratio of the actual and indicated output levels. This allocation is described by the equation:

$$\text{FIOAI} = 1 - \text{FIOAS} - \text{FIOAA} - \text{FIOAC}, \quad (6.1)$$

where the variables represent the Fraction of Industrial Output Allocated to Industry, Services, Agriculture, and Consumption respectively. The value of FIOAC is taken to be a constant in most model runs.

Since every unit of industrial output produced within the model consumes an amount of non-renewable resources, the industrial output results from the division of the industrial capital not allocated to obtaining resources by the industrial capital output ratio, that is the ratio of investment to growth. An employment subsector centres around a *jobs* parameter, which is the sum of potential jobs in the industrial, service, and agricultural sectors which themselves are produced as

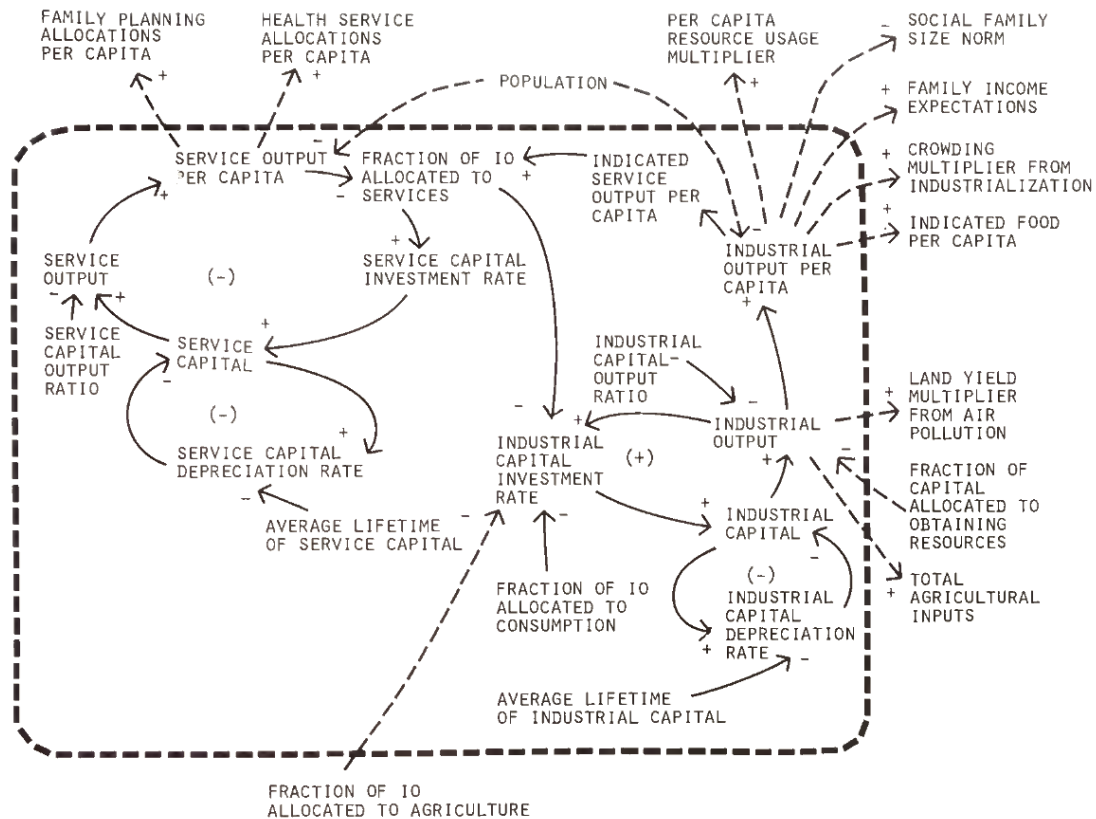


Figure 6.7: Causal loop diagram of the capital subsystem structure. Reproduced from Meadows et al. (1974), p213.

table functions of the relevant capital or land stocks. A ‘labour utilisation function’, in circumstances of high unemployment (i.e. when *jobs* is much higher than the working age population) acts to dampen industrial and service output.

The lack of any more detailed market mechanisms has received some critique across the literature (e.g. Nordhaus et al. 1992; Cole et al. 1973), including the failure to incorporate diminishing returns. It is however argued in Meadows et al. (1974) that this should not significantly effect long term behaviour modes, and should be worked into future versions of the model (p213).

World3: agricultural subsystem

The agricultural sector contains several separate feedback loops. The output of food is dependent on the arable land area and the intensity with which this land is cultivated. Agricultural investment is allocated to developing new arable land, as well as increasing the intensity of land use, the land yield, depending upon where more marginal productivity may be obtained. Additionally, the model assumes that intensive land use degrades the fertility of the land over time (represented by an

additional stock). A loop is included to restore, through agricultural investment, this 'land fertility', which is defined as the capability of arable land to produce crops with traditional inputs only. The effect of investment in modern technology is represented by 'land yield' being equal to land fertility multiplied by an input multiplier larger than one. Land fertility degradation may also result from pollution in addition to intensive use. A more serious issue than fertility degradation is that of land erosion, which represents an irreversible degradation of arable land. The rate of erosion is correlated to land yield, although this can be slowed with increased investment.

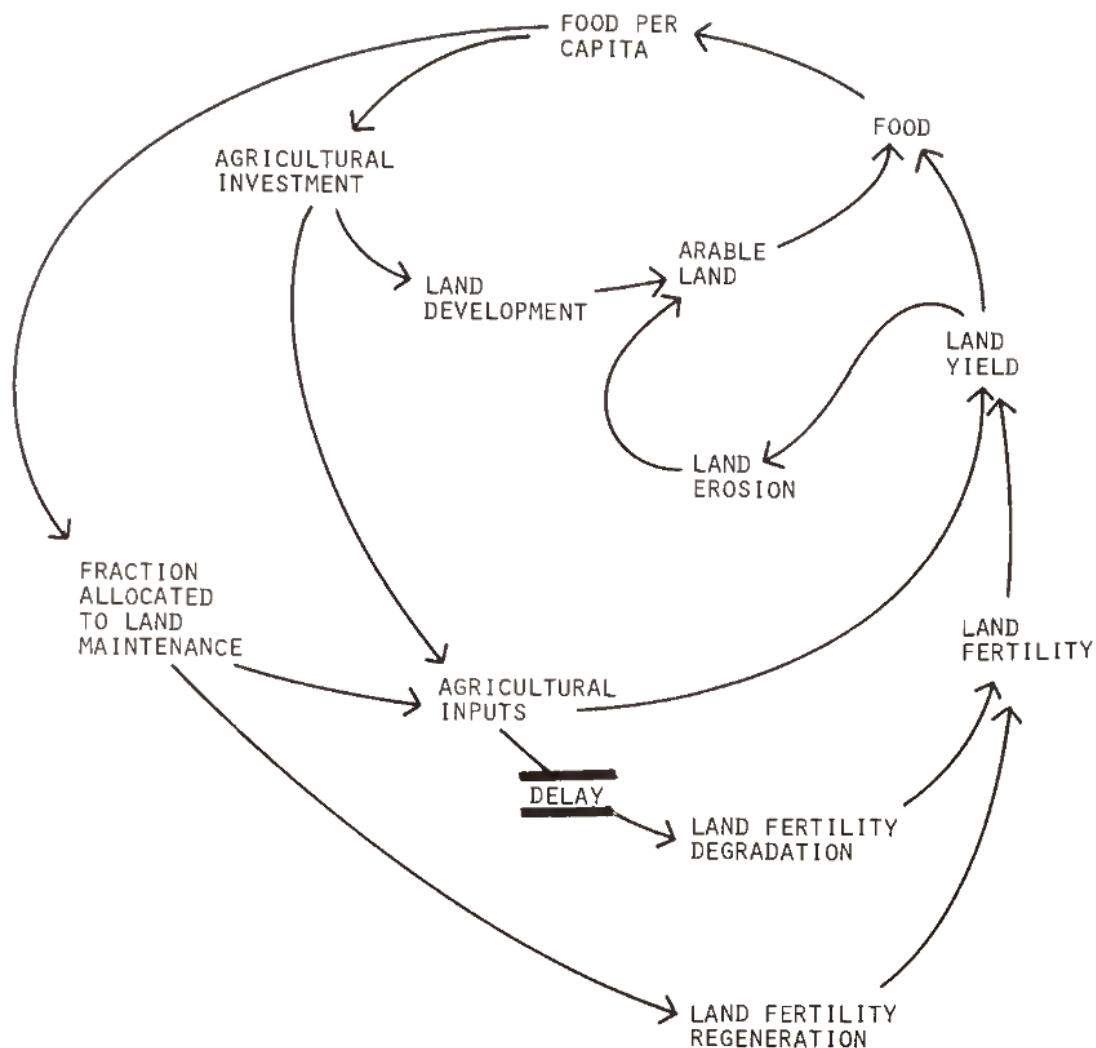


Figure 6.8: Causal loop diagram of the agricultural subsystem structure. Reproduced from Meadows et al. (1974), p269.

World3: resources subsystem

The non-renewable resources subsystem is relatively simple, represented by a single stock of non-renewable resources and a small number of parameters. With the usage

rate as a function of industrial output, the stock constantly decreases over time. Further, as the stock decreases, the capital cost of obtaining resources increases, representing a decline in easily accessible deposits. This cost may be offset by technological advances, but ultimately such advances cannot decouple the inherent relation between depletion and industrial output.

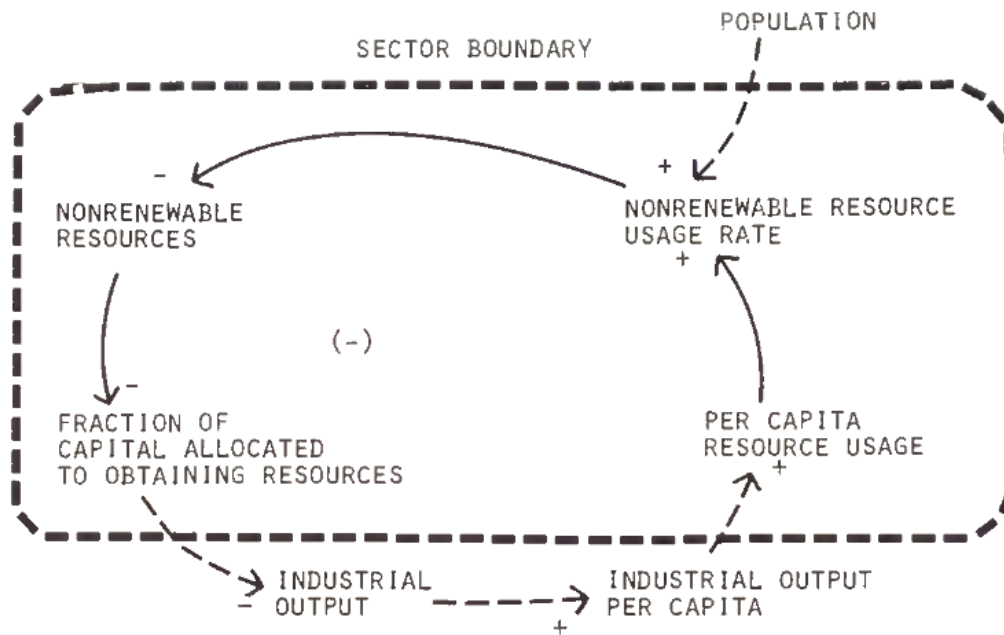


Figure 6.9: Causal loop diagram of the non-renewable resources subsystem structure. Reproduced from Meadows et al. (1974), p386.

World3: pollution subsystem

Within World3, 'persistent pollution' is produced from industrial and agricultural activities. This broad term covers a wide range of aggregated materials, such as chemicals, radioactive isotopes, and heavy metals, which "cause damage to some form of life, are released through many different forms of industrial and agricultural activity, and are sufficiently long-lived that they may be transported through the global environment by the planet's air or water streams" (Meadows et al. 1974, p422). The generation rate of the 'persistent pollution' stock is causally linked to the intensity of agricultural pollution, and non-renewable resource usage rate. The model implements a delay function to simulate the time taken for negative externalities of this to be exerted on the biosphere, thus delaying the impact on life expectancy and land fertility.

The model assumes that there is a capacity of the natural environment to assimilate persistent pollution, thus acting as a counter to its accumulation. The

assimilation rate is related to the level of accumulated pollution and an assimilation half-life which is itself dependent on the total level of pollution.

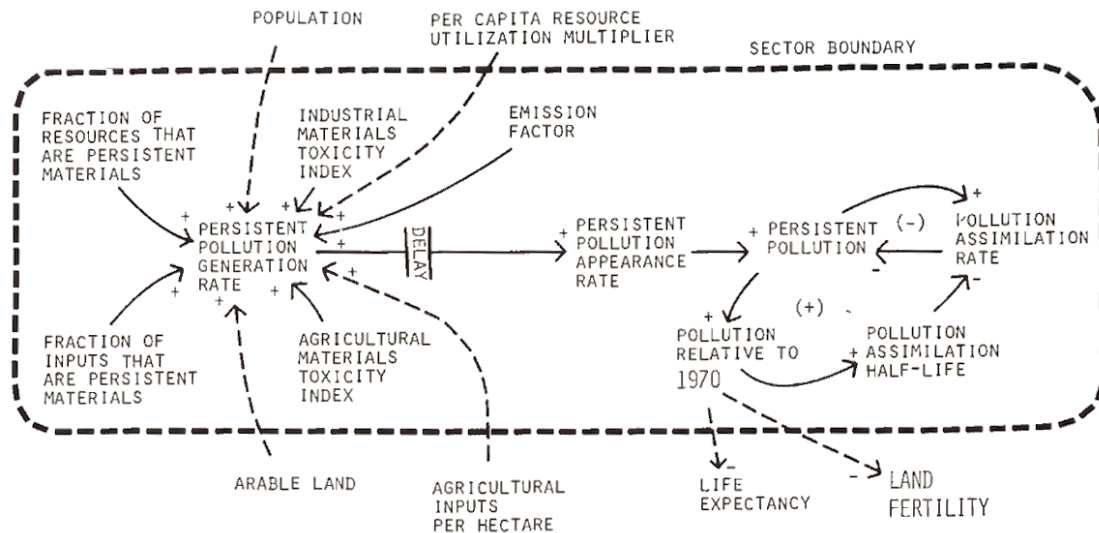


Figure 6.10: Causal loop diagram of the persistent pollution subsystem structure. Reproduced from Meadows et al. (1974), p426.

World3: indicators

For the 30 year update, Meadows et al. (2005) added two new parameters to their scenario outputs to provide a better visual representation of sustainability within the outputted scenarios. The ‘human ecological footprint’, HEF, is based upon the ecological footprint of Wackernagel (1994), and is intended to provide a measure of the impact of human activities on the Earth’s ecosystems through the reliance on natural capital. It is defined by Meadows et al. (2005) as the “land area necessary to provide for the current way of life”, and is the normalised sum of the arable land, urban industrial land, and the amount of absorption land required to neutralise pollutants (p291). The current estimation for the global figure, as a ratio of the number of planets required to sustain current economic patterns is 1.7 (Lin et al. 2018). Within World3-03, it has been calibrated by Meadows et al. (2005) to be equal to 1 in 1970, ranging from values of 0.5 in 1900 and values above 3 in late stage unsustainable scenarios (pp292-293).

The ‘human welfare index’, HWI, is an approximation to the UN Development Programme’s human development index, which itself is comprised of three indicators representing knowledge, a decent standard of living, and long and healthy lives (Anand and Sen 1994). Within World3-03 this is a function of the global average life expectancy and industrial output per capita (Meadows et al. 2005, p287).

It is notable that these ‘sustainability indicators’ closely align to social and environmental pillars of sustainability, with no explicit economic indicator given. This omission is not presented or discussed by Meadows et al. (2005), but may be representative of their growth sceptic ideological alignment. Industrial and service output may be considered proxies for GDP measures, however they do not receive the same emphasis as the welfare and footprint indicators.

6.1.4 World3 outputs: alternative scenarios

The LtG and subsequent updates have articulated a number of scenarios representing potential future outcomes based upon differing assumptions. Each scenario is run for 200 years, from 1900 to 2100 and various outputs are documented. The related publications outline a number of scenarios between them, the core scenarios are outlined here following the format and numbering of Meadows et al. (2005). Each of these scenarios builds upon the last, analysing the reasons for the previous collapse, and implementing measures aimed at mitigating the first limiting factor. In this way, the collapse of the system is slowly pushed back across successive scenarios, whilst building a deeper awareness of the underlying dynamics and feedbacks.

Scenario 1 - the reference, or standard run (Meadows et al. 1972, pp124-126, Meadows et al. 1974, pp500-502, Meadows et al. 2005, pp168-171) depicts a ‘business-as-usual’ approach, extrapolating the historical path into the future without the implementation of major policy change which ultimately collapses due to a ‘nonrenewable resource crisis’. Under this scenario, economic growth halts and declines a few decades into the twenty first century, primarily due to an increased costs of resource extraction leading to the diversion of capital investment away from the service and agricultural sectors. A subsequent decline in food and health services leads to a decreased life expectancy and therefore the total population peaks and drops off. As has been constantly stressed by the authors, this result is not a prediction and the timing of events is not meaningful, but “portrays the likely general behaviour mode of the system, if the policies that influence economic growth and population growth in the future are similar to those that dominated the last part of the twentieth century, if technologies and values continue to evolve in a manner representative of that era, and if the uncertain numbers in the model are roughly correct” (Meadows et al. 2005 p71).

Scenario 2 - more abundant renewable resources (Meadows et al. 1972, pp126-128, Meadows et al. 1974, pp503-505, Meadows et al. 2005, pp171-174), doubles the initial nonrenewable resource stock that was assumed in Scenario 1. Here expansion carries on for an extra couple of decades, although the overall behaviour

still represents overshoot and collapse, this time from a 'global pollution crisis'. This is caused by higher levels of industrial and agricultural output leading to a rapidly building concentration of pollution. These levels have a major impact on land fertility leading to food shortages and a declining population that is further marred by the health impacts of pollution. This scenario is illustrated in Figure 2.4 alongside Scenario 9, the 'stable world'.

Scenarios 3-6 develop successive iterations of 'technological policies' - more abundant renewable resources, pollution control technology, land yield enhancement, land erosion protection, and resource efficiency technology (Meadows et al. 1972, pp132-145, Meadows et al. 1974, pp510-537, Meadows et al. 2005, pp210-220). In the initial report, all changes were implemented in 1975 (compared to 2002 in the 30 year update), each successive run then represents effects of an additional policy designed to relieve the limitation of growth evidenced in previous run. Initially 'pollution control technologies' are implemented which reduce pollution associated per unit economic output by 4% a year, this postpones collapse further which ultimately arises due to a 'food crisis'. Scenario 4 thus shifts investment toward the increase of agricultural yield, ultimately this leads to increased erosion and is dubbed the 'land erosion crisis'. Land erosion protection is therefore implemented in Scenario 5, this further delays collapse until a combination of high costs, as well as food and resource crises occur in the latter half of the 21st century. Scenario 6 incorporates a program of resource efficiency, reducing the amount of non-renewable resources required per unit of industrial output. This scenario ultimately leads to a stable population by the end of the 21st century, although this is accompanied by a fall in living standards as reinvestment becomes too expensive.

Having argued that technological policies do not address the causes of overshoot, only seeking to buy time and move the limiting factor from one sector to another, the effect of 'social policies' is explored in Scenarios 7-8 (Meadows et al. 1972, pp158-163, Meadows et al. 1974, pp537-543, Meadows et al. 2005, pp240-244). Scenario 7 introduces a two child policy seeking to stabilise population, with no additional changes this scenario ultimately ends in collapse due to high levels of pollution. Scenario 8 accompanies this population control with measures to stabilise industrial output per capita corresponding to 'adequate but not excessive' standards of living, ultimately however pollution stresses agricultural resources leading to a decline in food and therefore population.

Scenarios 9-10 combine these stabilising social policies with the technological changes to produced 'stabilised world models' (Meadows et al. 1972, pp163-169, Meadows et al. 1974, pp543-549, Meadows et al. 2005, pp244-250). Scenario 9 thus

sees all the aforementioned policy changes implemented in 2002, and is displayed in Figure 2.4 alongside Scenario 2. Here the more restrained society overcomes the capital costs that caused the collapse in Scenario 6, and the world system reaches ‘equilibrium’ before the end of the 21st century with food, capital, population, and human welfare all stabilising whilst the ecological footprint declines. This scenario is held up by the authors as both feasible and desirable. The urgency for action is displayed by Scenario 10 which depicts the implementation of these same policies 20 years previously, resulting in the same stabilised equilibrium, but higher welfare, a better environment and more degrees of freedom. The argument is made that at some point it will become too late to implement change to avoid negative effects of reaching the limits to growth, and every delay reduces the number of options that are open to society. Such arguments are strikingly similar to conclusions currently been drawn within climate change discourse (Eastin et al. 2011).

Response

Rodger (2010) argues that critique of LtG broadly ran along three strands: technical criticism of the modelling, sectoral analysis, and the overall philosophy. Several avenues of criticism hold the model up as pessimistic, arguing that humanity will be able to provide technological fixes not accounted for by the model (e.g. Lecomber 1975; Cole et al. 1973; Nordhaus et al. 1992, see Ekins 1993; Costanza 2006 for further discussion). To an extent however this represents a misrepresentation of the further scenario runs which show that the system can stabilise if political and technological changes are made. Bardi (2011) claims that criticism of LtG peaked in the 1990s based upon claims that the collapse predicted by the model had failed to materialise (p2). In fact, even Scenario 1 carries through on a smooth trajectory into the first couple of decades of the 21st century. Thus whilst there are genuine criticisms to be made about the model and report, it seems a large portion of this criticism is based upon misrepresentation or misunderstanding (Randers 2012b; Jackson and Webster 2016; Lane 2019).

The world model employed in LtG has gained renewed interest more recently, with a number of authors arguing that its results stand up against historical data, nearly 50 years after its creation (Simmons 2000; Myrtveit 2005; Turner 2008, 2014; Randers 2012a; Hall and Day 2009). There is evidence too of consideration of LtG and related literature from a policy perspective, with the establishment of the ‘All Party Parliamentary Group on the Limits to Growth’ in the UK in 2016 (Jackson and Webster 2016), and the UN’s brief consideration of ‘planetary boundaries’ at the 2012 Rio Earth Summit (UN 2012b). Coupled with interest in

the discourse surrounding the report and model (Bardi 2011; Gómez-Baggethun and Naredo 2015; Eastin et al. 2011), and more technical aspects surrounding the World3 model (Pasqualino et al. 2015; Ansell and Cayzer 2018), it seems the model maintains a clear relevance to contemporary research.

Turner (2008) compares historical data to three scenarios from the original 1972 LtG report: Scenario 1, ‘the standard run’, and early versions of Scenarios 7 and 10 representing ‘comprehensive technology’ and a ‘stabilised world’ respectively. It is argued through a presentation of various collated data that out of these three scenarios, the standard run of Scenario 1 best represents observed historical trends. Turner (2012) updates this analysis with an additional 10 years of data, and argues that the historical trend still remains consistent with the ‘standard run’. Mappings of key variables are reproduced in Figure 6.11. Whilst these findings appear somewhat convincing, it should be noted that Turner uses the results of the original run of World3 rather than the latest World3-03 simulations, and no intermediate scenarios are considered.

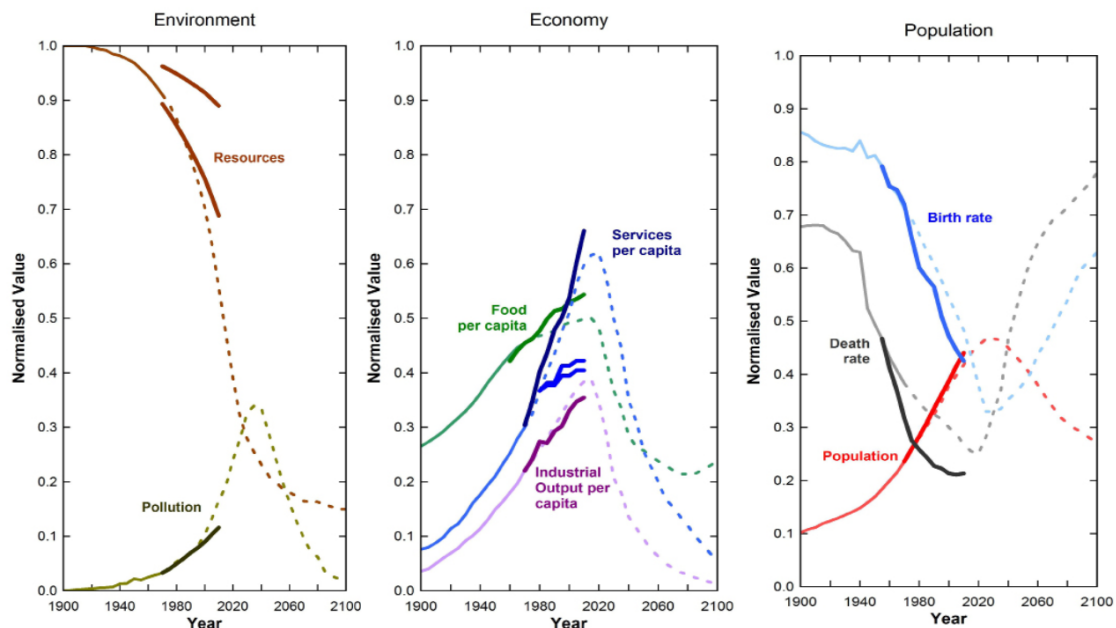


Figure 6.11: Reproduction of Turner (2014)’s mapping of historical data to the LtG 1972 ‘standard run’.

As a unique systems approach to sustainability, grounded in the historical roots of the sustainability literature itself, this world modelling methodology provides a lens through which ‘urban sustainability’ may be explored conceptually. Adapting World3 therefore provides not only a framework for understanding ‘urban sustainability’ but also a clear framework for understanding normative global

sustainability, and should thus provide a way of comparing and examining the two in tandem. Further, such a well defined model, backed up by (albeit old) data with its assumptions clearly outlined in Meadows et al. (1974), allows for the examination of a pre-existing framework rather than formulating a new one from the ground up, building upon the considerable intellectual effort that was invested in creating it. Of course, this limits the concepts traditionally falling under the umbrella of ‘sustainability’ which are considered, but in avoiding making subjective choices as to the phenomena included provides an inert, pre-defined environment for examination.

6.2 From World Model to Urban Model

The modelling approach was previously outlined in Figure 2.3 in Section 2.4.3, and consists of rebuilding World3-03, adapting each subsystem in isolation, coupling subsystems, coupling World and Urban subsystems, and running scenarios. This section details the initial three steps of developing an isolated ‘urban’ version of World3-03, as ‘Urban0.5’. It outlines all changes that were made, and the series of theoretical issues or otherwise that were thrown up during this transition from world to urban. Section 6.3.1 subsequently details the coupling of the resultant intermediary model with a copy of World3-03 to create a prototype multiscale model for simulation runs.

As a halfway point, the intermediary model developed here remains uncoupled from any global parameters, is effectively a closed system, and should not be considered a useful model of a true urban system. Whilst any scenarios produced by this halfway model are largely meaningless, it is nevertheless useful to run several scenarios with it to verify and validate the model thus far. The qualitative behaviour may be examined in reference to the outputs from World3 to ensure that the model is behaving as expected (Ford 2010; Jørgensen and Fath 2011).

6.2.1 Prelude

As illustrated in Figure 2.3 the preliminary steps involve rebuilding World3-03 subsystem by subsystem, and verifying it, before identifying data sources for its calibration.

Re-building World3

First a replica of the 1972 World3 model was built in full within *AnyLogic PLE*, using Meadows et al. (1974) as an ‘instruction book’. This was done subsystem by subsystem before coupling these all together to form the full model. This allowed each subsystem to be verified in isolation to ensure no errors had been made (Findeisen et al. 1978). The ‘*Beyond the Limits*’ update was then used to bring the table and constants in line with World3-91, with updates made to the parameters ALLN, DCFSN, and tables LYMCT, FMT, LMFT, LMHS2T, and PCRUMT (Meadows et al. 1992, pp239-249). The outputs produced by the model were further verified against the output of Fortmann-Roe (2014)’s copy of World3-91. Finally updates to the table function SFSNT from World3-03 were also incorporated, as well as the addition of structures for wellbeing and ecological footprint (Meadows et al. 2005, pp289-293). A screenshot of the final replica World3-03 model within the AnyLogic environment is displayed in Figure 6.12.

This replica World3 model allows for the rerun of the standard run and modified runs of World3 as implemented in LtG and the subsequent updates. This was performed in order to better understand both the decisions taken in the modelling by Meadows et al, as well as for later replication of a similar process within the urban model to come. This also allowed for final verification by comparing these outputted scenarios to Fiddaman (2010)’s copy of the World3-03 model. Rerunning these later runs of the World3 model, gives a better feel of what sustainability means within this modelling framework, and what factors affect this. It should be emphasised that this represents a specific interpretation of ‘sustainability’ within this paradigm, rather than claims to generality. However, it allows for sandbox style testing of this theoretical frame, and its use as a learning tool should allow for a better understanding of ‘urban sustainability’ relative to the global (Walker and Van Daalen 2013).

Identification of data sources

Initially the Urban model was proposed to be a representation of the City of Nottingham, UK. This was due in part to access to specific Nottingham resources and expertise, as well as the potential to produce avenues for future collaboration, as outlined in Section 2.4.3. Whilst this appeared to suggest a ‘Nottingham’ urban system dynamics model would be a good approach, ultimately for reasons related to data constraints this proved to be unrealistic for this current work.

Aside from the issue of Nottingham’s administrative boundary (as discussed in Section 4.1.2), deeper issues exist regarding the lack of access to detailed calibration

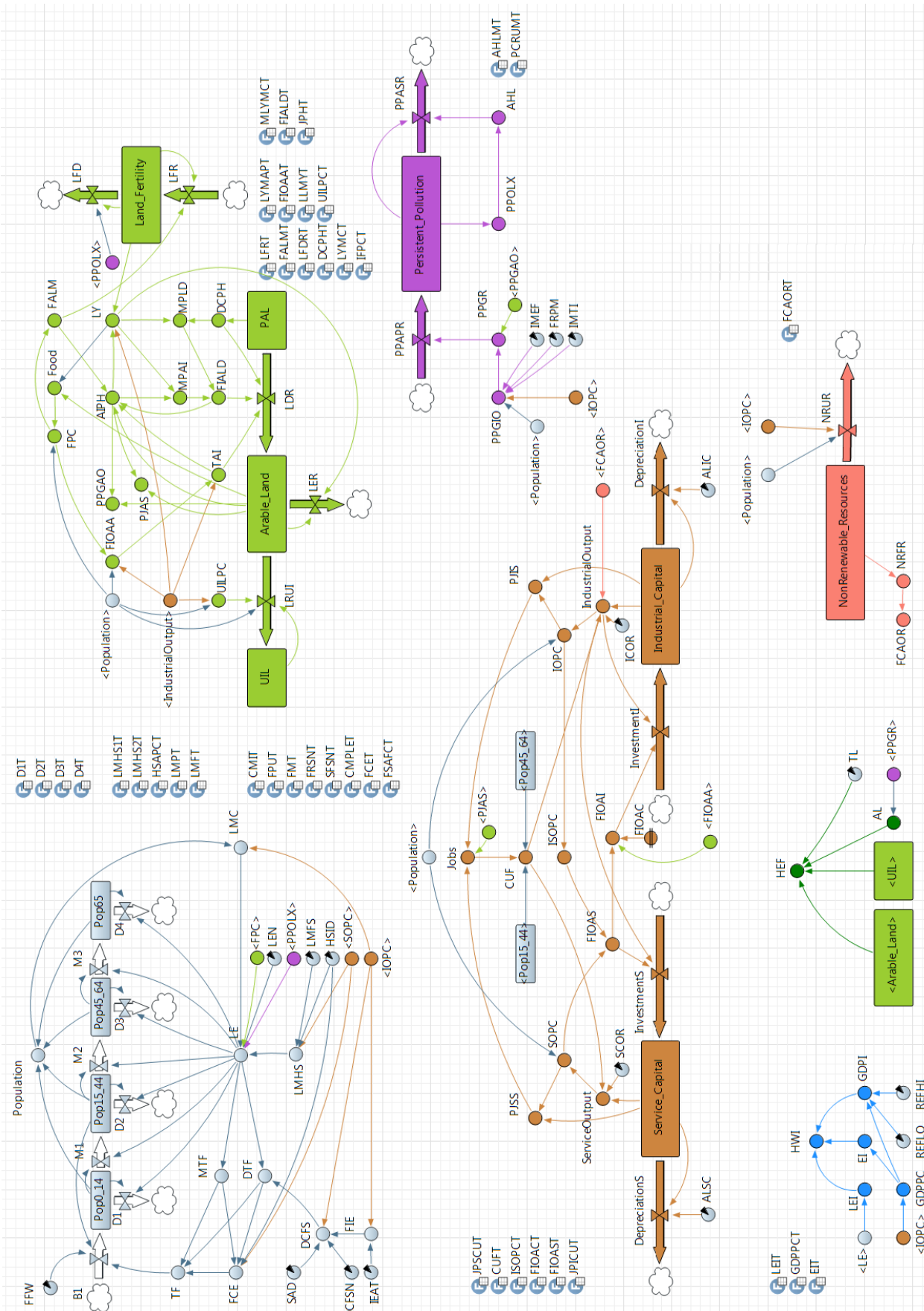


Figure 6.12: Screenshot of the replica World3-03 model built within AnyLogic. Each subsystem has been isolated for clarity and are linked through shadow variables (copies of existing variables which make for neater diagrams).

data comparable to that used in World3. First, detailed annual population data does not exist for the relevant time period. World3 uses annual UN population data going back to the initial simulation year of 1900. The Office of National Statistics (ONS) holds annual ‘mid-year’ population estimates for Nottingham back to 1991, but prior to this, census data provides a population count only every 10 years. This is inadequate for plotting an accurate representation over an extended period. This is further confounded by a seeming peaking of the population in 1961 followed by a gradual decline that only begins to recover by 1991. This could be a product of boundary changes or statistical techniques, or a consequence of de-industrialisation and economic decline, but there is simply not enough data or historical information to explain this. This draws to Louf and Barthelemy (2014)’s statement that in the absence of a theoretical model to explain observed data, one should refrain from drawing any conclusions.

As well as the lack of detailed Nottingham specific data for population, problems were also encountered in finding data to calibrate the economic model. Detailed economic data is not available for the city region, however Gross Value Added (GVA) data exists for the ‘Greater Nottingham’ area. This may be considered roughly equivalent to the GNP for the region as used by Meadows et al. (1974) in calibrating World3. This GVA data is helpfully broken down by Nottingham City Council (2018c) by sector, although this only exists going back to 2010.

Thus, the most basic data required to calibrate the model as a representation of Nottingham does not exist, due to both the lack of detailed time series data, as well as inconsistent use of administrative boundaries. Whilst it may be possible to use statistical techniques to overcome these barriers (see e.g. Honaker and King 2010), it was decided to fall back on readily available UK average data instead. This decision was largely based upon the failure to find detailed explanation as to why Nottingham’s population appears to widely fluctuate between census years. The individual data sets used as well as details of their adjustment is detailed within the section for each subsystem, a full list of data sources used is also presented in Appendix B.

6.2.2 Downscaling subsystems

Any adaptation of World3 to a smaller unbounded regional entity must confront boundary conditions. This intermediate model, remains ‘closed’ with respect to boundaries, with no interaction with the outside world. This section documents the construction of this intermediary Urban0.5 model, presenting the individual downscaling of each subsystem. As the table functions within the model capture

relations that are assumed to be universal, these remain unchanged through this adaptation. This initial adaptation primarily concerns re-calibrating the initial values of the stocks presented in World3, as well as several additional parameters.

The base year for this urban model was taken as 1951, due to it being the earliest census year from which economic data for the UK also exists in an accessible format. Parameters for re-calibration were identified on the criterion that a value for that parameter in an urban system would be expected to differ from the same parameter in a global system (e.g. initial population). Thus no parameters are re-calibrated simply because the data informing them is perceived to ‘be out of date’¹.

Population

The population subsystem presents relatively few parameters which require re-calibration, with only the initial population parameters meeting the given criteria. Parameters such as the social norm for family size could be argued to vary spatially according to cultural contexts, but this is beyond this initial work’s scope, and so the global average value given in World3-03 is therefore used.

A base population for 1951 was taken as 300,000, which is roughly equivalent to the population of small UK cities such as Nottingham around this time². Since the World3 model holds four age bounded population stocks, this total population was then multiplied by the relative age bands given for Nottingham in the 1951 national census (Great Britain Historical GIS Project 2017) to provide initial values for each of the model’s population stocks.

Further, the life multiplier from health services step function, *LMHS*, which in World3 accounts for a rapid advancement in global health services across the 1930s and 1940s (Meadows et al. 1974, p74), was removed since this is less relevant in the UK context, and the urban model itself does not start until 1951. All remaining parameters and table functions within the population remain identical to World3-03.

Capital

Downscaling the capital subsystem involves re-calibrating the initial values of the industrial and service capital stocks, as well as considering their units of measurement in light of inflation and a change in currency. These stocks may be thought of as urban infrastructure, such as buildings, roads, industrial areas, retail

¹These parameters were therefore last calibrated in 2004 by Meadows et al. (2005). Pasqualino et al. (2015) present a more recent re-calibration, but since no large deviations are observed the World3-03 values of Meadows et al. (2005) are used for consistency.

²The 1951 UK census gives Nottingham unitary authority’s population as 306,078 (Great Britain Historical GIS Project 2017)

units etc. These directly or indirectly create value, but also have a finite lifetime so reinvestment must occur in order for their maintenance.

An equation for calculating the initial industrial capital is adapted from Meadows et al. 1974 (p219):

$$IC(1951) = \frac{IOPC(1951) \times POP(1951) \times ICOR}{1 - FCAOR(1951)}. \quad (6.2)$$

Immediately, several variables within this equation may be evaluated; the initial population, $POP(1951) = 300,000$ as set above, the industrial capital output ratio³ $ICOR = 3$ years (as described in Meadows et al. 1974, p216), and $FCAOR(1951) = 0.05$ ⁴ (obtained globally from running World3-03).

A value of $IOPC(1951)$ must be calculated. In principle, an estimate of this may be obtained from the division of GDP produced in the industrial sector by the total population. A value for the UK population in 1951 of 50,300,000 people is obtained by census data (Office for National Statistics 2018c). ONS GDP data released in 2018 provides annual GDP data from 1951 in Great British Pound ‘chained volume measure’, adjusted for inflation, i.e. in 2018 GBP (Office for National Statistics 2018b).

Since the table functions within World3 are all based upon 1968 USD (Meadows et al. 1974, p207), it remains simpler to retain this unit for the adapted urban model and convert contemporary values, thus all monetary data used for calibration was converted to 1968 USD. An exchange rate of 1.30 was used, based upon its average value between 2017 and 2018 (OFX 2019), and an inflationary ratio of 7.22 for conversion from 2018 USD to 1968 USD (Official Data Foundation 2019). Using these values for conversion, the obtained ONS GDP data gives a value of 9.1×10^{10} USD (1968) for UK GDP in 1951. Employment sector data remains the only available proxy for determining the fraction of this value that is comprised of industrial sector output. UN data gives a value of 0.44 for the fraction of UK employment in the industrial sector in 1951 (University of Oxford 2019). Thus, $IOPC(1951) = 9.1 \times 10^{10} \times 0.44 / 50,300,000 = 796$ USD (1968) per capita. Finally, the initial industrial capital can be evaluated as $IC(1951) = (796 \times 300,000 \times 3) / (1 - 0.05) = 7.54 \times 10^8$ USD (1968).

³This may be interpreted as the number of years taken for one unit of capital to produce one unit of output, e.g. the number of years taken for a factory to produce a turnover equivalent to its capital cost (Allais 1962)

⁴The fraction of capital allocated to obtaining resources. In the urban context this can be thought of as capital allocated to energy production and distribution, e.g. electrical substations, and gas pipes; infrastructure for water supplies etc.

The initial service capital is evaluated similarly as:

$$SC(1951) = SOPC(1951) \times Pop(1951) \times SCOR \quad (6.3)$$

(Meadows et al. 1974, p230). The UN employment data provides a figure of 0.506 to be used as the service output fraction (University of Oxford 2019). Using the same data sources for GDP data, and a service capital output ratio of 1 (Meadows et al. 1974, p232), allows for the evaluation of the initial service capital as, $SC(1951) = [9.1 \times 10^{10} \times 0.506 / 50,300,000] \times 300,000 \times 1 = 2.75 \times 10^8$ USD (1968).

Agriculture

Adapting the agricultural sub-model requires the total amount of available land to be recalibrated, and the initial stocks of arable land, potentially arable land, and urban industrial land to be updated. It is helpful here to outline the definitions of land types used in World3 as given by Meadows et al. (1974): Arable land is that “used from time to time or full time to grow crops” (p278), this does not include non-arable land with grazing, and passes no judgement on the productivity of this land. Potentially arable land is then land which is not currently used to grow crops, but has potential to be, and is estimated within the model to be 24.2% of the planet’s land surface. Urban industrial land is not defined explicitly, but is implied to be any arable land that is lost to non-agricultural purposes, whether “dwellings and industrial plants; to roads, waste-disposal sites, and airports; to strip mines and power lines; and to recreational use of land (sports fields, golf courses, and parks)” (p319). The demand for urban industrial land is modelled as a function of industrial output per capita.

The population density of ‘Nottingham Unitary Authority’ is given in by the 1951 as 41 persons per hectare (Great Britain Historical GIS Project 2017). With a simulated population of 300,000 this means a total land area of the urban system of approximately 7400 hectares. Whilst UK wide data exists on the percentage of arable land going back to 1961 (where it is roughly 30%), this is not available historically at a local authority level, and thus crude estimates must be made. It may be possible to infer the composition of Nottingham’s land use by using geospatial techniques on old maps (see e.g. Fuchs et al. 2015). Here though it is necessary to consider discussion of functional boundaries and the ‘hinterland’ as raised in Sections 1.2.2 and 4.3.1. The size of the Unitary Authority is not a realistic estimate of the land that is needed to support such a population, particularly as Nottingham’s boundaries are tightly defined (see 4.1.2). It is therefore necessary to consider expanding the size of the system to incorporate a traditional hinterland.

It is possible to estimate the initial demand for urban industrial land that World3 estimates for the system from its industrial output. This may be calculated through the equation

$$\text{UIL}(1951) = \text{UILPCT}(\text{IOPC}) \times \text{POP}(1951), \quad (6.4)$$

where UILPCT is a pre-defined table function. Evaluation of this equation demands 11,700 hectares of land, more than that which is available without the inclusion of a hinterland. This reflects the unreality of the assumption that the urban economic system may be bounded and maintain the same economic output without reliance on this hinterland. Of course it should be noted that the basic World3 model does not account for mixed use land, which opens up new routes for agriculture in urban areas, from large scale to allotments and urban gardens (see e.g. McClintock et al. 2013 for discussions).

If the 7400 hectares figure is used, on running, the model quickly seeks to allocate existing arable land to urban-industrial land in order to maintain capital, this exhausts the supply almost immediately with the model crashing in a matter of years before there is time for collapse. A hinterland was therefore added. Such an approach is in line with historical practices such as Von Thünen's 'isolated state' system, in which the urban area is supported by concentric rings of hinterland to meet its needs (Fujita and Krugman 1995).

Some sensitivity testing was required to calibrate an appropriate value for the total land available to the system. As the free PLE version of AnyLogic which was used does not allow for such testing to be automated, this had to be done by manually changing these values in the model and observing the outputted scenarios (Oliva 2003). For lower values the model crashes as a fast decline in food per capita causes the life expectancy to drop to its minimum value. Alexander et al. (2016) provides figures for the approximate amount of land that is required on average to feed the world's population. These estimates give an approximate global figure of 0.65 hectares per person, with the most conservative figure given for India at 0.29 hectares per person (pSI-6). These values suggest a realistic range over which to carry out the calibration. From this, a figure of 100,000 hectares for the total size of the system was chosen, this lies towards a more conservative value, but allows for the simulation to run without crashing. Future work could investigate the sensitivity of this calibration of the urban system size and its effects on the simulated scenario in more depth.

From here initial values of land types were implemented as follows: 12,000 hectares of urban industrial land (satisfying the initial demand), 87,000 hectares

of arable land (sensitivity analysis determined this amount comfortably satisfied the initial demand of food per capita), this left 1000 hectares of potentially arable land. This represents an urban centre of concentrated population and industrial activity surrounded primarily by cultivated farmland, not an unfair representation of Nottingham in the 1950s.

Further to these initial land stock values, the parameter for the initial agricultural inputs in dollars per year, i.e. the annual agricultural investment that is not allocated to land development (Meadows et al. 1974, p292), must be recalibrated. The value used in World3 is an estimate made globally for the year 1900, and diverges significantly from the expected value from the UK economy in 1951. Since no reliable data for this parameter exists, a conservative estimate quoted from Meadows et al is employed of 45 USD (1968) per hectare multiplied by the initial arable land.

Pollution

Pollution is a particularly acute issue at the urban scale (Zheng and Kahn 2013). In World3 ‘persistent pollution’ is a general term representing an aggregate of industrial and agricultural chemicals, radioactive isotopes, and heavy metals. Whilst an imperfect assumption, pollution from the service economy is judged to derive solely from the consumption of *industrial* output (Meadows et al. 1974, p429). Thus public transport (service capital) produces pollution through the combustion of fuel which is considered an industrial output, the production of knowledge (service output) in a school (service capital) produces no emissions.

The persistent pollution transmission delay, PPTD, is defined as “the average number of years spent by a unit of persistent pollution between the time of its generation and the time of its full impact on the biosphere”, and is set to 20 years in World3 (Meadows et al. 1974, p435). Since the aggregated materials all have differing transmission delays and impacts, it is difficult to estimate a value for PPTD, although due to the lengthscales involved it is expected to be a shorter time. In an urban area the transmission delay of industrial air pollution can be assumed to be negligible relative to the model step time of a year, the delay in agricultural chemicals reaching groundwater is less clear however. Pérez-Lucas et al. (2019) for example, discuss in depth the processes by which pesticide use leads to groundwater pollution, acknowledging the possibility of long delays but not quantifying them. Meals et al. (2010) outline lag times in water quality in response to the implementation of best management practices, they state “the magnitude of lag time is difficult to predict in specific cases and generalizations are difficult to make” (p89), a table of example lag times for specific cases is however produced.

These response lags range from months to in excess of 50 years. A median of 10 years may be tentatively inferred for comparative studies, although this is difficult to justify statistically. A transmission delay of $PPTD = 1$ year is therefore (arbitrarily) chosen to reflect a bias towards air pollution transmission times.

The initial persistent pollution is constructed by Meadows et al. (1974) (pp440-441) as:

$$PPOL(1951) = (PPGIO(1951) + PPGA0(1951)) \times 1.4 \times AHL(1951), \quad (6.5)$$

the sum of the persistent pollution generated by industrial and agricultural outputs, multiplied by the assimilation half-life and a correction factor of 1.4. The industrial contribution is given by:

$$PPGIO(1951) = PCRUM(1951) \times POP(1951) \times FRPM \times IMEF \times IMTI, \quad (6.6)$$

that is the per capita resource use multiplier multiplied by the initial population and three constants representing the fraction of resources as persistent materials, industrial materials emission factor, and industrial materials toxicity index respectively. $PCRUM$ is evaluated as a table function of the industrial output per capita, this may therefore be evaluated using the initial value of $IOPC(1951)$ which was calculated above. It is thus established that $PPGIO(1951) = 3.78 \times 300,000 \times 0.02 \times 0.1 \times 10 = 22,680$ pollution units.

The initial persistent pollution generated by agricultural output is described by

$$PPGA0(1951) = AIPH(1951) \times AL(1951) \times FIPM. \quad (6.7)$$

The initial agricultural inputs per hectare, $AIPH(1951)$, may be extracted from its evaluation in the model. The initial value for the amount of arable land, $AL(1951)$, was set above to 87,000 hectares. Finally, the constant $FIPM$ which describes the fraction of agricultural inputs composed of persistent materials, is given by Meadows et al. 1974 as 0.01 (p433). Thus $PPGA0(1951) = 49.66 \times 87,000 \times 0.01 = 43,204$ pollution units.

World3 assumes an exponential assimilation rate of pollution. The assimilation half-life AHL depends only on the level of pollution present, and its 1951 value may be calibrated from an initial model run to 1.44. The initial pollution value may thus be evaluated from equation 6.5 as $PPOL(1951) = (22,680 + 43,204) \times 1.4 \times 1.44 = 132,822$ pollution units. Finally, the persistent pollution index, PPI , which is evaluated in World3 to have the value of 1 in 1970 (p441), uses here a normalisation year of 1951.

Resources

There are several possible choices in how the initial amount of non-renewable resources allocated to the urban system may be distributed. For simplicity the choice is narrowed to allocating World3's 1951 level of resources either per capita, or per hectare. Since it is reasonable to assume that a distribution clustered closer to settlements than an even distribution, the former allocation method was selected. The World3-03 'standard run' outputs 9.6×10^{11} resource units of non-renewable resources for 1951 and a population of 2.74 billion, thus for an initial population of 300,000, an initial non-renewable resource level of 1.05×10^8 resource units is used.

Welfare and ecological footprint

The normalisation of the ecological footprint indicator is set to equal the total system size, that is 100,000 hectares, as per Rees and Wackernagel (1997)'s urban ecological footprint. The human welfare index remains unchanged for this initial urban adaptation.

6.2.3 Urban0.5 'validation'

Before coupling this urban model to a world model, it is necessary first to 'validate' it. In the strictest sense it may already be surmised that the model, in effectively casting the urban as a 'closed' system is not a valid reflection of reality. Nevertheless, as an iterative process, validation should not be left until the final model is completed (Sargent 2010). In recalling the discussion of validation in Section 2.4.3, there remain several tests that are suitable to perform at this stage. It is already known that the model isn't useful in an operational sense, although it could be used for an abstract demonstration of what it would mean for an urban system to be 'closed'⁵. In this section then, 'validation' asks does the model behave as expected, given that it is an unrealistic closed urban system.

Within the 4 validation steps outlined in Section 2.4.3, steps 1) and 3) remain suitable here, 'face validation' and comparison to World3 output. Having calibrated this intermediate urban model then, a series of scenarios were output from these model runs to examine for validation. These followed from the previous studies of Meadows et al. (1972), Meadows et al. (1992), and Meadows et al. (2005) which built upon successive scenarios' limiting factor, making amends for this through

⁵Berger (2014) discusses the [impossibility] of closed urban boundaries in relation to an understanding of urban sustainability as 'self-sufficiency', declaring "modern cities are by definition open systems" (p368).

policy or technological interventions in subsequent runs. Since these scenarios are not meaningful in the sense of describing a ‘real’ system they are not detailed in full here. However, this process is documented in relation to the output ‘Scenario 4’ which was taken forward for comparison in the subsequent section.

In terms of qualitative behaviour these scenarios produced similar results to World3, showing population peaking and declining without policy or technology levers being implemented. A ‘face validation’ did not reveal any parameters that produced unreasonable results. The time of population peak occurred relatively early in these first scenarios (around 1970 in scenario 1), of course this is not what is witnessed within the data, but since this closed system intermediate step is not viewed as a valid reflection of reality this should not be seen as a concern.

Scenario 4 - resource efficiency technology

Scenario 4 of this intermediary urban model, utilises several technology and policy measures which were employed in Meadows et al. (2005)’s *Scenario 6*. This involves doubling the initial amount of available non-renewable resources, and the implementation resource efficiency technologies, which through a smoothing uptake delay function act to reduce the amount of non-renewable resources needed per unit of industrial output. Additionally, land erosion protection involves a switch in the table function describing the relation between the and life multiplier from yield and land yield itself, dampening the effect of increased yield on erosion rate (Meadows et al. 1974, pp316-318). Qualitatively this scenario resembles the ‘domed’ closed urban system briefly considered as a thought experiment in Section 5.2.2. This domed urban system and hinterland has good resource circularity and practices agricultural techniques which minimise soil erosion.

Some sensitivity analysis was performed to establish when these measures must be introduced to have any qualitative impact on the resultant scenario. Pushing back 20 years each iteration, the peak of industrial output is delayed and the pace of its subsequent decline reduced. Interestingly, the magnitude of this effect is non-linear, with the greatest impact in sustaining economic activity being reached by introducing these measures either 6 or 36 years into the scenario run. This indicates a trade off between boosting economic growth early on through resource intensive production and limiting early growth but quickly investing in circular resource practices and technologies. For consistency with LtG’s approach however, these practices were implemented in the third consecutive year in which a confrontable decline is witnessed, in this case occurring 7 years into the simulation run.

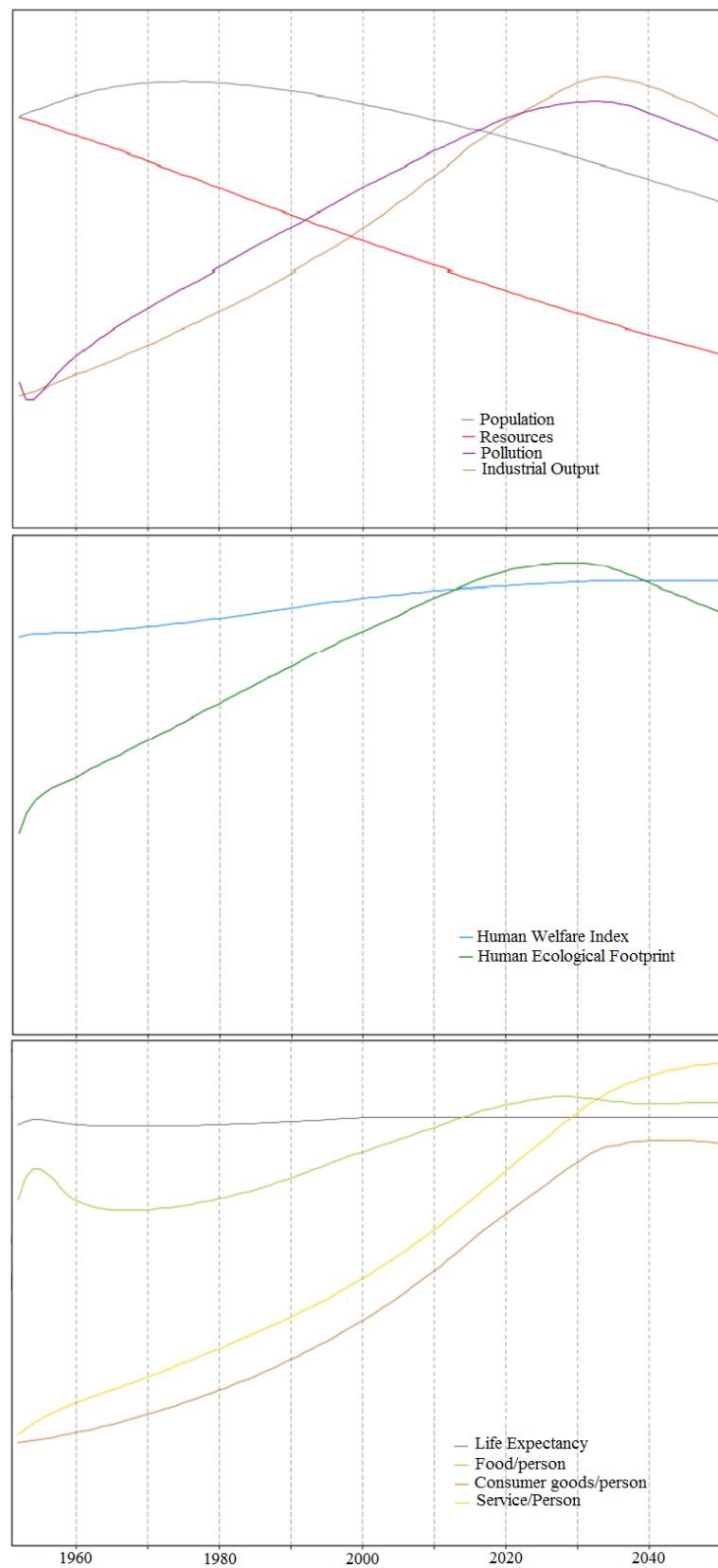


Figure 6.13: 'Urban 0.5' Scenario 4: 'land erosion protection with abundant resources and resource efficiency technology'.

This ‘Scenario 4’ is outlined in Figure 6.13. This follows the presentation of Meadows et al. (2005)’s scenario outputs, as three stacked graphs describing from the top, the ‘state of the urban system’ which provides an overview of the major stock variables, the indicators of human welfare and ecological footprint of the urban system, and variables providing indicators of the ‘material standard of living’. No y-axis is displayed, this is to avoid the reader examining the curves in a quantitative manner, when it is their qualitative behaviour that should be the focus. Nevertheless, some quantitative aspects are detailed in the text.

The top scenario diagram depicts an initially growing urban population which peaks and contracts at a moderate rate from the 1970s. The industrial output grows throughout most of the scenario representing a healthy industrial sector of the urban economy. Nevertheless towards the mid 21st century it appears that a steady depletion of the non-renewable resources available to the urban system proves to be a limiting factor in this growth. As more industrial capital has to be diverted towards mining these depleted resources rather than producing output, the industrial output peaks and begins to decline.

The bottom scenario diagram describes the material standard of living within the urban system through a series of variables acting as indicators. The life expectancy remains high throughout the scenario, remaining unaffected by the moderately rising pollution levels. The average amount of food available per person within the urban system rises at a modest rate throughout, showing that even as the industrial sector falters, the urban system does not yet experience food shortages. Consumer goods and services available per person also rise at a steady rate as the scenario plays out, representing e.g. improvements in healthcare and a higher individual purchasing power, roughly equivalent to what can be witnessed in the UK across the 20th century (MeasuringWorth 2020).

This scenario then passes a ‘face validation’, its outputs may be explained logically, and there are no misbehaving parameters. One potential issue is several discontinuities that may be observed in the first 5 years of the model running. This is observed primarily for the pollution, although after the first 5 years stable trajectories may be observed. This is due to imperfect equations, and a similar effect is witnessed in World3. The assimilation is a simple half-life equation, the natural effect is for the persistent pollution levels to decay over time. Since the accumulation rate experiences a time delay effect, it takes several years for this build up to overcome the assimilation decay and lead to growing levels of pollution.

6.3 Urban1: Coupling to a Global Commons

Having demonstrated that the downscaled ‘Urban0.5’ model, whilst being invalid in terms of a reflection of reality, nevertheless passes a ‘face validation’ check of operating as expected, the next step is to couple this with a copy of World3 to create a more realistic abstraction of an ‘open’ urban system which interacts with a global commons. As outlined in Chapter 2, this will be done by coupling the initial urban model with a copy of World3-2003. This process, and the output scenarios are used to address Questions 1a and 2c regarding the relation of urban sustainability to its global sense, and the nature of boundaries. Coupling is modelled as mono-directional, since the urban system produced in Section 6.2.2 is judged sufficiently small to impact significantly upon the global system. The critical mass at which a smaller urban system’s functioning does become significant is an interesting question for future research. The cumulative impact of the set of urban systems on the global system is potentially very significant, and may in future help to provide evidence in support of the need for urban focused policy interventions.

6.3.1 Opening functional boundaries

This section details the approach that was taken in coupling the Urban0.5 and World3-2003 models to produce the Urban1 model. First, all urban model variables were renamed with a prefix, to avoid duplication of variables from the original World3 model, thus the urban food per capita, **fpc** becomes **U_fpc**, and so on. The whole Urban0.5 modelling window was then pasted into that of a copy of World3-03, and any duplicate tables were deleted. Since Urban0.5 was initialised to begin on 01/01/1951, and World3 starts on 01/01/1900, this had to be factored into the attempt to couple the two models. Subsequently, each urban flow was thus set to zero for the first 51 years of the model run time; the time delays associated with implementing resource saving measures and arable land erosion protection were updated accordingly. Additionally, all the dynamic variables which included time dependent smoothing functions, **AIPH**, **RUF**, **CUF**, **FIE**, **LMHS**, were set to their initial Urban1 values of 50, 1, 1, 0, and 2 respectively for the first 51 years of the simulation.

Population

In coupling the urban system to a global commons, the migration flow across the urban boundary must be considered. Following from the approach used in Section 6.2.2 for the Urban0.5 model, data from the city of Nottingham was consulted to loosely calibrate what amounts to a ‘Nottingham - sized’ UK city. Detailed

migration data exists for Nottingham back until 2002, with net migration back to 1992, although the methodology behind these latter figures appears to be different (Office for National Statistics 2018a). These figures show a large population churn of around 30,000 people per year both inwards and outwards, with a slight net positive figure. This large churn is arguably due to the large student population of the city, 43,300 in 2018, or 13% of the total population (Nottingham City Council 2018b). This seems to be confirmed by a 2008 report that states that the only 5 year age-group with net gains is the 15 to 19 age band (Nottingham City Council 2008). More comprehensive up to date information is unavailable however, and it is difficult to draw any strong conclusions, especially in terms of theory. Thus, both a lack of detailed time series data regarding the age breakdown of migrants, and a theoretical model to link inward/outward migration with both endogenous and exogenous factors such as job availability hampers the development of a basic migration model.

A 2016 ONS report on UK internal migration provides more information that aids in the development of crude migration theory for modelling purposes (Office for National Statistics 2016a). Headline figures from the report suggest that ‘young adults’ are the most likely age group to move, peaking at both 19 and 22 representing a link to higher education. Since the ages between 17 and 45 stand out as a significant proportion of this internal migration, a crude migration model can get away with only dealing with the 15-44 age band population stock which is pre-built into the model. Numerous studies exist developing theory and models of internal migration, popular micro approaches relate to individuals maximising their expected utility function in terms of cost benefit analysis (Farwick 2009). Various factors may be weighted in this approach, both monetary and non-monetary, from gravity variables to environmental ones (Etzo 2008). This provides numerous variables that may effect internal migration already captured within the urban system dynamics model such as the capital utilisation function, *CUF*, human welfare index *HWI*, and human ecological footprint *HEF*, as well as macroscopic economic variables such as service and capital output. Despite several recent studies (Korpi and Clark 2015; Korpi et al. 2017) cautioning the selectivity of human capital approaches to internal migration, it was decided to use *CUF* as the main modelling variable. This is in part due to the lack of detailed theory applicable to the variables already captured in the model. Cost benefit approaches are of no use here, as the model is solely concerned with the destination node rather than inter-system migration.

An equation for net migration is thus posed of the form:

$$M = U_Population * NM * JAFT(U_CUF), \quad (6.8)$$

where NM is a normalisation constant and $JAFT(U_CUF)$ is a table function operation, the ‘job availability factor’, performed upon the capital utilisation function. The flow is assumed to be dependent upon the total population size, as per previous system dynamic studies capturing gravitational effects (Ghaffarzadegan et al. 2010). The table function $JAFT$ must take note that U_CUF is evaluated between 0.1 and 1 as a time smoothed ratio of available jobs to the size of the workforce, parsed through a table function, with a value of 1 corresponding to ‘full employment’, and 0.8 corresponding to 33% (Meadows et al. 1974, pp241-242). Thus a basic function is developed for $JAFT$, evaluating at 0 for $U_CUF = 1$ and 1 for $U_CUF \leq 0.8$ with a smooth transition between 0.8 and 1. ONS data for Nottingham’s net migration shows a figure varying between 0.02% and 1.58% per annum (from 2002), a value for the normalisation constant was taken of $NM = 0.02$, to give an upper bound on the net migration of 2% per annum. Figure 6.14 shows an outline of this subsystem in the AnyLogic modelling window. As can be seen, after some time (during which the capital utilisation function drops below one), the naturally declining population begins to grow due to inward migration. Qualitatively then, this migration structure represents an inward flow of young adults in response to available jobs within the urban system.

Capital

The capital sector poses an interesting problem in that in our contemporary world, local economic systems are so intertwined with the global economic system, as to be in many respects indistinguishable. The details and complexities of a localised economic system embedded in a global economic system are numerous, and beyond the scope of what remains a largely abstract model. Since, the proposed coupling is to exist between a single urban system, and what amounts to a global average system, justification may be seen in carrying on with a largely independent economic subsystem, although of course as per the population subsystem above, the labour market may now be seen as coupled with the global system. Whilst such an abstraction represents a dramatic departure from reality, it is not beyond the realms of possibility for a strict centrally planned urban economy to exist in relative isolation from a global economy.

The capital subsystem thus receives no update in the transition to an ‘open’ urban system dynamics model. Of course, in this sense the functional boundary of the urban capital subsystem remains ‘closed’ (although the labour subsystem is clearly not). This perhaps runs counter to the aims of this second modelling endeavour, however a lack of theory on how an urban economic subsystem based

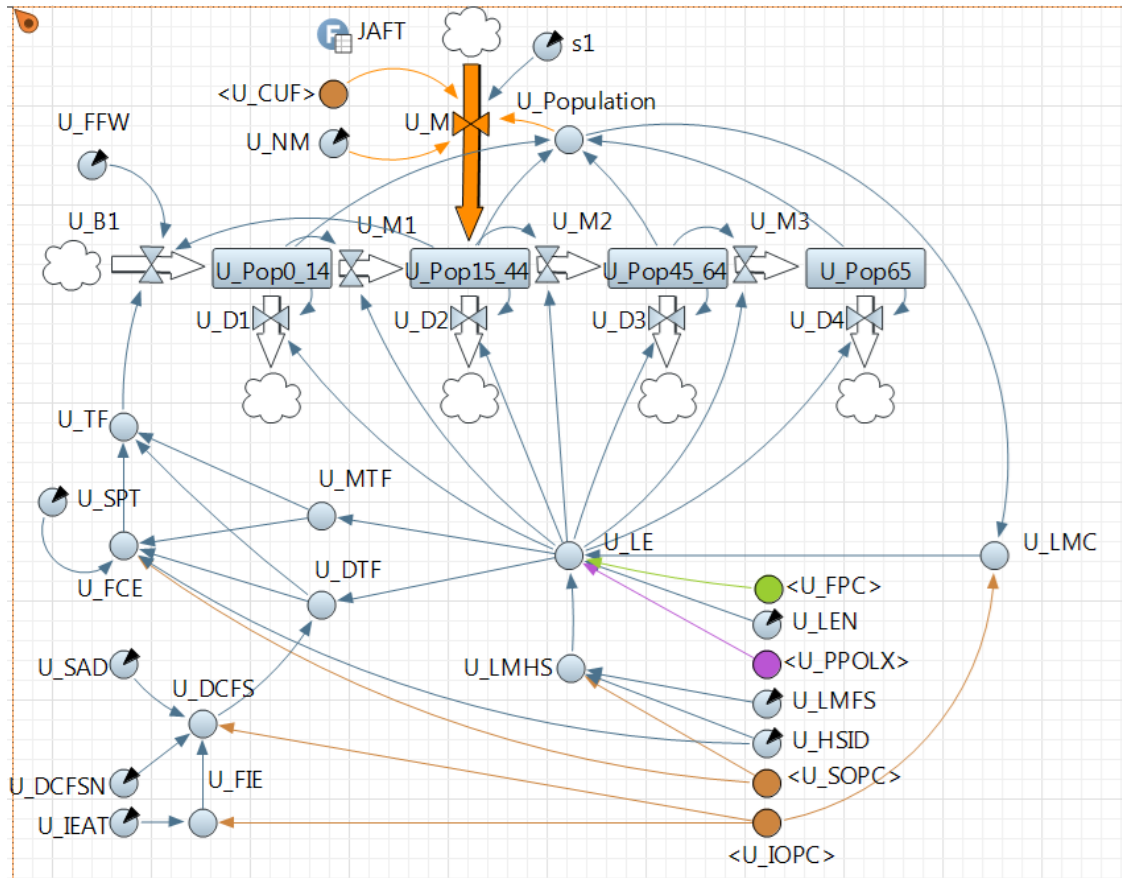


Figure 6.14: Modelling window for the updated urban population subsystem developed for Urban1.

upon capital allocation would couple to a global average economic subsystem in a manner approaching reality renders remaining ‘closed’ as the best approach. In future work, a hierarchical model might allow for the use of aggregate import and export data, or indeed a portion of this could be allocated on a per-capita basis. Further theoretical consideration is required.

Agriculture

Opening the agricultural subsystem presents an opportunity to reduce the urban system size to the 7400 hectare value which was considered at the beginning of Section 6.2.2. This would limit the ability for the system to self-sustain its food supply, providing a potential avenue for exploration. Nevertheless, the arguments of the necessity for a hinterland remain, and to allow for better comparison with the intermediate model the larger 100,000 hectare figure was retained. Since the land remains localised, the variables and structures related to this remain unchanged on considering open functional boundaries. The ability to import food to maintain food per capita however becomes a possibility.

Within World3 the total demand for food directly impacts the agricultural investment, with a higher demand raising the fraction of allocated industrial output. Thus, an inbuilt mechanism already exists for allocating capital to the purchasing of food through the total agricultural investment, TAI. In World3 this investment may be allocated during the simulation in two ways, to land development, i.e. converting potentially arable land to arable land, or it becomes ‘agricultural inputs’ for yield enhancement. The allocation works by weighting the ratio of the marginal productivity, or ‘crops per dollar’, of land development versus agricultural investment. A system open to the import of food should therefore weight the cost of importing food before determining the allocation between land development and agricultural investment.

The equations are therefore updated as follows. The total agricultural investment becomes:

$$U_TAI = U_Industrial_Output \times U_FIOAA \times (1 - U_FAIF), \quad (6.9)$$

having multiplied the fraction of industrial output allocated to agriculture, U_FIOAA by the newly introduced fraction of agricultural input for importing food U_FAIF . This in turn is defined by the equation

$$U_FAIF = U_FAIFT \left(\frac{U_MPIF}{U_MPAI + U_MPLD} \right). \quad (6.10)$$

Here, the new dynamic variable U_MPIF has been introduced as the ‘marginal productivity from importing food’, which is divided by the sum of the marginal productivities of agricultural input and land development respectively. The U_MPIF derives itself from the world average (World3) food per capita and is defined below. U_FAIFT is introduced as a table function that models the market operations in ‘choosing’ to allocate capital accordingly, it uses the same relation given by World3’s corresponding land development allocation table $FIALDT$.

Akin to the dynamic variables U_MPAI and U_MPLD , U_MPIF gives the amount of food in ‘vegetable-equivalent kilograms’ that may be obtained per dollar investment in importing food. U_FPC becomes the sum of grown food and imported food, divided by the population, $U_FPC = (U_Food + U_FI) / U_Population$. Having introduced the dynamic variable ‘food imported’ U_FI as the amount of food in vegetable equivalent kilograms imported from outside the urban boundary, with

$$U_FI = U_MPIF \times U_FIOAA \times U_FAIF \times U_Industrial_Output. \quad (6.11)$$

With all other variables defined and structures coded, U_MPIF remains to be linked to the scarcity of the food per capita in the global system. U_MPIF is inversely

proportional to the global average food cost, **GFC** in dollars per vegetable-equivalent kilogram. This in turn is inversely proportional to the global average food per capita, i.e. the lower the global average **FPC**, the higher the import food cost. The equations are therefore defined as:

$$U_MPIF = 1/GFC, \quad (6.12)$$

$$GFC = FN \times GFCT(FPC), \quad (6.13)$$

where **FN** is a normalisation constant which is multiplied by a table function of the global average food per capita. In World3 the maximum lifetime multiplier from food is obtained at 690 vegetable-equivalent kilograms per person per year, three times that of the subsistence value (Meadows et al. 1974, p282). Further, the indicated food per capita, **IFPC**, i.e. the per capita food demand as a function of industrial output per capita maximises at 1,250 vegetable-equivalent kilograms per person per year, and has a minimum of 230 for zero **IOPC** (ibid., p285). These values provide some scales for producing a function to parameterise the table function **GFCT**. This function should asymptote as the global average **FPC** tends to zero, to represent prohibitively high food prices during a food crisis. Further, it should pass through 1 at a sufficiently high values of global **FPC**, to allow for definition of the normalisation value **FN**.

Since Meadows et al's initial data from 1968 (ibid., p283), the world average calorie consumption has increased by around 550 kilocalories per person per day as of 2013 (University of Oxford 2019). Interestingly there is no mechanism in World3 for negative health impacts related to over-eating, something which was perhaps not globally pertinent in 1970. This average of 2884 kilocalories for 2013, multiplied by Meadows et al's conversion factor of 365/3500 gives a world average value of 300 vegetable-equivalent kilograms per person per year. Of course, this is an indicator of direct human consumption, and doesn't account for food waste or indirect consumption through animal products. Shepon et al. (2018) produce a series of values for 'lost calories' from the farming of various animal products, providing 'opportunity losses' from 96% for beef to 40% for eggs, i.e. 100kcal invested into producing beef or eggs will produce only 4kcal and 60kcal of consumable food respectively. Using these figures, and 2011 dietary composition figures from the UN's Food and Agriculture Organisation (FAO) (National Geographic 2014) allows for computation of the 'real' food consumption calories by dividing each animal product composition fraction by Shepon et al. (2018)'s retained calories, as shown in

Animal Product	Fraction calories in diet (FAO)	Retained calories (Shepon et al)	‘True’ calories
Eggs	0.01	0.6	47.8
Dairy	0.05	0.25	574
Poultry	0.02	0.5	114.8
Pork	0.04	0.1	1148
Beef	0.01	0.04	717.5
Other	0.04	0.5	229.6

Table 6.1: Calculation of ‘true’ calories for 2011 world average.

Animal Product	Fraction calories in diet (FAO)	Retained calories (Shepon et al)	‘True’ calories
Eggs	0.01	0.6	56.9
Dairy	0.1	0.25	1365.2
Poultry	0.03	0.5	204.8
Pork	0.07	0.1	2389.1
Beef	0.02	0.04	1706.5
Other	0.05	0.5	341.3

Table 6.2: Calculation of ‘true’ calories for 2011 United Kingdom.

table 6.1 and 6.2 for the world and UK averages respectively. Here, a figure for ‘True calories’, i.e. as an indicator of the amount of embodied vegetable-equivalent calories that go into producing the consumed amount of food product is calculated using the formula $\text{true calories} = (\text{fraction in diet} / \text{retained calories}) \times \text{total annual calorie consumption}$. These give daily average ‘true’ calorie consumptions of approximately 5200kcal for the World average, and 8500kcal for the UK, translating to 542 and 885 vegetable-equivalent kilograms per person per year respectively.

Using the headline figure of 50% imported food into the UK (DEFRA 2017)⁶, allows for the calculation of a rough estimate for a value of U_MPIF for 2011. Equation 6.10 implies that it should equal the sum of U_MPAI and U_MPLD at this time; a run of the model suggests that this sum is evaluated at a value of 7 for 2011, from equation 6.12 giving a value of $GFC = 1/7$. Using the derived global average FPC from the data above of 595, leads through equation 6.13 to a value for FN of $1/7$, with $GFCT$ evaluated at 1 for 595. From this, for want of better data, a basic inverse relationship is adopted based upon this single data point, with $GFCT(FPC)$ doubling every time FPC halves.

Figure 6.15 displays the updated agricultural subsystem. Whilst the urban system continues to have a hinterland primarily composed of urban land, it is also

⁶Unfortunately this appears to be the best figure available, as no accurate compositional data could be found.

For World3's standard run, the global average PPOLX dominates the coupled urban value, this is because the growth rate of the global economy is much greater than that of the urban system, despite the urban system operating at an above average capital output level.

Nonrenewable resources

Since the resource subsystem in the intermediate model was based upon an allocation from the World3 nonrenewable resource subsystem, it may now be coupled directly. There again remain several options for this concerning the allocation of resources. They may be distributed 'equitably' in that members of the initial population are each given an equal allocation of non-renewable resource at the start of the simulation, or in the spirit of Brundtland's 'intergenerational equity' an allocation per capita that updates over time. Of course, such equitable allocations are far from contemporary reality. Since the output of this subsystem feeds into the capital allocation through the fraction of capital allocated to obtaining resources mechanism, U_FCAOR, this should be considered in deciding how to couple the urban and world models.

Since in this 'open' model the capital system remains dependent on obtaining resources, the natural choice is to open the urban non-renewable resource system to the global resource pool, rather than use an initial allocation. Thus, the simplification of equations is permitted. There remains no need to maintain separate urban system values for the non-renewable resource fraction remaining, NRFR, fraction of capital allocated to obtaining resources, FCAOR, or the urban non-renewable resources stock. These are therefore 'switched off', and the urban industrial output updated to input the global FCAOR. The urban non-renewable resource usage rate is then adjusted to become a flow coming out of the global non-renewable resources stock. This urban rate is then subtracted from the global average rate, making explicit that the urban subsystem is a part of the global average system, rather than a separate entity, emphasising the monodirectional coupling within Urban1.

Indicators

Since coupling the urban system to the global commons and allowing for the import of food, the ecological footprint indicator must include the land used for farming that lies outside of the urban system boundary. This is defined as the 'imported food land area', IFL:

$$\text{IFL} = \text{FI}/(\text{LY} \times 0.63), \quad (6.14)$$

where FI is the food imported to the urban system, LY the global average land yield, and 0.63 is the constant employed within World3 to account for wasted food and productivity.

Additionally, an indicator to give the proportion of the total consumed food which is imported to the urban system is included. The imported food fraction, IFF is defined as,

$$\text{IFF} = \text{U_FI} / (\text{U_FI} + \text{U_Food}). \quad (6.15)$$

Finally, a new dynamic variable is introduced, the ‘equitable resource use fraction’, ERUF. This is intended to provide an indicator of how the urban system’s resource usage compares to the global average, and is defined as the ratio of the urban resource usage rate per capita to the global average resource usage rate per capita:

$$\text{ERUF} = (\text{U_NRUR} \times \text{G_Population}) / (\text{G_NRUR} \times \text{U_Population}) \quad (6.16)$$

where a prefix has been added for clarity to denote the global parameters. Testing for Urban0.5 Scenario 4 and double global resources shows this ratio starting at 6 in 1951, and reducing to just above 1 in 2051, reflecting both the growing global average resource usage rate, and a declining urban usage due to implemented technology.

Creating interactive controls

For the scenarios run with the intermediate model, each scenario was run as a separate model file, updated each time to implement the changes as detailed in a separate modelling file. For generating scenarios which use various additional adaptive loops or parameter changes this process becomes cumbersome, proving inflexible for quickly switching between various adaptations. A series of interactive controls were thus developed to allow better functionality for quickly switching between scenarios in the same modelling file.

These controls mirror those included on the World3-03 CD, allowing to switch on and off various ‘fixes’, as well as changing policy implementation years, and the initial non-renewable resources with sliders. These controls introduce sliders for the built in policy and technology introduction years in both the urban and world sectors of the model. Switches were also added for turning on and off each individual coupling mechanism.

Figure 6.16 displays the simulation initialisation window with the various options and switches available, the majority of these are time based sliders which control the implementation year of the various fixes implemented. These controls allow for the

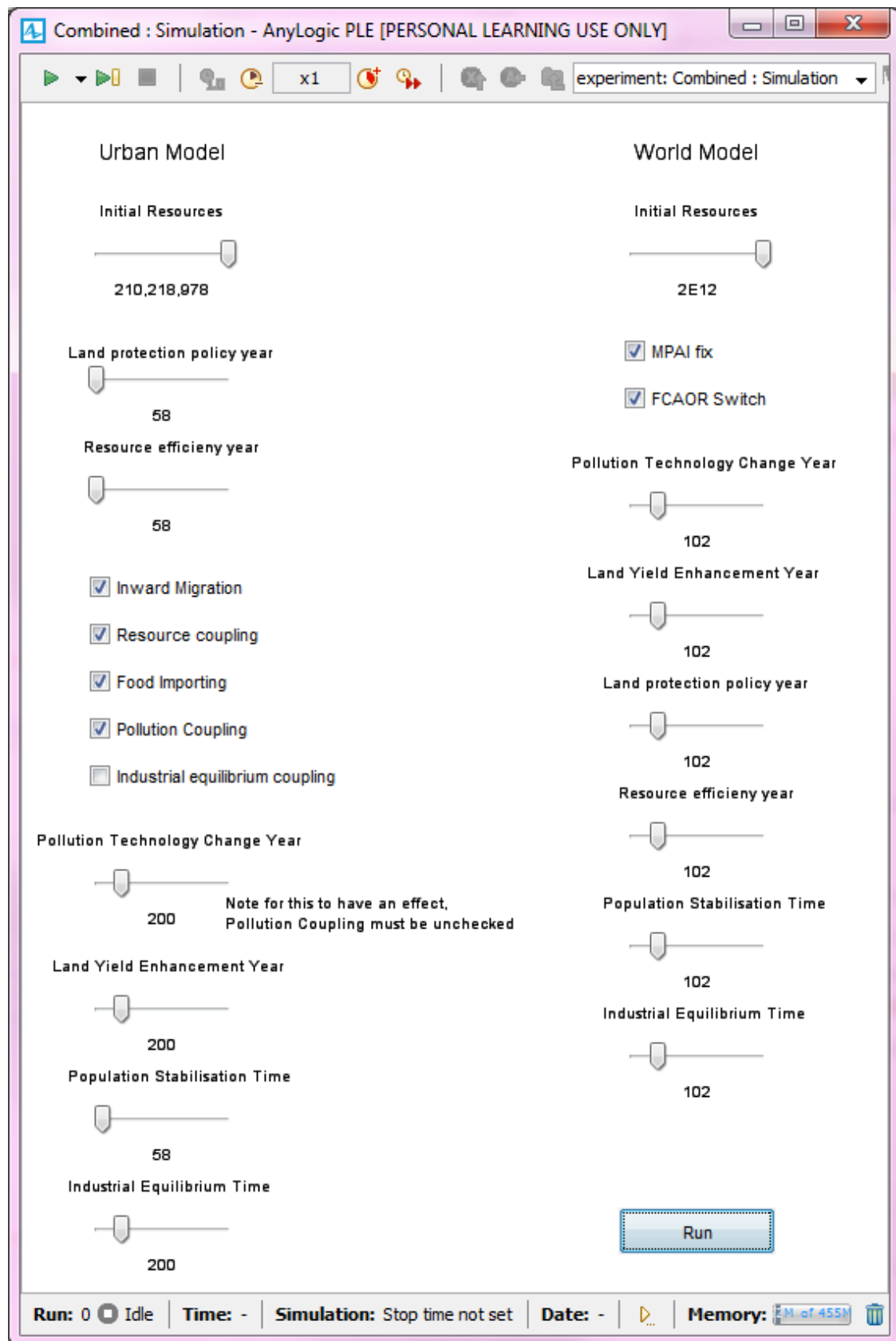


Figure 6.16: Controls for setting up modelling runs for the coupled model. The sliders control the implementation time of aspects in ‘in model time’ (i.e. model years since the model begins). The tick boxes control several ‘switches’ turning off fixes and coupling.

running of what amounts to the intermediate ‘closed’ model in parallel to World3, to the ‘fully coupled’ urban system described above. As well as the standard controls to the world model for allowing Meadows et al. (2005)’s Scenarios 1-10, a switch was also added to turn off the MPAI fix (described below) in order to fully emulate the original World3-03 model runs if necessary. Of final note is the ‘resources switch’, which controls the parameterisation of FCAOR, the fraction of capital allocated to obtaining resources. Included within World3’s Scenarios 2 onwards, this dampens the relation between FCAOR and the non-renewable resource fraction remaining, NRFR, simulating an offset in rising resource costs from extraction technologies.

6.3.2 Model validation

In Section 2.4.3, the process of validation was framed in terms of building confidence in the usefulness of the model. The first step for this was described as ‘face validation’ which necessitates an iterative process of analysing outputted scenarios and assessing how reasonable they seem. As an iterative process, this face validation is continuous, spanning from initial test runs whilst building the model through all outputs produced. Some of this has been described already relating to the specificities of each subsystem. Not all of this requires illustration here, however several issues that were resolved following an initial run of the coupled model are detailed and a brief note on comparison to real world data is made.

Face validation

One issue that the World3 model did not encounter in the published scenario runs was the potential of the global system running out of arable land. This however becomes a real possibility for the smaller urban system model, primarily as a result of land erosion. In the limit of $t \rightarrow \infty$, the equation for the land erosion rate tends to $\text{Arable_Land} / (1000 \times \text{LLMYT}(\text{LY}/600))$, where LLMYT is the table function describing the land life multiplier from yield. For large input values, the table function tends to 0.2. Thus, without any external input the Arable Land resolves to an exponential decay function, tending to zero at large times. Having been built into the original World3 model, this result suggests that a collapse due to depletion of arable land cannot be avoided under the model assumptions. This is clearly problematic, however it can be argued that Meadows et al never intended for the model to run past its initial 200 year run. It should be noted that the loss of arable land without being replaced is a problem persistent in the real world, and thus built-in collapse does not necessarily contravene the limits of possibility (Storkey

et al. 2012; Grantham Centre 2015). In-model solutions to this issue would require structural change to the model equations which go beyond the scope of this chapter.

Arable land as a finite resource then, is a reflection of reality (see e.g. Alexander et al. 2016), although techniques employing mixed land use for urban food growth such as vertical farming, hydroponics, or simply urban gardens and allotments may provide solutions to curbing this excessive demand on land. These results emphasise that soil is often over-looked as a non-renewable resource, and current agricultural modes must be adapted to reflect this and preserve arable land (Grantham Centre 2015).

Symptomatic of the flaw which does not account for the possibility of arable land being depleted, abnormalities were observed in the agricultural sector, where capital continues to be diverted to agricultural inputs after available arable land has degraded entirely. To remedy this, the urban U_MPAI was multiplied by the fraction of total land in the urban system that composes of arable land. For consistency, this was also applied to the global average $MPAI$, although has minimal qualitative effect on the outputted scenario. This required the re-calibration of FN to $1/3$.

Aside from these issues, the face validation was largely successful, and the model behaves as expected during the scenario runs where it was tested, with no abnormal behaviour or misbehaving parameters.

Comparison to UK data

One further aspect of validation outlined in Section 2.4.3 regards comparison of model outputs with real world data where available. For the synthetic urban representation developed here there is no single source of data which is appropriate for this. As noted in previous sections, the population time series for Nottingham has several anomalies that cannot be explained by the model, so it was departed from as a data source. Nevertheless, face validation revealed after some calibration, detailed already, that the modelled population growth is reasonable.

For the economic system, since it has been calibrated against UK national data, this may also be used for comparison of model output. This is shown in Figure 6.17 which displays the modelled service output per capita and industrial output per capita alongside the equivalent ONS data. As can be seen, the basic behaviour is consistent. The model, as should be expected, does not experience any fluctuations due to its simple aggregated structure ignoring a variety of other relevant variables, but the qualitative and quantitative behaviour is nevertheless similar.

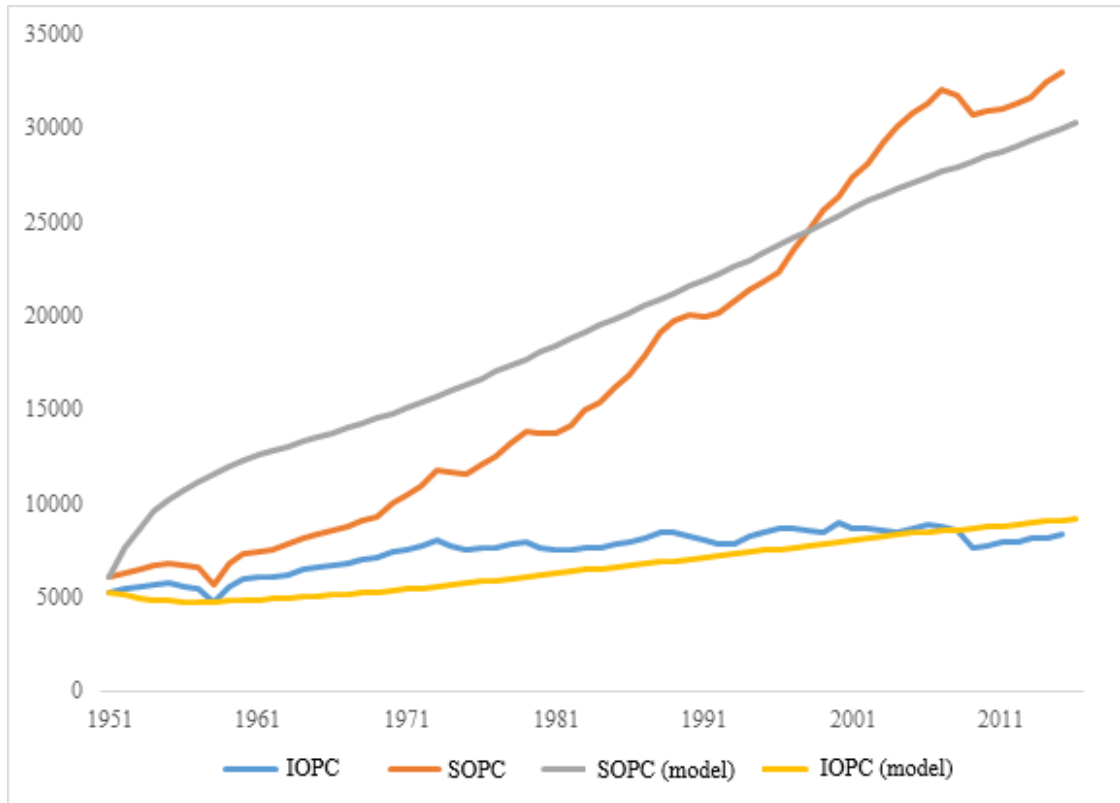


Figure 6.17: Comparison of modelled urban industrial and service output per capita with UK national ONS data for the same.

6.4 Coupled Scenarios

This section details an initial selection of coupled scenarios, following the successive adaption approach of Meadows et al. (2005), but paying particular note to the effect on the outputted system evolution from the multiscalar coupling.

A time window of 150 model years was chosen for the output scenarios of this chapter. This results from the coupling of World3 whose scenarios run from 1900 to 2100, and the intermediate Urban0.5 model, which initially ran scenarios between 1951 and 2051. This longer time period allows for the full scenario run of World3, and allow for a longer time period over which to analyse the coupling of the urban system model.

6.4.1 Scenarios 1-3

Figure 6.18 displays the output of the initial run, which uses Urban0.5's Scenario 4, Figure 6.13, coupled to World3-03's Scenario 2, i.e. an apparently stable urban system coupled to an unstable world system which collapses due to unsustainable pollution levels. The results of the equivalent uncoupled urban scenario are also

displayed on the top row of Figure 6.18 to allow for a better understanding of the effects of coupling. The initial discontinuities of both the coupled and uncoupled urban scenarios (primarily seen in the variables derived from the agricultural subsystem) are due to the nature of the delay functions in the modelling software adjusting to the urban system effectively becoming ‘switched on’ halfway through a modelling run, they should as such be ignored.

The initial column of Figure 6.18 shows the evolution of several headline parameters through the scenario run. It is clear from this that the coupling affects the qualitative evolution of the urban system. This is not a surprise if this is considered in terms of a real world urban system, and a hypothetical one with heavy restrictions on inward migration and the import of food. The abundance of unfilled jobs in the coupled urban system stimulates a steady inward migration flow, as workers relocate to within the urban system for these jobs. This causes the urban population to rise, despite the total fertility remaining below the equilibrium rate, and is buoyed even higher due to the typical young age of these incoming workers inflating the childbearing population. This growing population peaks around 2060 due to an increased mortality rate caused by a global food crisis and economic decline.

A larger urban population brings a larger demand for food to the urban system, something which is easily met through to the first few decades of the 21st century. As can be seen from the imported food fraction in the third row of Figure 6.18, initially most food is grown locally within the physical urban hinterland. This picture changes however as the surrounding arable land used to produce this food slowly erodes, and it becomes more cost effective to import food than grow it locally. By 2025 50% of food is imported, and by 2050 90% of food is imported. This is different to the picture we see in the UK in the real world, where international supply chains and markets mean very little food consumed within the urban system is grown or produced locally (Born and Purcell 2006).

Since the modelled urban system is relatively ‘rich’, indicated by its industrial output (a proxy for GDP), it is available to comfortably import food for some time. Unfortunately, due to the degradation of global land from unchecked persistent pollution, global food production peaks just before 2030 and slips into decline, this negatively impacts both the abundance and therefore affordability of food for import. Whilst the urban system manages to bear this increased cost for some time, the shift in the urban economy towards importing food at the expense of other sectors shrinking leads to economic decline. As the urban system’s food supply begins to fall, the industrial output and life expectancy follow. It is of note however, comparing panels 4 and 7 that the urban food supply falls less rapidly

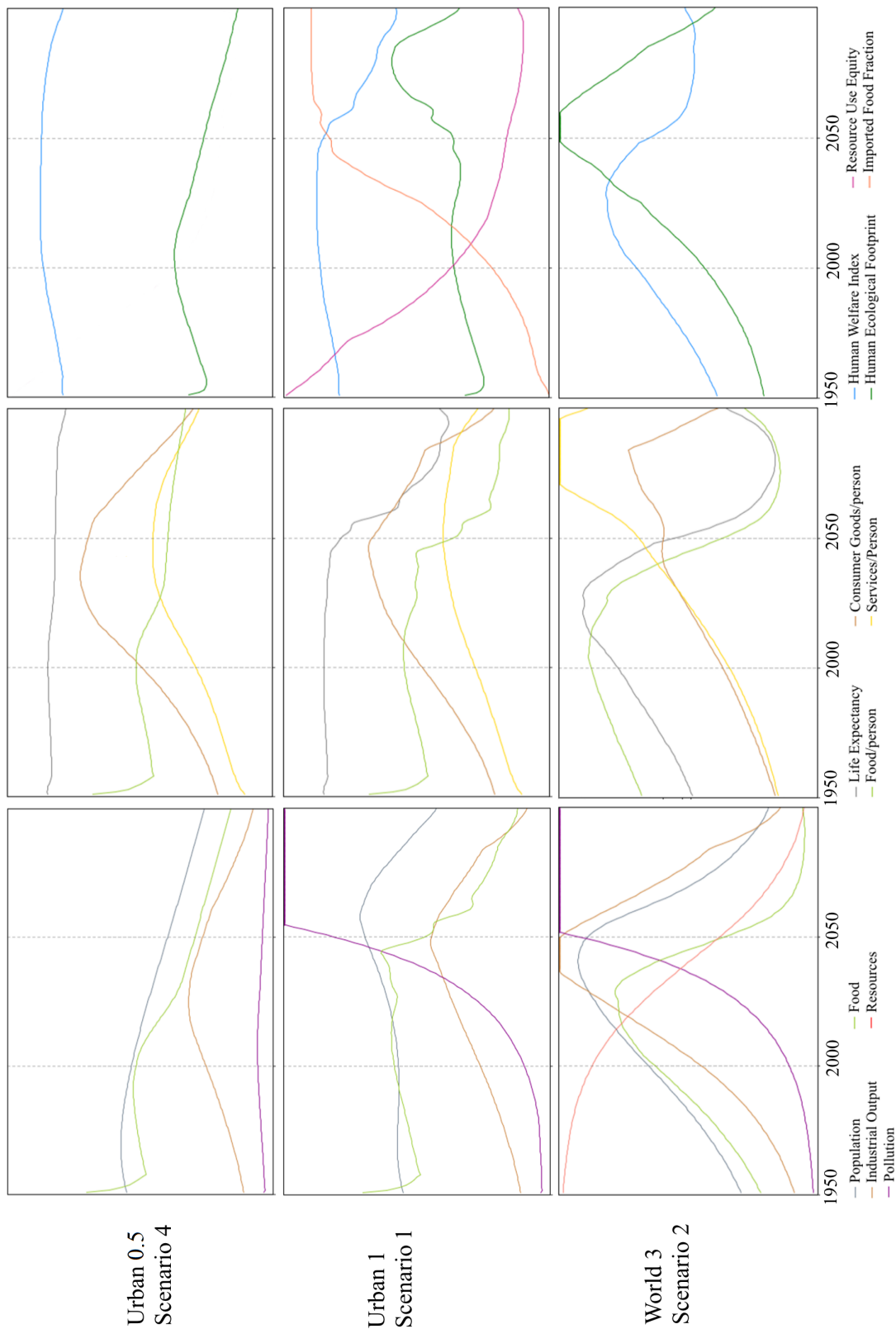


Figure 6.18: The coupled Urban1 Scenario 1, centre row, displayed alongside the outputs from the equivalent uncoupled intermediate scenario, top row, and the World3 Scenario 2 to which the coupling has been made, bottom row.

than a global one, with the higher purchasing power caused by a stronger than average economy providing a boon through food imports. Thus, for this initial scenario, whilst urban sustainability remains coupled to the sustainability of the global system, with a relatively strong economic position compared to the global average the urban system is able to delay the impacts of global decline.

Scenario 2

Scenario 2, shown in Figure 6.19, addresses some of the limiting factors that were observed in Scenario 1 relating to the global food crisis. This scenario assumes that there is action taken at the global scale to combat the negative effects of persistent pollution on food production (following the measures taken in Meadows et al. (2005)'s Scenario 3, p272). These pollution control measures, implemented in 2002 as per Meadows et al. (2005), result in a portion of industrial output being invested each year in 'pollution technologies', which reduce the amount of pollution generated per unit of output by up to four percent a year (p210). This may be understood as a global agreement which requires nations to make a fixed annual investment in research and development to create and implement these technologies.

This international agreement causes global persistent pollution levels to peak around 2050 before dropping off. This delays a global food crisis which nevertheless occurs due to the increasing costs of farming caused by intensive methods degrading land quality, as well as the impact of global economic decline. At the urban scale, the local land degradation is as marked as in the previous scenario leading to an increased reliance on imported food. The prolonged stability of global food production however allows the urban system to remain in a desirable state for a longer period. Regardless, by 2075, global food production, having recovered slightly through increased land fertility from a previous decline, peaks again and collapse follows. This cannot be avoided by the urban system which has beenv reliant on the global commons for its food supply.

Unlike the previous scenario, the resultant collapse experienced by the urban system here is remarkably sudden, with urban industrial output moving from steady growth to terminal decline in 2075, shortly followed by the same pattern with available food two years later. This happens because it coincides with a global tipping point related to dwindling resources. Due to diminishing global resource stock, the fraction of global capital used for extracting resources is no longer sufficient and begins to rise. The existence of such tipping points does not mark such a departure to what may be conceived in reality (see e.g. Maas et al. 2017), and may be understood for example as the extraction of a major resource suddenly

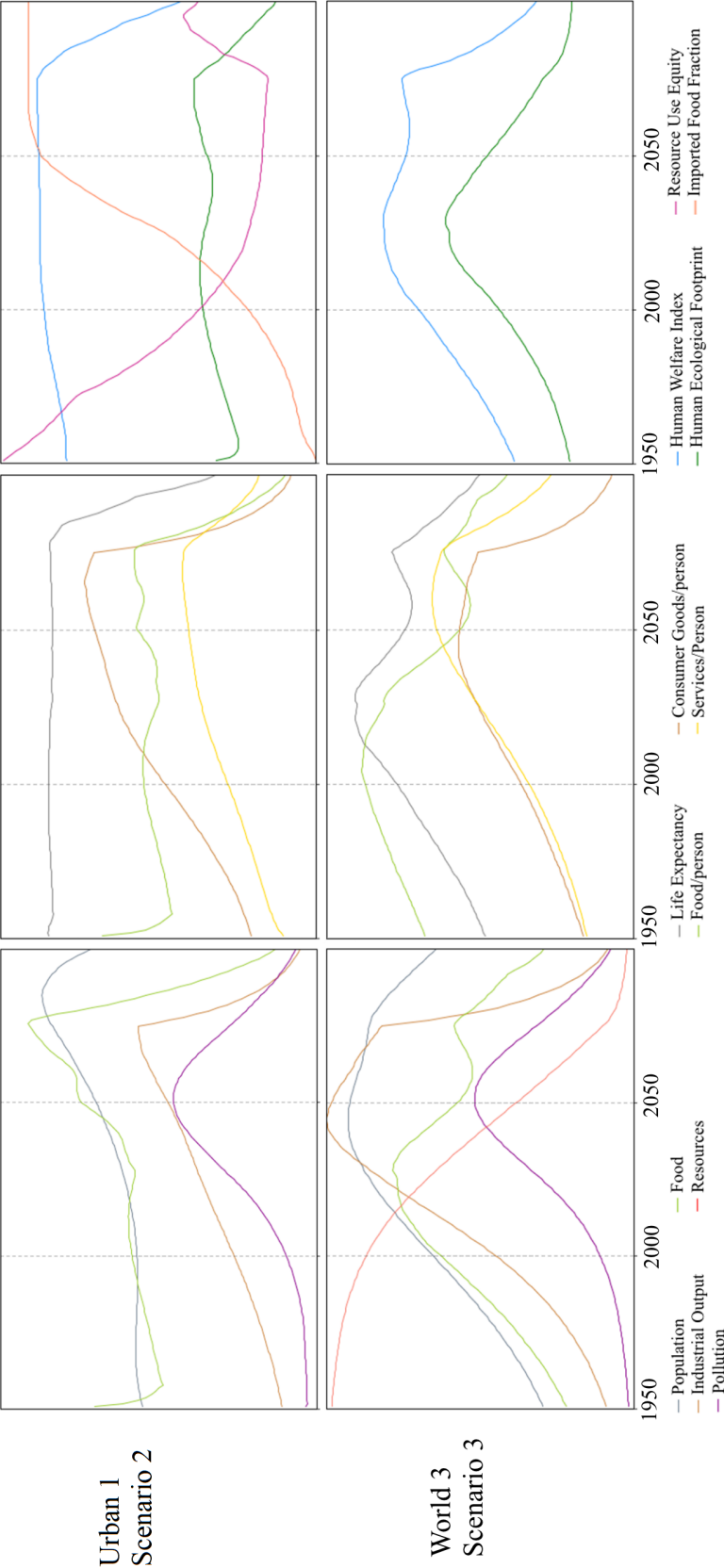


Figure 6.19: The coupled Urban1 Scenario 2, top row, displayed above the World3 Scenario 3 with which the coupling has been made.

becoming no longer economically viable, when market mechanisms have failed to provide a suitable alternative. Unsurprisingly this has major impacts on the global economy, which is witnessed in panel 4 of Figure 6.19, where global industrial output experiences a sudden rapid decline.

As can be seen in panel 1 of Figure 6.19, the relatively wealthy economic position of the urban system does nothing to protect it from this global economic crisis. The urban system is as unprepared for this resource tipping point as the global system and its economic collapse occurs in parallel. Due to the reliance on imported food the collapse in urban food available is even more rapid than the global decline in food per capita. This is in part because it has further to fall, however the lack of urban arable land contributes to this since the urban system has no choice but to import this food which, coupled with its simultaneous economic collapse, it struggles to afford.

Comparing the marginal productivity (food per dollar) of importing food into the urban system at this time, to the global marginal productivity of agricultural investment, a ratio of 1:12 is observed. Therefore, whilst the ability to import food clearly benefits the urban system in some circumstances, a reliance on it, at the expense of growing food within the system, becomes a crucial limiting factor to the urban system's survival under other circumstances. This coheres with theories of urban resilience, where resilience is understood as the system's ability to withstand sudden shocks (Leichenko 2011).

Scenario 3

In the absence of any additional options within the current modelling toolkit (other than increasing the size of the urban system) to remedy the decline in urban arable land, measures were applied in Scenario 3 to the global system instead. Following on from the previous scenarios, World3-03's relatively stable Scenario 6 is used for the global system. This implements land yield enhancement and resource efficiency technologies, and land erosion protection. These measures represent global consensus taken to divert a portion of annual industrial output toward research and development of technologies which increase land yield and resource efficiency respectively, with additional measures taken to combat land erosion. The output of this scenario is displayed in Figure 6.20.

Despite Meadows et al. 2005 describing this global scenario as a failure (pp218-220), it actually performs relatively well within the scenario time window. The authors argue that the cost of the universally implemented technology here leads to an adverse impact on the standard of living and steadily declining economic output in the latter part of the simulation run. This may be observed in Figure

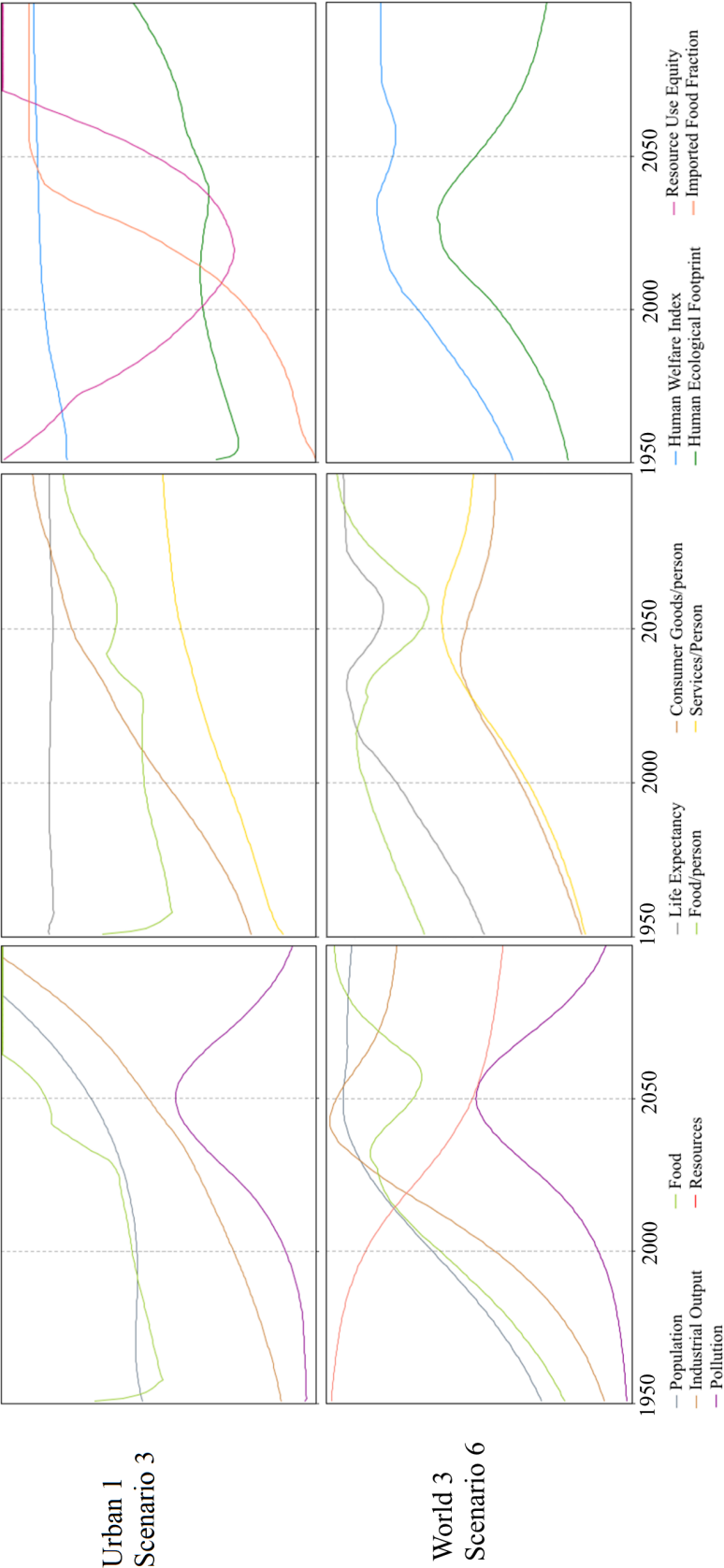


Figure 6.20: The coupled Urban 2 scenario 3, top row, displayed above the World 3 scenario 6 with which the coupling has been made.

6.20, however it arguably represents an overly pessimistic reading of the scenario, as the decline in the services and industrial sectors appears to be levelling off.

Regardless of the global picture, at the urban level this scenario represents the best success so far relative to previous runs. By 2100 when the scenario ends, population, industrial output, service output and food per capita continue to grow, despite the urban system being solely reliant on importing food from the global commons. A booming urban economy leads to sustained population growth which whilst placing strain on the environment as revealed by the growth in footprint, the urban quality of life remains high.

The shape of the ‘resource equity function’s evolution in panel 3 reveals that the early adoption of urban resource consumption measures relative to the global fails to keep the equitable fraction used low after the global system implements these same changes. This means that whilst the urban system has a strong economy here it is at the expense of a resource consumption per capita greater than the global average.

Of particular interest in this scenario is how the urban system continues unaffected by the global dip in human welfare observed in the mid 21st century. This is achieved through having a relatively wealthy economy which can import food and absorb a global rise in food prices with minimal negative effect. This provides a contrasting example to what was observed regarding the resilience of the urban system in relying upon importing food. With a strong economy the urban system can ‘buy its way out of’ a period of global food scarcity. Of course, in a more advanced hierarchical model with bi-directional coupling reflecting the set of urban systems, this effect may be less pronounced with competition arising among other wealthy urban systems.

6.4.2 Examining coupling mechanisms

It is possible to run a multitude of scenarios with additional combinations of world and urban scenarios whilst providing a commentary on any interesting features, this section however explores additional scenarios under extremes. The aim here is to investigate, under this framework, to what extent the urban system may survive a global collapse. This is achieved through expanding the current policy toolbox to switching on and off various aspects of the coupling between the urban and global systems. Whilst arguably limited in terms of a reflection of reality, it produces a series of tools to use to further probe, Question 1a regarding the relation between global and urban sustainability.

Global collapse, urban sustainability?

Since the survival of the urban system here is so dependent on the amount of arable land available to it, there is little within the current toolbox to overcome this. Several scenarios were explored at this point which attempt to overcome this limiting factor, but with little success. The conclusion here is that the urban system, under this framework of non-renewable arable land, can delay but not escape the effects of a global food crisis.

World3-03's Scenario 5 represents the only 'collapse' scenario where global food per capita remains relatively stable following the collapse in industrial output due to dwindling resources. This presents a test ground under which coupling may be more closely examined. Despite the somewhat extreme nature of some of these tests in terms of reflecting reality, the results provide an important method for analysing the qualitative relation between the sustainability and dependence of the two coupled systems. A slightly extended time window is used for closer examination of this coupling, whilst acknowledging the limitations of projecting so far into the future. The evolution of the selected global scenario is shown in the top panel of Figure 6.21. Caused by a failure to adapt to declining non-renewable resources, the global economic system experiences a sudden collapse towards the end of the 21st century. This is accompanied by a collapse of healthcare systems globally, forcing life expectancy down to around 32 years causing population decline.

The lower panels of Figure 6.21 show several urban system scenarios in which different combinations of measures available have been taken to dampen the effects of global decline within the urban system. All involve the land protection and resource efficiency measures implemented in previous scenarios, as well as the addition of land yield enhancement and pollution technologies implemented at the same early time in the system's run (year 58). The second panel presents the urban system with all coupling parameters turned on. As the curves show, this urban system experiences total collapse. This mode of urban collapse strongly resembles that of Scenario 2 earlier in this chapter, outlined in Figure 6.19. Again, the urban system fails to adapt to a sudden increase in resource costs, leading to sudden collapse across all sectors of the urban economy and an inability to grow or import food. Here the urban system becomes quickly unviable, and the population either leaves or perishes. Again, similarly to Scenario 2, the urban decline is quicker and more severe than that experienced globally due to the inability of the urban system to produce its own food.

The third panel shows the same urban system, but here the resource coupling is negated. This means that the urban system is initially allocated its own portion of

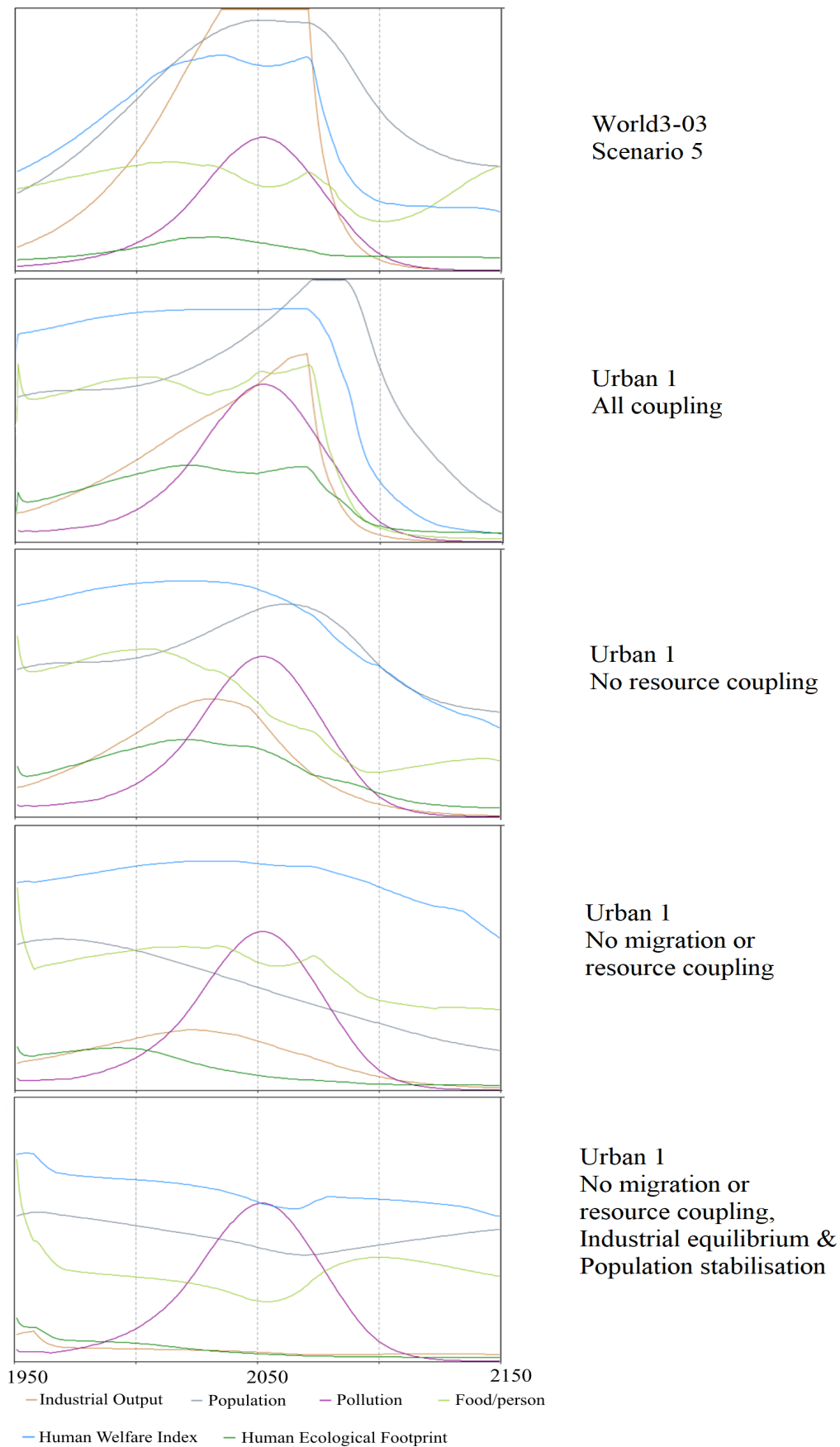


Figure 6.21: Scenarios exploring the coupling of the urban to a global system which maintains a supply of food post collapse. Panels 2-5 document several urban systems where available tools supplied by the limited modelling framework are employed in an attempt to circumvent the urban system's collapse.

renewable resources and consequently is not reliant on the global commons for its resource demands. In this respect it may be thought of as partly having achieved the goal of a circular urban economy. Urban policy makers implement measures to preserve this circularity by actively investing an annual portion of their budget into the research and development of resource efficient technology. Under this regime a more limited pool of resources means that the urban economy is unable to grow to the extent it would otherwise be able to. This means it does not become wealthy enough to buy its way out of the global decline in food per capita and consequently experiences as measured decline. Thus, by managing its own resources, the urban system, whilst not escaping a collapse in industry achieves a more managed decline. Nevertheless, by the end of the scenario run it maintains a similar position to the global system as an agrarian economy with a low level of human welfare.

In panel 4, as well as resource rationing, the population growth is mediated through a restriction of inward migration into the urban system. Whilst this leads to an even more measured decline in food availability and standard of living within the urban system, it nevertheless results in urban decline, with the population slowly leaving a relatively poorer urban system. The early implementation of industrial equilibrium and population stabilisation measures to the urban system does little to improve the system as shown in panel 5. These measures equate to implementation of a two child rule and economic measures designed to stabilise industrial output prior to a collapse. These measures in fact have a negative effect, with the human welfare index within the urban system lower than global average. This is due to the forcing of equilibrium before the urban economy has had time to grow sufficiently.

What these scenarios show is that despite all available (from this modelling paradigm perspective) measures that may be taken by urban policy makers, the trajectory of the urban system is still tightly dependent on the sustainability of the wider global system. Furthermore, it is shown that with a finite resource pool and amount of available land, the system has an inherent tendency towards collapse. The urban system has more degrees of freedom to dampen this collapse (at the expense of the global system), but within a constrained global system, preventing decline without a larger amount of land or share of non-renewable resources becomes impossible.

Several further observations that may be made from this exploration regard the necessity of some level of economic growth, as demonstrated in panel 5. This coheres to received wisdom in the early development literature considered in Chapter 3 (e.g. Barbier 1987) that development is necessary in some locales to raise people out of poverty. Further, regarding the ‘resilience’ of the urban system, it is clear that without the option to produce its own food the system is more susceptible to collapse, regardless of how wealthy it is.

Urban behaviour in a sustainable world

Having investigated attempts to withstand global collapse through urban policy within this framework, now the behaviour of a system which takes no measures to curb ‘unsustainable’ behaviour is investigated within a ‘sustainable’ global system. Scenario 10 from Meadows et al. 2005 was therefore taken as the base global scenario, this represents a ‘stable world’ where all available measures within the model are implemented ‘early’ 82 years into the modelling run, this is displayed in the top panel of Figure 6.22. Note the second panel has had the pollution, population, industrial output and ecological footprint curves dampened to fit on screen, and the heights of these are therefore not comparable with the panels below. Here it can be seen that the global population stabilises sometime in the 21st century with a high standard of living, a strong stabilised economy, and low levels of persistent pollution.

The second panel in Figure 6.22 displays a fully coupled urban system which implements no measures to curb its activities, despite global measures being in place. As a consequence, the urban system here witnesses exponential economic and population growth. This is coupled with a high standard of living and an abundance of available food, but comes at the expense of rising pollution and ecological footprint. By 2150 the urban system has a population of around 2 million, and an ecological footprint of 40. This scenario represents a case in which a bi-directional coupling could be of interest, since with its excessive levels of growth, this urban system no longer represents a negligible population bubble globally. This presents an interesting avenue of further investigation within an adapted framework, as to what extent subsystems can offset the stabilisation of the global system.

The subsequent three panels show the same urban system each with a different coupling relation negated. These show that each of these coupling effects are key in preventing collapse. Without migration, the urban system slowly stagnates as the birth rate remains lower than the maintenance level, thus despite ample food and a high level of human welfare the urban system fails. This is something that has been witnessed in various contexts in the real world, particularly with small rural communities which have been observed to decline and disappear without the creation of jobs to boost population through inward migration (Li et al. 2019).

The fourth panel switches off resource coupling, with the urban system attempting to maintain its own stock of resources. With no measures taken to limit the use or invest in resource efficiency technologies, this supply quickly dwindles and the urban system experiences economic decline and depopulation in the latter half of the 21st century. The final panel shows the urban system without the ability to import food. With arable land being quickly depleted following no

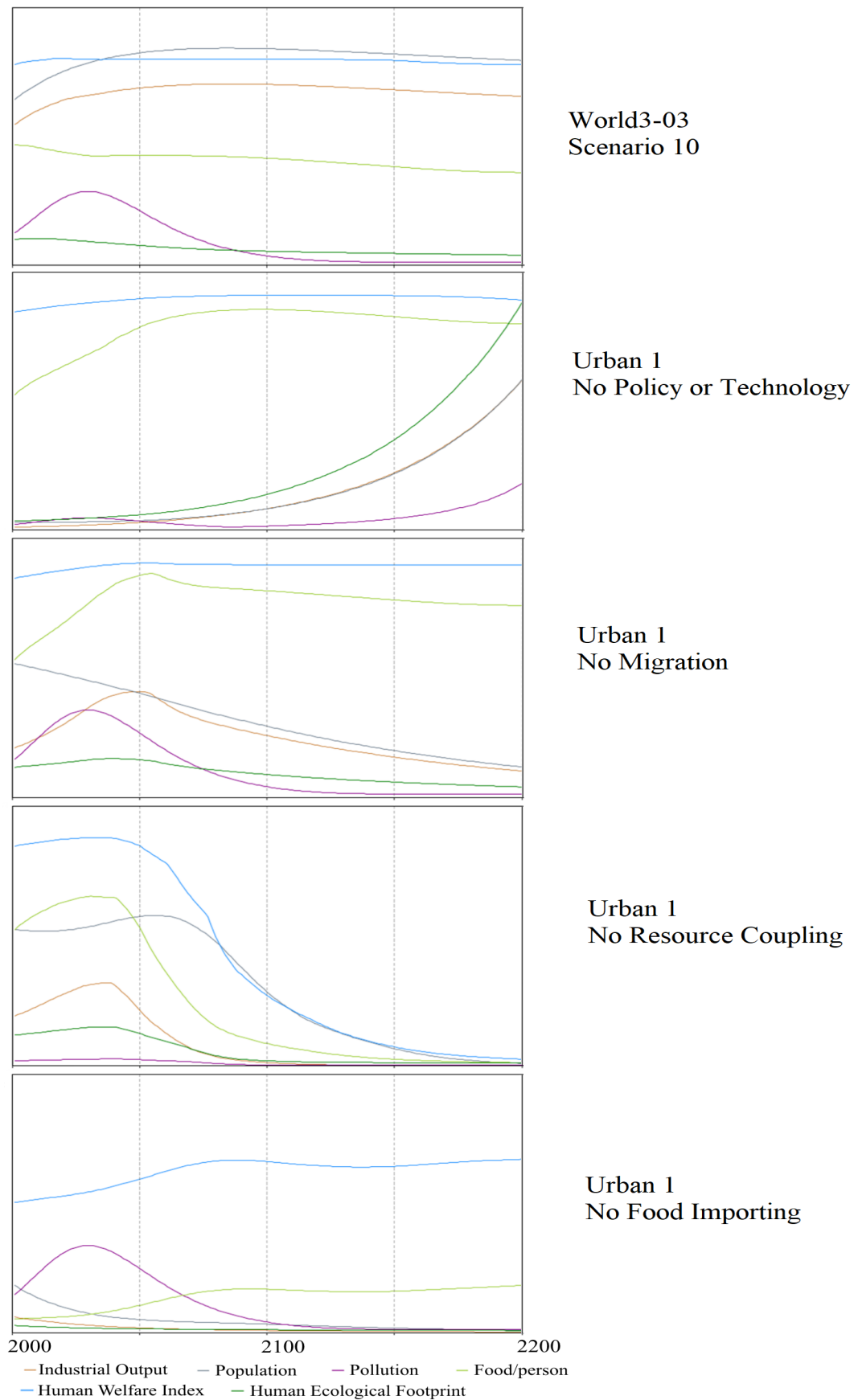


Figure 6.22: Investigating the effect of coupling various urban scenarios to World3-03's early stability Scenario 10. The first panel shows the stability of the global system, with lower panels illustrating the behaviour of a 'poorly behaving' urban system which implements no policy or technological fixes to make its behaviour more sustainable.

action to improve urban agricultural practices, the system is in terminal decline at the start of the 21st century.

These scenarios demonstrate how reliant the urban system is upon its connection to the global commons, through flows of resources, labour, and food. Whilst the model seems to suggest that an urban system can persist in a sustainable world despite engaging in unsustainable practices, the mono-directional coupling present in the current iteration of this model prevents more detailed exploration of this.

6.5 An Appraisal of System Dynamics

In coupling Meadows et al's World3 system model, with a scaled representation of the urban system, several implications of the nature of this coupling have been encountered. By exploring coupling across the urban system's functional boundaries to feedback from the global system, the interaction between global and urban pollution, food, population flows, and resource consumption have been explored. Whilst this initial coupling is only exploratory and requires further grounding in theory, it provides a sandbox environment for exploring the effects that basic coupling has on the system's evolution. A subsequent study would develop stronger theoretical grounding for these initial links, and more fully explore how the economic system can be modelled across hierarchical scale. Such an approach would mark a departure from the constraints of a framework largely confined to the pre-grounded theory of World3.

This section then provides a frank overview of how the approach taken in this chapter has helped in developing an understanding of urban sustainability, and the promise that system dynamics and world modelling might have for operationalising it.

6.5.1 Understanding

The modelling of the urban system in this chapter has presented a theoretical framework for exploring and developing a better understanding of 'urban sustainability' within this conceptual frame. Within this, urban sustainability is not measured but shown through the means of visual scenarios displaying the potential evolution of the urban system into the future under prescribed conditions. This approach stands in contrast to many of the sustainability measurement frameworks discussed in Chapter 1 in terms of indicators, and the failed entropy approach of Chapter 5.

In many respects the scenario visualisations are less arbitrary, providing a built in descriptor of the system of interest, however this is due to them displaying

indicators of a tightly defined proscribed system rather than a real one. Further, being qualitative and open to interpretation this approach allows for a more dynamic future looking perception of sustainability. Whilst the time horizon has been chosen somewhat arbitrarily, there is flexibility in its choice, and arbitrary time goals are something which those dealing with sustainability assessment are used to. Whilst the prototype model and scenario visualisations presented in this chapter capture a top-down expert-led picture of sustainability, the approach lends itself to stakeholder engagement, and model and scenario co-design can lead to a third way between top-down and bottom-up (Turcu 2013).

6.5.2 Operationalising

In terms of Dao et al. (2017)'s definition of operationalisation presented in Section 1.3, the approach outlined here has fallen short of moving to the empirical level. Nevertheless, it represents a first step on the way. Adapting the World3 model for the urban context has produced a wealth of interesting results, and there remain further avenues yet unexplored. Due to the rigidity of the underlying World3 model, and the relatively few additions to it that were made in this chapter, the development of different future scenarios was found to be limited, for example measures to mix land use, and further halt the erosion of arable land. Such measures could easily be implemented as an add on to the current framework with consultation of the relevant literature, stakeholders, and relevant 'experts' to provide better underlying theory.

Clearly numerous avenues exist for developing more advanced models using Urban1 as a starting point, yet how and why would such models be operationalised? A reminder again is supplied that the outputted scenarios are not a forecast, so their ability to project accurate predictions of what a future may look like based upon proposed policy measures are limited. This is not to say that the outputted scenarios are meaningless though, and they could act to supplement other methods of forecasting whilst highlighting potential feedbacks and behaviour that would not otherwise be anticipated. Assunção et al. (2020) argues that system dynamic models can help stakeholders to better understand urban sustainability by indentifying main influencing phenomena (p13). Like World3, the Urban1 model is well purposed here as both a 'thought experiment', and a learning tool, encouraging holistic decision making and fostering a greater sense of futurity.

6.5.3 Limitations

The framework developed in this chapter, whilst in its infancy, provides a starting point for a realistic urban system dynamics model. Successive adaptations could employ bi-directional coupling and additional policy/technological measures, as well as considering additional hierarchical scales. Thus, whilst the functionality of the current model is limited it represents an opportunity for future exploration.

Data constraints

The largest stumbling block to creating a fully operational urban system dynamics model of this kind surrounds data. This issue has been sidestepped to an extent here by imagining a synthetic urban system based upon scaled national UK data, rather than the initially proposed approach of using Nottingham data. Nevertheless, this must be addressed if this technique is to be employed for operationalising sustainability at the urban scale. The absence of fine grain data is problematic, and since time series data is ideal, the solution is not simply a matter of initiating the collecting of such data. This represents not only a problem for calibration, but also in developing and validating underlying theory for the coupling in a more sophisticated model.

A solution to this issue may perhaps be found by employing statistical methods to develop more ‘realistic’ synthetic datasets when specific urban scale data is missing or incomplete (Honaker and King 2010). Detailed exploration of historical documents may also be required in the cases where underlying theory is required to explain inconsistencies in existing datasets.

‘Urbanness’

One further criticism that may be levelled is over the ‘urbanness’ of the Urban1 model. In taking the approach that an urban system may be captured by an adequately scaled and open global model, it fails to capture many urban specific phenomena such as transport or the built environment. This leads towards other avenues for adaptation of the current Urban1 model which could consider including zoning, or agent based methods (Duran-Encalada and Paucar-Caceres 2009; Irwin et al. 2009). Such techniques would enable scenarios to better reflect spatial aspects of the urban system, which could e.g. better reflect internal inequalities through the use of a synthetic population (Robinson 2019). Other considerations could include further coupled systems, introducing multiple urban systems with different urban

contexts and comparing trajectories. This would overcome some of the limitations of over-generalisation the current approach has employed.

A further benefit of introducing more ‘urbanness’ to the model would also help shift the model further towards bridging urban science and urban studies as discussed in Chapter 4. Whilst the presentation of scenarios in Section 6.4 has attempted to engage with the urban reality, the inclusion of urban phenomena would make this an easier process. Nabavi et al. (2017) argue that system dynamics represents an ideal approach for bridging ‘hard’ and ‘soft’ sciences, and therefore presenting the model and its outputs in a form that is accessible to both urban science and urban studies scholars represents a first step in realising this.

Onwards

This chapter has delivered an early theoretical framework for analysing ‘urban sustainability’. It has presented a novel way of understanding and operationalising ‘urban sustainability’ encouraging holistic future-looking thinking. It is therefore the task of the final chapter to draw together the variegated threads presented in these first six chapters to provide and explicitly confront the research questions outlined in Section 1.4.1.

*I have yet to see any problem, however complicated,
which, when looked at in the right way, did not
become still more complicated*

— Poul Anderson, *Call Me Joe*

7

Discussion

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The preceding chapters have, through various methods fostered a deeper understanding of the concept of urban sustainability and provided thoughts as to how it might best be operationalised. Through this, recurrent themes have emerged surrounding boundaries, pluralism, and theoretical framing. This final chapter reviews and synthesises the findings of the previous chapters as a whole in light of the research questions presented in Section 1.4.1.

In doing so the research questions surrounding understanding are addressed in Sections 7.1 and 7.2 respectively. Section 7.3 outlines the barriers regarding data, stakeholder engagement, and depoliticisation which were encountered throughout

this work, discussing ways in which they might be addressed. Finally, Section 7.4 provides some final reflections on the outcomes of this thesis.

7.1 Towards a Better Understanding of Urban Sustainability

This first section reviews the first research question:

1. *How can urban sustainability be understood? ('Define' → 'Understand')*
 - (a) *In a globalised world where the notion of the urban as a singular physical location is contested, how does 'urban sustainability' differ from 'sustainability' proper, normatively conceived as a global project?*
 - (b) *What part should consensus building or pluralism play to confront the fractured literature relating to urban sustainability?*

This provides an arranging structure for the presentation of the following sections, which address each part individually and how they have been confronted in this work.

7.1.1 Urban sustainability in a global world

Section 1.2.3, in articulating various understandings of urban sustainability presented in its working definition, following authors such as Hanson (1989) and Mitlin and Satterthwaite (1996), an understanding of urban sustainability as a contextual reapplication of a broader, global notion of sustainability. Here it was noted that some authors take the urban as a given, without examining the contestations surrounding its definition, as well as the additional phenomena it introduces. Other authors were seen to conceptualise urban sustainability as the desire to sustain the city itself, such as Rees (1996). This understanding is commonly presented in relation to boundary considerations, and the reliance of the urban area on an external hinterland for its continued functioning. In this respect, the 'sustainable city' is regarded as an oxymoron or unrealistic ambition by authors such as Owens (1992) and Blassingame (1998), who take a self-sufficiency interpretation (Berger 2014).

The urban context

Chapter 4 presented a review of how cities and the urban have been conceptualised and understood across ‘urban studies’ and ‘urban science’. This confronted the nature of what is considered urban and what is not in a globalised world. Through exploration of the literature on the urban-rural dichotomy, it was shown that no clear line exists in distinguishing what may be considered urban (Dewey 2002). The conflation of rural with agriculture was shown to be an oversimplification, ignoring a trend towards large-scale farming, as well as a rise in urban agriculture, and thus, it was argued that only the remotest areas fall outside of the influence of the urban. Such a testament resonates with the more postmodern literature putting forward a notion of ‘planetary urbanisation’ which places the urban as a multiscalar global process rather than a discrete physical entity (Brenner and Schmid 2015). In particular, this work is positioned as critiquing the restrictive language of ‘the city’ as an object, and holds merit in this deconstruction for emphasising the lack of correspondence to neatly bounded social units.

Nevertheless, it was acknowledged that clearly bounded ‘cities’ often do exist in the policy sphere, the very place at which much change may be acted (Shaw 2015). Thus, operational theories must confront this reality. Institutional definitions of what may be considered urban in different national contexts were shown to vary vastly, although often based upon a collection of administrative, economic, and population size based criteria (UN 2014). The UK context of how ‘city’ status is conferred was presented, and shown to be largely arbitrary (Beckett 2005).

The ‘urban science’ literature covered was less introspective regarding a definition of the urban, instead exploring ways in which its functioning may be conceptualised and understood. Here the ‘functional boundary’ is emphasised for delimiting the urban which may be defined for a variety of phenomena and is often statistical in definition, employing density cut-offs (Cottineau et al. 2017). Here too, the notion of the ‘urban system’ emerged as a loose conceptualisation of the urban in terms of its functioning, bridging physical and biological interpretations as well as considerations within urban studies (Midgley 2011).

Bounding the urban

Whilst the globalised nature of the urban and a difficulty in delimiting boundaries as emphasised in the critical urban studies literature was endorsed in Chapter 4, this proved more difficult in translating into practice in Chapters 5 and 6. In particular an operational framework requires boundaries, both geographical and

functional, to outline its scope of application. This presents problems for engaging with literature which contests such boundaries. For Chapter 5's thermodynamic case (if it were to have proved worthy of further study) clear physical boundaries are required. System dynamics however appears to offer a more flexible approach. Whilst the definition of functional boundaries is required for model definition, the modelling framework allows for coupling relations and the initial urban size to be easily adjusted. This therefore offers potential to explore more postmodern concepts such as planetary urbanisation by further interrogating these coupling relations, and interaction across hierarchical scales.

The nature of the urban is therefore left relatively open within the system dynamics modelling approach taken in Chapter 6. Whilst the limitations of conceptualising the urban as a smaller sized, open world system, differing little in functional terms, was noted in Section 2.4.2, future adaptation is not tied to this. Such flexibility allows the system dynamics approach to be recast in relation to differing interpretations and conceptualisations of the urban. Different boundary choices may be implemented, and adaptations incorporating phenomena of interest to the researcher may be built in. Here the Urban1 model is not necessarily pushed as an integral first building block that requires adaptation, but it serves as an example for similar approaches that may construct alternative images of the urban and examine their evolution.

Learning from models

The reliance of the urban on a hinterland was supported by early simulation runs of Chapter 6's intermediate uncoupled model. Here a tightly bounded, population dense, urban area was unable, due to insufficient arable land, to feed its population and quickly collapsed. This argument relies on often arbitrary, pre-defined administrative boundaries (see the discussion of Nottingham City's tightly defined boundaries in Section 4.1.2), and was dismissed within the intermediate verification process, expanding these geographical bounds to create a hinterland with sufficient arable land for supporting the population.

This example highlights the fundamental conflict surrounding boundaries that sits at the heart of conceptualisation of urban sustainability. Whilst these issues emerged throughout Chapters 1, 4, and 5, Chapter 6 demonstrates explicitly that the boundaries chosen can be crucial for judging whether the urban system is sustainable. In coupling the urban model to a global model, Section 6.3 exploded the physical boundaries of the Urban1 model by expanding the urban system's functional boundaries, allowing it to import food and resources. This represents a moving from

Von Thünen's local hinterland model (Fujita and Krugman 1995) to a globalised hinterland more closely aligned with Sassen (1991) and Brenner and Schmid (2015)'s conceptualisations. This emphasises that a hinterland conceived as a physical area bordering the administrative boundary is an inadequate reflection of reality.

Thus, the positioning taken by some authors that 'urban sustainability' is an oxymoron, equivalent to self-sufficiency of the urban system, cannot be endorsed here, as it represents a problematic choice of urban boundaries. Certainly, it would be difficult, if not impossible, for an urban system to sustain itself whilst closed to global interaction outside of restrictive administrative boundaries, yet why would it wish to? With the freedom to define an understanding of urban sustainability, it seems illogical to pick a definition which is impossible to achieve. On the other hand, completely ignoring boundaries leads to issues with 'exporting' unsustainable behaviour to the wider global system, as discussed in Section 1.2.2, and demonstrated within the scenario shown in Chapter 6's Figure 6.22. Therefore a balance must be struck between impossibly strict boundaries, and excessively lax ones. It is here that a well-defined theoretical framework becomes useful. Since this thesis argues that there is no singular understanding or framework that is best, such a position remains open to interpretation. Nevertheless, several guidelines should be followed to ensure robust operationalisation, as discussed in Section 7.2.

Selecting boundaries

The urban footprint measure developed by Rees and Wackernagel (1997), and implemented within Chapter 6 provides an example for the difficulties surrounding boundary selection. Defined as the estimated amount of land relied upon by the urban system to sustain itself (and counteract pollution emissions), as a ratio to the actual size of the system, this footprint varied between 1 and around 80 for the scenarios produced in Chapter 6. What does this mean? The World3-03 model uses the global footprint as a proxy for environmental impact (Meadows et al. 2005, p289), and it has intuitive meaning at a planetary scale. For the urban system however such a definition is tied to the, often arbitrary, choice of physical boundaries. Rees and Wackernagel (1997) present several calculations of large urban areas including London and Vancouver giving overshoot factors of 120 and 178 respectively (p545). Vancouver is then compared to its larger basin region (an overshoot factor of 13.8), and it should be noted that the current estimation for the global figure is 1.7 (Lin et al. 2018). Whilst this reveals that densely populated areas have a higher impact on the environment, the quantities themselves are largely redundant. Indeed more recent work by the global footprint network tends

to quote figures per capita rather than a ratio to the bounded urban area size (Global Footprint Network 2019). This represents a move away from measures that explicitly consider the system boundaries.

Nevertheless, to distinguish urban sustainability from a global notion, boundaries must be picked. An ‘optimal’ selection is context specific, and depends on the purposes of the framework. Often administrative boundaries will be selected since they dictate the bounds of local government influence (Shaw 2015). Ideally however, the choice of physical boundary should not greatly impact the result of any operationalisation, and competing options for this choice should be carefully examined in the creation of a theoretical frame. Functional boundaries must therefore be chosen to ensure ‘interspatial’ equity as well as intergenerational equity, meaning a sustainable urban system shouldn’t be allowed to employ accountancy tricks by exporting unsustainable activity elsewhere (Spangenberg 2010).

Urban versus global sustainability

How then does urban sustainability differ from the global project of sustainability proper? This thesis supports the view of previous authors that urban sustainability is a contextual re-application of global sustainability to the local scale as outlined in Section 1.2.3. It is however not a one to one mapping, since the urban context brings with it phenomena such as transport and land use which are less pertinent at the global scale (Gibson et al. 2000). This is something that it was argued that the prototype system dynamics model presented in Chapter 6 failed to adequately capture in its current iteration. The choice of relevant phenomena is necessarily contested, and the outline of indicator approaches to urban sustainability in Section 1.3.1 criticised the often arbitrary selection of indicators. This is where co-creation of frameworks offer a solution by combining citizen-led and ‘expert-led’ approaches, as taken by Turcu (2013). Here it is necessary to be wary of universalising approaches, as the urban context varies widely across the globe (Brenner 2018).

Whilst urban sustainability may be viewed as a reapplication, it is not independent of the global notion, on the contrary the two are tightly coupled, as demonstrated by the Urban1 model scenario runs in Section 6.4.2. With a heavy dependency on the globalised commons, there is no path for urban sustainability in an unsustainable world. This concurs with Berger (2014)’s view that the ‘self-sufficient’ city is a fiction. Sustainability is a global endeavour and requires global co-operation across scale. With world urbanisation trends, the focus on urban sustainability is needed, but should be contextualised against the backdrop of multi-spatial global developments (Angelo and Wachsmuth 2020). Some authors, such as Hall (2017), suggest this indicates global per-capita limits to consumption.

7.1.2 Consensus building or pluralism?

This thesis has recurrently encountered a plurality of interpretations of urban sustainability, epistemologies, and methods for conceptualising it. Chapter 3 encountered competing interpretations of the economic paradigm in conceptualisation of sustainability. Chapter 4 presented two ‘fields’ researching the urban from different perspectives and problematised the lack of dialogue between them. In Chapters 5 and 6 methods for approaching operationalisation of urban sustainability were explored each with a divergent underlying epistemology. In Chapter 2 the divergent contestations exhibited in the broad interdisciplinary literature considering urban sustainability were cast as ‘fractures’. What part then should consensus building or pluralism play in confronting this fractured landscape?

Consensus building

The notion of consensus has been encountered multiple times throughout this thesis. Section 1.1 discussed the consensus of urban sustainability as benign necessity (Tulloch and Neilson 2014). The lack of consensus around defining sustainability, was encountered in Section 1.3.1 as an issue for selecting indicators selected to describe it (Tanguay et al. 2010). The institutionalisation of sustainable development was argued in Section 3.1.3 to have progressed via “consensus building through compromise” (Lélé 1991; Castro 2004; Tulloch 2013) with the ‘integration’ of conflicting actor’s priorities neutralising radical critique of the economic status quo (Huckle 1991; Carruthers 2001). Chapter 4 encountered Brenner and Schmid (2015)’s planetary urbanisation which argued against the ‘consensus’ equating the urban with a spatial unit or settlement type. Similarly, the language of ‘integration’ has recurred throughout, from integrated assessment modelling, the integrative goal of interdisciplinarity (Repko 2012), the method of ‘integrative review’ (Snyder 2019) used in Chapters 3 and 5, the discussion of a ‘holistic, integrated urban science’ (Wu 2014; McPhearson et al. 2016b), the integration of the three pillars pushed in institutional literature (World Bank 1992; OECD 1997; UN 2002, 2015a), and the proposed integration of thermodynamics and economics analysed in Chapter 5.

The need for building consensus is routinely brought up in literature discussing the operationalisation of urban sustainability, whether this is fostering agreement from citizens as to the benefits of a project (Doelle and Sinclair 2006), or passing policy through governance structures (Bulkeley and Mol 2003). Whilst the challenges of reaching consensus are acknowledged, it is normatively regarded as an integral part of bringing forth empirical results (Bender and Simonovic 1997; Doelle and

Sinclair 2006). Popular methods for building consensus include multi-criteria decision making (Velasquez and Hester 2013), the Delphi method (Rayens and Hahn 2000), and the DeGroot method (Degroot 1974).

Aside from the practical difficulties of building consensus, the goal itself may be criticised for its blindness to power differentials (Mouffe 1999; Huault et al. 2014). Not every actor has an equal voice, compare lobbyists for powerful corporations to marginalised communities, or the biosphere itself which does not have its own voice. It is for this reason that consensus has been described as an illusion or ‘myth’ by some authors (Pimlott 1988; Peterson et al. 2005)

‘Scientific consensus’ is a common phrase within the climate discourse, it has also been used in reference to sustainability by authors such as Upham (2000). Such framing however acts to depoliticise consideration of sustainability. This has been discussed by Grundmann and Stehr (2010) in the context of climate change, where science studies scholars have shown an unwillingness to critique dominant approaches as it could be seen as “politically counterproductive” (p900), with arguments becoming weaponised by bad faith actors.

Pluralism

Pluralism offers an alternative to consensus. This has been encountered too throughout this thesis. First encountered in Chapter 1, “methodological pluralism” was articulated by Frame and Brown (2008) as an approach to dealing with wicked problems in Section 1.2.3, as well as by Turcu (2013) in her discussion surrounding measurement epistemologies relating to urban sustainability. Section 4.3.2 then elaborated ‘pluralism’ as an emergent theme from the literature fractures surrounding the three pillars of sustainability and the urban. Here it was linked to interdisciplinarity and the prospect for disciplinary silos to complement each other in a methodological and epistemological ‘engaged pluralism’ rather than lying in competition. It was also invoked in Chapter 5 in the criticism of the desire to ‘integrate’ thermodynamics and economics without confronting epistemological differences.

Spash (2009) argues that the role of human agency in determining outcomes creates strong uncertainty, and the lack of causal mechanisms and universal laws demand a plurality of explanations and modes of explanation. This resonates with the explorations made in this thesis with Chapter 5 meeting the inapplicability of universal laws. Further the inherent uncertainty of the system dynamics scenarios produced in Chapter 6 means that they would benefit from parallelised alternative approaches which can be used to further test validity. Söderbaum and Brown (2010) argue that pluralism is necessary for truly ‘democratic’ approaches

to confronting sustainability, echoed by Barthold and Bloom (2020)’s call for ‘radical democratisation’ of environmental sustainability discourse. This implies the necessity for urban sustainability research to become more participatory (Keshavarz and Maze 2013).

The concept of ‘dissensus’ was briefly encountered in Section 1.1, and is defined in opposition to consensus approaches. Kaika (2017) argues that focusing on sources of conflict, rather than seeking to neutralise dissent, can empower citizens, and “move beyond stale indicator frameworks... toward an urgency driven framework of global socio-environmental equality” (p99). Di Paola (2019) argues that there is potential for knowledge exchange between urban activist movements and sustainability science through dissensus-driven alternatives. Thus dissensus endeavours to move beyond pluralism to a ‘radically democratic’ notion of sustainability (Barthold and Bloom 2020).

7.1.3 An understanding

Chapter 4’s exploration of the urban literature revealed there to be an incredible diversity of approaches to conceptualising and understanding the urban, an endeavour seemingly explored by every discipline within the academy. This leads to a rich pluralism of approaches to understanding, and it can be argued that the literature is better for this. It was emphasised however that a clear divide exists between the urban studies and urban science literature, with a relative lack of dialogue and cross-pollination. This may be a consequence of traditional academic structures impeding true interdisciplinary work, but is not aided by diverging epistemologies from constructivist versus positivist traditions. Such an epistemological barrier is often an intractable issue causing the imperfect translation of concepts across disciplinary boundaries. The case of entropy explored in Chapter 5 is a key example of this, whereby the inability of authors to import the context specificity of the laws of thermodynamics led to underdeveloped theory which ultimately eluded rigorous application. This can also be seen in criticism of LtG from orthodox economists for its treatment of economic factors (Bardi 2011; Jackson and Webster 2016).

Whilst this thesis strived to bridge urban studies and urban science, it remains largely rooted in the latter tradition. Nabavi et al. (2017) champions the epistemological flexibility of system dynamics, and there remains space to explore this further, particularly regarding co-production across disciplinary boundaries to explicitly bridge the urban fracture. Further, by moving towards a hybrid modelling framework which allows for disaggregation, pluralism and decision making may be investigated explicitly within the model.

Section 1.2.3 articulated a working definition of urban sustainability:

Urban sustainability is a reapplication of ‘sustainability’, in a global sense, to the urban context. This brings sustainability as a semantically open concept of what it means ‘to keep something going’ (Ramsey 2015), together with the contestations surrounding the urban, typically understood as relating to agglomeration at the local scale, and the numerous contextual specificities this brings. The multidimensionality of urban sustainability necessitates consideration across traditional disciplinary boundaries including environmental, social, and economic factors. The emphasis on locality highlights interaction across boundaries and scales, as well as consideration of an ‘interspatial equity’ in parallel to the more typical focus on intergenerational equity.

The resultant work in this thesis explored this understanding. It fleshed out urban sustainability as a reapplication of global sustainability, with the additional concepts and contestations which come with this local scale. The focus on pluralism emphasises urban sustainability as a semantically open concept, with numerous interpretations regarding priorities, relation of components or ‘pillars’ of sustainability, and the definition of the urban spatial and functional boundaries. This pluralism reaches across the traditional disciplines, across divergent epistemologies and methods, and should empower marginalised communities as key stakeholders. As Spash (2009) states, “pluralism does not mean accepting everything” (p256), urban sustainability is political and ideological, this should be championed, not erased in order to approach a radical interpretation of urban sustainability focused around intergenerational and interspatial equity.

7.2 Operationalising Urban Sustainability

The second research question surrounding operationalisation is now addressed:

2. *How can such an understanding be operationalised to explore coherent ways of improving upon it? (‘Measure’/‘Model’ → Operationalise)*
 - (a) *To what extent may thermodynamic concepts be employed to provide a ‘physical basis’ for sustainability?*
 - (b) *How should an integrated assessment model be designed to be useful for such a purpose?*
 - (c) *How can the issues of boundaries be confronted?*
 - (d) *What barriers exist moving from theory to practice, and how might these be overcome?*

7.2.1 A physical basis for sustainability

Chapter 5 explored a ‘physical basis’ for operationalising urban sustainability through a measure related to thermodynamic entropy. Whilst this concluded with the desire to avoid future thermodynamic system conceptualisation of the urban in the manner described, the journey offered a turning point in the work’s metanarrative, and elicited points for further consideration of operationalisation.

One reason why the thermodynamic conceptualisation failed was through its attempt to apply a theoretical framework based upon microscopic phenomena, usually reserved for use in ‘simple’ well-defined systems, something which the urban is very much not. The complexity of the urban system is alluded to throughout the literature, but it is arguably the lack of a common understanding of how the urban system is understood, as discussed in Section 4.1.1 which presents a larger barrier for application (Petts et al. 2008; Alberti 2017). The thermodynamics of ‘complex systems’ is a well-studied area, although a difficult one with frequent contestations (see e.g. the arguments surrounding photosynthesis mentioned in Section 5.4.1), where these differ is that whilst complex they are usually well-defined. It is when they are not that issues surrounding boundary conditions and other confusions appear (Dao et al. 2017). Thus, the lack of a clearly defined system hampers any thermodynamic analysis. This contrasts to the system dynamics model developed in Chapters 6 where the urban system, whilst being a simplified abstraction of reality, remained well-defined with physical and functional bounds and a predefined theory. Such a model then allowed for clear repeatable analysis to be made.

Thus, whilst ‘complexity’ does complicate matters, and can limit clear conclusions being made (e.g. it often proves difficult to pinpoint causes and interventions to be made in system dynamics models (Martinez-Moyano and Richardson 2013)), it is argued here that a clear specification of scope is instead integral for successful application. Of course, a more complex system can limit the success of finding a clear uncontested abstraction for experimentation, but it is in the description rather any complexity itself where the problem lies. Filchakova et al. (2007) note a correlation between the difficulty of calculation and the thermodynamic rigour behind approaches within the literature (p228). Such an observation may be extended more broadly with the argument that there is an inherent trade off between comprehensiveness and simplicity in making an abstraction of the urban system. This is perhaps obvious, but it is worth emphasising here; any simplified abstraction is likely to come at the expense of valid critique of its ability to capture what is traditionally considered as ‘urbaness’. Vice versa, any abstraction which is comprehensive in its coverage of urban phenomena and relations is likely to

meet resistance to the complexity of its outputs which would likely be difficult to interpret and validate. Such a dilemma brings to the fore questions as to what a model's intended purpose is; comprehensiveness for the sake of it, is not necessarily a useful goal on its own. What is required is appropriate complexity, so that the model becomes both tractable and useful (Wilson 2016). This latter stipulation is perhaps not given adequate attention in some places. It is arguably for this reason that integrated modelling approaches remain unpopular relative to specific models addressing specific phenomena.

Any operationalisation of urban sustainability then demands a clear theoretical framework of the object that is being operationalised, defined by physical and functional boundaries and a suitable abstraction if appropriate, as well as a theoretical framework for the operationalisation itself. This latter point received some attention throughout Chapters 5 where notions of 'reversibility' were explored in relation to the entropy associated with the urban system's outputs and inputs, and the nature of efficiency discussed.

The thermodynamic entropy approach proposed within the literature to offer a 'physical basis' for sustainability (Csernai et al. 2016) was shown through analysis to be inadequate due to such physically grounded methods being inappropriate for capturing qualitative and subjective measures for handling the adverse consequences of anthropogenic activity. The continuing popularity of such an approach, despite the failure for any quantitative frame to materialise, was argued to be due to conflation of the strictly defined thermodynamic definition of entropy with a figurative definition. Thus, this thermodynamic approach to operationalisation was judged to be a dead end for future work. Outside of specifically operationalising sustainability, application of thermodynamic entropy to efficiency measures was outlined as a possible application, as well as merits of the statistical definition of entropy to various phenomena.

This exploration problematises approaches which fixate on the need for a "scientific, objective, and value free" measure of sustainability (McCool and Stankey 2004). Additionally, it re-emphasises issues regarding measurement highlighted in Sections 1.3.1 and 2.3 involving data constraints, bias towards quantifiable concepts, and universalism.

7.2.2 Integrated assessment modelling

Chapter 6 presented a proof of concept of the use of an integrated assessment model for operationalising urban sustainability. This followed from the method outlined in Figure 2.3 and the hypothesis that a global IAM may be downscaled with consideration of boundary conditions to form an urban IAM. Through the outputted scenarios of this model, a novel framework was forwarded which presents a visual future-looking understanding of urban sustainability. Whilst the Urban1 model is limited in its scope in encapsulating the urban, further revisions and new directions of adaptation for similar models are possible.

The selection of Meadows et al. (2005)'s World3-03 model for this purpose specified the path of system dynamics as the modelling method. Whilst this global IAM was criticised in the 20th century, its results have been argued by numerous authors to have withstood the test of time (Bardi 2011; Jackson and Webster 2016). Ravetz (1998) argued that urban modelling has much to learn from IAM, and the preliminary exploration of Chapter 6 seems to confirm this. First, as discussed in Section 7.1.1, the process of this adaptation acted as a learning process for better understanding urban sustainability. This came in confronting the nature of urban boundaries, and the relevance of phenomena across different scales, as well recognising the weaknesses to be addressed by future modelling.

By integrating phenomena and coupling systems both within the urban scale and in relation to a global aggregate system, this approach is well placed to identify levers and unexpected behaviour (Meadows 2008). This was shown in Section 6.4 in exploring the trade-offs involved in the import versus the local production of food, and the relation between the sustainability of the global and urban systems.

Whilst limitations were outlined with the model and approach as it stands, particularly regarding the absence of stakeholder engagement, and the 'urbaness' of the model, this is not something that cannot be confronted in future work (see 8.2). Section 6.5.2 stressed the necessity of engagement with stakeholders and citizens within the modelling process for the operationalisation of urban sustainability through IAM to be truly realised. This is revisited in Section 7.3.2.

7.2.3 Boundaries

Section 4.3 articulated three types of urban boundary, which were encountered throughout the subsequent case study chapters, the physical, the functional, and the institutional or administrative. The institutional boundary was argued to be largely arbitrary in practice, yet paradoxically highly influential due to the direct impact of

policy being largely constrained within these borders. It is for this reason that most operationalisations of urban sustainability tend to focus on these arbitrarily drawn institutional boundaries, as it is here that change may be engendered, and indeed such approaches are often drawn up for the use of such institutional actors. Thus, whilst a more idealised theoretical work may prefer physical boundaries (which are not without their own issues in defining), or even reject the notion of boundaries in their entirety, a pragmatic approach to identifying avenues for change must seriously engage with such inconvenient boundary decisions. It is the functional boundary that may make amends for this by capturing leakage effects or exporting of ‘unsustainability’ through a notion of ‘interspatial’ equity. Such boundary choices are integral to an understanding of urban sustainability which reflects on the urban system’s place in the wider multi-scalar global system.

The issue of urban boundaries, as first explored in Section 4.3, received prominent attention across subsequent chapters. Chapter 5 sidestepped consideration of physical boundaries by employing an abstract domed boundary. Instead it explored the meaning of ‘open’ and ‘closed’ boundary conditions, both across popular understanding, and their specific meaning within thermodynamic theory. It was noted that there appears to be confusion within popular parlance as to the specifics of a close-bounded system, which in thermodynamics allows the exchange of energy. This was seen to be often conflated with a thermodynamically isolated system, where the second law of thermodynamics applies, which prohibits the exchange of energy across its boundary. It was through this unclear stipulation of bounds that much confusion was seen to precipitate regarding the applicability and subsequent consequences of the second law. Open and closed boundaries were again encountered in Chapter 6, where the adaptation was made from an effectively closed global system model, to an open urban one. The construction of Urban1 therefore confronted what it meant for the functional boundaries of its subsystems to move from closed to open. For the more physical systems such as population or resource flows this transition was successful. For the more abstract economic system however, disentangling the urban from the global was judged too complex to adequately model reality, and a deeper theoretical grounding, perhaps involving a less granular scale, was argued to be needed to allow adequately conceptualising this boundary.

The modelling approach encountered problems relating to drawing physical boundaries as well as functional ones. A large cause of this was due to data constraints, and the manner in which data required had been collected. This meant that for consistent data, the choosing of boundaries was nominally restricted to

administrative urban boundaries. Further issues arose from this due to inconsistencies in data collection, as well as the redrawing of these over time. Ultimately such problems proved of little relevance when the data transpired to be inadequate for translation of a real city into the system dynamics model, however any future consideration that attempts a real case must confront these issues. It was also shown in Section 6.4.2 that the choice of boundaries (in effect both physical and functional) helped dictate the long term sustainability of the system. This was particularly obvious when the amount of land available in the system, which in turn dictated the available food, strongly impacted the direction of the system's evolution through investment of capital. To an extent this is a product of the underlying World3 model used and its functioning, however it raises more general questions surrounding similar frameworks such as urban footprint related analysis.

7.3 Confronting Barriers

The final research question regarding operationalisation asked what barriers exist in moving from theory to practice. This final section then, outlines these, and discusses what may be done to overcome them.

7.3.1 Data

The largest stumbling block to creating a fully operational urban system dynamics model surrounds data. Data availability has come remarkably far since the first calibrations of the World model in the early 1970s, with open data, 'big data', and novel avenues for collecting (Satterthwaite 2010; Kitchin 2014; Rathore et al. 2018). Nevertheless, there remain issues that must be confronted.

The first concerns the greater demands placed upon data requirements by the finer resolution of the urban scale (Spielman 2017). This becomes increasingly problematic at finer scales such as the neighbourhood or community level, where data either does not exist or is closely safeguarded due to its sensitivity and commercial value, not to mention the ethical concerns surrounding using it (Elwood and Leszczynski 2011; Contreras and Chamorro 2019). It also remains uncertain these finer scales may be meaningfully modelled anyway.

A finer scale also increases the noise existing in historical time series data. For example, the city of Nottingham in the UK was initially considered in Section 2.4.3 as a source of calibration data for the urban model. From census data, the population of the city appears to have fluctuated throughout the 20th century (Great Britain Historical GIS Project 2017). There is no clear explanation for this fluctuation,

it may be due to changing boundaries, or the decline in industry (Bourne 1980). Without a clear explanation for this fluctuation which may be coded into the model however, caution should be taken in using such data. A second issue also surrounded the large student population of Nottingham, estimated to comprise 13% of the City's population in 2019 (Nottingham City Council 2018c). This large transient population introduces extra noise into any model, particularly as this population is largely confined to a narrow age range, and cannot be considered for employment.

There exist three approaches which must be undertaken in addressing such data issues. The first involves consideration in the planning process of the model, i.e. in selecting spatial and temporal scales, and phenomena of interest, by considering what relevant data exists or can be feasibly collected. This can be complemented by producing mental models (Greca and Moreira 2000) with relevant experts in reference to historical information sources to identify causal relations which can explain data idiosyncrasies. Finally, as briefly discussed in Section 2.4.3, statistical methods may be employed to interpolate across missing data gaps, as well as making inferences across spatial and temporal scales where necessary (Snyder 2001).

7.3.2 Stakeholder engagement

Stakeholder engagement has been a recurring concept throughout this thesis and has emerged as an oversight which denies the system dynamics methods explored becoming fully operational. In Section 1.2.3, it was shown that Frame and Brown (2008) hold stakeholder engagement as a necessary compliment of methodological pluralism in confronting wicked problems. Various other works were encountered such as Dao et al. (2017) who problematises the divide between policy and science, Turcu (2013)'s mixed expert-led/citizen engaged approach, and Mathur et al. (2007) who question who stakeholders are and how they might be identified. In Section 2.5.2, it was acknowledged that in being outside of this work's scope, the lack of stakeholder engagement presents a barrier to any claims to an 'operational' modelling framework.

If operationalisation is understood as the movement from the abstract to the empirical level (Mueller 2004), some form of engagement with relevant actors is required. The level of engagement though may vary from co-production and design across the whole research process, to simply implementing policy recommendations (Manetti 2011). The question of who the stakeholders are is a salient one, and may be largely informed by the research approach taken; Colvin et al. (2016) describe the process of identifying stakeholders as both an art and a science, with intuition and past experiences deemed as valid as a more systematic approach. Mitchell et al. (1997) categorise stakeholders in terms of power, legitimacy, and

urgency, arguing that these attributes define the desirability of the stakeholder for engagement. Such a framework however reinforces the marginalisation of those without power, thus alternative approaches exist seeking an equitable and socially just process seeking meaningful engagement and empowerment of the voiceless (Suarez-Balcazar 2020). The identification of stakeholders then is as much political as it is a practical choice. Thus, whilst ‘policy makers’ may seem the obvious choice for the system dynamics approach outlined in Chapter 6 they are not the only one.

Aside from the selection of stakeholders, barriers also exist to engagement, as well as the realisation of meaningful impact. These involve financial and time constraints, the mediation of competing views, communication barriers, and the navigation of institutional and legislative structures (Reynolds et al. 2006; Manetti 2011; Tseng and Penning-Rowsell 2012). This latter barrier in particular depends on context, with the openness of ‘gatekeepers’ and the culture surrounding access varying internationally (Tofarides 2018). Thus, a research design proposing linear ‘stakeholder engagement’ is insufficient, it must draw upon the literature from policy and management sciences (see e.g. de Gooyert et al. 2017), in order to anticipate and confront these barriers.

7.3.3 Depoliticisation

Having argued that the choice of stakeholders is a political one, it is necessary to reify that urban sustainability itself is an inherently political concept. Chapter 3 argued that the three pillars conceptualisation of sustainability arose from the radical critiques of the economic status quo from social and environmental perspectives becoming neutralised through the consensus building through compromise approach of the UN. In effect, the radical, counter-hegemonic foundations of sustainability were depoliticised into a platform for legitimising and obscuring the economic status quo (Tulloch 2013). Similarly in the urban literature, McDougall (1973) criticises the trend to a ‘scientific’ approach to planning for the erasure of the “ideological and political nature of the planning act” (p79), and Viitanen and Kingston (2014) accuse the perceived benignity of the ‘smart city’ discourse for outsourcing “environmental and social resilience to the global technology sector” (p815). Depoliticisation is a frequent stay in urban studies, with privatisation of the urban commons perceived as leading to a ‘post-political’ city (Swyngedouw 2011; Beveridge and Koch 2019).

Whilst Chapters 3 and 4 emphasise the political nature of urban sustainability, this thread becomes somewhat lost in the abstract theoretical approaches of Chapters 5 and 6. It is necessary then to reflect on depoliticisation within this work, and how this may be better engaged with. As Gómez-Baggethun and Naredo (2015)

argue, a shift from a political to a technocratic sustainability discourse must be resisted, yet modelling approaches are often guilty of reducing sustainability to a technical challenge. This would certainly have been the case with the entropy approach, which focused solely on material flows through the city, and derives from an epistemology in search for universalising physical ‘laws’. System dynamics, whilst being reductionist, remains more open to the political nature of sustainability. This has already been discussed in relation to participatory modelling, and the openness of system dynamics to constructivist epistemologies (Pruyt 2006). Whilst it is difficult to see system dynamics modelling as a radical emancipatory method (Crookes and De Wit 2014), it certainly has potential to be used as part of a pluralistic toolkit here (Lane 2001; van den Belt and Dietz 2004), particularly if social aspects are better captured through dialogue with stakeholders and the inclusion of agent-based techniques. These considerations emphasise the importance for bridging the ‘fracture’ between urban science and urban studies.

The dangers of depoliticisation from a modelling or operationalisation perspective were articulated in the consideration of modelling ethics in Section 2.5.3. The modeller has a duty to reflect on how their model may be weaponised for political aims in a manner that has adverse consequences (Palmer 2017). This is particularly pertinent for the type of model presented in Chapter 6 which deals with sensitive issues such as migration in an abstract manner devoid of the human context. This again highlights the importance of methodological pluralism, and perhaps suggests that a single model and its scenario outputs alone is not sufficient, something which might be addressed in the participatory process.

7.4 Reflections on Operationalising Urban Sustainability

It was concluded in Section 4.3 and emphasised subsequently throughout that any clear operationalisation of urban sustainability must be constructed upon a strong theoretical frame. Such a framework was argued to require a full declaration of its scope, and present a clear articulation of the problem being addressed, as well as an assessment of any shortcomings. This is integral, since any approach which isn’t clear about its purpose and aims and rooted in a coherent logic is difficult to judge the success of, as well as impeding replication. Thus, it is important to reflect upon what operationalisation of urban sustainability means and why it is desirable.

Arguably there are two purposes to operationalising urban sustainability: measuring, and making change. Foremost is to improve upon the current situation and

move towards a more sustainable state. This requires some understanding of where this direction lies, and what changes must be made towards moving in this direction. Simply producing a measurement of ‘urban sustainability’ does not automatically allow for this. Of course it is possible to create measures for urban sustainability, purposed e.g. for comparison with other urban areas, or for demonstrative reasons (e.g. activism to show that change is needed, or for PR reasons to sell the area in a positive light). These are limited in usefulness however if they do not allow for hypothesis testing or identify avenues where change may be made.

‘Shallowly theorised collections of indicators’ were critiqued in Section 1.3.1, what then constitutes a better framework?

Maxwell et al. (2015) and Hák et al. (2016) articulate ‘SMART’ criteria for environmental targets (specific, measurable, ambitious, realistic, and time-bound), such specifications are somewhat arbitrary although do act to focus indicator or target based approaches. The reference to time is of particular note, and it recalls Brundtland’s ‘intergenerational equity’, and the notion of futurity or “what it means to keep something going” which Ramsey (2015) argues sustainability is fundamentally about. Such a time oriented framework then should not allow for the prioritisation of short term gains against future stability, instead taking a broader time horizon in its entirety. ‘Measurable’ harks back to the various discussions made regarding data and quantification; the thermodynamic system approach failed to live up to expectations because entropy was not measurable under such a frame. By insisting upon ‘measurability’, less quantifiable aspects are marginalised. A better stipulation is perhaps then insisting on tangible results that are actionable upon. This allows for a greater pluralism of approaches which do not insist upon ‘measurable’ quantitative outputs. Such qualitative or mixed-method approaches then include the scenarios produced in Chapter 6 which whilst actionable, as they allow the identification of pressure points, are not necessarily ‘measurable’. A confrontation of reality is deemed necessary, it was in this that certain interpretations of planetary urbanisation were cautioned for ignoring the political implications of administrative boundaries. An operationalisation of urban sustainability should then make a concentrated attempt to engage with the realities of the urban system it is conceptualising, incorporating real-life contextual factors as well as confronting barriers to change.

It is here that the Urban1 framework’s limitations, being largely abstract and divorced from a real urban system, are clear. A future framework, as previously mentioned should better engage with the real local context through e.g. co-production with stakeholders to develop and refine theory based upon local issues in

order to better determine what is ‘useful’ here. Nevertheless, as a prototype for future operationalisation, it does well to cohere to future thinking whilst presenting actionable results.

7.4.1 Operationalising what?

With urban sustainability presented as an umbrella concept open to re-contextualisation, questions remain as to why or how it should be operationalised as a whole. Is it a diversion attempting to operationalise the broader concept when volumes of valuable work already exists in various individual constituent issues? To some extent such ‘high level’ abstract theorisation is a luxury when there is urgent work to be done on the ground (cf. planetary urbanisation). This however leaves out considerations of holism regarding interrelated issues and feedbacks that may otherwise be ignored. A main reason why sustainability discourse arose in the first place was to confront such interrelated issues and short-sighted thinking (see e.g. Caldwell 1984’s consideration of ineffective development projects). Thus, such broad investigations can complement in depth work done within particular areas under the umbrella of urban sustainability, and collaboration among researchers can lead to insights both in refining broad frameworks, and considering previously unconsidered interactions.

Despite the benefits of broad frameworks, the limitations of one-size fits all approaches to conceptualisation should be noted. Broad issues of global sustainability abound, many of the ‘urban sustainability’ issues facing real urban areas are localised and context specific. Crime, affordable housing, sea levels, access to public transport, sense of community, such wide ranging factors and priorities vary greatly in their importance for each specific urban case. A good framework should reflect these context specific priorities. Of importance too is diverging governance frameworks for tackling such issues, both local, and regional, as well as different historical and national contexts. A broad universalising framework, in being blind to such specificities is limited in its applicability. Of course this does not preclude broad structures of a universal approach being developed, or guidelines being developed, where the details are filled in at the local scale (such as Turcu 2013’s indicator based approach, and the framework of Chapter 6).

The final emergent theme is therefore one of theoretical framing. This first appeared in the critique of various indicator based approaches which seemingly chose indicators for determining sustainability based on convenience rather than any underlying logic in Section 1.3.1. A counter-example of this was presented in Turcu 2013’s indicator work which engaged with local stakeholders and ‘experts’.

An adequate framing then should state the approach it takes to understanding urban sustainability, making clear its scope and aims. As far as possible this should engage with the relevant critical literature, and justify its approach in light of this, presenting a solid grounding in previous works. As a political concept, any framework engaging with urban sustainability at some point must make value judgements, this is inherent and thus decisions made should be clearly outlined with justification presented. Openness of frameworks allows for easy replication and understanding; this too requires a frank assessment of any shortcomings such a framework may have. The integrated assessment approach of Chapter 6 was presented as a potentially fruitful framework for further analysis due to its emphasis on holism and focus on interactions. The thermodynamic entropy approach of Chapter 5 was deemed an inappropriate framework due to its inadequacy in producing tangible outcomes. It is not sufficient then for a framework to simply ‘measure’ urban sustainability, any successful operationalisation should have diagnostic power to identify routes to improvement.

*The last landing place can only be the infernal city,
and it is there that, in ever-narrowing circles, the
current is drawing us.*

— Italo Calvino, *Invisible Cities*

8

Conclusions

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This thesis set out to progress towards a better understanding of urban sustainability and explore novel modes of its operationalisation. Section 1.4.1 posed two sets of research questions relating to this understanding and operationalisation. Through the research design detailed in Chapter 2, Chapters 3 and 4 furthered an understanding by examining two ‘fractures’ within the sustainability and urban literature respectively. Chapter 5 presented an examination of proposed methods to operationalise urban sustainability by exploring a ‘physical basis’ for unsustainability, and Chapter 6 detailed the first steps in the production of a novel urban integrated assessment model for this purpose.

This thesis has emphasised that urban sustainability should be understood as a semantically open concept with no overall claim to its meaning. Nevertheless, it is an inherently political concept, and researchers should remain mindful as to how their work engages with this political aspect, or whether it may inadvertently contribute to depoliticisation. The focus upon the urban scale may be considered a reapplication of a global concept, but this brings with it additional complexities surrounding boundaries, localised phenomena, and issues of interspatial equity. Thus, whilst it is argued that there is no path for urban sustainability in an unsustainable world, it remains a useful concept. The openness of urban sustainability, and contestation surrounding its meaning is not a problem requiring a fix, instead a pluralism of

worldviews and methods may be viewed as a strength, and there is much to be learnt from the exchange of knowledge across these boundaries. Calls for consensus should be engaged with critically, and it is important to be mindful of the power relations in play in any consensus building exercise.

The need to operationalise urban sustainability comes from desire to bring about real change on the ground. There are of course numerous barriers to realising this in practice however, at the forefront of these is data requirements, and the nature of stakeholder engagement. It is unlikely for positive change to come about solely from isolated academic work in this area alone, engagement with citizens and policy makers is necessary, both to better understand contextual challenges to sustainability and lead to the implementation of new programmes or policies. This is not a straightforward linear process and it is necessary to pre-empt the challenges this might present within the research design with reference to the literature on stakeholder engagement.

Two divergent approaches moving towards operationalisation were explored in this work. The first explored the thermodynamic concept of entropy and through analytical techniques probed its proposed use as a ‘physical basis’ or measurement of unsustainability. Ultimately this proved not to be a suitable avenue, however the journey highlighted some key insights which informed the meta narrative of this thesis. Foremost, in conflation of a rigorous thermodynamic description of entropy with a metaphor, it was emphasised that in pluralistic approaches it is not sufficient to import methods from other disciplines without developing a deeper understanding of the underlying epistemology. This presents a key barrier that must be negotiated in pluralistic approaches, as epistemological groundings are not always explicitly obvious.

The presentation of a prototype framework for an urban system dynamics integrated assessment model engaged with the recurrent themes of boundaries, pluralism and theoretical framing, demonstrating a novel future avenue for operationalising urban sustainability. Such an approach demands serious consideration of both functional and physical boundaries in its modelling design. It remains open to pluralistic input from domain ‘experts’ and local stakeholders, which is indeed encouraged for any future model application. Finally, it describes a clear and open theoretical framework for understanding and operationalising urban sustainability which considers the system’s evolution over time. It is hoped that future work might lead to application of such a model that would fully meet the stipulations laid out here.

8.1 Summary of Contribution

As described in Section 1.4.2, the contribution of this thesis is primarily theoretical and methodological, though it builds towards future operational use. The primary deliverable is the prototype multi-scale urban system dynamics model as a novel methodology for operationalising urban sustainability. This remains novel in combining methodology borrowed from climate science and global environmental assessment with reference to literature within urban studies and urban science. The model has been made publicly available with documentation, as detailed in Appendix A. In its current form it is significant for researchers across disciplines engaged in work relating to urban sustainability, though it may also be of secondary relevance to policy makers and other urban stakeholders. It is hoped that the publication of an article on this modelling process, and the open access sharing of the model will spur other researchers to build upon it.

The Urban1 model is held up as a first step towards a novel approach for operationalising urban sustainability. On the border of ‘soft’ and ‘hard’, and quantitative/qualitative approaches, it is open to pluralism, and the desire for a collaborative approach to model design would open this pluralism up further. Through its scenario building it presents a clear time-oriented theoretical frame for understanding urban sustainability, which in a more developed form engaging with a real urban context, would allow for tangible, actionable results. The framework also allows for multi-scale interactions to be examined and the comparison of the urban system’s status and evolution in the context of the global or mid-level systems. Finally, the issue of boundaries is integral to model design; such a system dynamics framework must confront both functional and physical boundary issues during its development. These decisions are therefore integral to the process and cannot be ignored.

A secondary theoretical contribution comes in the form of the literature syntheses presented in Chapters 3 and 4. These confront underacknowledged fractures within foundational literature, and the analyses of these has brought to light potential avenues for future interdisciplinary exploration of urban sustainability concepts. The divide between urban science and urban studies has highlighted the need for dialogue and pluralism, as well as serious attempts to confront and understand epistemological divides. The bridging of this fracture is important for developing new knowledge and understandings. The three pillars of sustainability paradigm was also investigated, and a historical review of the early literature argued that it comes without any rigorous theoretical basis. These findings were published in Purvis

et al. (2019b) which subsequently won ‘honourable mention’ in the *Sustainability Science Best Paper Awards 2019*. The argument that the economic pillar may be regarded as a historical artefact rather than a logical necessity is significant for the development of critical theories which seek to question the primacy of the economic status quo in considerations of sustainability.

Finally, the ‘failure’ of the entropy approach represents a contribution attempting to fence off this area as a conceptual dead end. Entropy in its thermodynamic context has a very specific definition and limited scope of applicability; it is therefore not suitable as a measure or indicator relating to subjective concepts such as sustainability or utility. These findings were affirmed in Purvis et al. (2017) and Purvis et al. (2019a).

8.2 Future Work

Whilst Section 2.5.2 bounded the scope of this work, this final section presents potential avenues that are perceived as fruitful for expanding this scope in future research. These avenues are identified in two primary areas, expanding the model, and the wider process of operationalisation.

The model

There are several directions that future evolution of the Urban1 could be taken in. Ideally these should be determined in consultation with relevant stakeholders to ensure a focus on ‘usefulness’, although there are still merits to exploring in a more abstract ‘sandbox’ manner.

Of key interest for exploration is a multi-scalar model which considers more than just a single system and a global average. The regional approach taken by Mesarovic (1974) presents a flavour of this, with such regional granularity allowing for spatial variations as well as better accounting for hierarchical modes of governance. This would allow an extra level of functional boundary, and perhaps allow for the economic subsystem to be better represented at a regional level where spatially resolved data is more readily available. Such an approach presents further avenues for exploring the place of urban sustainability in a multiscalar globalised world. Such spatial disaggregation may also be considered within the urban system itself through consideration of a zonal model. This would allow for exploration of spatial inequalities within the urban system, although obtaining data to calibrate such fine-scaled disaggregation may prove a barrier here.

Another avenue of exploration lies with calibration and testing of model ‘validity’. This could involve comparing different data sources as well as performing sensitivity tests of various parameters to probe the robustness of model behaviour and increase confidence in outputs. This was largely done ‘by hand’ in Chapter 6 due to software limitations denying a more systematic approach. Monte Carlo sampling of parameter probability distributions could be used to produce confidence intervals of future model evolution (Doubilet et al. 1985). Such approaches may allow for further thoughts for better understanding urban sustainability and developing more detailed scenarios.

By moving away from the restrictive framework of World3, there are numerous avenues that a more developed model could take. Foremost would be expanding on the ‘urbaness’ of the model by introducing more relevant sub-systems such as energy, housing, or transport. This process would be aided by increasing the modularity of Urban1, this may necessitate porting the model to a less restrictive software environment. Increased modularity would also encourage a more collaborative approach to model design, allowing subsystems to be adapted by other researchers in parallel. An evolution away from World3 also opens the modelling approach up to other simulation techniques such as incorporating ABM through a hybrid approach. This would help to confront the limitations of system dynamics’ aggregate approach, allowing for pertinent social issues such as inequalities to be explored.

The modelling process

As emphasised in previous chapters, co-ordinated stakeholder and ‘expert’ engagement is held as a necessity for truly operationalising urban sustainability. Through this, key urban functions and phenomena could be scoped out, and through collaboration with domain experts, theory could be developed for the integration of such factors into the existing urban system dynamics model. It is here where relevant expertise is important so that such a model may be grounded in relevant theory rather than the attempts of a single modeller. Co-specification with relevant policy makers could also allow for a model to incorporate relevant for the testing of policy based scenarios which are of interest locally. Any model co-production however needs to remain mindful of the power dynamics at play, and should act to engage and empower marginalised groups.

Research design is important here. Whilst there is a wealth of literature detailing modelling approaches related to urban sustainability, there is little written about how the policy modelling interface plays out in practice. Here literature within the management sciences on ‘stakeholder theory’ may be relevant (de Gooyert

et al. 2017). Greenberger et al. (1976) notes that “both model designers and sponsors share a general impression that the actual uses of modelling in government have fallen short of expectations. The gap between expectation and achievement is widest in the policy applications of modelling”. Writing about large policy models over forty years ago, House and McLeod (1977) similarly argued that such models were often “oversold and underdelivered”. There is an urgent need to update this work in reference to the modelling and policy interface today.

The communication of modelling outputs also requires further understanding. This is particularly pertinent given the failure of World3 to have immediate policy impacts following the publication of *Limits to Growth*, despite its results still being held as ‘valid’ nearly 50 years later. This may be down to the power of the economic status quo, but with widespread misunderstanding and misrepresentation of the model outputs, there is a need to question the presentation of these results by Meadows et al.

Appendices



The Model

The final urban systems dynamic model used to generate the scenarios in Sections 6.3 and 6.4 has been made available at <https://github.com/benpurvis42/Urban0>, alongside a copy of Appendix B. This is made freely available under a GNU GPLv3 license. It may be inspected and run by installing AnyLogic PLE, available at <https://www.anylogic.com/downloads/personal-learning-edition-download>.

B

Data sources

This work has consulted a variety of data sources in the scoping, construction, and validation of the model presented in Chapter 6.

Nottingham City Council’s *Nottingham Insight* website, <https://www.nottinghaminsight.org.uk/> provides maps, documentation, and data sets for Nottingham City and the surrounding area. This work made use of several of its reports, as well as datasets for Nottingham’s population, GVA, and migration.

The International Labour Office’s *ILOSTAT*, <https://ilostat.ilo.org/>, provides historical labour market statistics. This was used in the calibration of the urban jobs subsystem.

The Office for National Statistics website, <https://www.ons.gov.uk/> provides numerous national datasets and reports. This was primarily used for various data reports and analyses, and various datasets were accessed through *Nottingham Insight*.

The United Nations’ *Our World in Data*, <https://ourworldindata.org/>, provides numerous historical national and global datasets. This was used both in the calibration of the urban model, and for sectoral GDP datasets which were used in the validation of the modelled urban economic system.

The University of Portsmouth’s *A vision of Britain* website, <https://www.visionofbritain.org.uk/>, provides a range of historical data available at local and national levels. This was used to view census data for Nottingham’s population,

as well as other statistics such as age composition and sectoral composition. It also holds information on local boundary changes and provides a selection of historical urban maps.

The World Bank's *DataBank*, <https://data.worldbank.org/>, provides historical national accounts data. This was used to generate time series of the sectoral composition of the UK economy from which initial calibrations of the economic system were made.

Maybe it's worth thinking another way, as if we cared
and we made a difference, even if it's just groping in
the dark.

— Donella Meadows, *Groping in the dark*

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