Waste not, want not:

Putting urban metabolism into practice

A thesis submitted by

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Abstract

Urban Metabolism is a promising analytical method for sustainability planning. There exist several robust tools and analytical methods as well as related disciplines to comprehensively carry out the practice and address the social, environmental and economic dimensions of sustainability. Yet in North America, no urban municipality has used urban metabolism in sustainability planning. Despite the aim of many cities to be sustainable, very few planning documents reflect systemic or "strong sustainability." In order for the urban metabolism practice to bridge this gap there must be greater outreach by professionals, advocacy on national levels, adoption of standards, and application on specific issue municipal plans.

Chapters

Chapt 1. **Introduction** - Thesis objectives, research questions, methodology and chapter summaries.

Chapt 2. **Urban Metabolism: Definition, History and Practice**- This section will provide a brief, conceptual definition of urban metabolism and frame it within the context of sustainability and other analytical methods and constructs. The history of urban metabolism will be summarized as well as some of the specific methods of quantifying urban flows, such as life cycle analysis, ecological footprinting, material flow analysis, etc., and each of their relative strengths and weaknesses.

Chapt 3. **Literature Review** - Literature will examine a spectrum of perspectives of urban metabolism and any examples of its having been deployed within city government planning. This will include case studies to find some of more prevalent urban metabolism methods, as well as limitations within the methods. Literature also will examine existing research into the state of sustainability planning practice within North American cities.

Chapt 4. **Survey of Sustainability Planning** – This chapter will examine the planning documents and practices of various North American cities, which either have shown to be leading in sustainability planning or are considered, at minimum a regional anchor. Common themes and practices, if any, will be discussed.

Chapt 5. **Conclusion** – The final chapter will discuss how well the tools of urban metabolism meet the goals of city planning and how the discipline can become more adaptable to city planning in the U.S.

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Thesis
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Chapter 1: Introduction

We are well into the Anthropocene age. **Fifteen years past when Nobel Prize winning chemist Paul Crutzen introduced the term at a scientific conference (Kolbert, 2011) and well past the later stages of the 18th century when Crutzen says this age began (2005). The term and idea that human activity is driving force on the planet has taken such traction that news blog Vox.com named "Anthropocene" as one of the "10 Words to Understand 2015." As evidence of humankind's increasingly dominating impact on the planet, Crutzen has cited, amongst others, the use of nearly half the planet's land and more than half of the accessible freshwater by mankind, the rise in greenhouse gases to levels not seen in 400 millennia and the associated global temperature increases, (2005). Couple this with the well-known fact that more people now live in cities globally than in rural areas and it is clear that the Anthropocene age is also an urban age**. Photo essays such as those like Michael Wolf's (2015) skyscraper apartments in Hong Kong reveal the almost-impossible densities of the world's most populous cities **and these cities have enormous impact on the planet (Kolbert, 2011).** As planners, we are preparing for "the coming of the global city," (Braudel 1984) or the megalopolis anchor of the megaregion (Calthorpe and Fulton 2001). Whatever it is named, we know it will be big and we will have to make it sustainable (Niza, Rosada, and Ferráo et al. 2009, 387). The question we now wrestle with is, "How? "

Starting with the widely adopted Brundtland Commission definition, that sustainability, "meets the needs of current generations without compromising the ability of future generations to meet their own needs," (Brundtland 1987, 41) two important questions follow: "What do we need to meet our own needs?" and "How do we leave enough for future generations?" It follows then that sustainability requires some quantitative and qualitative answers to these questions.

The triple-bottom line model tells us that we must consider three, key dimensions of environment, economics and equity (Elkington 1997), sometimes summed up as people, profits and planet. It also dictates that the interaction between each dimension is just as important. Thus, sustainability planning must have a holistic and systemic understanding to be successful (Niza, Rosada, and Ferráo et al. 2009).

One would be hard-pressed to find a government agency that is not aware of sustainability and paying it some kind of regard. One is also sure to find a broad spectrum of initiatives labeled as "sustainability." Many of these efforts are likely environmental in focus (Mostafavi et al. 2014, 54), but lack forethought into the social and economic dimensions. These initiatives are also not conscious redesigns of an urban system to make it less impactful to the environment, but rather just point in a generally environmental direction or address specific problems in a narrow dimension.

Consider the fairly common municipal goal of increasing open space. Such an effort likely contributes in some way to all three dimensions of sustainability. The open space acts as a carbon sink, increases surrounding property value, and improves quality of life for residents. However, is this pursuit of open space forgoing other, perhaps more pressing, goals of economic development or housing? Is the open space equitably distributed or is it only giving more benefits to the well off? Without a high-level, system-wide understanding of civic goals along each dimension of sustainability, initiatives can counteract each other and fall short of sustainability (Mostafavi et al. 2014, 54).

Within the environmental dimension, "sustainability" initiatives must also be understood as systems- based and interrelated (Mostafavi et al. 2014, 58). Considering the same open space goal, opportunities to manage storm water should be enveloped into the open space consideration. The maintenance cost of open space, in terms of water and energy, also need to be considered as those considerations can counter the benefits.

In total, very few North American governments are engaged in sustainability planning in which the physical and social processes, basically the metabolisms, of the city are understood and in turn inform policy and initiatives which make those metabolisms more sustainable (Ferráo and Fernandez 2013). Ferráo and Fernandez have used the term "strong sustainability" to describe such practice **(2013), while others like Kennedy (2011) and Foster (2015) use the term "deep sustainability." This thesis will borrow both of those terms and use them interchangeably**.

Understanding the whole of a metropolitan system is, at best, difficult, if even possible. In 1967, Abel Wolman proposed the concept of urban metabolism as a way to approach the analysis of city systems. The concept has been defined as, "the sum total of the technical and socio-economic processes that occur in cities resulting in growth, production of energy and elimination of waste" (Kennedy, Cuddihy and Engel-Yan 2007, 44). In short, the discipline seeks to understand what the city takes in, uses, and then disposes. In relation the Brundtland definition, urban metabolism is a tool to understand, first, "What do we need to meet our own needs?" This question is addressed both in terms of materials consumed and in terms of impacts to the environment or how we "use" material sinks. The next question is, "How are we meeting our needs?" Mapping and understanding metabolic flows, whether water, energy, construction materials, or foods, through the city leads to an understanding of the city's impact and insight into how the flows can be redesigned more sustainably (Niza, Rosada, and Ferráo et al. 2009, 388). Not surprisingly, most flows in most cities are linear (Brunner 2007, 12). They enter the city from a hinterland which can be surrounding farms that provide food, or Chinese factories that provide nearly everything. The aforementioned materials and energy are metabolized by any number of processes and become part of the city's stock and/or leave to a different hinterland as waste (Brunner 2007, 12). Ideal flows are circular and mirror ecological processes in which there is high reuse and practically zero waste (Ferráo and Fernandez, 2013). In referencing natural systems as a baseline of sustainability, the metabolic analysis gives us the groundwork to answer, "How do we leave enough for future generations?"

Inquires in line with the Brundtland definition address the environmental dimension of sustainability, but again we need to address the economic and social dimensions and their interactions. Thus far, analysis in urban metabolism has been largely an endeavor along the environmental dimension. However, it can also offer insight into social and economic dimensions (Brunner 2007, 11). The field has been growing robustly over the past 20 years and new methods and models for understanding metropolitan systems have been developed (Mostafavi et al. 2014, 54). Broto, Allen, and Rapoport (2012, 852) have found recurring themes in urban metabolic research that reach into the economic and social dimensions, such as mapping the distribution of various material goods to show that they are not distributed equitably. Other studies have gone as far as to incorporate livability metrics into their analysis (Newman 1999, 222). There have been more than 75 papers published on urban metabolism(Kennedy and Hoornweg 2012, 780), but despite the academic interest and progress, there have only been a few examples of the practice being used in sustainability planning (Yan 2003) in North American cities.

Objectives

The central aim of this thesis is to investigate how urban metabolism can be more widely adopted in city government planning. This aim rests on several assumptions 1) that city government planning wants and needs to be more sustainable and specifically in holistic and systemic manner, and 2) that urban metabolism provides a ready and advantageous framework for conducting holistic sustainability planning. The research questions and literature review aim to test these assumptions. The Survey of City Planning will investigate is urban metabolism is being used at all in city planning, how sustainable those planning efforts are and how readily an urban metabolism framework can be adopted. As we will discover, one of this thesis's critical findings is that the discipline is largely confined to academic inquiry and needs to become more accessible. A resulting objective of this thesis will be to lay out the discipline and practice so it is accessible to a broader array of users.

Research Questions

Is urban metabolism an applicable tool to government-led sustainability planning? - Assuming that most city governments would like to be sustainable, specifically deeply sustainable, what can urban metabolism do to facilitate those goals? Government planning, sustainable or otherwise, functions within several well studied parameters of politics, budgets, legal constraints, and time frames. On the opposite side of the ledger urban metabolism relies on a spate of analytical tools that can be matched to the nature of the analytical issue (Ferráo and

Fernandez 2013). Many of these tools focus on environmental analysis, but some research has shown further application, such as the incorporation of livability metrics (Newman 1999, 222). In theory, this analysis would ground policy decisions, but it is important to assess whether these tools and methods can function within the governmental context. A study that takes four years is of little use to an administration that will be out of office by the time it is complete.

How does urban metabolism need to evolve in order to be a widely used tool? - There is certainly an awareness of the importance of sustainability within government planning, and likely an understanding of the need for sustainability planning to have a holistic frame (Mostafavi et al 2014, 58). The holistic frame would connect independent initiatives to the larger systems in which they operate and assess the impacts throughout the system. Why then, do we not see this holistic frame? There are disconnects that could occur at any or all of several levels: Operationally, it is too costly or difficult; politically, it does not have the popular support; vision-wise, the goal of sustainability has not been clearly defined; and several others. What then can be done to address these disconnects? Do the methods of urban metabolism need to be further developed? What new planning methods have been successfully adopted, and how? Are there complementary tools that need to be developed? What have been the results where it has been deployed?

Methodology

The questions above address the gap between the practice of urban metabolism and of government-led city planning in North America. To better understand what the gap is, each side of it must be analyzed.

Investigation into the practice of urban metabolism:

a) Building from Ferráo and Feranadez's toolbox (2013), research urban metabolism methods to find the most predominantly used methods and assess them according to applicability, reliability, ease of use.

b) Research case studies of urban metabolism and assess their applicability to current government planning.

c) Research recommended methods for adoption of urban metabolism into government planning and assess if these realistically meet government constraints, of time, budget and politics.

Investigation into government led city planning in North America:

a) Research literature that has undertaken a survey of sustainability planning within the U.S.

b) Evaluate the planning documents from North American cities within a simple metabolism construct and the triple bottom line sustainability construct. The plans goal and initiative (and similar) statements will be assessed and scored as to the number of metabolic processes and the triple bottom line dimensions of sustainability they address. The cities selected have either shown to have leading-edge sustainability practices, or are considered to be "global" and will therefore have the greatest impact.

c) Research conference proceedings from U.S. planning organizations, such as the American Planning Association, for emerging holistic sustainability practices.

Chapter 2: Urban Metabolism: Definition and History and Practice

Definition

The academic literature has introduced a number of definitions for urban metabolism, but as the goal of this thesis is to connect urban metabolism to the realm of government planning, perhaps it best to steer away from academic definitions for the moment and simply say that urban metabolism asks, "What does the city use?" "How does it use it?" and "How and what does it get rid of?" The concept can also be understood as a fluid combination of two metaphors: One is of the city as an organism. It eats, digests and excretes. This is the simpler of the two metaphors and works on large scale of analysis of the city, particularly in relation to the hinterland. Two is the city as an ecosystem, which functions on a much more complex level with the thousands of processes that make a typical day: millions going to work, buying (and tossing away) cups of coffee, driving over sensors in the road to turn a traffic light green, turning on a water faucet, and throwing a bottle into the recycling container. Looking at the city as an ecosystem means it also has a measurable metabolism in its exchanges of material and energy. The complexity in the millions of interactions between people and systems correlates to the millions of processes and interactions within a natural system and gives us a model for efficiency.

Returning to academic definitions, it is useful to trace these through time and reveal how the urban metabolism concept has evolved. Over the past two decades, there has been a renewed interest in urban metabolism as sustainability has become a major concern. Seventy five papers have been published worldwide on the topic (Kennedy and Hoornweg 2012, 780). With the importance of sustainability and immediacy of environmental consequences, the urban metabolism field has broadened and evolved (Daigneau 2014, 20). There has been work to broaden the discipline to encompass triple bottom line aspects.

The first definition comes from Abel Wolman, who introduced the concept of "urban metabolism" in a 1967 edition of Scientific American. He defined it as, "all the materials and commodities a city's inhabitants need to sustain themselves at home, at work, and at play (1967, 180)." Forty years later, Kennedy, Cuddihy and Engel –Yan's definition is more widely used, as: "The sum total of the technical and socio-economic processes that occur in cities resulting in growth, production of energy and elimination of waste. (2007, 44). Important in this definition is that it adds dimensions of energy and waste (which Wolman included in his study but not definition) and also considers growth. In one of the more comprehensive methodological works on urban metabolism, Ferráo and Ferandez rely on the metaphorical construct of industrial ecology and construct the metabolism of urban systems in "[its] interactions... with nature, particularly how it exchanges matter and energy (2007, 3)." This construct brings in the important consideration of the how the city affects the hinterland. In Ferráo and Fernandez's (2007) construct, the "hinterland" is a global hinterland, so the scale of urban metabolism ultimately reaches to planetary scale and urban sustainability becomes deeply intertwined with global sustainability. In a reverse angle, Goodland and Daly use the concept of urban metabolism to define sustainable development as, "development without increases in the throughput of materials and energy beyond the biosphere's capacity for regeneration and waste assimilation (1996)." S.P. Tjallingii (1993) took the metaphorical construct of the city as an ecosystem to be more absolute, saying, "(it is) a concept of a real city. The social, economic and cultural systems cannot escape the rules of abiotic and biotic nature. Guidelines for action will have to be geared to these rules.''

A common thread in the above definitions is that they are concerned with materials and processes enacted through the city. These processes are the metabolic flows. Generally, the material flows through a city are from the city's global hinterland—used or "metabolized" in the city and usually in some combination added to the city's stock or eliminated to another possibly global hinterland in some form of waste. (Brunner 2007, 12). There are many ways of quantifying these flows, as energy, in bulk by material, by toxicity and many methods that are appropriate different scales and scopes which will be discussed further. In deploying many of these tools and layering them on each other, the metabolic flows of a city can be understood and mapped (Ferráo and Ferenandez, 2013). The important take away is that the flows can then be redesigned (Niza, Rosada, and Ferráo et al. 2009, 388) from the unsustainable, linear, hinterland-city-hinterland flows (Brunner 2007, 12) to more sustainable circular flows which follow ecological models (Ferráo and Fernandez 2013).

These definitions and methods of urban metabolism are largely concerned with concrete, quantitative measures that focus mostly on environmental concerns. But, again, those seeking sustainability must also consider economic and social aspects. Further, urban metabolic analyses need to integrate social, economic and environmental flows of a city (Mostafavi et al. 2014, 59). Newman(1999) proposed an "expanded metabolism" model, which incorporates livability metrics and goals into the analysis. Consideration of these social dimensions is important in making the metabolism model into one that truly addresses sustainability. What is metabolized is not just simply turned into a product, or eliminated as waste, but also turned into some form of human capital. "Synergycity," by Kapp and Armstrong (2012), looks at "creative capital" as the ultimate product of metabolizing the various material and energy inputs of the city (2012). In this sense the concept of a city's stock includes its livability (Mostafavi et al. 2014, 62). This can best be illustrated by energy, in which the metabolization of fuels adds to the physical sink in the form of greenhouse gases (GHGs) but not to the city's physical stock. Instead, that fuel has been metabolized into energy which was metabolized into livability, by providing light and safety to a street. There also are processes beyond the physical processes. Many physical processes are directed or enabled by a social process, such as purchasing the fuel. Disciplines related to urban metabolism examine these processes and argue or their inclusion and perhaps primacy into metabolic studies of the city. In examining the state of urban metabolism and industrial ecology where the scholars are constantly trying to expand the field, Broto, Allen, and Rappaport (2012) found the following as major areas of study:

(1) The city as an ecosystem
(2) Material and energy flows within the city
(3) Economic–material relations within the city
(4) Economic drivers of rural–urban relationships
(5) The reproduction of urban inequality
(6) Attempts at re-signifying the city through new visions of socio-ecological relationships

Related Disciplines

The term "urban metabolism" draws a parallel of the city as a living thing or living system. This metaphorical relationship is not a novel invention of the urban metabolism discipline. Organic constructs of the city date back well past Wolman's 1967 article and well past the 20th century to Vitruvius (Kapp and Armstrong 2009). In the first of his, "Ten Books on Architecture" he equates the effects of the elements on the human body with those on the city (Vitruvius and Morgan 1960). The 17th century philosopher Thomas Hobbes who conceived of the Leviathan, where the populous was akin to a large, single creature and reacted similarly to external stimuli. Victorian Era "renaissance man," Patrick Geddes' was an original champion of the city as the height of civilization and center of its accumulated knowledge (Cumming 2002) and as a node for energy flows (Martinez 2003, 44). He analogized its components of "folk, work and place," to the environmental sphere in organism, function and environment, stating that *"*environment and organism, place and people are inseparable (Tyrwhitt 1947).*"* His formal training as a botanist and vigor for cross-disciplinary pursuits (Cumming 2002) likely aided in creating this view. Karl Marx saw civilization as created by man metabolizing nature through his labor (Swyngedouw and Heynen 2006). Ferráo and Fernandez (2013) saw a duality in the urban systems as *"*both a unique anthropogenic construct and simultaneously evocative of the most complex biological organisms.*"*

Naturally, there have evolved a spate of disciplines that rely on the organic metaphor of the city. These include urban ecology, landscape ecology, urban political ecology, ecological economics, political economy and political ecology. These related disciplines can either frame or augment the urban metabolism practice to analytically include social and economic processes.

Urban Ecology analyzes the city in ecosystemic terms. Central to this branch of study is the idea that man and nature are tied together in the same system (McDonnell 2011). Traditional ecology has always dealt with the flux of energy and matter within a natural system, (McDonell 2011). This is by definition an examination of the system's metabolism. However, initial definitions of ecological studies conceived of man and nature as separate, confining investigations to the realm of "untouched" nature (McDonell 2011). As "untouched," nature became more and more rare, the influence of man on nature had to be acknowledged (McDonnell 2011). From this perhaps unfortunate truth, the discipline of urban ecology emerges. It acknowledges both the role that humans and human created environments play in the larger environment. With the introduction of urban metabolism, there comes to be thought that not only is there ecology *in* the city but there is ecology *of* the city (Grimm et al. 2000, 574). In this combined discipline, both natural and social science disciplines are drawn upon to understand the urban ecosystem. This includes understanding its metabolism (McDonell 2011).

Landscape Ecology broadens the scale of urban ecology. A criticism of urban ecology is that it draws a boundary around the urban system, when in fact complex systems theory would argue for many interacting systems between the urban and natural ecologies. Landscape ecology examines these changing patterns and processes across a broadly defined "landscape." This includes manmade environments such as cities (landscape-ecology.org, 2015). A central inquiry of urban metabolism is the flow of energy and materials between the city and its hinterlands (Ferráo and Fernandez 2013). In this way urban metabolism is a landscape ecology investigation into the relationship between two distinct landscape patterns and their related processes.

Political Ecology looks at the political influences within the ecosystem, in particular to investigate ways to become more sustainable (Robbins 2004). Robbins (2004) offers the example of game populations across the African savannah, in particular between Tanzania and Kenya, where game populations are notably lower in Kenya. While ecological studies are decidedly apolitical, political ecology acknowledges that political constructions like the border between Kenya and Tanzania do matter (Robbins 2004). Characteristic of this field, though not definitive of it, is a concern with global environmental justice issues and a proclivity toward indigenous methods of environmental management (Robbins 2004). This discipline brings the social aspects, both cause and effect, into the urban metabolism question.

Urban Political Ecology looks not only at the political realm but a broad range of social landscapes and processes and how they create "urban natures" (Swyngedouw and Heynen 2006). In this school of thought, "urban natures" and the human actors within it are no less natural than the untouched wild (Swyngedouw and Heynen 2006). Indeed, a primacy is given to the study of manmade or socio-political metabolisms as agents which in turn enacts natural metabolisms and then creates and recreates inequitable urban natures and systems. Consider Swyngedouw and Heynen's conclusion regarding sustainability when the urban environment is conceived of as a new nature. "…There is no such thing as an unsustainable city in general. Rather, there are a series of urban and environmental processes that negatively affect some social groups while benefiting others" (2003, 901). The particular slant of Marxist urban political ecology is explicitly focused on these inequities and how political processes mobilize natural processes to perpetuate and expand these inequities (Swyngedouw 2006).

Both political ecology and urban political ecology have been critiqued for ignoring ecological processes as having their own agency or effect back on "urban natures (Nygren and Rykoon 2008, 768)." This critique may not be unfounded. If we look at Stuart Oliver's examination of the historical metabolism of the River Thames, the author, in perhaps a great academic feat, analyzes the personality traits of two commissioners of the Thames and how they "metabolized" the Thames through series of lochs and dams. That is the extent of the river in this discussion. It is an object upon which a process happens. The river owns its processes—essentially its ecology and the intrinsic value thereof is not considered. Thus, this school of thought can give insight to the agents that control and govern the metabolic processes, but a sustainability effort must keep the ecological focus in sight. Spaargen, Mol, and Bruyninckx (2006) have attempted to find a balance in between the social, political, and environmental interplays. They begin with environmental flows in material terms, waste and CO2 being particular examples which cross traditional political borders (Spaargen, Mol,and Bruyninckx 2006). They also analyze how these flows are directed by political and social processes and how these flows in turn shape new emergent governances (Spaargen, Mol,and Bruyninckx 2006).

Industrial Ecology is often mobilized as a method of design in manufacturing processes where the goal is to mimic natural processes, particularly with respect to waste reduction and efficiency (Graedel and Allenby 2003; Frosch and Gallopoulus 1989). Graedel and Allenby describe it in terms of design, however they encourage broader application (Graedel and Allenby 2003). Hollander (2001, 3) provides an excellent breakdown of the scales and practices of industrial ecology: "…industrial ecology operates on a facility/firm level through product policy; industrial ecology operates on an inter-firm level through industrial symbiosis; and industrial ecology operates on a regional/global level through more holistic watershed change thinking." Hollander (2007) provides an eco-industrial park model as a viable example of industrial ecology at the inter-firm level. Ferráo and Fernandez (2013) on the other hand, adopt the broader "watershed change" interpretation and nestle their methodology and prescription for urban metabolism within the "metaphor" of Industrial Ecology. They state that "…industrial ecology provides a vision for a paradigm shift that may bring our society closer to sustainability (2013, 8)."

From its origin the metabolism metaphor was designed to assess the physical health of a city. There are robust albeit labor intensive tools available to assess that physical health. But the physical health construct alone is too strict to assess the other dimensions that create a healthy city and to assess the energy external to the city including those between hinterlands and between other cities. Other disciplines and their related dimensions , methods, and metrics need to be incorporated into constructing an approachable metabolism framework and study.

Urban Metabolism Methods.

Assessing the metabolism of a city is not a uniform endeavor. There are numerous techniques with different resultant metrics that are appropriate to different scales and issues. The organism and ecosystem metaphors of urban metabolism serve to define an inter- or intra- scale of analysis. Those analytical tools which analyze what the city as a whole takes in and disposes, such as bulk material flow analysis or ecological footprinting, rely more on the city-as-organism metaphor. The analytical tools that track materials and processes within the city, such as input-output tables, rely on the ecosystem metaphor. Some tools such as Substance Flow Analysis can function at both levels.

Material Flow Analysis (MFA) is one of the tools most often used to develop and understanding of city's metabolism. MFA examines the material flows into and out of a system and by inference the condition of the external systems, the stocks accumulated within the system, and the relation between processes within the system and the material flows (Hendriks et al. 2000, 314). There are several ways of carrying out material-flow analysis, depending upon the scale and granularity needed. The first of these is bulk material flow analysis. This measurement is concerned with the total of a material or material type entering a system and its throughput of it out of the system—either as waste or as another product. This analysis can provide useful indicators of the economy as a whole.

Eurostat uses the following indicators to track the Bulk Material Flow of EU countries (ec.europa.eu, 2015)

- *The physical weight and raw material equivalents (RME) of materials (excluding water and air) available to an economy*
- *Domestic extraction from the natural environment*
- *Physical imports into the economy*
- *Direct material input (DMI) is the input all materials can be used in economic production and consumption = Domestic extraction + Physical imports*
- *Physical exports other economies*

- *Domestic material consumption (DMC), measures the total amount of materials used by an economy = Domestic extraction + Physical imports - Physical exports = Direct material input - Physical exports*

Substance Flow Analysis (SFA) is a more granular MFA tool that tracks particular, usually toxic or rare, substances of interest (Ferráo and Fernandez 2013). The substance path is tracked through given geographies and exchanges through manufacturing and economic processes (Ferráo and Fernandez 2013). SFA has been used to evaluate the consumption of particularly rare materials and predict their scarcity or to evaluate the need for sinks of toxic or unrecyclable materials (Brunner 2012). Considering that SFA is concerned with tracking a particular chemical or element, it has a certain accountability built in (Brunner 2012, 294). The substance in question cannot just vanish and the equations have to balance (Brunner 2012, 294). This is of course theoretically true, however, difficulties in finding data on a substance level can interject uncertainties. (Brunner 2012, 294)

Emergy – Howard Odum (1983) introduced the concept of "emergy" which utilized energy fluxes as a common measurement amongst diverse systems and diverse methods of characterizing systems across disciplines. In his methodology all systems could be characterized by energy flows and mapped via a common diagrammatic language(1983). Materials, information and currency could all be considered as sharing the same flow characteristics and an energy equivalent (H. Odum 1983). Odum (1983) employed solar equivalents, which is sensible considering it is the primary source of energy on this planet. His characterization of energy flows distinguished qualities of energy and related them inversely to quantity (Odum 1983). This implies that ultimately things are linear and end in a heat sink. Even in modeling economic transactions through energy, the transaction costs can be seen as this dissipated loss. This model also included feedback loops of higher quality energy returning to the system (1983). While not widely adopted the concept of a common measurement and analytical map can be important as metabolism studies expand (Mostafavi et al. 2014, 55).

Economic Input-Output Tables mathematically describe the inputs and outputs of various economic sectors and an employ a linear relationship between them (Ferráo and Fernandez 2013). Using this tool provides an overview of processes and flows within the city and can be used to estimate how activity in one sector draws on the inputs and affects the outputs of another (Ferráo and Fernandez 2013). For example, the construction industry draws largely upon the power generation and supply; iron and steel mills; cement manufacturing; and oil and gas extraction sectors of the economy. Increased activity in these the construction sector will result in increased activity and hence increased inputs and outputs, in these related sectors.

Since Wassily Leontief first created economic input out tables and with them crafted a Nobel Prize winning model of the U.S. Economy (Hendrickson, Lave, and Matthews 2006), more dimensions have been added to the tables to expand their capabilities. Physical input/output tables comprise a set of these expanded tables, basically substituting physical materials in place of monetary values (Ferráo and Fernandez 2013). As such a physical input output table uses the economic input output table framework to conduct material flow analysis.

The Economic Input Output – Life Cycle Analysis table is a physical table that accounts for environmental effects. The initial inputs from nature, such as wood fibers or mineral ores, and the waste ouputs, such as CO2 or mercury, of each sector can be quantified and tracked across economic sectors (Ferráo and Fernandez 2013). The United Nations uses a standard system, the System of Integrated Environmental and Economic Accounting (SEEA) for tracking natural resources and wastes in economic terms (Ferráo and Fernandez 2013). In this method there are four principal "accounts:" pollution, energy and materials; environment protection and resource management expenditure accounting; natural resource asset accounts; valuation of non-market flows and adjusted aggregates. As these tables are structured similarly Economic Input-Output Tables they can form a illustrate the relationships between environmental and economic value. (Ferráo and Fernandez 2013).

The Carnegie Mellon institute provides an online Economic Input Output – Life Cycle Analysis tool at www.eiolca.net. It is an operationalized input/output table and can estimate sector-to-sector effects, including increases in energy consumption and outputs of pollutants (Hendrickson, Lave, and Matthews 2006). As an example, $8.9 billion dollars (the 2007 value of new commercial and institutional construction in Massachusetts) (US Census, 2014) of nonresidential commercial and health care structures produced the following greenhouse gas output:

Sector	Total t CO2e
Nonresidential commercial and health care structures	1,920,000
Power generation and supply	988,000
Iron and steel mills	374,000
Cement manufacturing	327,000
Oil and gas extraction	222,000

With regard to input/output tables, one could argue that their generic nature would fail to capture locational nuances. Presumably, construction in Hawai`i, which is dependent on both imported fuel and building materials, would have a higher carbon footprint than in Oregon, which can rely on local sources of materials. Certainly there are degrees of specificity that could be programmed into any input/output table. As an example, the Carnegie Mellon EIO-LCA tool allows you to build custom tables (wwweiolca.net). The trade-off is of course time and effort. The Carnegie Mellon tool represents the low- effort, low-accuracy end of the spectrum: the opposite end is Life Cycle Analysis.

Life Cycle Analysis is a micro-economic and process focused effort which tracks a product from cradle to grave (or more ideally to cradle) and attempts to account for its environmental effects through each process (Ferráo and Fernandez 2013). A complete and thorough Life Cycle Analysis of most major products is practically impossible due the complexity of many individual components (Hendrickson, Lave, and Matthews 2006). But just as input/output tables can be scaled up in complexity, Life Cycle Analysis can be simplified. The Society of Environmental Toxicology and Chemistry and the Environmental Protection Agency have built the research which formed the International Standards Organization's prescription for an LCA method (Hendrickson, Lave, and Matthews 2006). Critical in this method is choosing the scope of the study. Conducting an LCA of a generic American car, where the investigation was bound to the analysis of major components and overlooked transport, took two years and cost eight million dollars (Hendrickson et al., 2006). Conducting a reasonable LCA study then involves putting reasonable bounds around the process (Ciambrone 1997) and trusting that those bounds will provide sufficiently accurate and detailed information. The proper information can lead to valuable insights. A California State Polytechnic assignment by three teams of students on "paper vs. plastic" bags led to the counterintuitive finding that the petroleum based plastic bag had less impact than the “natural” paper bag (Ciambrone 1997). Thus, LCA can be deployed at proper scales and find information useful in redesigning production processes, making informed consumer decisions and estimating future material stocks and the need for future sinks (Ciambrone 1997).

Life Cycle Activity Analysis (LCAA) is a hybrid tool developed by Freire, Thore and Ferráo, combining *activity analysis* and *life cycle analysis*. The neoclassical economic tool of activity analysis aims to optimize production processes and maximize profit. In LCAA, environmental impact metrics considered in life cycle analysis are added into the model (Friere, Thore, and Ferráo 2001). A typical life cycle activity analysis would work with three types of goods: primary goods (natural resources or materials), intermediate goods and final goods or outputs (Ferráo and Fernandez 2013). LCAA adds in environmental dimensions through the inclusion of what is called “environmental goods,” but really accounts for “environmental bads,” such as pollution and sinks (Friere, Thore, and Ferráo 2001). Accounting for these environmental impacts allows a life cycle activity analysis to optimize the process with regard to environmental impacts and maximize the environmental good. In a cross disciplinary context, LCAA takes an industrial tool and develops it into an industrial ecology tool (Ferráo and Fernandez 2013).

Ecological Footprinting is one of the more familiar and broadly used sustainability metrics (Venetoulis and Talberth 2008, 442). The metric assesses the amount of productive land and water needed to support the city and land to serve as sinks to take in its waste (Ferráo and Fernadez 2013). The further details of how to arrive at that footprint are subject to intellectual debate (Venetoulis and Talberth 2008). For instance, there are equivalency factors used for differing types of land that is based on agriculture land (Venetoulis and Talberth 2008, 443). The basis for that factor is worth questioning, as well as the basis for that which is included in the footprint (Venetoulis and Talberth 2008, 444). For example, Venetoulis and Talberth (2008) argue that the footprint metric should include space for biodiversity . There is no doubt that methods can always be improved, but the strength of the ecological footprint is in these alleged weaknesses (Ferráo and Fernandez 2013). It is not a number that is bogged down in details, but a simple, readily comprehensible and compelling number. Consider the calculation that currently we overshoot the planets’ biological capacity by a factor of 1.23 (Venetoulis and

Talberth 2008, 443). Consider further that if all 7 billion of the Earth's population lived in the same fashion as the U.S., we would need just over four Earths to make that possible (Krulwich, 2013). The simple figure is compelling. It may contain inaccuracies and lack a detail that could lead to actual policy, it can frame a debate and frame it in terms of holistic resource-oriented sustainability.

Santa Monica, Calif. measures its footprint as part of its sustainability indicators. In 2000, the city had a footprint of 2,747 square miles compared to its actual area of 8.3 square miles (www.smgov.net). Obviously Santa Monica cannot simply go out and acquire an addition 2,739 square miles and so it looks to internal policies to reduce its footprint. The city has actually done this and the between 1990 and 2000 reduced its footprint by 5.7 percent, but notes that it is still 16 acres per capita above the Fair Earth Share. This demonstrates that the measurement can also provide a ready assessment of overall sustainability and global equity.

Qualitative Tools and Metrics.

By their very nature there are few analytical tools to assess qualitative aspects of urban metabolism. Newman and coworkers published a State of the Environment report for Australia in 1996 in which he proposed an "extended metabolism," which included livability indicators of "Health, Employment, Income, Education, Housing, Accessibility, Urban Design Quality and Community." Livability continues to be a subject of the State of the Environment report in 2011, however, some of the indicators (employment, income, accessibility and education) have been dropped and indicators such as water quality, air quality, transport, noise and natural environment have been added.

EcoBUDGETS

EcoBUDGET is a tool developed by ICLEI to manage natural resources in the same manner that financial budgets are managed. Similar to fiscal budgets, a budget cycle consisting of the following is prescribed: An environmental resource budget is prepared based on the current baseline environmental situation; Management initiatives and strategies are put in place to meet the EcoBUDGET; At the end of the cycle the EcoBUDGET is reconciled (ICLEI, 2016). The *Managing Urban Europe 25* Project had its 25 "city partners" assess the current available environmental management systems (Salonen, 2009), including EcoBUDGET. The EcoBUDGET

tool was the highest ranking and the only one that was thought to be scalable to a regional level (Salonen, 2009). The system does seem to be an effective policy tool, particularly in terms of accountability and adaptability, however it would still be dependent on an informed baseline budget since the budget officer needs to understand connections between systems in order for effective budget reconciliation to occur.

Computer Models

In a 1949 conference on Activity Analysis, Marshall K. Wood and George B. Dantzig recommended that in order to keep track of the numerous calculations comprising their model of the economic sectors , "all necessary information and instructions be systematically classified and store on magnetized tapes in the 'memory' of a large scale digital computer (1951, p. 17)." We can now access on-line models preprogrammed with data that can in seconds calculate beyond what the Wood's and Dantzig's program could compute. Perhaps nothing has progressed as fast as computing power, so it is no wonder that computer simulations are pursued to evaluate and predict complex urban systems.

In terms of flows, the majority of systems available today is focused toward transportation or to a lesser extent, energy modeling. It also relies on some accepted economic model to simulate behaviors and frames this in a modeled layout of the city. Some, such as UrbanSim, have progressed to account for more complex parameters (Wadell 2002). However, numerous factors—climate, technology and natural forms—should be taken into account as well as their linkages (Mostafavi et al. 2014, 62). Said links would then measure numerous other flows, some of the more critical of which would be water, waste and nutrients (Mostafavi et al. 2014, 62). As such, many urban modelling programs - robust as they may be—cannot accurately predict outcomes of various policy choices (Noth, Borning, and Wadell 2003).

Online Tools

MIT's Urban Metabolism Group created an online tool that can estimate, map and report the population density, material usage, and energy use within the larger American Cities. The tool uses data from the U.S. Census, methods from the Metropolitan Area Planning Council and the Texas Transportation Institute, and by third party via zip code energy estimates (www.urbmet.org). The results are, of course, rough. In investigations of the tool, it was easy to navigate and parse down to selected areas, however it froze when attempting to generate reports on selected areas. Lacking context, it is difficult to make useful interpretations on the numbers, however the comparison ability of the tool helps give this context. It is surprising to see that the affluent Boston neighborhoods of Beacon Hill and the Back Bay have similar energy and material consumption per capita to the more marginalized community of Roxbury.

Portland State University in partnership with the US Forestry Service has developed an online tree canopy assessment and planning tool. The number of cities included is limited, 13 but for those included cities you can map and assess tree canopy, heat islands, air quality and population characteristics (http://map.treesandhealth.org/). The tool can then estimate the amount of trees of a given size needed to reach various goals within selected neighborhoods. This tool is not specifically a metabolism tool, but it does demonstrate the type of platform on which a metabolic analysis could be dispatched.

Engaging the Tools

The idea of metabolism invokes the idea of health both in terms of a body and in terms of a body and an ecosystem. It would follow then that the goal of planning within a metabolic framework is to create a healthy urban ecosystem. It is easy to look at many of our cities and relate the terms of an unhealthy metabolism within an organism; obesity in the form of sprawl; clogged arteries of traffic; a buildup of toxicity in the cells. Health has also been used to describe the desired state of ecosystems and other complex constructions such as the economy and communities, however the health of these systems do not draw such ready parallels as that of functioning body. The International Society for Ecosystem Health founded in 1994 (Rappaport, D.J. et al, 1999) aimed at formalizing ecosystem health as a discipline. A review of the ISEH's journal "Ecosytem Health" shows attempts to define the concept and field of study. Various key indicators and qualities such as "diversity" (Rappaport D.J. 1998, 1), "the ability of the ecosystem to maintain and renew itself (Bertolo 1998, 33)," or "maintains its organization and autonomy over time (Patil 2001, 308)," appear from their first issue in 1998 to its last in 2001. This fledgling discipline had to defend itself against criticisms of being too broad and proposing a one size fits all solution (Rappaport D.J. 2001). Whether in response or of their own prompting, ecosystem health practitioners proposed indicators appropriate to specific environments including the manmade and frameworks for selecting indicators (Bertolo, 1998)(Patil 2001). Urban metabolism offers a refined method of selecting these indicators and defining the relationships between them, however the question of what is a healthy urban metabolism still remains. Through an ecological lens, the health of the city and its urban ecosystem would rely on the same criteria as do the traditional defined natural ecologies: the ability to sustain its functions (Vale and Vale 2013). There are available global parameters of planet viability that have been established such as the 80x50 carbon reduction goal and the Fair Earth Share ecological footrprint[1] (Vale and Vale, 2013)for benchmark indicators of an ecologically healthy city. However there are many ways a city can go about achieving these benchmarks. The carbon benchmark can be achieved by reducing fossil fuel use, increasing efficiency, or increasing sink capacity . The health of the city would also include equally complex health measures of economy and community. Thus a metabolic study of these flows and its subsequent initiatives needs to be carried out within a vision of the sustainable city. The goal metabolic analysis is to discover the system interventions and the related indicators and standards that will create a stable urban ecosystem, able to maintain and renew itself over time(Ferráo and Fernandez 2013).

It is important to note that engaging every analytical tool discussed here and even those not discussed here will not result in a complete understanding of a city's metabolism. Such a goal is both unrealistic and unnecessary. Several scholars including Donella Meadows and Ferráo and Feranandez cite the dynamic nature of cities and flows changing with time. The understanding of a city's metabolism must grow at the same time that policy and management strategies are deployed. Meadows and Marshall (2001) metaphorically constructs this as "dancing with systems." Ferráo and Fernandez (2013) create a more rigorous construct of a Drivers, Pressures, States, Impacts and Response feedback model. The Drivers are social and economic actions and constructions, commonly some form of human consumption. These in turn create Pressures on the environment such as intense resource use, which changes the State of the environment, such as created a now denuded forest. This lessened state of the environment will have an

[1] Vale and Vale calculated this to be 1.7 global average productive hecatres (gha) (2013). In comparison they calculate the ecological footprint of Vancouver to be between 4-7gha and Santa Monica estimates its own footprint to be 8.66 hectares (City of Santa Monica 2015)

Impact on society, such as less available water and in some way we must Respond. The response can be to any point in the model, to lessen the Drivers by limiting consumption, to lessen the pressures by limiting the type of consumption, improve the State of the environment, or attempt to lessen the Impacts. Understanding the metabolic flows of a city helps choose the right response and trace its effectiveness.

The more appropriate goal for a metabolic study is, "What do I need to know about my city?" Understanding this question in of itself is an ambitious planning undertaking, but it is the one that is regularly answered through a city's master plans.

Chapter 3: Literature Review

The analytical methods described in the previous section would each on their own discover a particular aspect of the city's metabolism such as quantifiable totals of energy or water, variations within the flows as the move through city, or the pathway of a particular substance. A city seeking to form a sufficient—not to be confused with complete— understanding of its metabolism needs a framework into which to place these various scales of analyses together. This literature review will describe the state of urban metabolism as a government practice. This will include:

- The current aims of urban metabolism, or, "What problem(s) is urban metabolism trying to solve?"
- The arguments for engaging in urban metabolism studies, or "Why is urban metabolism the best way to solve those problems?"
- The proposed frameworks for incorporating urban metabolism into city policy, or, "How does one go about doing a metabolism study?"
- The areas of urban metabolism needing development for successful implementation, or, "What is right now stopping us from carrying out a metabolism study?"

The investigation into the literature begins with Paulo Ferráo and Johnathan Fernandez's 2013 book "Sustainable Urban Metabolism," which reviews related disciplines and key advances in methodology.   Studies and authors commonly referenced were reviewed and introductory texts to the related disciplines were researched and reviewed. A concise anthology of urban metabolism studies can be found in Yan Zhang's 2003 article in Environmental Pollution, "Urban metabolism: A review of research methodologies." The studies named in this article were also reviewed. In addition to Abel Wolman who founded the discipline and Paulo Ferráo who co-wrote "Sustainable Urban Metabolism", commonly mentioned authors were Christopher Kennedy, Eugene Odum, Paul H. Brunner and Elizabeth Rappaport. Additional works by these authors were also explored.

Aims of Urban Metabolism

In discussing the aims of urban metabolism, it is appropriate to first revisit in more detail the problem its proponents are seeking to address. The basic problem has already been defined on a large scale for humanity: Our current consumption levels are unsustainable, given our current technology and the biocapacity of the planet (Venetoulis and Talberth 2008, 443). A number of authors make the case that the best place to address our global unsustainability is in the city, citing the current impact and project growth. Cities already use 67 percent of the primary energy and generate nearly 71 percent of greenhouse gas (GHG) emissions globally (International Energy Agency, 2008). The issues that prompted Wolman's original study into Urban Metabolism—deteriorating air and water quality—are still with us today (Kennedy, Cuddihy and Engel Yan 2007, 44). Cites have been—and are projected to continue to—be the loci of population growth and hence population impact. In addition to population, cities also will grow in area. Conurbations will continue with urban sprawl, particularly in China and India (Martinez-Allier 2003, 47). Smaller cities will get bigger and will do so faster than larger cities (Mostafavi et al. 2014, 54). Further, cities with some exceptions are using more per capita, as Kennedy, Cuddihy and Engel-Yan discovered in reviewing a series of metabolism studies (2007). The projected scenario is one of bigger cities, more cities, and more impactful cities.

The exact nature of how and why cities are unsustainable is debated. Some authors see it as a matter inherent to physical form. Martinez -Allier (2003, 50) asserts that cities are too densely populated to be able to rely upon their own resources to be sustainable and notes that this is a "by definition" characteristic of the urban environment. Current urban consumption patterns certainly support this view as do several authors: Niza, Rosado, and Ferráo (2009), Kennedy, Cuddihy, and Engel-Yan (2007), Ferráo and Fernandez (2013) all describe cities as drawing resources from and disposing wastes to their hinterlands. Hodson and Simon (2014), say cities "are open systems that will always require sources (resources) and sinks (for wastes) that are located outside their borders."

But a city that relies on its hinterland could be sustainable. Haughton (1997, 190) identifies four types of cities; re- designing, self-reliant, externally dependent, and fair share, each of which can be sustainable. The self-reliant city may be the far-end game concept that many sustainability planners strive for, but the externally dependent city, one which has access to hinterlands with sufficient biological and regenerative capacity, is also sustainable (Haughton 1997, 192).

Haughton (1997, 194) leaves it up to city's inhabitants to decide which form of sustainability they should pursue, however, most scholars find the hinterland city model problematic (Broto, Allen and Rappaport, 2012, 854). First, how many cities have this luxury of readily available hinterlands? Most cities are surrounded by suburbs and exurbs which cross into other jurisdictions. Brunner argues that this arrangement leaves the city vulnerable. In this relationship, Eugene Odum (1993) characterized the city as a parasite on the biosphere, relying on natural systems for life support. It should be mentioned that Odum (1993) continued this metaphor to include coevolution, where the parasite would not eliminate its host and, in doing so, itself. The relationship would eventually evolve to be mutually beneficial, and this was where humanity needed to proceed in its relationship to the biosphere (E. Odum 1993). Proponents of the city, such as Glaeser, may take offense at the parasitic metaphor; however, it still holds (Tarr 2002, 511). Virtually all cities are dependent on their hinterlands (Niza, Rosado, and Ferráo 2009, 387).

The city-hinterland relationship necessarily involves a structural inequity (Broto, Allen, and Rappaport 2009,) as the prosperity of the city comes at the expense of the hinterlands. Daly and Farley (2004) connects this inequity to the nature of the economy which, "is seen as embedded in an "ordered system for transforming low-entropy raw materials and energy into high entropy waste and unavailable energy." Particularly it is that economies are predicated on growth which requires accumulating stocks of capital and higher throughputs of resources (Broto, Allen, and Rappaport, 2012, 854). Thus, as the city's prosperity increases, so does its environmental load on the hinterlands (Martinez Allier 2003, 43). Molotch's (1995) fairly durable theory of the city as a "growth machine" would then predict that cities will constantly push more and more environmental loads to an ever expanding hinterland.

In addition to exchanges with the hinterlands, processes within the city are also unsustainable. Largely this has to do with questions of equity and how materials, both beneficial and harmful, flow and accumulate in the city. Mostafavi (2014) cites social equity issues as important for planners to understand. Brunner, Cuddihy and Engel-Yan (2007) assert the large material extraction of cities leads to problems in just access to resources.

Retooling, reimagining and even reinventing cities to be sustainable has international attention. Newman (1999, 219) points out that, "awareness of the need to include cities in the global sustainability agenda, is now universally recognised by environmentalists, governments and industry," and goes on to list The Organization for Economic and Cultural Development, the European Community and even the World Bank as global organizations with sustainable cities programs.

Where most scholars may see these efforts as lacking is in the holistic and systemic applications. Cities cannot continue to be linear reactors, but must instead look to increase self-sufficiency and close resource loops (Broto, Allen and Rappaport 2012, 853) Hodson, Marvin, Robinson and Swilling (2014) point out that reducing waste and improving efficiencies have great potential, but this can only do so much in the face of a growing population. In essence, it will only delay the inevitable overshoot of resources. In essence the system of how a city obtains, uses, and disposes resources needs to be redesigned.

Capabilities of Urban Metabolism

Clearly urban metabolism proponents and scholars see the practice as the ideal conceptual framework and analytical methodology to holistically address the sustainability of cities. Statements emphasizing the need for cities to gain a holistic and measured understanding of their metabolism are repeated throughout the literature.

If we are to truly make gains towards achieving sustainability in local communities, then future environmental and resource policies should examine environmental and resource management systematically in order to develop effective long-term regional solutions (Hendriks et al. 2000, 312).

Based on the assumption that the characterization of the physical nature of human economy is vital for understanding the sources and full nature of impacts of urban systems upon the natural environment and that effective strategies toward sustainable development will rely on understanding the interaction between economic activities and their physical dimension as represented by material flows (Ferráo and Fernandez 2013).

One of the best ways to approach the sustainability of a city, a region, or a country involves analyzing it much as one would a living organism, by characterizing its metabolism (Niza, Rosada, and Ferráo 2009, 387).

But in large part the literature on urban metabolism does not make the connection of why this type of systemic understanding is so critical to sustainability. It is just understood to be so. Any argument as to why a city should be paying attention to its metabolism is usually made in the introductions and consists of familiar statistics relating to how municipalities overshoot global capacity and the impact of cities in this overshoot.

There are nonetheless salient points to be gleaned from the arguments for adopting urban metabolism as a practice. Broto, Allen, and Rappaport (2012) see power in the way urban metabolism can shift perceptions. Thinking of the city in terms of flows can create new understandings and conceptions of it beyond a physical construct but as a biophysical and socioeconomic entity. There exist in the city "arrangements in which some forms of flow, or of "being in flow," that are "prioritized and/or marginalized …" and Material Flow Analysis could be powerful tool for community action to correct his marginalization (Broto, Allen, and Rappaport 2012, 851). In this view, solutions need not necessarily be structural, but can be focused on changing flows.

Kennedy is one of the few authors who, writing alone and with co-authors, lays out the arguments for the benefits of urban metabolism studies. Kennedy and Hoornweg (2012, 780) argue that urban metabolism should be a mainstream practice stating that, "understanding energy and material flows through cities lies at the heart of developing sustainable cities." Their argument maintains that there is sufficiently robust methodology and academic study to allow for cities to quickly be collecting metabolism data (Kennedy and Hoornweg, 2012, 780). The practical application of such data would be in developing meaningful holistic sustainability indicators and modeling the effects of policy decisions and form the basis of sustainability planning (Kennedy, Pincetl & Bunje 2011, 1996). Accepting, again, that a city is dependent on a global hinterland with an increase in the city's metabolism (i.e. consumption) would likely come increases in loss of farmland, forests, and species diversity, as well as burden infrastructure and increase pollution (Kennedy, Cuddihy and Engel-Yan 2007, 56). Understanding the city's metabolism and the capacity of associated resources can inform policy decisions to avoid depletion (Kennedy and Hoornweg 2012, 780) and enable the development of policy, management and technology that would reduce waste and pollution and eventually begin closing resource loops.

Continued monitoring of a city's metabolism allows assessment of the city's development track (Kennedy, Cuddihy & Engel-Yan 2007, 44). While there have yet to be longitudinal studies of a city's metabolism, Kennedy, Cuddihy and Engel-Yan (2007) have assessed the case studies from eight different cities: Vienna, Lisbon. Accounting for intervening variables such as affluence, climate and development, they found a general trend of increasing metabolism and also an accumulation of processes (Kennedy, Cuddihy & Engel-Yan 2007, 56).

Challenges in Urban Metabolism

Glaeser calls the city, "humankind's greatest invention" (2011). It is also our most complex and dealing with that complexity is the great challenge of urban metabolism (Ferráo and Fernandez 2013). The complexity of urban systems is not just one of a large and intricate system that, if hacked away through enough analysis, can be broken down and understood. Urban systems are layer upon layer of complexity in multiple interacting dimensions.

Ferráo and Fernandez, in a dedicated chapter of "Sustainable Urban Metabolism," discuss the many types of complexity present in urban systems. These include changing spatial attributes, varying temporal scales, resource, material and energy flows, political, institutional and cultural frameworks, population and demographics. Mostafavi et al (2014) repeatedly points to the importance and challenge of determining how the systems and attributes interact with each other. All of these attributes can layer over one another. Changes in demographics, can force changes within the spatial layout and quality of a city and these shifts may have different effects over different periods of time. Effect of diverse land uses and urban forms on actual resource consumption has not been adequately studied or modeled (Ferráo and Fernandez, 2013).

A critical goal of urban metabolism is to understand flows into and out of the city. This brings in the complexities of other biospheres and determining the location and nature of the interface between the boundaries of the urban and non-urban, the manmade and the natural, the infrastructure and the ecosystem (Ferráo and Fernandez. 2013). However, the urban system that is bounded will ultimately differentiate the city from its hinterland, but the hinterland carries its own complexities. Rural ecologies serve as part of the city's hinterland but also have their own draws from other broader hinterlands (Ferráo and Fernandez 2013). Global hinterlands bring in larger questions of equity between the developing and developed world (Ferráo and Fernandez 2013).

Complexity of human behavior and choice is a persistent thorn in predictive sciences. Consider the ideology of neoclassical economics where assumptions of rationality and self-interest do not always hold true and in so limit the real world application. Interestingly, both Mostafavi et al (2014) and Ferráo and Fernandez (2013) approach the human behavior issue as one that is no more difficult to deal with than others embedded within the urban system. Both describe models, cellular automata, multi-agent models, fractal growth, neural networks, rule-based urban decision making, evolutionary models (Ferráo and Fernandez 2013) , discrete choice theory and disequilibrium in markets (Wadell 2002) that have been successful in replicating patterns of individual decision making (Ferráo and Fernandez 2013).

Practically all studies suffer from a lack of specific and/or reliable data (Niza, Rosada, and Ferráo 2009, 385; Ferráo and Fernandez 2013). A pioneering 1994 study of Bünz Valley, Switzerland had uncertainty rates of 20 percent due gaps in data, in particular, knowledge of product compositions (Niza, Rosada, and Ferráo 2009, 385; Ferráo and Fernandez 2013). To overcome this, Brunner and his team used economic tables to estimate values (Ferráo and Fernandez 2013). Brunner has since suggested using material flows as reliable metrics (2012, 11) but neglects to note what these metrics are. Eurostat methodology is prescribed both in a 2010 MIT conference (Kennedy and Hoornweg 2012, 780) and by Ferráo and Fernandez (2013). A 2003 material flow analysis of Hamburg by Hammer and Giljum used this methodology (Niza, Rosado and Ferráo 2009, 389). With regard to materal flow, Niza, Rosado and Ferráo (2009, 388) note that the throughput of a city can be difficult to correctly identify, particularly in the case of port cities which serve as hubs for distributions of goods. Friere, Thore, and Ferráo (2001) approach this problem in their study of Lisbon, Portugal and used economic indexes of purchasing power to estimate the throughput of goods. In analyzing previous metabolism studies, Kennedy and Hoornweg (2012, 781) find issues of questionable data with regard to specific air pollutants. Further creative methods to extrapolate data like that used by Friere or more data collection focused on metabolism will be needed to execute metabolism studies (Kennedy and Hoornweg 2012, 782) (Niza, Rosada, and Ferráo 2009). Forecasting this data gap into the future, Niza (2009, 387) and Brunner (2007, 293) all predict that the accumulated stocks of a city are both the city's largest potential resource base and pollutant source, but comprehensive information about these stocks do not yet exist. Overarching the concern with data quality and data availability is a question of selecting the relevant data sets.

In the 2014 article, "A New Urban Metabolism" author Elizabeth Daigneau mentions "big data" as one of the factors allowing urban metabolism to spread as a practice. There is no questioning the analytical computing capacity that can be applied to metabolic studies and that more data makes for better analysis. Using big data however is not a wide-reaching cure-all to the problem of data availability. There are sets of the best data out there that cannot be accessed due to privacy reasons. Every credit card sale is tracked and so it is possible to know nearly every material consumption in a city and there is the computing capability to analyze it. But this material is held privately and is proprietary. There are also privacy concerns to having an individual's purchases be public. Even aggregating data do not adequately shield this as the data can be analyzed and reverse-engineered to return to specific individuals (Gaff, Sussman, and Geetter 2014).

Ferráo and Fernandez are one of the few authors to recognize the difficulties in getting governments to adopt metabolic studies (2013). They identify the classical economics argument of unlimited wants and limited resources. Any given city already has to take care of infrastructure, health, record keeping and the diversity of residents assures a practically limitless diversity of needs (Ferráo and Ferenandez 2013). At the same time, there are limited budgets, employees and time (Ferráo and Ferenandez 2013). This makes understanding metabolism and enacting policies an expensive challenge in terms of money and/or opportunity costs (Ferráo and Fernandez 2013). Ferráo and Fernandez (2013) also identify the problem of lock-in. Cities are made up of large fixed objects, buildings, highways, and bridges that cannot be reworked without significant cost. Thus even a full knowledge of the city's metabolism may yield little useful policy. In addition, metabolism studies take time, while cities are under pressure to act, whether from the pressing quality of the situation or the nature of political cycles (Ferráo and Fernandez 2013). Therefore there is often the need to act without definitive information (Ferráo and Fernandez 2013). Arguing from the government-half of the equation, Zeemering (2009, 248) asserts that sustainability research should focus on what the term and practice means to government officials who carry out the policies.

A 2011 OECD report finds three major roadblocks to successful urban modeling; a diversity of methods, a disconnect between model makers and model users, and the fragmentation of research among different fields. Not surprisingly then, their call is for a standardized method and accounting across countries.

One somewhat bleak sentence from Ferráo and Fernandez (2013) sums up the challenges in carrying out a comprehensive urban metabolism study: "Considering the environmental and ecological consequences of urbanization while simultaneously accounting for resource demands of urban activities is a huge undertaking riddled with fundamental methodological questions and plagued by a lack of reliable information and high quality data. (2013)"

Suggested Practice

The idea of how to undertake an urban metabolism study is where most of the academic literature on the subject is focused. Much of it points to a need for standardization in methodology, framework and data collection in order to make urban metabolism a widely engaged in practice and comparable between cities. Case studies primarily focus on the first step of a metabolism study, accounting for flows, but a few have reached farther and been used for planning and policy analysis (Kennedy, Pincetl, and Bunje 2011, 1966). Further, the literature acknowledges the multidimensional complexity of urban sustainability and there are proposals of multidimensional frameworks in which to conduct urban metabolism studies.

Many authors have laid out overarching methodologies to successfully engage in urban metabolism: To construct a meaningful urban metabolism study. Hendriks (2000) has proposed that an urban metabolism study and subsequent policy include:

a) *Quantifying material flows and the growth of material stocks;*

b) *Assessing the consequences of flows and stock accumulation on several levels, namely environmental, economic, and social;*

c) *Controlling and shortening material flows (namely through dematerialization strategies, closing of materials cycles, and materials and energy source substitution) and considering sustainable development objectives*

Ferráo and Fernandez (2013) have constructed one of the more complete prescriptions for urban metabolism to date. Their methodology is very complete from data gathering through to implementation. It is also, perhaps necessarily so, very dense. The authors describe, intricately, several layers of structure to analyze and act upon urban metabolism data. At the base are the numerous methods they have assembled into a “toolbox,” characterized on three dimensions, Environmental, Social and Temporal. Each tool is then deployed in a matching layer of analysis. The layers they propose are:[2]

- Urban Bulk Mass Balance
- Urban Materials Flow Analysis

[2] A summary table of each layer and the proposed analysis can be found in Appendix 2

- Product Dynamics
- Material Intensity of Economic Sectors
- Environmental Pressure of Material Consumption
- Spatial Location of Resource Use
- Transportation Dynamics

Providing sufficient data in each layer ultimately constructs a relatively complete picture of a city's metabolism. The working understanding of a city's metabolism must then be put to use in some kind of policy or management form. Ferráo and Fernandez (2013) recommend doing this through predictive models that rely on system dynamics and a Drivers, Pressures, State, Impact, Response (DPSIR)[3] modeling framework in which to enact and refine new policy based on the urban metabolism data. Overarching this is the Industrial Ecology metaphor, which gives the general guidance to policy decisions to mimic natural processes. This creates a multi-dimensional, robust model which would be a challenge for any urban government to manage and deploy.

In addition, Ferráo and Fernandez (2013) propose a city typologies based on its metabolism. Four widely available independent variables of affluence, population, population density and climate are used to predict the consumption of key flows within the city: Total energy, total materials, electricity, water, fossil fuels, industrial minerals and ores, construction minerals, biomass and CO2 emissions. This has resulted in 15 types of cities ranging in patterns of consumption. The typologies can be used as immediate proxies in the interim of longer data gathering, as starting points for said data gathering, and as basis for comparisons between cities.

Ferráo and Fernandez (2013) are cautious to emphasize that the study be launched within an overall vision for the city and how it means to be sustainable. This should be taken as more than just a catch-all warning for the field of public policy, but rather as having a well-defined vision of the sustainable city will be essential in unraveling its level of complexity. Ferráo and Fernandez (2013) and Broto, Allen, and Rappaport (2012) invoke the field of systems theory (also called systems dynamics), as a way of unraveling the complexity of the city. The first thing to recognize

[3] A more detailed description of the DPSIR model can be found in Appendix 3

is that an attempt to understand the whole of the urban system is, “doomed to failure” (Ferráo and Fernandez 2013). In fact, one of the most celebrated systems thinkers, Donella Meadows, (2001) contends that systems cannot be fully understood. Systems dynamics, however, can help in the process of modeling questions (Meadows and Marshall 2001). The right questions lead to an understanding of the city that serves in achieving the vision. Broto, Allen, and Rappaport (2012) expand the uncertain nature of complex systems theory to the response and policy imperatives, stating that the goal is not designed stability, but a resilience to inherent instability.

Mostafavi et al(2014) also recognizes the need for a standardized metabolism approach and one that recognizes the interrelations of the various dimensions of urban sustainability. The critical dimensions of sustainability that they cite are measured in indicators, particularly: Land use, energy consumption, material flows, water and resources, and air quality, sectors of urban activities which enact metabolic processes, specifically residential, commercial, industry, education, government, transportation and open space. The these metabolisms then generate management issues such as, water and material consumption, sewage and waste production, energy use, emissions to the atmosphere and urban heat island effect. These metabolisms occur within a physical network of buildings and the spaces that connect them together . To that end, they propose an Integrated Urban Metabolism Analysis Tool (IUMAT).

IUMAT is premised upon a high-level model of urban metabolism that is basically uniform: A city takes in resources (food, water, land) and metabolize them through processes governed by the city’s unique characteristics (physical form, cultural practices) into livability (housing, culture, recreational space) and waste (sewage, grenn house gases). This leads to the conceptual model, based on the three-legged stool that the analysis of a city’s metabolism can be framed along an environmental-economic axis as well as an environmental-societal axis and the flux of materials and energy between these sectors.

The functional parameters for IUMAT are to provide data support, monitoring, feedback and comparative modeling for policy and management initiatives. Ultimately IUMAT redefines the urban footprint, uncovers trends of flows, helps to understand relationships between various dimensions of sustainability and provides a coherent structure for strategic planning. Further development updates on IUMAT were not available at the time of this writing.

Very few authors propose ways to bridge the knowledge gap between the highly detailed and complex study of urban metabolism and the broad knowledge needed by policy makers. Speaking strictly of substance flow analysis, Brunner (2012, 294) recommends Sankey diagrams to depict flow, but overall recommends, “the art of presenting SFA results should be further developed.” Hendriks (2000, 314) proposes workshops to policy makers and stakeholders in order to effectively communicate the results and interpretations of a MFA study.

Proposed Metabolic Framework

The majority of the literature in urban metabolism treat it as physical process, meaning that it is tracking the movement of a resource or substance. Still there is a significant acknowledgement in the literature that social processes should be included and many of the modeling tools incorporate the infrastructure of cities. The literature overwhelmingly looks at existing cities as linear reactors; It draws in resources from the hinterland, and subsequently disposes waste to a hinterland. Diagrams such as those in Figures 1a and 1b are common within the urban metabolism literature.

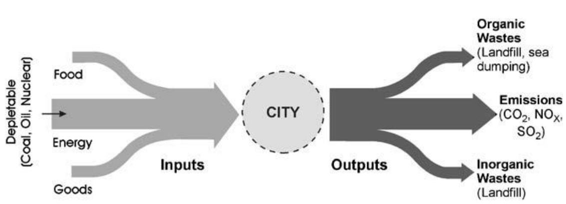


Figure 1a. High consumption linear reactor city from “Sustainability and the built environment at and beyond the cityscale” Doughty and Hammond, 2004

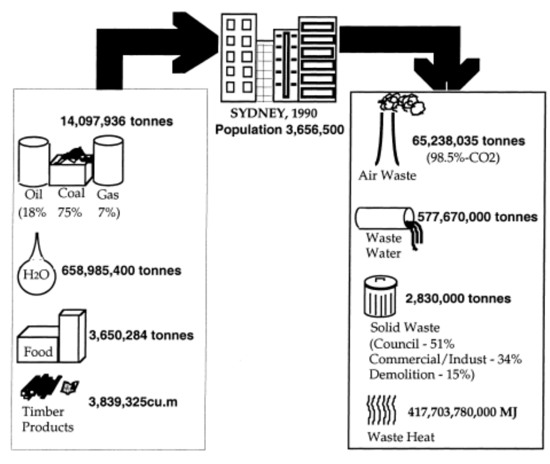


Figure 1b. The linear metabolism of Sydney from “Sustainability and cities: expanding the metabolism model.” Newman, 1999

Within the city is where the processes occur and the literature points to three primary type: 1.) Physical processes, such as the combustion of gasoline into energy, 2.) Social processes, such as the exchange of capital or political actions, and 3.) Structural processes, such as road networks, which create the physical and environmental parameters in which other processes take place. Graphically, a simple model incorporating these three processes is represented in Figure 2.

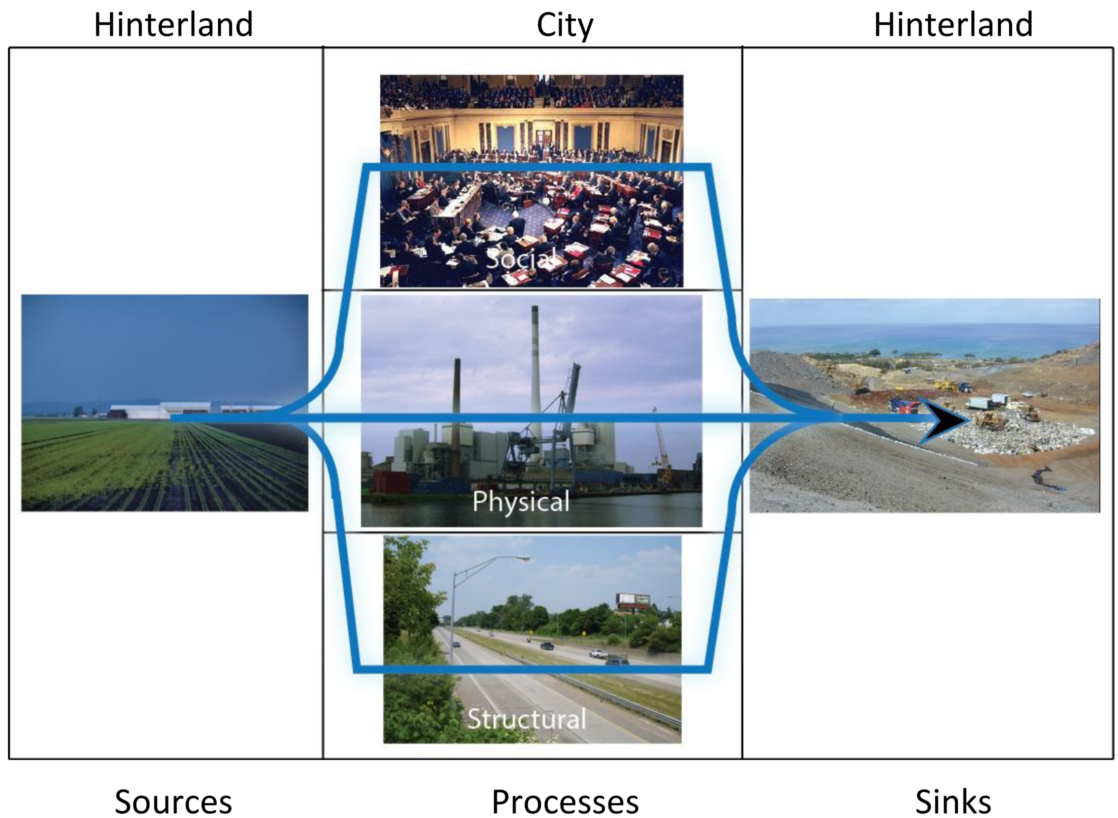


Figure 2. Metabolic framework used for plan evaluation. – Photos used: "Fields of Rain" by Michael Gil from Toronto, ON, Canada - Fields of RainUploaded by OSX. Licensed under CC BY 2.0 via Wikimedia
"Landfill Hawaii" by Eric Guinther - English Wikipedia, user-contributed.. Licensed under CC BY-SA 3.0 via Wikimedia Commons -
https://commons.wikimedia.org/wiki/File:Landfill_Hawaii.jpg#/media/File:Landfill_Hawaii.jpg

The literature also acknowledges that the defining boundaries between city and hinterland are by no means clear. Cities will sprawl into hinterlands, hinterlands today are global, and in some cases one city serves as another city's hinterland. As this thesis is examining city planning efforts the municipal boundary of the city will be the most relevant boundary to use. This is not to say the metabolic frameworks should automatically dismiss larger scales beyond their boundaries, but for the purpose of city planning the most readily affected processes are those within the municipality's jurisdiction.

Sustainability Planning Practice

There is little doubt that sustainability has made its way into the mainstream of governance and business. Zeemering (2009, 247) points to an “ever expanding” body of research calling for cities to rise to the challenge of sustainability. Ferráo and Fenrandez (2013) point out the 1,060 mayors who have signed the U.S. Conference of Mayors' Climate Protection Agreement.

Similarly, Brunner (2012, 293) finds ample evidence in programs that the study of urban metabolism is gaining ground. The Public Interest Energy Research Program in California (PIER), Sustainable Urban Metabolism for Europe (SUME) and the World Bank Eco2 all rely on a metabolism framework (Brunner 2012, 293).

However, a majority of research finds that while the concept of sustainability has taken hold within governance, there is little evidence that holistic “strong sustainability” has become widely practiced. Zeemering (2009, 249) observes that sustainability initiatives are more likely to be piecemeal and depend on instead on the applicability of the initiative. Others in the urban metabolism field doubt that such piecemeal programs are truly contributing to sustainability. In discussing the Integrated Urban Metabolism Tool, Mostafavi et al (2014, 54) theorizes that such programs likely have a net-positive effect on sustainability but their overall contribution is unknown. Ferráo and Fernandez (2013) also find that the majority of urban sustainability initiatives are not examples of strong sustainability, but rather created with incomplete knowledge of the urban and ecological systems they hope to effect. They do, however find potential in these disjointed initiatives forming a bridge to strong sustainability (Ferráo and Fernandez, 2013).

A concrete example of this piecemeal vs. systemic approach is given by Daigneau (2014) recounting an effort to plant a million trees in Los Angeles to combat air pollution. Ecologists calculated that that effort would increase water consumption by 5 percent. This is an exceptionally important consideration given the California drought and L.A. water crisis.

One of the broadest inquiries into sustainability practice was done by Kent Portney in 2009, in which he examined sustainability initiatives across government and found 45 cities with populations of 100,000 or greater had adopted “comprehensive” sustainability planning. The list includes not just the traditional early adapters of green ideology— such as Portland, Ore., or Boulder, Colo.—but former rust belt cities such as Cleveland, Detroit—and those found in the sprawling sunbelt—in Phoenix, AZ (Portney 2009).

The most widespread practices and issues addressed Portney found were:

- Smart Growth
- Land Use Planning
- Transportation
- Pollution prevention
- Energy and Resource Conservation
- Sustainability indicators
- Environmental Justice
- Gov't and organizational coordination

Portney (2009) did note that taken as a whole, these programs taken may or may not contribute to making the world more sustainable. He deferred answering that question. It should be noted that the eco-industrial park was included as a "smart growth" initiative indicating that there may be more industrial ecology roots in these cities than survey categories may indicate.

Indicators are a fairly-widely used method of sustainability investigation and tracking. Newman (1999, 223) compiled a listing of commonly used indicators with an eye toward expanding metabolism to include livability. He categorized them as follows:

a) Energy and air quality
b) Water, materials and waste
c) Land, green spaces, and biodiversity
d) Transportation
e) Livability, human amenity and health

With regard to indicators, Ferráo and Fernandez (2013) note the tension between generic indicators such as those proposed by ICLEI, and more customized lists which are over-expansive and lack useful hierarchy.

In 2010, the International City/County Management Association compiled a survey of more than 2000 local municipal governments on sustainability priorities and practices. The survey did not ask if "sustainability" was a priority, but rather if a set of eight policy issues were considered priorities. The issues were the environment, economy, social justice, climate change, green jobs, energy conservation, fair and equitable housing and public transit. The results were as follows:

Policy issues	Not a priority (% reporting)	Somewhat a priority (% reporting)	Priority (%reporting)	High priority (% reporting)
a. The environment	5.2	33.2	40.7	21
b. The economy	1.2	4.6	25.9	68.3
c. Social justice	20.2	41.7	29.4	9.2
d. Climate change	46.3	34.6	14.1	5
e. Green jobs	28.9	41.8	22.8	6.5
f. Energy conservation	2.9	27.5	45.7	23.9
g. Housing for all income groups	15.4	36.9	33.6	14
h. Public transit	31.8	33.9	25.4	8.9

Table 1. International City/County Management Association Local Government Sustainability Polices and Programs, 2010

All of these fit into one or more of the triple-bottom line categories of sustainability. But there is a clear priority placed on the economy. Consider that 94.2 percent of the responding municipalities rated the economy as either a priority or high priority and that the economy is the issue most reported as a high priority, by a factor of nearly 3 over the next highest issue (energy conservation). The next most important issue (both in terms of being a high priority and being either high priority or priority) is energy conservation. Using the term, "conservation" frames the issue as mainly an environmental problem. However, it has a significant economic dimension. Energy conservation is often justified in monetary terms of "cost savings" and "return on investment."

Reading slightly more into the nuances of the survey, the environment is the third-highest priority. However, the more specific environmental actions of green jobs and climate change are relatively low priorities. Generally, the survey paints a picture of municipalities looking to address environmental issues, but not necessarily sustainability issues.

Much of the case studies and analysis in urban metabolism have occurred in Europe, including the previously discussed Bunz Valley and Lisbon studies. (Niza, Rosada, and Ferráo 2009). Various studies into the metabolism of Vienna in the 1990s, using selected indicator materials, illustrated the relationship of Vienna to its hinterlands, predicted its resource needs given its current development track and found opportunities in its current resource stock (Hendriks et al. 2000). The findings of these studies are being used in Viennese strategic planning . A unique example is the neighborhood of Hammarby Sjöstad in Stockholm, Sweden, which was planned using a metabolism model (Broto, Allen, and Rapoport 2012, 853). It should be noted that the neighborhood was designed in a bid for the Olympic Games, which puts it outside the normal planning process (Iveroth, Johansson, and Brandt 2013, 716). The town uses less non-renewable energy, less water, and produces less ozone and global warming potential than its baseline counterparts (Suzuki et al. 2010). Overall it is more sustainable than traditional development, but falls short of its zero-net energy closed loop goals, largely due to an inability to change outside infrastructure (Iveroth, Johansson, and Brandt 2013, 718). One of its successes, however, was in establishing a closed-loop metabolism through digesting sewage into biogas which, in turn, powers the city's cars, thus repurposing the waste of one process to the inputs of another (Spiegelhalter 2010).

In North America, the inputs and outputs of indicator materials for greater Toronto were analyzed by Sahely, Dudding and Kennedy (2003) for a 12-year period using a wide array of data collected by various levels of the Canadian government and institutions. An important contribution of this study was to illustrate the potential of and deficiencies in existing data, as well as to demonstrate the city was getting more efficient per capita. In the U.S, Joel Tarr conducted a detailed historical study of the metabolism of Pittsburgh. He recounts water use, air quality and land use from 1800 and later. In doing so, he describes an arc of environmental degradation to improvement that is yet to be fully realized. In the wake of Hurricane Katrina in 2005, David Quinn working with John Frenandez (2007) used a metabolism model for housing construction in New Orleans with the goal of linking the "construction ecology" to other systems and establish an efficient industrial ecology . Ferráo and Fernandez (2013) did find some U.S. cities with sustainability plans: Austin, TX; Boulder, CO; Seattle, WA; Santa Monica, CA that serve as models for best practices, particularly in use of indicators. Venetoulis and Talberth (2008,

445) assert that a number of cities have engaged in studies of respective ecological footprints. These are some hopeful exceptions on tightly focused scales, but as recently as 2013, Ferráo and Fernadez found that sustainability indicators were still not taken into account in policy making. In 2014, Mostafavi et al found that there was still a need to develop a scientific method to holistically assess urban planning initiatives. Overall it appears that urban metabolism has yet to make its way into government-led urban planning.

Survey of City Planning

Given the presence of sustainability in everything from the United Nations Millenium Goals(UN 2015) to corporate charters and strategic plans, it's likely that any North American city plan would mention sustainability in some form. But are any of these cities engaged in strong sustainability? Or are they just hoping to piece together various, green initiatives? Review of academic literature points to the latter. Despite the claim that urban metabolism provides an ideal framework for sustainable urban planning, none of the literature reviewed cited a U.S. city that has engaged in an urban metabolism study. There have been academic studies of U.S. cities, such as that of Pittsburgh by Tarr (2002) and conceptual plans being put together by the labs of leading thinkers such as MIT's Urban Metabolism Group. But these works have not carried over into policy.

As mentioned in the objectives of this thesis, this section intends to investigate if urban metabolism is being used at all in city planning, the sustainability of those planning efforts and how readily an urban metabolism framework can be incorporated into city planning.

To accomplish this the sustainability and master plans of several North American cities will be examined within an urban metabolism construct and a sustainability construct and three metrics will score the plans within these constructs.

Planning documents regularly consist of typical parts of visions, goals, objectives, initiatives and outcomes. Although the language of goals, objectives, initiatives etcetera lend to broad interpretation, and as such each term is not used consistently across planning documents, there is a common hierarchy from broader to more specific statements that comprise a planning document's structure. Each of these component statements can be assessed within the proposed metabolism and sustainability frameworks to gauge the plan's sustainability and metabolism readiness. In a more interpretive evaluation, the survey will also search for specific initiatives that could benefit from a metabolic approach.

Evaluation Constructs and Methods

The metabolic nature of the plans will be assessed within the urban metabolism construct proposed in the literature review. This construct involves five points on a metabolic process, sources, physical processes, social processes, structural processes, and sinks. Each of the plan's goals, initiatives and similar statements can be assessed to as to whether it affects or acts upon any of these five metabolic points. A complete metabolic plan would account for the source, the physical, the social, and the structural processes of the city, and the final sinks of the metabolic process in achieving its stated goals. In other words it would touch in some way all five points. Each statement will be scored as the number of metabolic processes it consciously engages. A statement that says affects just the sink would be given score of one and tallied under sinks. A statement that affects sinks and physical processes would be given a score of two and tallied under both sinks and physical processes. The total number of statements in affecting each metabolic is tallied for the plan and the metabolic focus areas can be visualized by graphing the number of statements along a liner process. Under this metric a consciously metabolic plan would resemble Figure 3a when graphed. However, most plans are not metabolic and instead have initiatives that address one or two points, perhaps three along the process. As a result the typical urban plan resembles Figure 3b.

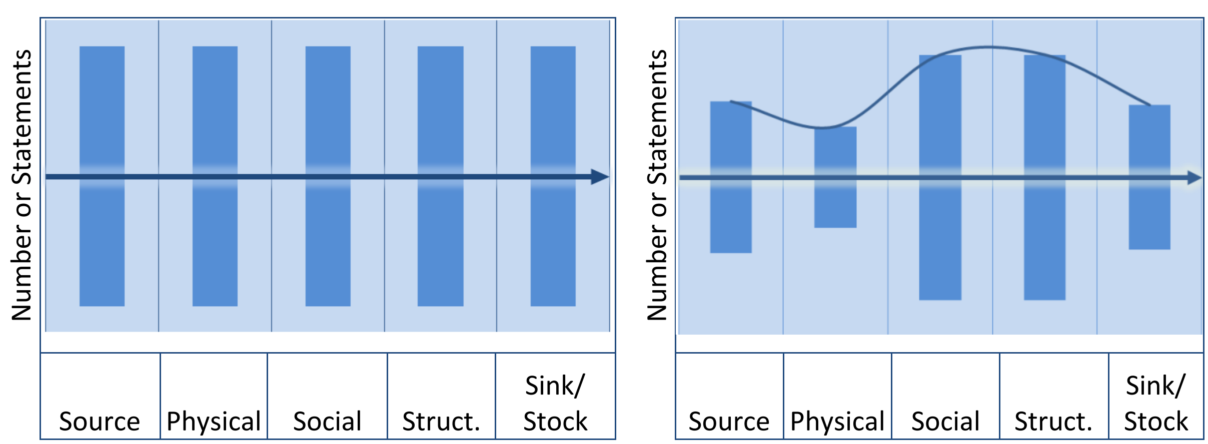


Figure 3a: An urban plan created in a metabolic framework would address the steps of a sustainable process approximately equally.

Figure 3b: Typical urban plan initiatives address some points along the metabolic process and generally focus on one point specifically.

A similar tally and score can be used with the Triple Bottom Line model of sustainability. The various plan statements can be assessed as to which dimensions of sustainability they address. A statement which addresses just an environmental issue would be scored as one and tallied under the environmental category. A statement which addresses both the environmental and economic issues would be scored as two and tallied under both the environmental and economic categories. The tally of statements for each category in a plan that fully meets the triple bottom line criteria would be an equilateral triangle. As prescribed by the triple bottom line model each dimension of sustainability would be equally addressed. Again most plans are not fully sustainable and the tally of statements will be represented some form of skewed triangle.

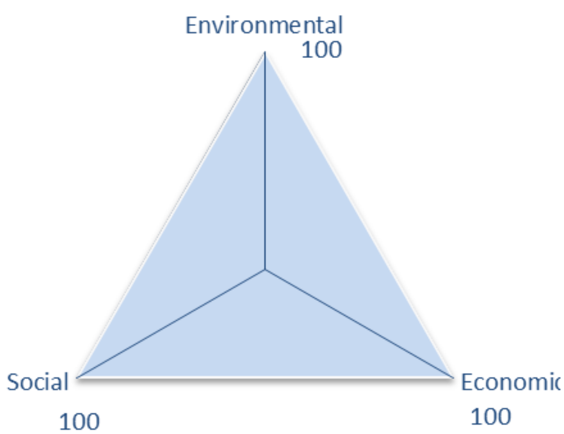


Figure 4a: Sustainable urban plans in accordance with Triple Bottom Line models would address all three dimensions

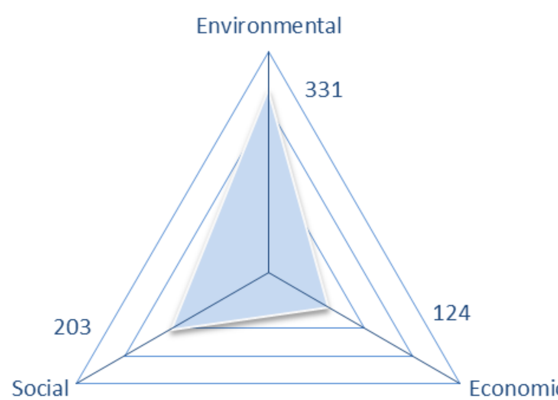


Figure 4b: Typical urban plans more commonly address the dimensions of sustainability unequally.

The previous tallies of statements in relation to metabolic processes and dimensions of sustainability evaluate the plan in total. The plans should also be evaluated as to the general character of their statements. A plan may by sheer coincidence end up addressing all the points of a metabolic process and all dimensions of sustainability equally, but not necessarily construct the connections to be systemic or holistic. For example a plan could have 20 ways to protect a water source, 20 ways to increase power plant efficiency, 20 pieces of legislation to improve equity, 20 ways to improve roadways, and 20 ways to improve waste diversion. This plan would equally address the sources, physical processes, social processes, structural processes and sinks, all the points of the metabolic construct but not with any connected process. To account for this potential distortion, the statements are scored individually as to how many points of the process they affect and averaged for the plan. A plan in which all statements address each dimension of sustainability would have an average score of three. A plan whose statements all address the five points on the metabolic construct will have an average score of five. Again most plans will average less.

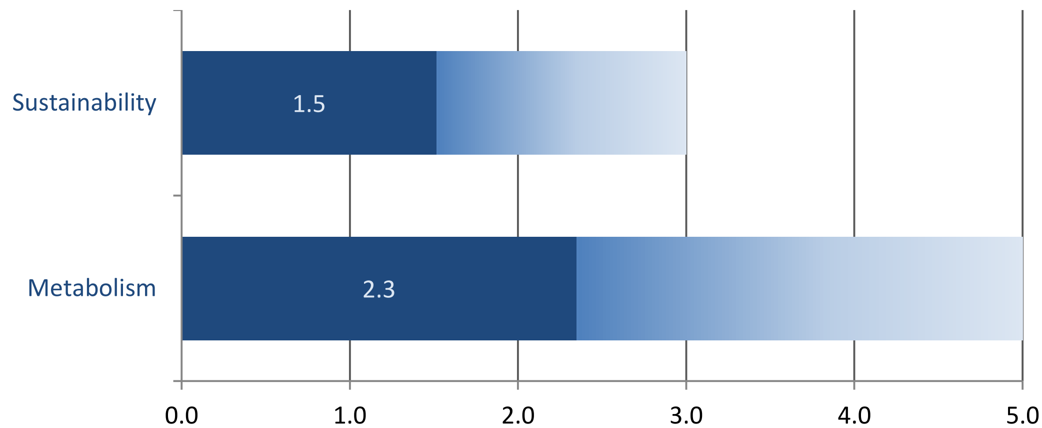


Figure 5. Average scoring of plan statements. A plan can address a maximum of three dimensions of sustainability and five metabolic processes. The average for the plan is represented in relation to the

Lastly the tally of statements in each category will be expressed as a percentage and compared across plans. A matrix of each plan's assessment can be found in Appendix 4.

__Limitations__

In assessing these plans, several cautions need to be kept in mind: First, is to note that by design, urban metabolism and sustainability are broad and all-encompassing concepts. Any given initiative will have environmental, economic or equity components and have an effect up and down the metabolic flow. The assessment must be careful not to make the logical leaps and connections not made by the plan itself, but instead look at what the initiative is addressing directly.

As an example, consider these statements from Boulder County's Environmental Sustainability Plan arranged within the plan's hierarchies.

<table>
<tr><td rowspan="3">Water</td><td colspan="3">Provide ongoing leadership for water efficiency and water quality efforts to ensure sufficient clean water for current and future generations</td></tr>
<tr><td rowspan="2">Target</td><td colspan="2">Reduce Boulder County's internal indoor water usage to 20% below the calculated plumbing code requirement* by 2020 in county buildings in aggregate, and concurrently reduce outdoor water usage</td></tr>
<tr><td>Short Term Strategy</td><td>Reduce water use in aggregate by 30 percent from baseline use</td></tr>
</table>

Table 2. Boulder County Water goal, target and short term strategy.

The short term strategy, "Reduce water use in aggregate by 30 percent from baseline use," affects the water source, the physical process of consumption, the social processes of changing consumption behavior, the structure of the processes, such as those found in the efficiency of fixtures, and the sink as all water ultimately ends up as wastewater. The initiative would also have environmental and economic benefits. But none of this is clearly spelled out in the short term strategy itself. Looking up the hierarchy of the plan, the initiative states, "Reduce Boulder County's internal indoor water usage to 20 percent below the calculated plumbing code requirement* by 2020 in county buildings in aggregate, and concurrently reduce outdoor water usage." The water section of the plan states an overarching goal of "Providing ongoing leadership for water efficiency and water quality efforts to ensure sufficient clean water for current and future generations." Further informed by these broader goal and target statements, the strategy is tallied as affecting the source (ensure sufficient clean water for current and future generations), physical process(reduce indoor and outdoor water usage)and structural process (below plumbing requirement) of the metabolic framework, and the environmental dimension (water quality) of sustainability and given a metabolism score of three and a sustainability score of one.

Second, it should be noted that the plan itself is a social process. It will at time dictate other social processes such as "create legislation." When these recommended social processes are specific, the initiative will be assessed as affecting or acting in the social processes. Conversely, when the processes are vague, such as "encourage the use of fuel efficient vehicles," the social process is too vague to be considered anything more than part of the social process of the plan itself. A change in physical process is really what the initiative is seeking. Such a statement would be tallied in the physical process only.

The final caution is that this assessment is not meant to be a qualitative assessment of any of the plans or the city's efforts toward sustainability. The caution of not creating a plan that "sits on the shelf" is familiar across the planning profession. It is well known that there is a difference between what cities plan and what cities do. This survey of city planning is instead intended to see how city's plan for sustainability and what the urban metabolism discipline can do to make that effort more systemic.

Each plan was reviewed twice as the process of reading one plan can influence how another is understood. For further study it would be interesting to assess plans such as these with broader survey methods such as sending a random sample of statements to various classes of sustainability stakeholders such as government officials, planners, and academics and compare that assessment to complete readings of a single plan by similar groups.

Global cities

New York, Los Angeles and Chicago are the U.S. cities that have been consistently cited as "Top Global Cities" in the AP Kearney Global Cities index, which measures business activity, human capital, information exchange, cultural experience and political engagement. New York City is a constant No. 1 and Los Angeles and Chicago have stayed within the top ten. It comes as no surprise then that these cities are the leaders in sustainability planning, as they have the most financial and creative wealth to create the best practices and popularize them through their economic, political and cultural influence. It is a hopeful sign that all of these cities have sustainability plans, and while all of them fall short of truly tying their initiatives systemically together, they do, in limited ways, recognize the interconnectivity. They also show some initiatives that could be easily expanded to and benefit from metabolic-level analysis.

New York City, NY

The New York City Mayor's Office of Sustainability and the Mayor's Office of Recovery and Resiliency has put forth OneNYC, which has an excellent Web interface. The plan has four visions of the city, of the first of them being: “Our Sustainable City.” The plan states the appropriately ambitious goal that: “New York City will be the most sustainable big city in the world and a global leader in the fight against climate change.”

The plan has six goals, with six corresponding “Challenges and Opportunities” statements, and is further supplemented by 29 Initiatives. The majority of these 41 total Goals, Challenges and Opportunities and Initiatives are aimed at the affecting the sink portion of the metabolic process (30 statements) and improvement on the environmental dimension of sustainability (39 statments) (see Figures 6m and 6t). Twenty-nine statements address two or three points on the metabolic process, and 33 address one or two dimensions of sustainability. The average score for the Goals, Opportunities and Challenges, and Initiatives were calculated as follows:

Five point statements	0	x5	0	Number of statements / Cumulative Score
Four point statements	4	x4	16	= 96/41
Three point statements	14	x3	42	**=2.3 = Average Metabolic Score**
Two point statements	15	x2	30	
One point statements	8	x1	8	
		Cumulative Score	96	

Table 3. Method used to calculate the average statement scores.

On average the statements of OneNYC hit 2.3 points of the metabolic process and 1.8 of the dimensions of sustainability (see Figure 6s).

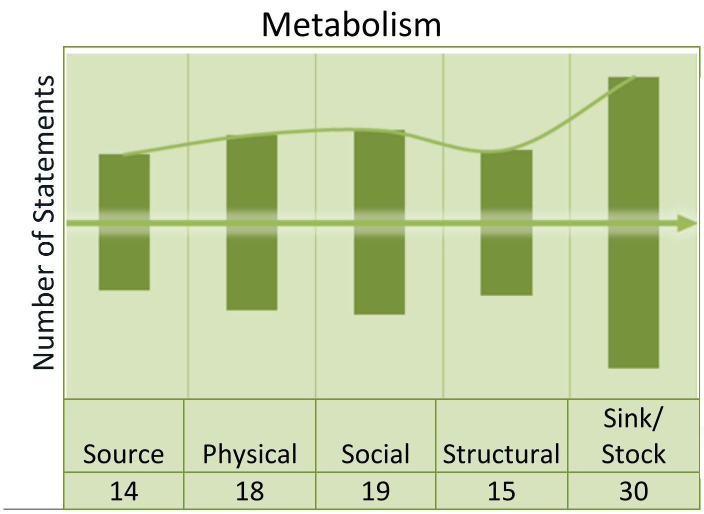


Figure 6m. Tally of statements in each metabolic process category for OneNYC.

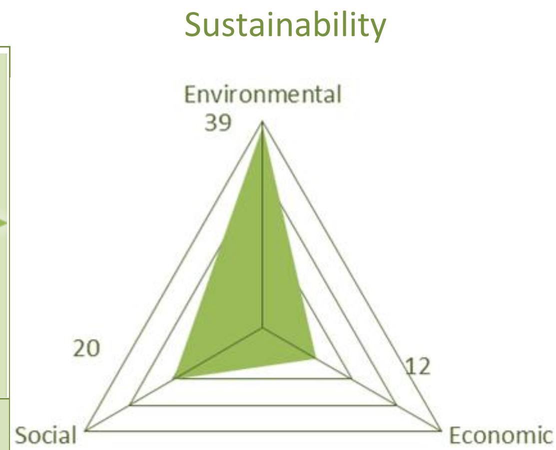


Figure 6t. Tally of statements in each Triple Bottom Line dimension for OneNYC.

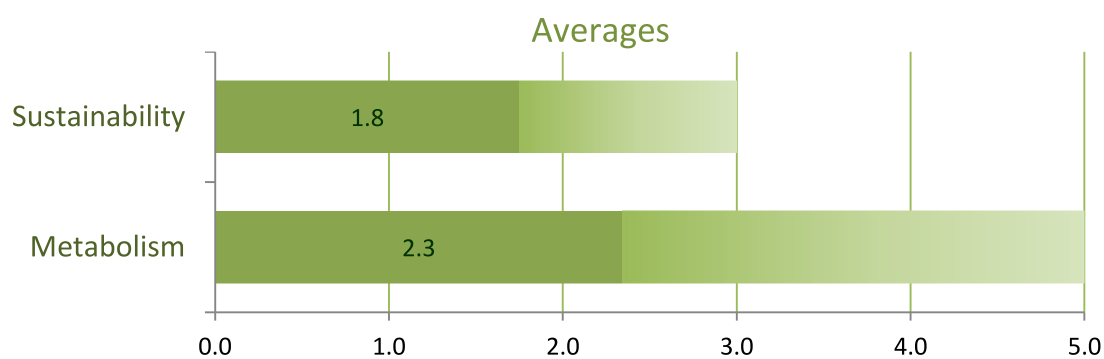


Figure 6s. The average sustainability and metabolism scores for each statement in OneNYC.

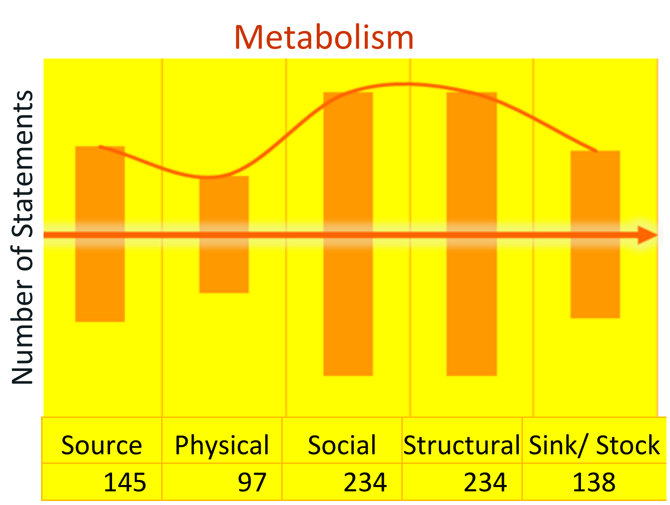
The plan's most complete metabolic goal as well as its most sustainable is Brownfields with an average of 2.8 and 2.4 respectively. Additionally, OneNYC does mention water in a way that begins to string together the metabolic processes, "Water is one of our most precious resources and must be valued and managed wisely. Safeguarding this invaluable natural resource while delivering high-quality drinking water, wastewater services, and stormwater management to residents of New York City requires a holistic approach to water management." The statement involves the source(s), structural and physical processes and the eventual sinks. Further the statement specifically involves a holistic approach.

Los Angeles, California

Los Angeles, California has acknowledged that sustainability is a triple-bottom line endeavor by organizing its "Sustainable City pLAn " into Environment, Economy, Equity sections and engaged in a branding exercise with the capitalization of, "LA" in "plan" as a reference to the city. Each of the "pLAn's" sections then contains related topic areas with vision statements, supplemented by short- and long-term outcomes and strategies. The strategies are further supplemented by initiatives.

In total, the plan contains 442 of these statements (see Fig. 7m) . One hundred and forty five of the statements involve source issues, 97 involve physical processes, social and structural processes are both in involved in 234 statements and 138 involve sink/stock issues. One hundred and ninety-six of these statements involve two points on the metabolic process, 150 involve only one, 79 involve three points, and 16 involve four. One statement calling for a comprehensive plan to implement local solar was assessed to involve all five points on the metabolic process. The average metabolism score for the statements was determined as follows in Table 4: The statements average 1.9 for points on the metabolic process.

In regard to dimensions of sustainability, 331 statements address the environmental dimension, 203 address the social dimension and 124 address the economic dimension (see Figure 7t). Systemically, there are references in various initiatives to other sections of the plan, but such connections are not standard for the plan. Largely the initiatives stand alone, with 243 only addressing one dimension of sustainability and 182 addressing two. A rare few, 17, are aimed at the all three dimensions of sustainability. On average, these statements involve 1.5 dimensions of sustainability (see Figure 7s).



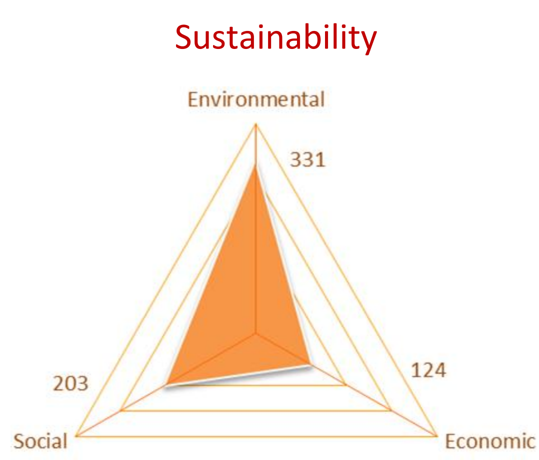


Figure 7m. Tally of statements in each metabolic process category for pLAn.

Figure 7t. Tally of statements in each Triple Bottom Line dimension for pLAn.

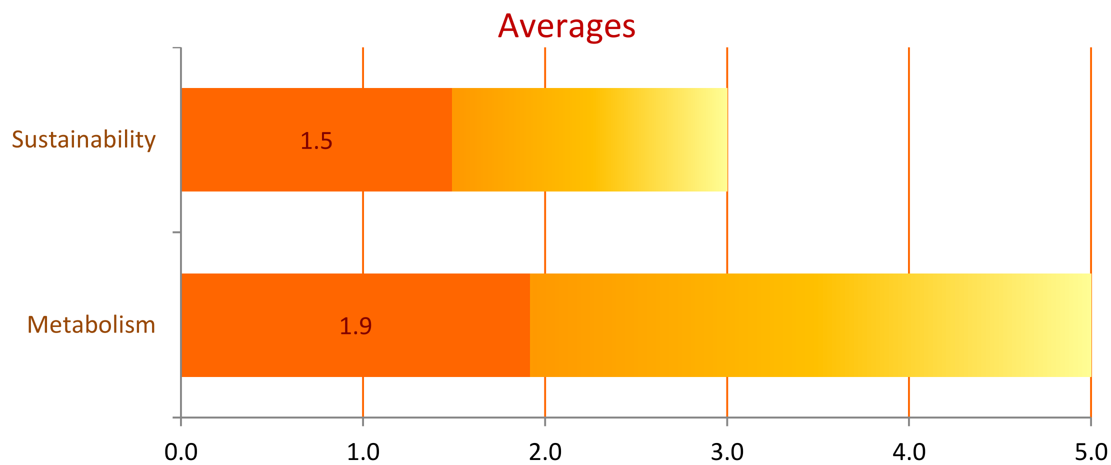


Figure 7s. The average metabolism and sustainability scores for each statement addressed by pLAn.

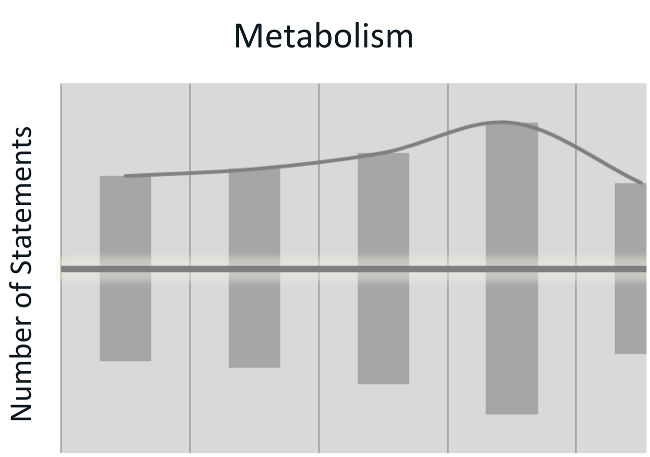
The Sustainable City pLAn has several strategies and goals that could be connected metabolically, such as water, which include local sourcing and efficiency, and energy which incorporates source goals in solar, process goals in efficiency and sink goals in GHG reduction. The Zero Waste goal, which includes cradle to cradle economies, and transparency in tracking waste destinations, is particularly suited to metabolic study and design. The cradle to cradle strategy is by definition a circular metabolism, one that is the ideal of the industrial ecology metaphor. Understanding the quantities and dynamics of materials that are or can be recycled through cradle to cradle economies will be critical to assessing the success of such a strategy.

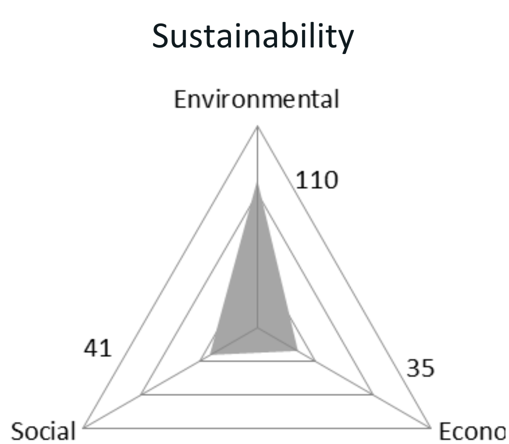
Some of the related metabolic disciplines and processes begin to show up in the LA plan. The goal to "improve the GHG efficiency of Los Angeles's economy …by 55 percent," invokes Odum's concept of measuring the energy involved in more abstract transactions such as purchases or information. The section on housing and development states goals of both increasing housing stock and reducing the cost burdened households. Borrowing Newman's method of using livability indicators to measure a metabolism and Mostafavi's assertion that materials are metabolized into livability ties these housing goals together. The construction inputs (materials and energy) are metabolized not just into housing stock but also livability through a decrease in rent burdened households.

Perhaps the most hopeful place for urban metabolism to take hold in the LA Plan is the urban ecosystem framework. It is also hopeful that is in the Equity section of the plan and has a goal for city biodiversity.

<u>Chicago, Illinois</u>

Chicago's "Sustainable Chicago 2015" plan was adopted with a vision of "making Chicago the most livable, competitive, and sustainable city in the 21st century." The plan is laid out in seven categories, with 24 supporting goals and 102 key actions. Of these 126 statements, 40 involve source issues of the metabolic process, 43 involve physical processes, 50 involve social processes; 63 involve structural processes; and 37 involve the sink or stock end. Sixty of these statements address only one point on the metabolic process, and 46 address two. Twenty five address three and two address four points. None of the statements addresses all five. On average the statements address 1.8 points on the metabolic process. One hundred ten of the statements address the environmental dimension of sustainability, 35 address the economic dimension and 41 address the social dimension. Thirty nine address all three dimensions, 39 address two and 85 statements address a single sustainability dimension. Considering the systemic nature of sustainability, the introduction of Sustainable Chicago 2015 states that, "The seven categories are related and reinforce each other - success in one can lead to or amplify success in another." However, without more explicit development on the linkages it is difficult to say the p;an is consciously systemic. On average, the statements address 1.4 of the dimensions of sustainability.





Sourc e	Physical	Social	Structural	Sink/ Stock
40	43	50	63	37

Figure 8m. Tally of statements in each metabolic process category for Sustainable Chicago 2015.

Figure 8t. Tally of statements in each Triple Bottom Line dimension for Sustainable Chicago 2015.

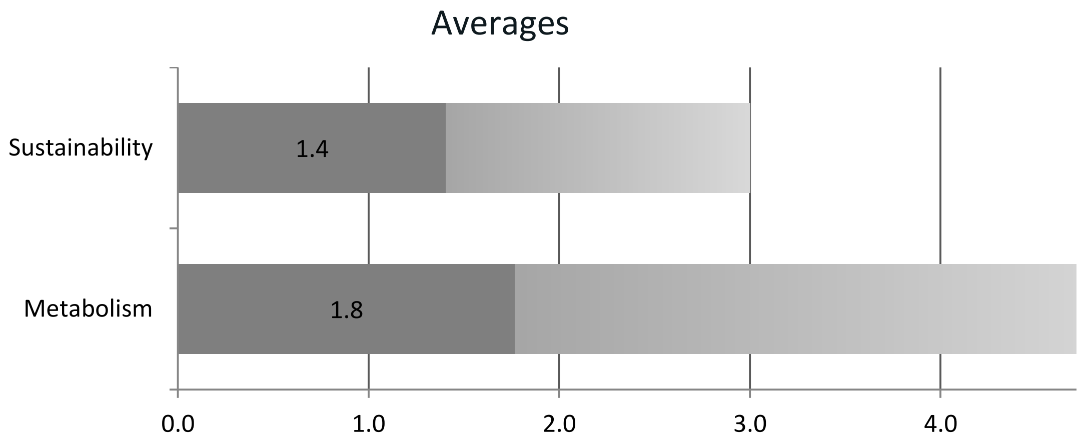


Figure 8s. The average sustainability and metabolism scores for each statement in Sustainable Chicago 2015.

Global Cities Plans Analysis

	Total	Source	Physical	Social	Structural	Sink/ Stock	Environmental	Economic	Social
New York	41	14	18	19	15	30	39	12	20
% of Total		34%	44%	46%	37%	73%	95%	29%	49%
Los Angeles	442	145	97	234	234	138	331	124	203
% of Total		33%	22%	53%	53%	31%	75%	28%	46%
Chicago	126	40	43	50	63	37	110	35	41
% of Total		32%	34%	40%	50%	29%	87%	28%	33%

Table 4. Global cities tally of statements and percentage relative to total related to each metabolic process point and triple bottom line dimension of sustainability.

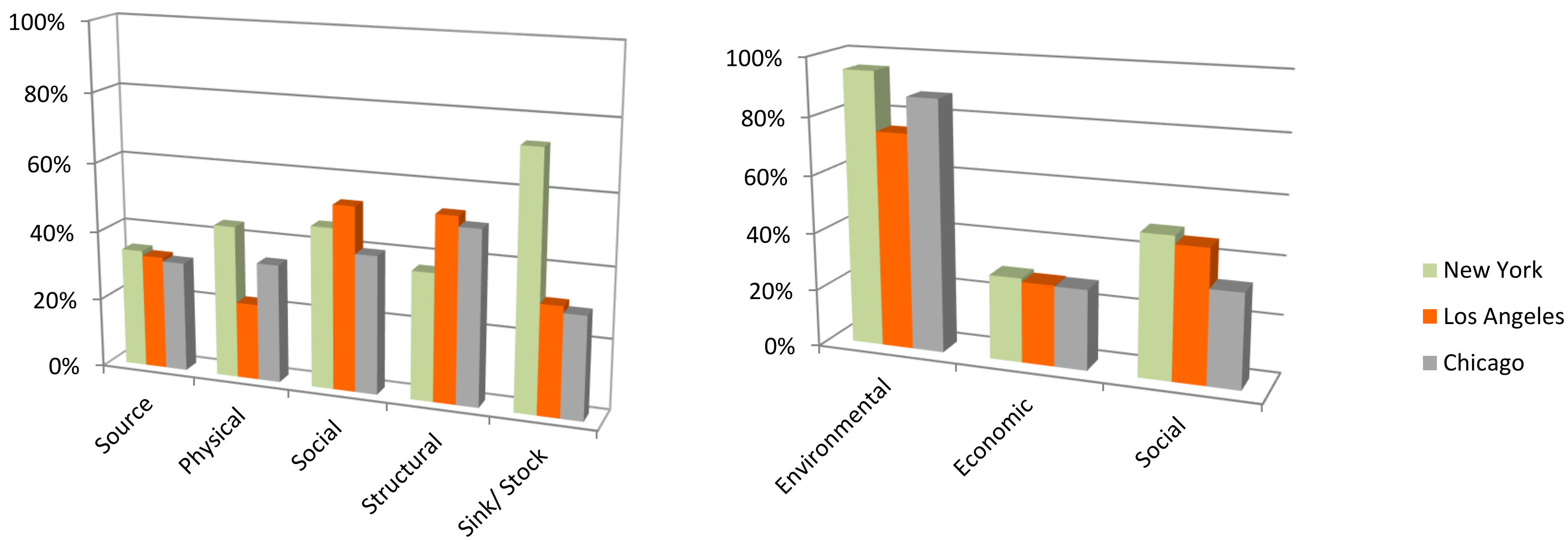


Figure 10. Global cities percentage of statements relative to total statements addressing each metabolic process and dimension of sustainability.

Model Cities

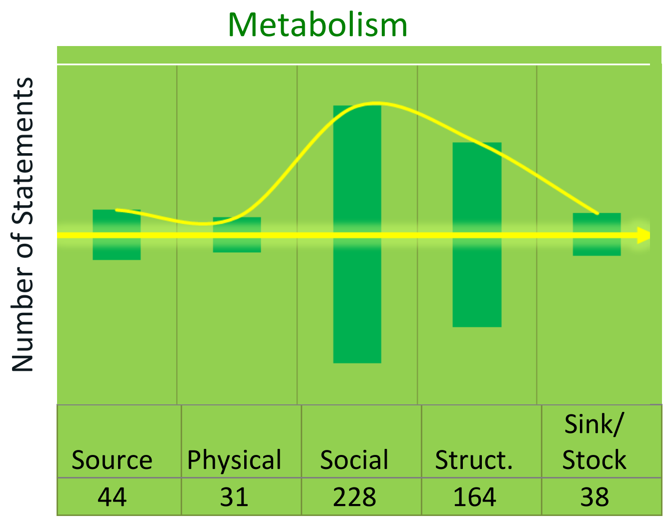
Literature on urban metabolism and sustainability points to few cities worldwide that have leading edge practices in sustainability and metabolism. The North American list usually begins with Portland, Oregon. and the urban growth boundary instituted around the Willamette Valley. Boulder, Colo. is often mentioned as a leader in sustainability and the author know personally the city's environmental conscience. Santa Monica, Calif. is pointed out for its use of indicators. Boston was recently the highest ranking U.S. city in a global ranking of sustainable cities (Ecowatch 2015).

Portland, Oregon

Portland has long been held as the paragon of good planning. It has led on such tools as regional planning with Metro (Seltzer), one of the stronger regional planning agencies in the nation, instituted an urban growth boundary, diverted highway funding to transit and pedestrian corridors, and instituted smart growth (Ozawa 2004). Portland is also strongly environmental. It was one of the first cities to pass a bottle bill and aggressively purchase open space (Ozawa 2004). Thus, if urban metabolism is to emerge as a practice it would likely be found first in Portland. The Metro regional planning agency continues to hold the urban growth boundary as well as promote several environmental (systemic) environmental initiatives, such as a Climate Smart Strategy, Brownfields Recycling strategy, and Waste Management Roadmap (www.oregonmetro.gov).

Planning in the city of Portland is under the Bureau of Planning and Sustainability, which has a mission to "Advance a sustainable city that is prosperous, healthy, resilient and equitable." This Bureau is currently carrying out an update of its Comprehensive Plan, which is the third in a series of successively more detailed plans. The first is Vision PDX which was completed in 2007. This was followed by The Portland Plan which functions as the city's long range plan. It focuses on policies, objectives and five year actions. The current (2015) Comprehensive Plan update follows with even more detail, giving direction down to street types and specific neighborhood goals. Given the multitude of high level city plans, the 2012 Portland Plan was chosen for analysis as it is more recent than the Comprehensive Plan and more action oriented than Vision PDX.

The Portland Plan is organized into three “Integrated Strategies;” ”Thriving Educated Youth,” ”Economic Prosperity and Affordability,” and “Healthy Connected City.” In total it contains 302 Strategy Elements, Guiding Policy, Objectives, and 5 Year Action Plan statements. As the three strategies would indicate, the plan is distinctly focused on the social metabolic processes and the social dimension of sustainability. Two hundred and twenty eight of the statements are related to social processes and 250 are aimed at the social dimension of sustainability. Structural processes are also significant as they are addressed in 164 of the statements. The source, physical and sink/ stock processes are all much less represented with only 44, 31, and 38 statements, respectively. The economic dimension of sustainability is addressed by 120 of the statements and the environment by 88 of the statements. The majority of the statements, 164 involve just one metabolic process. Eighty-six of the statements involved two processes; 39 involved three processes; Eight involved four processes; and 4 involved all five. One hundred sixty-one of the statements address one dimension of sustainability; 120 address two dimensions and 19 address all three. On average the plan addresses 1.7 points of the metabolic process and 1.5 of the dimensions of sustainability. Almost contradictorily the plan contains a high number of single focus statements and a relatively high number of systemic statements. The overarching goal stated in the “Thriving Educated Youth” Strategy which states “Ensure that youth (ages 0–25) of all cultures, ethnicities, abilities and economic backgrounds have the necessary support and opportunities to thrive — both as individuals and as contributors to a healthy community and prosperous, sustainable economy,” acknowledges how improvements in the social dimension will lead to improvements in the economic and environmental dimension. As such that section has a more qualitatively systemic than other plans.



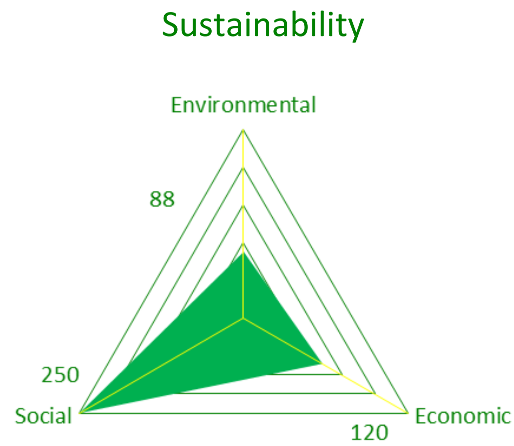


Figure 11m. Tally of statements in each metabolic process category for the Portland Plan.

Figure 11t. Tally of statements in each Triple Bottom Line dimension for the Portland Plan.

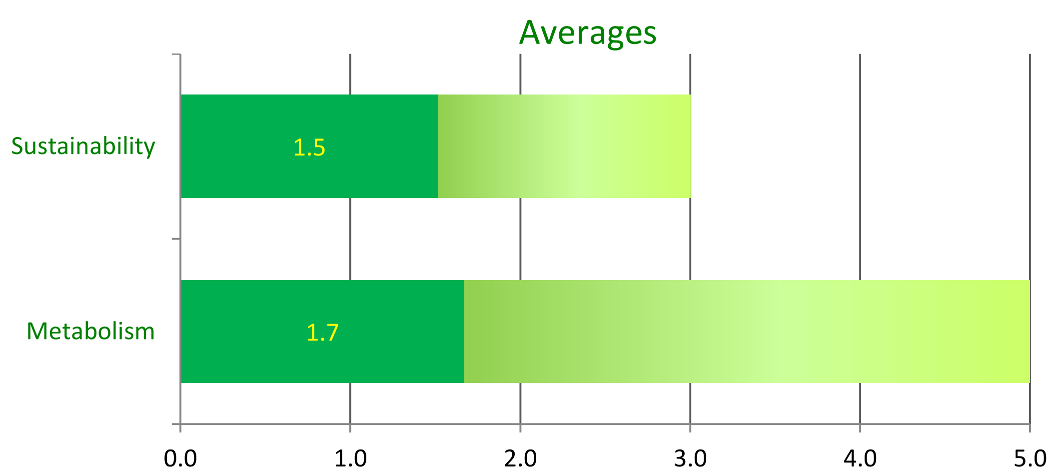


Figure 11s. The average metabolism and sustainability scores for The Portland Plan.

Portland's most waste management initiatives taken together begin to sketch out a metabolic process. Admittedly the proposed programs start by addressing the sink, but do so by envisioning waste as a resource. This creates the mandates for closed loop systems described by industrial ecology. Using a metabolic model will include assessment of the structural processes for collection of waste and subsequent distribution of goods. Engaging the related disciplines of political ecology and urban potitcal ecology will improve the effectiveness of this initiative by involving the social processes of consumer behavior .

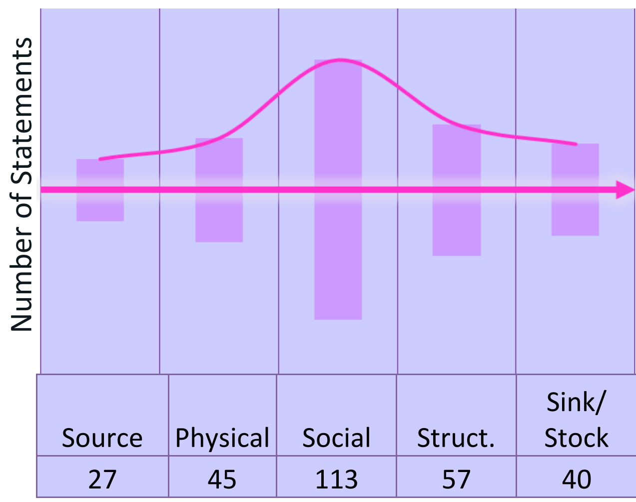
Santa Monica, California

Ferráo and Fernandez (2014) mention the Santa Monica "Sustainable City" plan as one of the best examples of sustainability planning. Other scholars have noted that the city use the indicators from its sustaintbility plan in reporting and evaluating the city government. The plan begins with the Brundtland definition of sustainability and eleven "Guiding Principles" that guide how the plan is to be used in decision making. The action areas of the plan is comprised of nine goal areas, with defining statements and indicators and targets.

In total there are 202 of these principles, goals, and indicator statements. Twenty seven (27) of these statements involve source functions of the metabolic process, 45 involve physical processes, 113 involve social processes, 57 involve structural processes and 40 involve the sinks and stock of the metabolic process. The majority of the statements, 127, involve just one point on the metabolic process, 50 involve two points, 22 involve three points, and one involves four points. Not one statement covered all five points in the metabolic process. On average, the statements involved 1.5 points on the metabolic process.

With regard to sustainability, 101 of the statements address the environmental dimension, 27 addressed the economic dimension, and 113 addressed the social dimension. The majority of statements, 142, addressed just one dimension, 53 addressed two and two statements addressed all three. On average the statements addressed 1.3 dimensions of sustainability. There were four (4) statements that were not thought to address any dimension of sustainability and two (2) which were not thought to be directed at a metabolic process outside the plan itself. These were the guiding principle statements and one goal statement which was to "minimize or eliminate..the risks that environmental problems pose to human and ecological health (Sustainable City, Santa Monica 2014)," which is more a general goal of the plan rather than a directive to any process. The Sustainable City plan refrences a Goal/Indicator Matrix which may strengthen systemic connections. The Santa Monica Office of Sustainability and the Environment was contacted to obtain the plan but no response was received.

Metabolism Sustainability



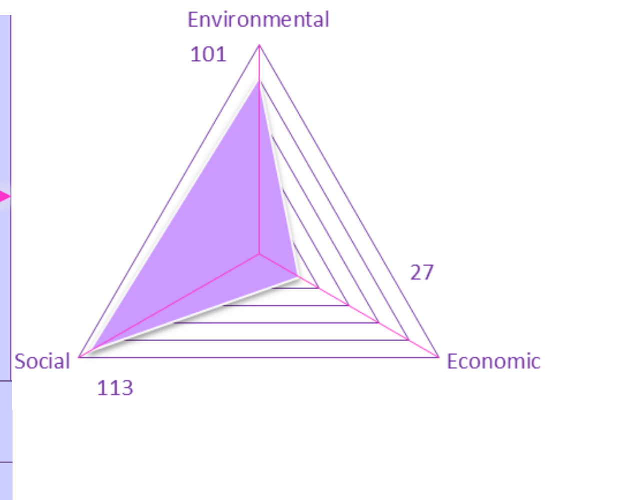


Figure 12m. Tally of statements in each metabolic process category for the Santa Monica Sustainable City Plan.

Figure 12t. Tally of statements in each Triple Bottom Line dimension for Santa Monica Sustainable City Plan.

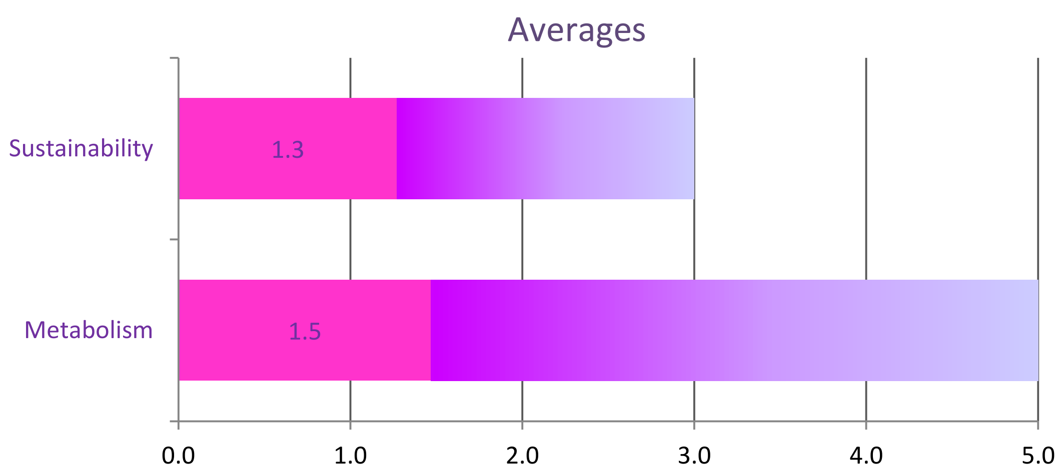


Figure 12s. The average sustainability and metabolism scores for The Santa Monica Sustainable City Plan.

The plan shows an awareness of the systemic nature of sustainability in their desire to address the "root causes" and not just symptoms. The plan has numerous goals such as this one under "Resource Conservation," "Within renewable limits, encourage the use of local, non-polluting, renewable and recycled resources (water, energy, and material resources) (Sustainable City, Santa Monica 2014),"which ostensibly follow a metabolism informed and industrial ecology regime, however it does not seem they were actually based on any metabolic study.

Boulder County, Colorado

The Boulder County "Environmental Sustainability Plan" also uses the triple-bottom line definition as well as an expanded Bruntdland definition that adds in "ensuring protection and enhancement of naturally occurring ecosystems and their native species populations."   The plan also prefaces itself in the introduction as taking a "systems wide" approach and highlighting linkages between the three bottom lines.

The plan is made up of nine goals, which are supplemented by targets, which can be internal and external, policy priorities, and "Take Action" recommendations which are focused on individual or household actions. The "targets" are further supplemented by long term and short term strategies. In total the plan contains 395 of these statements. Ninety-two of them involve source functions of the metabolic process, 145 involve physical processes, 240 involve social processes, 69 involve structural processes, and 127 involve the sink/stock process of metabolism. Slightly under half, 182, of the statements involve two points on the metabolic process and another 168 involve only one point. Thirty eight statements involve three points, six involve four points. One statement, "Create an inventory of all flows of water within Boulder County, including quantity and quality, to create a countywide water quality data base," involved all five points of the metabolic process. The broadness of this goal and its inherent metabolic phrasing "all flows" certainly give it a metabolic flavor. On average, the statements address 1.7 points on the metabolic process.

With regard to the triple-bottom line the bulk of the statements, 325, address the environmental dimension of sustainability, 87 address the social aspects and 43 address the economic conditions.   The bulk of the statements, 338, also address one dimension of sustainability, 52 address two, five statements address all three. On average the statements address 1.2 of the dimensions of sustainability and 13 were thought to be systemic.

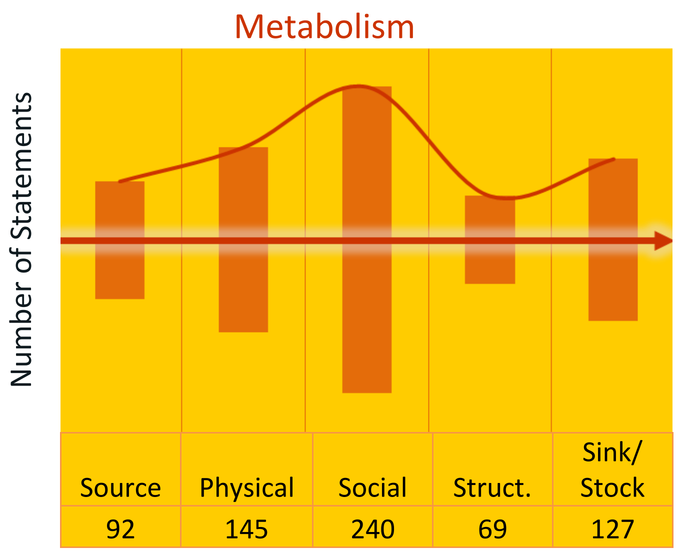


Figure 13m. Tally of statements in each metabolic process category for the Boulder County Environmental Sustainability Plan.

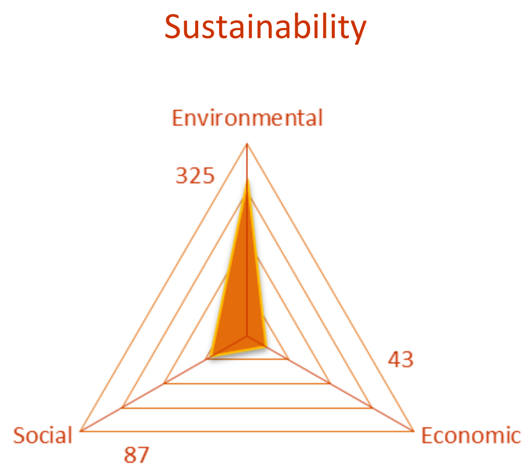


Figure 13t. Tally of statements in each Triple Bottom Line dimension for the Boulder County Environmental Sustainability Plan.

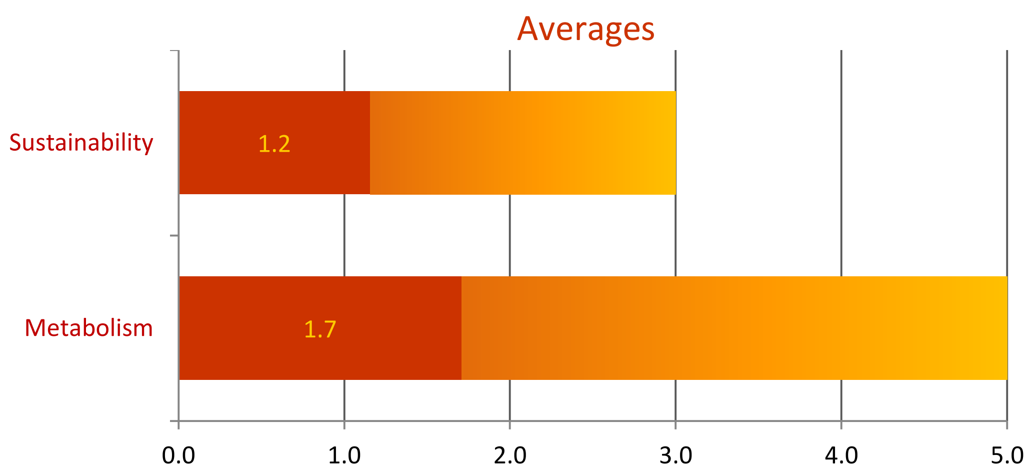


Figure 13s. The average metabolism and sustainability scores for The Boulder County Environmental Sustainability Plan.

Despite the clear majority of statements in the Boulder County Plan involving social processes, many of the terms are prefaced by softer social process verbs such as "empower residents" or "support policies," which indicates that although they are present, the social aspects of these statements may need to be refined to more specific actions and given stronger direction for implementation.

Boston, Massachusetts

A 2015 ranking of cities worldwide by "people (social), planet (environment) , and profit (economic)" done by the firm Arcadis ranked Boston as 15th overall and the top U.S. city. It was the top performing U.S. city by the people index, largely due to its educational institutions. In the Planet category New York City outdid Boston by one spot and San Francisco, Chicago and New York City ranked higher in the profit category.

Boston's best example of a sustainability plan is its Climate Action Plan, which in the 2014 update has been expanded to include economic development and equity. The plan is organized into sectors, goals and strategies for reducing the emissions from each sector.

The Climate Action Plan is one of the more broadly systemic plans in this analysis. This can be attributed to the fact that they have consciously taken a plan addressing a singular issue, and incorporated its systemic elements of economy and equity. The plans contains 201 Policy priority, goal and action statements. The majority of the plans statements, 133, affect a social process, both in terms of regulations and aiming for more equitable involvement. The plan's titular goal involves reducing carbon emissions and building resilience, and so it is not surprising that 116 of the statements address the sink end of the metabolic process and another 80 address the structural process. Fifty six address physical processes and 41 address sources. The Climate Action Plan had nine statements that covered entire metabolic process. The greatest number of statements, 69, involved two processes; 59 involved three points; 47 involved one; and 16 involved four processes. Slightly more than three quarters of the statements, 154 affect the environmental dimension. Fifty-eight affect the economic dimension and 80 affect the social. Ten of the statements are systemic. On average the plan involves 2.9 points along the metabolic process and addressed 1.7 dimensions of sustainability.

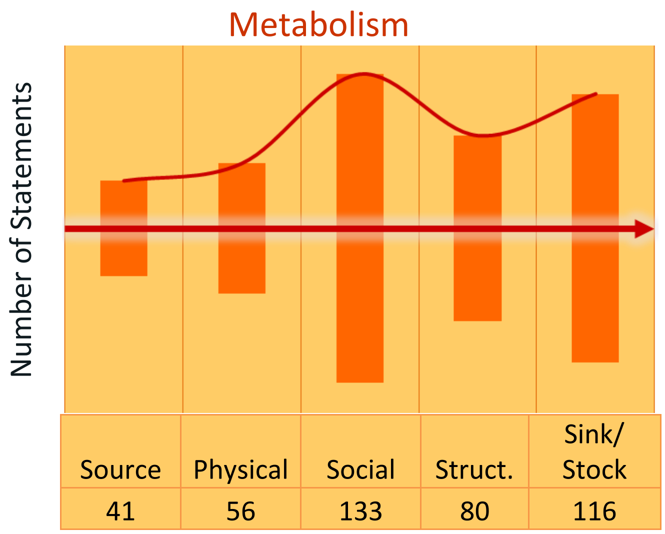


Figure 14m. Tally of statements in each metabolic process category for the Boston Climate Action Plan.

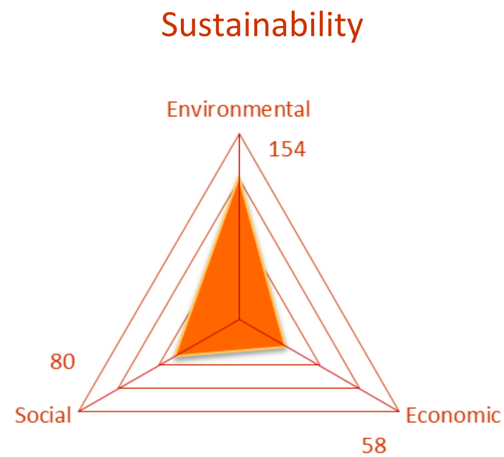


Figure 14t. Tally of statements in each Triple Bottom Line dimension for the Boston Climate Action Plan.

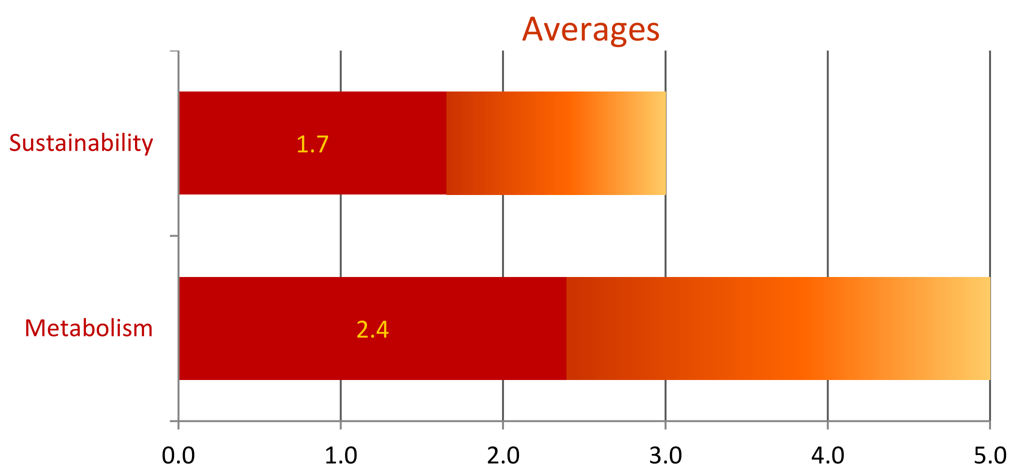


Figure 14s. The average metabolism and sustainability scores for The Boston Climate Action Plan.

Toronto, Ontario, Canada

Toronto has been one of the primary North American cities which involve urban metabolism and sustainability. It also was the top ranked North American city for sustainability by Arcadis (2015) coming in at ninth overall. One of urban metabolisms leading scholars Christopher Kennedy practices at the University of Toronto. With regard to civic planning, Toronto is has a Climate, Clean Air and Sustainable Energy Action Plan and Live Green plan which stems from a recommendation in the Climate, Clean Air and Sustainable Energy Action Plan. The Climate, Clean Air and Sustainable Energy Action Plan acknowledges the interconnectedness of the triple bottom line in its introduction stating “In a sustainable city, a clean and healthy environment goes hand-in-hand with strong community engagement, a thriving economy and access to opportunity for all residents (2007).” Similarly, the vision statement for the Live Green Plan calls for the city to have “a clean, reliable and affordable energy supply that meets our environmental, economic, social and consumer needs…”

Together, both plans have 184 goal and action statements. The plans have a clear focus on social processes with regard to their effect the environment. One hundred and forty-two of the statements involve social processes and nearly all, 183, affect the environmental dimension of sustainability. The environmental focus is explicit as these plans are created to address climate change, and their chosen tools are social processes such as incentives and regulations. With this goal sinks should also be involved in nearly all the statements, however they are involved in just over half, 97. The remainder of the metabolic processes are involved as follows: Sources are involved in 82 of the statements; Physical processes are in 59 of the statements; Structural processes are involved in 52 of the statements. Forty six of the statements affect the economic dimension and 50 affect the social dimension. One statement which called for further planning was thought to be systemic.

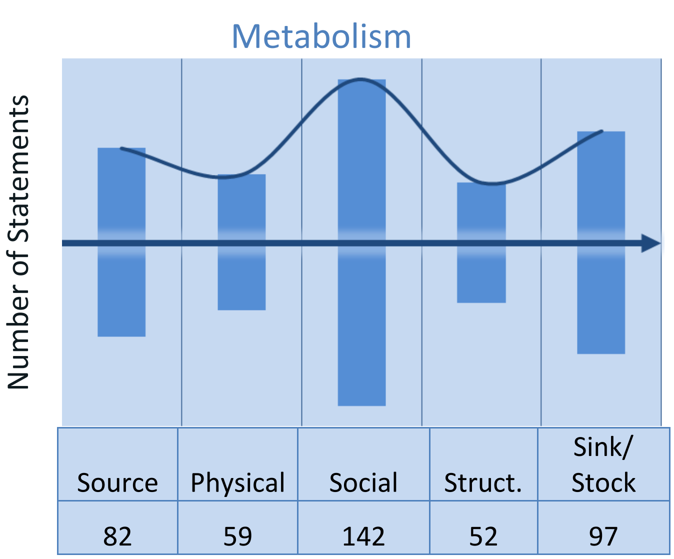


Figure 15m. Tally of statements in each metabolic process category for Toronto’s Climate, Clean Air and Sustainable Energy Action Plan and Live Green Plan.

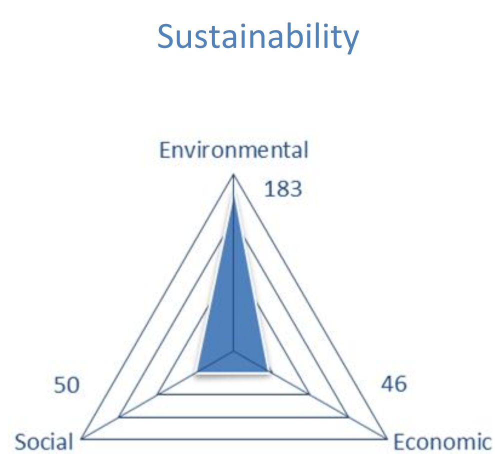


Figure 15t. Tally of statements in each Triple Bottom Line dimension for Toronto’s Climate, Clean Air and Sustainable Energy Action Plan and Live Green Plan.

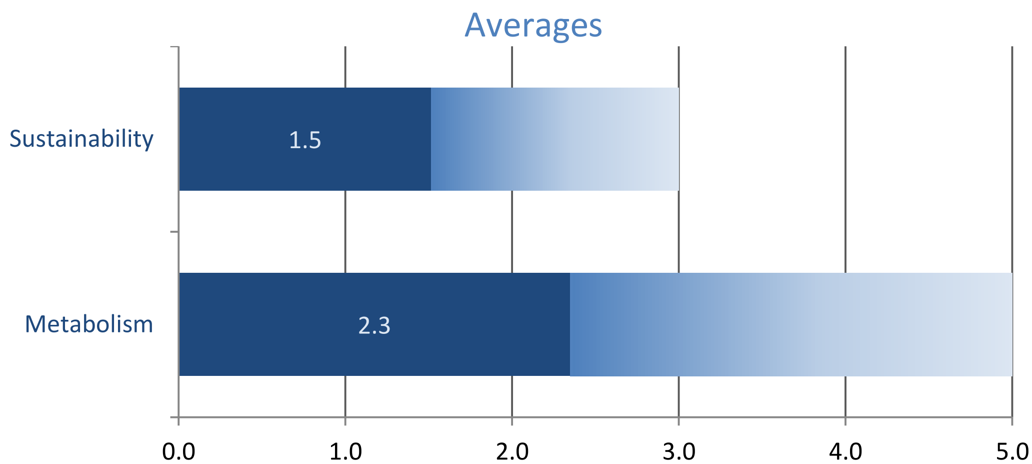
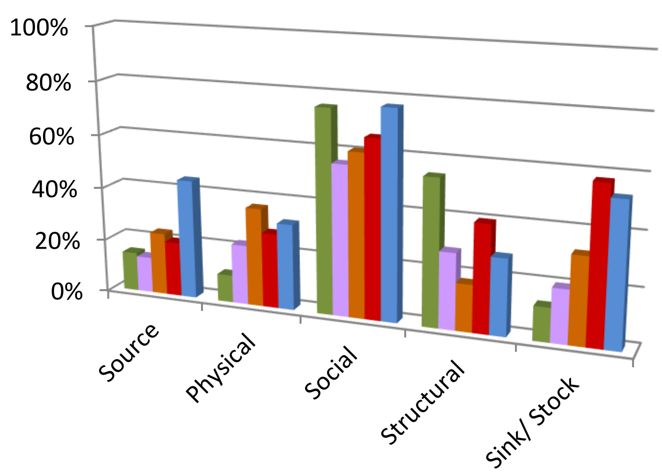


Figure 15t. The average metabolism and sustainability scores for Toronto's Climate, Clean Air and Sustainable Energy Action Plan and Live Green Plan.

Model Cities Plans Analysis

	Total	Source	Physical	Social	Structural	Sink/ Stock	Environmental	Economic	Social
Portland	302	44	31	228	164	38	88	120	250
% of Total		15%	10%	75%	54%	13%	29%	40%	83%
Santa Monica	202	27	45	113	57	40	101	27	113
% of Total		13%	22%	56%	28%	20%	50%	13%	56%
Boulder	395	92	145	240	69	127	325	43	87
% of Total		23%	37%	61%	17%	32%	82%	11%	22%
Boston	201	41	56	133	80	116	154	58	80
% of Total		20%	28%	66%	40%	58%	77%	29%	40%
Toronto	184	82	59	142	52	97	183	46	50
% of Total		45%	32%	77%	28%	53%	99%	25%	27%



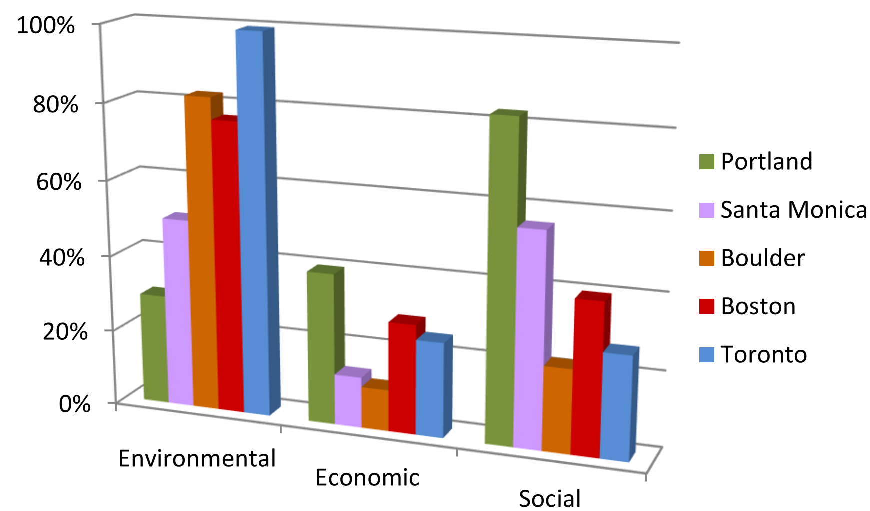


Figure 17. Model cities percentage of statements relative to total statements addressing each metabolic process and dimension of sustainability.

Emerging Practice

The program of the 2015 American Planning Association National Conference was surveyed to find mentions of urban metabolism or other systemic methods of measuring and planning for sustainability. The conference had more than 330 lectures, panel discussions, workshops, plenaries and meetings. As expected, urban metabolism was not listed as a topic or in the session summaries. Coming close was a session on "Planning for the Triple Bottom Line," which involved using big data to understand "urban dynamics." Sustainability was mentioned in the title or program summary of 23 of the sessions and reflecting various degrees of systemic integration. The "Business Sustainability, Start-Up to Grown-Up," speaks to sustaining a business practice while the "Connecting Climate Action, Transportation, and Sustainability" session which discusses the integration of climate action plans and transportation master plans in Boulder, Colo., shows a more systemic use of the term "sustainability."

There were also sessions that discussed topics that draw very immediate metabolic links such as "Innovation in Urban Water Systems," which discussed net-zero water, one-water and the water-sensitive city. The Seattle Sustainable Neighborhoods Assessment Project examined data collection in measuring sustainability. There were numerous mentions of green infrastructure sessions and three sessions on Ecodistricts including one on generating and using energy at a neighborhood scale.

The American Planning Association maintains blog posts from previous conferences. Some of the more metabolism-related topics included "Biomimicry as a Neighborhood Planning Tool," which aimed to replicate patterns of nature in transitional zones and Reconsidering Ian McHarg: The Future of Urban Ecology from the 2013 conference (www.planning .org).

Findings

In "Sustainable Urban Metabolism" Ferráo and Fernandez (2013) describe the current state of sustainable urbanism as "neither strong enough nor aspiring toward strong sustainability." Other authors such as Niza (2009) and Portney (2009) have reiterated this finding. The surveyed municipal plans and conference materials reinforce this conclusion, but they also support Ferráo and Fernadez's postulation that these efforts can be a bridge to strong sustainability. There are particular common (2013) elements to the plans that can be ready points for expanding into a systemic and holistic plan for a sustainable city. The plans all acknowledge that sustainability involves related goals and initiatives, whether by broad mention as Chicago does or by specifically noting "Cross Cutting Themes," as Boston does. Los Angeles uses a triple-bottom line framework and Santa Monica uses the Brundtland definition. Boulder County uses both. There are initiatives within the plans that inherently capture a metabolic flow such as zero waste, water and wastewater, and green infrastructure. This goal from Boston's Climate Action Plan practically describes a metabolic study: "consumption-based greenhouse gas inventory that accounts for emissions associated with things we buy and consume." Nonetheless it remains a goal and no metabolic studies are either used or specifically prescribed. Further there is not quite enough cohesion to say that any of the plans function systemically, even where the relationship between initiatives is acknowledged. There is, however, both a demonstrated understanding that sustainability is a systemic concept and sufficient opportunity to incorporate urban metabolism. In short, urban metabolism is very much a relevant tool for today's city planning efforts.

Conclusion

As stated in the previous chapter, the gap between the current urban planning practice and the discipline of urban metabolism—and by inference, strong sustainability—is largely the same as it was when assessed in 2013. This section will discuss how well the tools of urban metabolism meet the goals city planning and what can be done to overcome that gap.

Challenges and Opportunities

In outlining a methodology for an urban metabolism study Ferráo and Fernandez (2013) point to several difficulties within their layers of analysis including; A lack of clear boundaries in the Urban Bulk Mass Balance; A lack of sufficient data in the Material Intensity of Economic Sectors; Reconciliation of global and local scales in mapping the Spatial Location of Resource Use; and the various systems of goods movements within and between urban environments that factor in to Transportation Dynamics. Taken together these challenges likely make a full urban metabolism study unfeasible at least in the near term. A risk averse government is more likely to rely on familiar processes and uncertainties within the process or lack of definite answers can be deal breakers.

However individual layers of analysis and specific flows have been successfully studied. Niza, Rosada, and Ferráo have investigated the urban bulk mass balance of Lisbon and Friere, Thore and Ferráo have conducted a Life Cycle Analysis of bottled water in Lisbon. The city plans have initiatives that could be similarly examined as layers of an eventually comprehensive urban metabolism study. In carrying out these initiatives it must be remembered that sustainability is a holistic concept and ecosystems function as integrated wholes. To study layers or components of that whole without an awareness of the larger systems and their interactions would have the effort fall short of sustainability. This almost produces a Catch 22 in that the whole cannot be known without understanding the parts and the parts cannot be understood without knowing the whole. Urban metabolism must then be studied and understood in a sort of Hegelian dialectical thinking (Spence and Krauze, 2015) as the parts must subsume to the greater whole. As such there is a need for a certain amount of top down direction, not necessarily of knowing the whole, but of knowing how to understand the whole, most importantly through the links within the systems. Metabolic studies need to be conducted in a standardized framework that allows each component study to couple with and build upon other studies. As an example a transportation study and a carbon budget may be conducted as separate studies, but they need to be formatted and modeled so that they each readily informs the other and relies on similar assumptions and interoperable methodology. Creating such large scale standards has been a goal of Urban Metabolism practitioners for some time (Kennedy and Hoornweg 2012). The realization of such standards and frameworks may be close in those forthcoming from the OEC.

Carbon and GHG reduction is a goal ready for such study. All of the large city governments surveyed Los Angeles, Boston, New York, Chicago, Toronto) have adopted the 80 by 50 goal of reducing greenhouse gas emissions to 80 percent below 2005 levels by 2050. This is based on a 2007 Intergovernmental Panel on Climate Change report which modeled a reduction between 50 and 85 percent in GHGs and a 2.0 and 2.4° C rise in global temperature and a .4 to 1.4 meter rise in seal level. The goal is based on climate science and modeled scenarios and has been condensed to a simple metric. The state and impact parts of a DPSIR model (Ferráo and Fernandez 2013) have been completed by this high level study. Policy makers have been given a clear goal, that has scientific backing and can with that begin to metabolically model the response. Municipalities, such as Boston, Toronto and Boulder County have in fact begun parts of these metabolism studies by inventorying their GHG emissions. Such an inventory begins to construct the bulk mass balance of carbon and the material flow analysis prescribed by Ferráo and Fernandez (2013).

To implement the 80 by 50 goal OneNYC calls for further planning to reduce GHG emissions from the power generation sector and implement zero waste. Both of these initiatives are excellent places to implement metabolism studies. Power generation looks at a limited number of geographically constrained physical processes and would track the source and ultimate sink of carbon emissions. Zero waste presents a broader array of sources, but limited structural processes in terms of collection and presents an opportunity to model the industrial ecology metaphor in reuse and repurposing of waste.

Similarly, Boston's 80 by 50 initiatives call for expanding "energy efficiency programs through targeted outreach and new financing mechanisms, increase local and low-carbon energy sources, including expanding district energy and co-generation, re-envision Boston's transportation system to dramatically reduce emissions from this sector." Similar to New York City, there is potential in the power generation and transportation goals, but there is also a chance to evaluate the social processes through energy efficiency programs. All three could be assessed and planned in a comprehensive study.

Santa Monica, CA provides an example of one of the best uses of an urban metabolism tool, the ecological footprint. In measuring their footprint at regular intervals they are given a simple, easily deployed metric of their sustainability and their performance in becoming more sustainable.

The universal issue of lack of data can similarly be solved by beginning to build the layers of an overall metabolism study through already state city initiatives. Municipalities have named data collection and reporting as a goal. Boston is aiming to create a performance measurement system that includes neighborhood level data. Los Angeles is looking to understand the energy and water use of its building stock. Boulder County is looking to share forestry data with other municipalities and levels of government across geo-spatial platforms. While the assertion that sustainability indicators are not taken into account in policy making may still hold true (Ferráo and Fernandez 2013) recent planning documents show that cities are looking to track and use indicators. In the academic realm, the literature shows active investigation into new ways to find and collect data on urban metabolism. There is no reason why this shouldn't be done in tandem with municipal efforts. In fact, Chicago is aiming to partner with its universities to gather data about climate change.

Beyond this there are questions as to whether even analyzing all the data would ever be able to unravel the complexity of system dynamics (Meadows 2001). Increasing computing power and sophistication in programming may mean that analytics could catch up. Google would seem to think so as it has announced that it will take its (some fear nigh-omnipotent) analytics into city planning (Fehrenbacher 2015). But in the nearer term dealing with the complexity of urban dynamics will be a challenge. If ultimately urban metabolism can unravel complexity no better than conventional planning can, why then should any government invest in a lengthy process that only a few individuals can do? The answer to this for urban metabolism must be that “urban metabolism can do it better.”

Convincing a municipal government that urban metabolism can indeed be planned better will take a measure of sales. In order to sell the concept, one of the first things the discipline must answer specifically and directly for any city is, “what can urban metabolism do for you?” The large (and true) answer of “providing a connected, measured analysis and plan of what your city needs to do in order to become truly sustainable,” is both too broad and too ambitious for the traditionally risk-averse government (MAPC Data Day, 2015) field. In the Journal of Urban Affairs Eric Zeemering (2009) said “The dialogue on sustainable communities would benefit from a clearer understanding of what sustainability means to the officials in local governments who have day-to-day responsibility for growth and economic development.” Fortunately, what governments want in terms of sustainability has already been laid out in their plans. It is therefore up to the urban metabolism practice to approach government and demonstrate how urban metabolism would better serve those initiatives.

Returning to Boston’s Climate Action Plan as an example, the metabolic characterization could find within the transportation, power generation, and efficiency metabolic processes the most opportune places to reduce GHG emissions and characterize a path to reaching the 80x50 goal. Proposals such as “a zero-carbon municipal vehicle fleet by 2030,” could be refined through metabolic to hypothetically say, “the city vehicle fleet currently contributes to between 10-12% of the city’s GHG emissions. The largest contributor is snow plowing which has historically emitted between 100,000 and 150,000 metric tons depending on the winter. Switching all trucks to biodiesel and biogas would eliminate between 50 and 75 thousand metric tons. Biodiesel and biogas supplies would have to be enhanced. The city’s foodwaste ban provides an opportunity to create that supply locally, which would eliminate an additional 25,000 metric tons associated with importing and distributing fuel. Proper distribution of the fueling infrastructure would further reduce the carbon footprint by 20,000 metric tons, and result in a nearly carbon neutral fleet.”

Indeed if urban metabolism can answer some of the questions currently asked in sustainability planning, it *is* doing it better. Further, even if urban metabolism cannot tame complexity, it will be able to adapt to it better than conventional planning. Providing the base metrics and understanding how they fit in various flows will allow cities, to as Donella Meadows says, "dance with systems."

It does truly seem that one of the clearest answers to popularizing urban metabolism as a practice is to tell people about it. Despite an understanding of the need to by systemic and the initiatives that lend well to metabolism studies, the discipline remains largely unknown. The discipline does not appear in the conference programs of the nation's largest planning organization. At least one e-mail to a model city revealed that city planners are not familiar with the discipline and personal experience in Boston shows there is little awareness of the concepts. This is despite the presence of one of the leading practitioners in the field working across the Charles at MIT.

Professional Outreach

Professional conferences would be the most apt venue to "tell people about it." The 2015 APA conference included sessions on data collection for sustainability, "Sustaining Places with Comprehensive Plans," integrating climate action and transportation plans, Ecodistricts, climate change and sustainable development to name a few. The APA puts out a call for sessions and urban metabolism practitioners should respond to that call. In doing so, the discipline should be presented in relation to goals important to planners. Issues already raised in current plans and topics already raised in conferences should be presented through a metabolic lens with an illustration of how urban metabolism can better address these issues.

Conference outreach should only be the first step. Professionals need to be able to take the practice to municipalities. Following up on conferences there should be various degrees of professional training designed for professional practice. This could run from day long seminars to short multi-day courses with corresponding levels of certification and include topics such as available data sources, methods of collection, analytical methods, scope and timelines, and presentation. The World Bank's Eco2 Cities: Ecological Cities as Economic Cities by Suzuki et al

(2010), provides practices for firms and governments that bridge the technical science and the public interface. These include joint forecasting, which involves engaging a broad number of stakeholders to develop future scenarios, environmental accounting, life cycle costing, and metadiagrams, which are expanded source to sink Sankey diagrams, and the use of GIS for expanded McHargian analysis.

Government Outreach

Probably the best way to allow governments to engage in metabolic studies is to have them ask for it through a Request for Proposals (RFP) for services for a metabolism ready initiative named in their planning documents.

Boulder County has readily-accessible RFPs on its website (www.bouldercounty.org) to serve as a template. An internal goal in the climate section of their plan is to achieve carbon neutrality for county operations and the short term strategies together address the source, processes, and sinks of a metabolic process . An RFP for a metabolism study based off this goal could be prepared as follows:

Critical Success Factors

RFP evaluations will consider, but are not limited to, the following criteria:

1. Costs and timeline for professional services to complete the study.

2. Vendor's experience with metabolic studies, carbon production and sequestration inventories, and energy efficiency in buildings, vehicles and operations, land management.

3. Deliverables.

4. Reference responses from previous customers.

5. History and stability of vendor.

Background

In 2005, Boulder County joined more than 200 cities and counties within the United States in making a commitment to address global climate change at the local level. Boulder County's 2012 Environmental Sustainability Plan lays out key strategies to reduce emissions 40% below 2005 levels by the year 2020 based on the 2006 Greenhouse Gas Inventory Report. An internal goal of the Environmental Sustainability plan is for county operations to achieve carbon neutrality through several strategies which address greater energy efficiency in buildings, alternative energy sources, operational changes, and use of carbon sinks. Boulder County wishes to coordinate these efforts through a metabolic study of its operations and action plan based on the study results.

Deliverables

The final report should include:

- An updated inventory of the GHG emissions of the county operations.
- An inventory of the sequestration capacity of the Boulder County owned or managed forests, open space and parkland.
- Development one to five year short-term strategies based on the strategies in Environmental Sustainability Plan and the expected GHG reduction or sequestration from each: The prioritized list should include detailed implementation of the following initiatives.

- Install onsite solar photovoltaic (PV) systems to power county-owned buildings, including a building by building analysis of PV potential and recommended installations.
- Expanded purchase of renewable energy from local utilities.
- A recommended anti-idling policy by vehicle and operation type.
- Employee commuting management.
- Vehicle conversion including biofuel and possible sources.
- Management options for park lands to increase sequestration potential
- Expansion of wind or solar energy for on-farm electrical needs on Parks and Open Space–owned agricultural land.

- A minimum of three recommended five-year adoption plans for the any or all of the above strategies to be created with relevant stakeholder groups such as employees, open space and park users, utilities, tenant farmers.
- Metadiagrams of current operations and of the end state of the three adopted plans.
- Evaluation of the three adoption plans with regard to their environmental, economic and social impacts.

Scope of Work

Phase 1. Inventories

a. Update and refine the relevant findings of the the 2006 Greenhouse Gas Inventory Report with a breakdown by county operational type (i.e. maintenance, administration), department, and source (i.e. buildings, fleet, operations)
b. Perform an inventory of the sequestration potential of Boulder County owned, forests, parks and open space broken by type, usage, location and per area unit and total capacity.
c. Assemble findings into a metabolic flow analysis of carbon through county operations. The flow analysis should include:
    i. Sources (renewable or non-renewable and type),
    ii. Distribution – including storage and fueling facilities and power grid.
    iii. Usage – including type and location.
    iv. Management – the administrative and social processes governing the use of energy
    v. Sinks

Phase 2. Alternative modeling

a. Reductions expected given a change in energy source
b. Reductions expected given a change in technology and efficiency
c. Reductions expected given a change in distribution and use structure
d. Reductions expected given changes in usage policy
e. Reductions expected given a change in sink condition

Phase 3. Recommendations

a. Perform outreach to stakeholders presenting goals and findings to find preferred options and feasibility of implementation
b. Present three alternative adoption plans including timeframe and expected reductions per phase to public and to the Parks and Open Space Advisory Committee, Planning Commission,
c. Revise options based on public and stakeholder input
d. Present final three recommendations for adoption of final recommendation by County Commissioners.

The intent of this work is to provide a measured and holistic approach to implementation of the County's goals with regard to the Environmental Sustainability Plan. The urban metabolism framework is intended to provide a structure that accounts for the interactions of various systems involved in carbon production and sequestration. The adopted framework should be adaptable to other goals of the plan so that efforts can be coordinated as they are designed and implemented.

Social Processes and Community Outreach

The first step that Ferráo and Fernandez (2013) lay out in their prescribed metabolic method is to “establish a vision.” This has been done through each city’s plans. It is now time for the next step, to “characterize the urban metabolism.” Lacking this information, the target goals are left open ended or decided on by political consensus of working with stakeholders to find what is reasonable. Such input does not serve as a substitute for scientifically constructed metrics, but is it also not to be casually disregarded,

Boston’s Climate Action Plan makes a conscious to address equity as part of the plan. The Santa Monica, Calif. plan has the less specific “Human Dignity” as a goal area which includes equal access to economic benefits and minority representation in leadership. Within the Equity section of Los Angeles’s pLAn there is a section on Environmental Justice which addresses neighborhood air quality, food access and access and the green economy. Environmental Justice advocates go beyond just the initiatives of the plan and point out that science is subject to social constructions and there are inherent biases within the process that are exclusionary. There is pushback from some scientists such as Nygren and Rykoon (2008), who argue for the ecosystem as its own distinct construct apart from the social. This debate sits within a larger societal debate about the role of science in society and within a spectrum of rejections to the deterministic nature of science, including centerfolds leading anti-vaccination movements and climate change deniers. An urban metabolism study carried out as part of a government effort would necessarily be functioning within the social sphere. The city plans have required, to varying degrees, consideration of equity factors. An urban metabolism study would not however need to navigate the social and ecological spheres as a balance between two tensions. Inclusive processes as joint fact finding, expanded peer review and “street science” (Coburn 2005) can serve to strengthen the scientific inquiry by focusing it at problem areas, providing necessary context information and broadening data collection. By the same process, a social interest would not be able to out rightly reject a scientific finding in favor of a personal truth, but they would need to come to the table equally and rectify the situation. This type of expanded peer review, is not only just in terms of a community’s right to have input to its policy, but it would also allow the scientific finding to function better within the community

In some of the more hands-on methods on joint fact finding the community has taken on the scientific tools and been a part of data gathering (Loh 2015). This process of putting the science in the hands of the people would have the benefit of helping to spread the practice at a grassroots level. Metabolism and urban ecology studies have already been used to examine equity (Broto, Allen, and Rappaport 2012) and grassroots movements have forwarded the cause of sustainability (Martinez-Alli er2003). If put to practice, is popularized among EJ movements it would both give underserved communities a powerful tool with which to analyze, advocate for, and generate solutions to their causes, and give the urban metabolism discipline a strong ally in getting the practice adopted by municipalities.

Scales

While much can be done within cities and executed the city government level, metabolism studies will eventually need to be spread beyond city walls so to speak and begin to be coordinated across municipalities (Portney 2009). Regional planning agencies can take the lead in this field. Massachusetts Metropolitan Area Planning Council already acts as a data clearing house for the region and could gather and standardize metabolic data. Portland's Metro which has already shown to be a strong, quasi-legislative agency as shown by the urban growth boundary. They could take the lead in analyzing metabolism on a watershed scale. Boulder, CO is part of the Denver Council of Regional Governments which serves as the regional planning agency for communities along the northern frond range of Colorado. The Council's planning philosophy follows Calthorpe and Fulton's "Regional Planning"(2001) in the land uses it specifies and focus on transit. The DCORG has the geographic advantage of encompassing a range of environments from mountainous open space that begin watersheds, dense metropolitan areas, and open farmlands of the plains. They have the broad land pieces to construct sustainable metabolisms.

On a national scale, the U.S. would need to make serious commitments in executing the urban metabolism programs of the Organisation for Economic Cooperation and Development (OECD). The OECD has published a four volume guide on material flow analysis. The last volume which is on "implementing national MF accounts" is forthcoming. As part of this guide the OECD has created an inventory on member countries' MFA activities. The US performs MFA research on specific environmentally harmful substances, provides economy wide MFA data, through regular reporting sources, which is mostly focused on consumption and inputs (OECD, 2008). Most of the leading US research is done by universities with government funding. The guide goes on to prescribe methods of accounting for material flows and constructing indicators with the intent of having “harmonised” methods across countries.

The U.S. Council of Mayors is very active in sustainability (Ferráo and Fernandez 2013). As they are the heads of cities and functioning as a national organization, they can best take up the cause for metabolism studies and standards on a national level.

Summary

In his history “Urban Planning Theory Since 1945,” Nigel Taylor (1998) sites only two major paradigm shifts in the discipline. One brought on systems based thought and the rational process and the second was the post-modern rejection of that rationalism. Sustainability may become in hindsight a third shift if it be carried out comprehensively and holistically. There is definitely enough recognition of the urgency of sustainability among planners and government to make it the next paradigm shift. For the discipline of urban metabolism this means that despite issues with data availability and the ever-present issue of complexity, there is a specific and ready need for its services. Municipalities have initiatives underway which could be performed more completely and with more direction by engaging the urban metabolism. Despite the analytical tools needing development in some areas, there already exists the capability to analyze specific metabolic flows. Beginning with these flows will allow the practice to grow both in adoption and capabilities and eventually build to a comprehensive metabolic model of the city. Urban metabolism advocates and practitioners should perform outreach at professional, government, and community levels to get the practice adopted. There should be an effort to assure that the discipline is carried out with equity.

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Appendices

Appendix 1 - Computer Models

iTEAM (Integrated Transportation and Energy Activity-Based Model), represents a general modeling framework in which decisions taken by the agents (individuals, firms, households) are placed within the urban parameters and converted into energy demands (Almeida et al., 2009). The end goal of and iTEAM is to output the resources consumed by the agents' activities into a set of transparent metrics to inform policy decisions(Gauche, 2010)

Chingcuanco and Miller propose using the Integrated Land Use, Transportation, Environment (ILUTE) model system (ILUTE *)* as a base software which can be expanded to model the urban energy system (2011). ILUTE currently uses dwelling units, households, firms, individuals, as the building blocks of the urban area and simulates the behavior of these agents (Chingcuanco and Miller, 2011). In its current form ILUTE can tie together two dimensions of the urban system, human agents and urban form, in one metric, energy, but Chingcuanco and Miller believe the platform can be expanded to a multitude of dimensions (2011). To test this hypothesis, they used ILUTE to model residential space heating demands.

SynCity was developed by BP Urban Energy Systems project at the Imperial College London. It uses three submodels, the physical layout of the city, the agent choice model and the technology resource model, which then feed into specific energy models, such as transit or electricity (Kierstad, et al).

CitySim is a program developed at the École Polytechnique Fédérale de Lausannethat that models energy flows on a building scale, which can then be aggregated to the urban scale(citysim.epfl.ch, 2015).

UrbanSim is an open source software designed in response to Federal requirements that land use and transportation planning be linked (Wadell, 2002). It relies on several well established economic models such as discrete choice theory, spatial interaction and disequilibrium in markets (Wadell, 2002).

Example model platforms include SIMBOX (Baccini and Bader, 1996) and STAN (Cencic and Rechberger, 2008; Brunner and Rechberger, 2004). These models include representation of sub-processes, stocks and flows within the metabolism, sometimes linked to economic input output models.(Kennedy et al., 2010).

Appendix 2 – Sustainable Urban Metabolism Layers of Analysis (Ferráo and Fernandez 2013)

Table Appendix 2		
Layer	Description	Tools
Urban Bulk Mass Balance	The high level view of a city’s metabolism. Sum total of what goes in, stays in and comes out	Bulk Material Flow Accounting
Urban Materials Flow Analysis –	more detailed my material and type. Uses classification from MatCat. Allows to trace flows for recapturing materials	Product Composition Analysis
Product Dynamics –	incorporates time for stocks and when stocks can be recaptured. Couple MFA with LCA	Life Cycle Analysis
Material Intensity of Economic Sectors –	basically types of use and interactions between.	Physical and Economic Input Output Tables.
Environmental Pressure of Material Consumption	(This is the layer I think missing from many other studies) – uses various foot printing tools and has the capability to	Economic Input Output Tables Life Cycle Analysis

	answer some direct environmental questions.	
Spatial Location of Resource Use.	used to try and close loops efficiently. The multi-regional nature of resources needs to be captured in the intermediate demand, that occurring in urban areas. So far the models to do this are inadequate. The urban scale then becomes important to analyze and locate materials. Zones can be delineated and the question of equity in distribution can also be addressed	GIS. Spatial Economic Activities Matrix.
Transportation Dynamics.	hugely complicated and adequate modeling has not yet been developed. Need to incorporate trucking	Agent Based Models

Appendix 3 – City Planning Documents Evaluation

In separate file.