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Urban fabrics and urban metabolism – from sustainable to regenerative cities

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ABSTRACT

This paper uses urban metabolism as a way to understand the sustainability of cities. It suggests that the city organism can reduce its metabolic footprint (resource inputs and waste outputs) whilst improving its livability. Like organisms, different cities have different metabolisms. This paper demonstrates that different parts of a city (walking, transit and automobile urban fabrics) also have different urban metabolisms. A detailed case study from the city of Perth, Australia, is used to demonstrate metabolic variations in different parts of the city. Understanding urban metabolism and the processes that drive it is the key to transitioning from ecologically extractive to sustainable cities. Through targeted improvements it is even possible for some elements of the city to become regenerative so that they restore parts of the degraded urban environment thus reversing damage to the biosphere.

1. Introduction

1.1. Aims and objectives

The objectives of this paper are twofold. The first objective is to demonstrate how different urban form and infrastructure (urban fabrics) play an important role in determining urban resource flows i.e., different urban fabrics have different urban metabolisms. While most early studies on urban metabolism tended to focus upon the whole city or city regions e.g., (Baccini, 1997; Kennedy et al., 2011; Newman et al., 1996; Warren-Rhodes and Koenig, 2001), the case study presented in this paper describes differences that have been observed in different parts of Perth, Australia – a medium sized city of two million people. We suggest a causal link between reductions of urban metabolism and the underlying urban fabric.

The second objective aims to apply this knowledge in a practical manner to help deliver a regenerative city. In this sense urban metabolism may be used as a design tool by city makers to optimize the efficiency of the underlying urban fabric, calibrate development to maximize regenerative design outcomes, and catalyze urban sustainability transitions. This is necessary because the present generation of the human population is facing unprecedented global grand challenges including rapid population growth, increasing consumption patterns, resource scarcity, climate change, biodiversity loss and social inequity (Bina et al., 2016) and cities can do more than just reduce their impact but can regenerate past impacts.

Recent work on the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2011, 2015) suggests that a failure to shift the trajectory of current environmental impact presents an existential risk to *homo sapiens*. In their assessment of planetary boundaries Steffen et al. (2015) suggest that policy, governance and business approaches to the two core planetary boundaries – climate change and biosphere integrity – need to change.

There have been numerous papers on the need to find a 'safe operating space' for human activity that lies within planetary boundaries (Costanza, 2008; Du Plessis and Brandon, 2014; Rockström, 2009; Rockström et al., 2009; Seitzinger et al., 2012). However, the justification to rapidly respond to these grand challenges has recently moved beyond an ethical reason to a political one. The ratification of two major international policies by most member states of the United Nations – the Sustainable Development Goals (SDGs) (United Nations General Assembly, 2015) and the Paris Agreement (United Nations, 2015a) put in place a global political mandate for change. While both of these policies outline clear targets or objectives to direct humanity away from a potential existential crisis caused by present unsustainable human activity, they do not offer the mechanisms for achieving the required shift.

This paper offers some potential solutions. It does this by demonstrating how the underlying urban fabric heavily influences urban metabolism. By better understanding this relationship, science can help inform urban decision-makers to deliver not just

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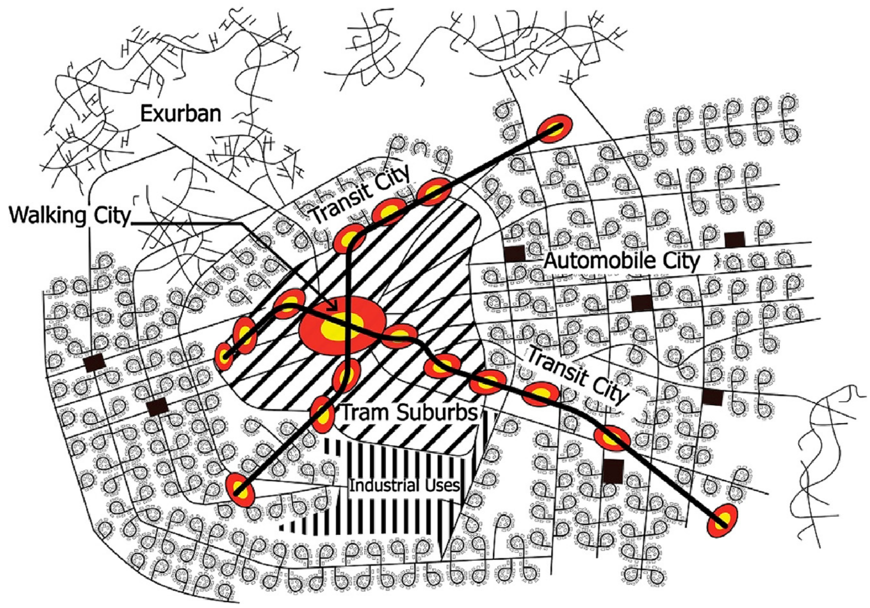

Fig. 1. Automobile urban fabric, transit urban fabric and walking urban fabric, a mixture of three urban fabric types of a typical city.
Source: Newman and Kenworthy, 2015

sustainable but regenerative built form that is capable of driving local and regional transitions that can seriously address planetary boundaries. If this can be done at scale, then a global network of regenerative cities has the potential to play a major role in this global challenge.

Cities present an opportunity because the human population is rapidly urbanizing. In 2014, 54% of the world's population were residing in cities and by 2050 this figure is expected to be close to 70% concentrating sustainable development challenges within cities" (United Nations Department of Economic and Social Affairs Population Division, 2014). Harnessing this wave of urbanization as a means for delivering sustainable human settlements could represent a major opportunity for reducing ecological footprint. Indeed the *New Urban Agenda* coming out of Habitat III in October 2016 calls for an urban paradigm shift that will "redress the way we plan, finance, develop, govern and manage cities and human settlements, recognizing sustainable urban and territorial development as essential to the achievement of sustainable development and prosperity for all". Actions to achieve this would include "integrated urban and territorial planning and design in order to optimize the spatial dimension of the urban form and to deliver the positive outcomes of urbanization" (United Nations, 2016, pp. 3–4). But to do so would require calibration and improvement of urban performance through ongoing urban metabolism assessment to ensure urban sustainability performance targets are met or exceeded so that cities can be a major force in reversing planetary boundary challenges.

Kennedy et al. (2011, p. 1968) describe the potential of the data rich urban metabolism for practical application to urban design and planning. Through the urban metabolism analysis presented in this paper we offer some conclusions that will be useful to urban planners to understand where the best leverage points may be to help provide infrastructure that best supports citizen efforts to reduce and then reverse the ecological footprint of cities.

The paper offers a brief overview of the historic origins of cities that have led to the widespread creation of unsustainable urban form, it describes our approach to urban metabolism and the use of regenerative design as an aspirational target for delivering the regenerative city, before presenting an urban metabolism analysis prepared on Perth. This is the first study we are aware of that has been developed to demonstrate the variations in urban metabolism across different urban fabrics within the same city and can be used to show the kind of dramatic changes that cities need to address.

1.2. Background

1.2.1. Historic origins of cities

Over the last 10,000 years since the advent of agriculture, *homo sapiens* transitioned from nomadic hunter-gatherer to farming settlements (Zvelebil, 2009). This transition marks a shift from living within an ecosystem to extraction from an external ecosystem to support human life. The agglomeration benefits for culture and trade increase with the size of the settlement (Florida, 2002; Glaeser, 2011; Rawnsley and Spiller, 2012). This condition has resulted in increasingly larger urban settlements. Modern cities have been generally designed as extractive engines drawing resources from natural systems, processing these resources to generate value, and producing wastes whose impacts are externalized. These input output transactions were likened to an organism by Wolman (1965); and this way of thinking has experienced a resurgence in popularity in recent years (e.g, Baccini and Brunner, 2012; e.g. Gandy, 2004; Girardet, 2010; Newman and Kenworthy, 1999). Just as organisms have metabolism, cities have a metabolism – an urban metabolism to maintain their structure, grow and respond to their environment and which can impact heavily on its local, regional and global environment. Not only do different cities have different metabolisms, different *parts* of the city also demonstrate considerable variations in urban metabolism. This paper will seek to quantify urban metabolism in these different city parts. This new understanding of how cities work can show how such cities may shift from being extractive to regenerative so they once again allow human society to live within local, regional and global ecosystem boundaries.

1.2.2. The nature of the problem

To reflect the central role of human activity upon the geology and ecology upon the current phase of earth history, it has been proposed and widely accepted that this geologic epoch be called "the Anthropocene" (Crutzen and Stoermer, 2000; Steffen et al., 2011). Material and substance flow analysis (Baccini and Brunner, 2012;

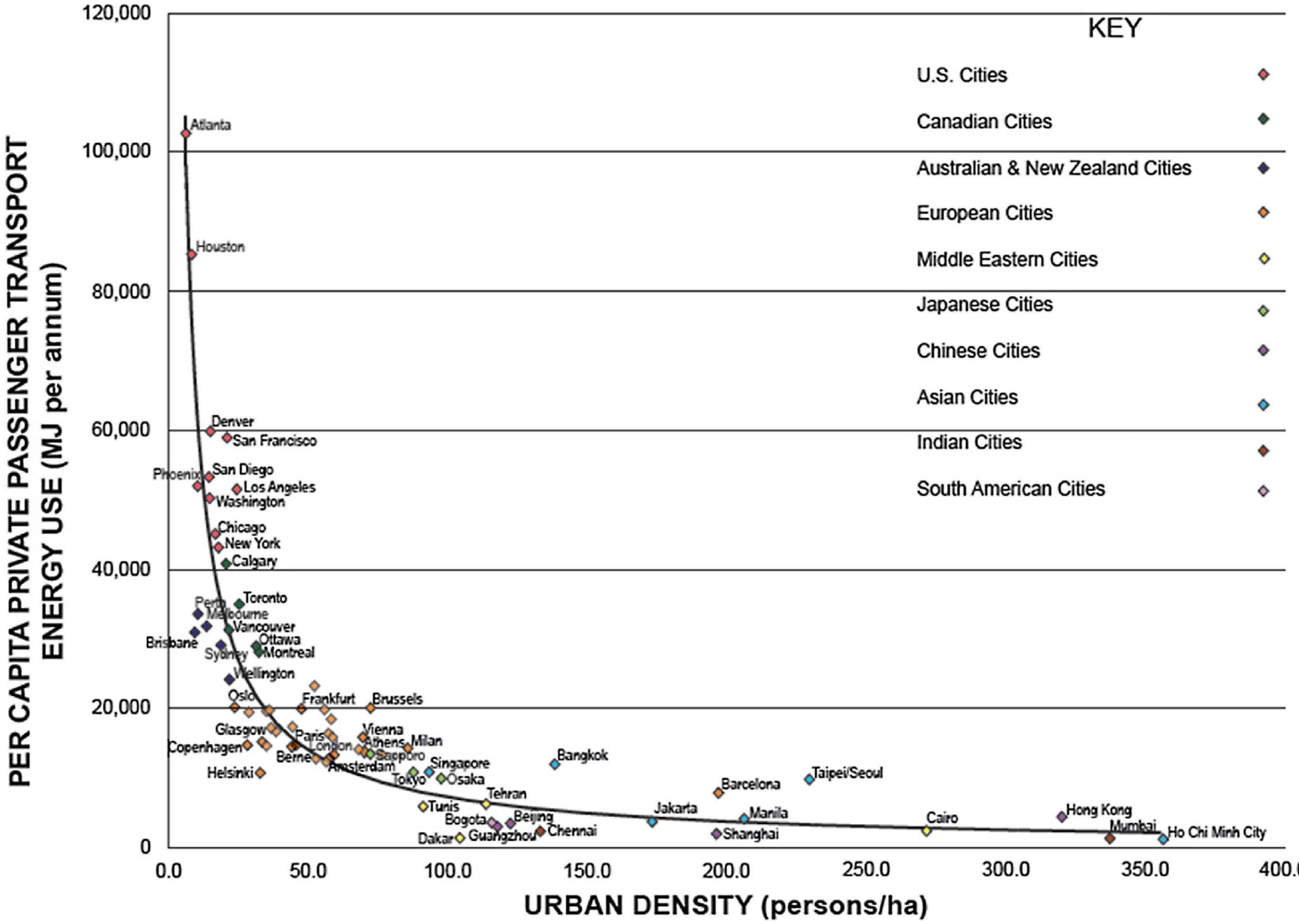

Fig. 2. Urban density and transport fuel in global cities, 1995.
Source: Newman and Kenworthy, 2015; Global Cities Database.

Kennedy et al., 2007; e.g. Newman and Kenworthy, 1999) demonstrate that human impact upon the ecosphere is ubiquitous, with the extraction and processing of resources from natural systems to generate economic value resulting in the accumulation of waste materials and substances in the atmosphere, biosphere and hydrosphere faster than they can be replenished or processed (Global Footprint Network, 2016; Wackernagel and Rees, 1998).

In 2015 the 'ecological overshoot' was estimated to be '54% above the planet's biocapacity' meaning we need 1.5 planets to live sustainably (Global Footprint Network, 2016). Quantifying anthropogenic environmental impact has been given a more detailed scientific basis by Rockström (2009) and Steffen et al. (2015) through planetary boundary analysis.

2. Regenerative design and urban fabrics

2.1. Regenerative design

The degeneration of the ecosphere witnessed in the Anthropocene is an unconscious outcome of human system design. Is it possible then, to use our emerging knowledge of urban metabolism, to consciously design systems that support human needs while also regenerating the ecosphere?

It is. The concept of regenerative design has been applied to landscape architecture for a quarter of a century. Most famously by John Lyle who describes the process as "*replacing the present linear system of throughput flows with cyclical flows at sources, consumption centers and sinks*. . .*(It) has to do with rebirth of life itself, thus with hope for the future*" (Lyle, 1999, pp. 11–12). It is possible to apply these principles to entire human settlements such that the Anthropocene becomes resilient and sustainable.

For millennia humans were agrarian or nomadic but now rapid urbanization and rapid population growth are concentrating human activity into cities. This is important as we will demonstrate in this paper that urban form and infrastructure play an important role in determining urban resource flows (cf. Newman and Kenworthy, 2015, 1999), so redesign of urban areas can help facilitate sustainability by optimizing resource flows and developing circular metabolisms (GIZ and ICLEI, 2014).

Redesigning urban areas as "regenerative cities" builds upon the work of landscape architects such as Lyle (1996) but applies the concept to the whole urban system. This paper will use recent research to discuss the various aspects of the ecological-infrastructural system of cities as they relate to urban metabolism. By recognizing where opportunities lie and where limitations exist it becomes possible to understand how urban systems may be optimized whilst continuing the historic role of cities as the generator of economic and social opportunities for a growing urban population.

The notion of the Regenerative City was outlined in 2010 by the World Future Council as a city that regenerates its ecological footprint not just minimizes it (Girardet, 2010). Girardet (2015) defines a truly regenerative city as one that exhibits the following characteristics:

- An environmentally enhancing, restorative relationship between the cities and the natural systems they depend on;
- renewable energy systems; and
- new lifestyle choices and economic opportunities which will encourage people to participate in this transformation process.

The opportunity for regenerative cities applies equally to new or retrofit urban areas but the greatest opportunities lie in the vast urban areas yet to be built. The analysis below helps give substance to these possibilities by relating how urban growth can help or hinder in this regenerative process by focusing on particular urban fabrics.

The application of regenerative design to cities may represent the greatest opportunity for a rapid planetary sustainability transition. The vast potential of cities may present an alternative to geoengineering to avert climate change as described by Fink (2013) and a regenerative overlay to this can bring additional benefits to the planet's burgeoning cities (Rauland and Thomson, 2015).

Defining the vision for a new urban agenda as attempting to develop regenerative cities creates a paradigm-shifting goal. Such a goal will require urban metabolism analysis to seek opportunities for the continual optimization of urban performance. The Global Footprint Network (2016) assess that the world went into ecological overshoot in the 1970s and since this time the world's population has doubled. Global population projections suggest growth of another 3–4 billion people by the end of this century (United Nations, 2015b). Rather than seeking a net balance of zero to maintain equilibrium in order to 'meet the needs of future generations', the goal must now be to use this growth to regenerate the depleted ecosphere and to build up stocks of natural capital wherever possible through regenerative design applied to human settlements and systems.

2.2. Urban metabolism studies in Australia

Australian cities have very high ecological footprints around three times the global average (Turner and Foran, 2008). Several urban metabolism studies have been prepared as part of the State of the Environment Reporting for the Australian Government,[1] the first of these reports in 1996 included a comprehensive urban metabolism assessment for Sydney (see: Newman et al., 1996).

Subsequent reports track progress against a range of indicators and the most recent urban metabolism assessment of the major capital cities in the 2016 State of the Environment Report (Jackson et al., 2016) demonstrates that per capita trends for energy, water and transport fuel are generally decreasing (see Table 1).

What is most striking is the significant increase in sustainability measures including a 67% increase in renewable energy, 27% increase in recycling, 17% decrease in car use per person and a modest increase in public transport patronage of around 2.5% after previous declines.

The variations in resources, wastes and livability across cities are significant, but recent studies have demonstrated that significant variations are also found between different parts of a city.

This paper seeks to relate how any city can target a simultaneous reduction in their footprint whilst improving their livability through a better understanding of different parts of the city. It uses the new theory of urban fabrics to explain the relationships and to suggest how a city can respond to urban metabolism through urban planning and transport planning, two of the most powerful tools available in urban development. Finally it will discuss how the concept can move beyond the sustainable cities vision to a regenerative cities perspective.

2.3. Urban fabrics

Having a perspective on how cities as a whole region or urban ecosystem function with a metabolism based process is useful for understanding how urban metabolism can be reduced. However, cities are made up of different structural parts which vary considerably in their resource input requirements and waste outputs (Newman and Kenworthy, 2015). Examining the fundamental causes of these differences enables us to go beyond bland policies to much more specific ones that are based upon true cause and effect within transport and town planning professional practice. This paper seeks to determine how three fundamental urban fabrics that are found in any city, can be related to their metabolism and hence how the theory can enable policy formulation to reduce footprints.

2.4. The theory of urban fabrics

The theory of urban fabrics is developed in Newman and Kenworthy (2015) to show how transportation systems create city form and function. The ideas are influenced by earlier work related to transportation and urban form (Muller, 2004; Newman and Kenworthy, 1999) but have been developed further[2] and are now being used in some Scandinavian urban planning and research (Söderström et al., 2015).

2.5. History of urban fabrics

Cities are shaped by many historical and geographical features, but at any stage in a city's history the patterns of land use can be changed by altering their transportation priorities, this topic is given detailed treatment in Newman and Kenworthy (2015), and are summarized in the following paragraphs. Marchetti (1994) and Zahavi and Talvitie (1980) demonstrated a universal travel time budget averaging around 1 h/person/day. Kenworthy and Laube (2001) found the *Marchetti constant* applied to every city in the Global Cities Database, as well as in data on UK cities for the last 600 years (Standing Advisory Committee on Transport 1994). Further analysis of 2005-6 complete travel data by mode (walking, cycling, public transportation, cars and motorcycles) on forty-one global cities using average modal travel speeds, showed that the mean and median travel time per day was 66 and 65 min respectively (see Kenworthy (2014) for the travel data used).

The Marchetti constant therefore helps us to see how cities are shaped (Newman and Kenworthy, 1999). Cities grow to being about 'one hour wide' based on the speed with which people can move in them. If they go beyond this they start to be dysfunctional and therefore begin to change infrastructure and land use to adapt again to this fundamental principle (Van Wee et al., 2006).

Below we will show how different urban fabrics have developed from different transport types and how they should be recognized, respected and regenerated and can indeed help us achieve a reduced urban metabolism.

[1] Reports have been prepared every 5 years since 1996, all Australian State of the Environment reports may be downloaded from: https://www.environment.gov.au/science/soe.

[2] For more detail and development of some of these ideas and their application to practice see: urbanfabrics.fi.

Table 1
Trends in urban metabolism in Australia, 201–15. Author's calculations, data.

Metabolism Factor	Trend in Australia, 2011–2015
Energy	Household energy consumption per person dropped 7%; Renewable energy by households increased 67%. Household energy intensity decreased 20%, Manufacturing energy intensity increased 3%, Commercial and Services decreased 2%. Commercial building energy intensity decreased by 0.3%
Water	Water consumption per capita decreased 2%, with large variations across cities.
Transport	Car use per person declined 17%; Public transport increased 2.5% per annum.
Land Take	Urban footprint increased but per capita land take decreased
Solid Waste	Waste produced increased 9.1% but waste recycling increased by 27% so overall there was a 15% decrease in waste to landfill (60% of waste now recycled). Household waste 29%, high recycling; Construction waste 29%, least recycling; Manufactured waste 19%, most recycling.

Source: State of Environment Report 2011 (Hatton et al., 2011) and State of the Environment Report 2016 (Jackson et al., 2016).

2.6. Characterizing three urban fabrics

The theory of urban fabrics was developed by Newman, Kenworthy and Kosonen (2015) to help planners see that there are three main city types, not one (automobile fabric) as suggested by modernist city planning since the 1940′s. The theory enables planners to create strategies for managing the different fabrics and especially how to see that some urban fabrics have inherently more sustainable properties that need to be optimized and extended to other parts of the city.

There are three city types from history that form the basis of urban fabric theory: walking cities, transit cities and automobile cities. Most cities today have a mixture of all three urban fabrics. The fundamental problem with 20th century town planning has been the belief that there is only one type of city: the automobile city. As will be shown below it is the automobile city that is the most resource consumptive type of urban fabric. A resurgence in the other urban fabrics has begun to reduce automobile dependence as a city planning paradigm and thus focuses our ability to reduce and eventually regenerate urban footprints.

A conceptual diagram of the three city fabric types is set out in Fig. 1 and are outlined in their historical development based on the above principles.

Walking Cities are the oldest typology as walking, or at best animal-powered transportation, was the only form of transport available to enable people to move across cities. Dense, mixed-use areas generally over 100 persons per hectare characterize walking urban fabric. The slow transport speeds averaging around 3–4 km/h limited most cities to three or four kilometers diameter with the most intensively developed areas usually around a central focal point such as the main city square or market.

Walking cities were the major urban form until the 1850s and many modern cities are built around a nucleus of an older walking city, but they struggle to retain the walking urban fabric due to the competing automobile city fabric which now overlaps it (Newman and Kenworthy, 2015). Reacting to this competition many modern cities are now attempting to reclaim the fine-grained street patterns associated with walkability (Gehl, 2011) but often don't have the tools to do so as modernist planning manuals rarely focus on pedestrian needs, however this is slowly changing for example the new NACTO manuals (National Association of City Transportation Officials) that emphasize the importance of the human experience.

Transit Cities from about 1850–1950 were based on trains (from 1850 the steam train began to link cities and then became the basis of train-based suburbs) followed by trams (from the 1890s) that extended the old walking city. Both could travel faster than walking – trams at around 10–20 km/h and trains at around 20–40 km/h.

Trams and trains supported corridor development where densities could be reduced to around 50 persons per ha yet walking fabric still remained around transit stops. Such urban fabric could now spread out forming the inner city transit urban fabric 10–20 km across (5–10 km radius with an average around 8 km) and with trains forming the outer city transit urban fabric 20–40 km (10–20 km radius) (Marchetti, 1994; Newman and Kenworthy, 2015).

More recently, fast trains have enabled the transit urban fabric to extend well beyond a 20 km radius (McIntosh et al., 2013) and where fast trains averaging 80 km/h are built across big cities a polycentric transit fabric emerges around major stations.

Automobile Cities from the 1950s onward were no longer constrained to fixed corridors. The flexibility and speed (average 50–80 km/h on uncongested roads) of the automobile allowed cities to spread well beyond a 20 km radius with some cities achieving an 80 km diameter (40 km radius) in all directions, and at low density with zoning separating uses, to further disaggregate urban intensity.

Low urban intensity reduces the potential for cost effective transit and as a result sprawling suburbs became the basis of automobile dependence (Newman and Kenworthy, 1989) and automobility (Urry, 2004). Cities in the new world from around 1950 have used their growth to build automobile dependent suburbs as their main urban fabric (Newman and Kenworthy, 2015).

There is a need to see that there are real issues associated with the dominance of automobile urban fabric, especially where it extinguishes the best features of walking and transit fabric and creates a much bigger urban metabolism. If the data on planetary boundaries is assessed in detail (see Steffen et al., 2015) it is obvious that a dramatic increase in impact occurred after 1950 in most of the factors considered to be causal; the automobile city fabric has been the main urban development focus in this post 1950 period.

3. Metabolism and urban fabric

Newman and Kenworthy (2015) have shown that there is a significant set of differences between these three kinds of urban fabrics in their areas, elements and qualities that can form the basis of statutory and strategic town planning. Each fabric can also be shown to have different metabolism qualities.

3.1. Energy

The term automobile dependence was developed in the 1980′s to express how cities were now being built around the car; this was dramatized using a graph of density versus transport fuel in 32 cities (Newman and Kenworthy, 1989). There are now around 100 cities in the database and the same graph is evident showing how transport energy exponentially reduces with increases in density (See Fig. 2). As we explain further in Section 3.3 low density automobile urban fabric has other implications on energy, both embodied and operational.

Table 2
Resource input variations between urban form types (see Appendix A for table assumptions).

INPUT (Per Person Per Year)	Automobile Urban Fabric	Transit Urban Fabric	Walking Urban Fabric
Resources			
Fuel in Megajoules (MJ)[1]	50 000	35 000	20 000
Power in Megajoules (MJ) [2]	9 240	9 240	9 240
Gas in Megajoules (MJ) [2]	4 900	2 940	2 940
Total Energy in Gigajoules (GJ)[2]	64.14	47.18	32.18
Water in Kilolitres (Kl)[2]	70	42	35
Food in Kilograms (kg)[3]	451	451	451
Land in Metres Squared (m^2)[4]	547	214	133
Urban Footprint in Hectares (ha)[5]	2.29	1.97	1.78
Basic Raw Materials (BRM) for New Building Types Per Person[6]			
BRM 1) Sand in Tonnes (T)	111	73	57
BRM 2) Limestone in Tonnes (T)	67	44	34
BRM 3) Clay in Tonnes (T)	44	29	23
BRM 4) Rock in Tonnes (T)	66	43	33
Total BRM in Tonnes (T)	288	189	147

Table 3
Waste output variations between urban form types (see Appendix B for table assumptions).

OUTPUT (Per Person Per Year)	Automobile Urban Fabric	Transit Urban Fabric	Walking Urban Fabric
Waste			
Greenhouse Gas (Fuel, Power & Gas) in Tonnes (T)[1]	8.01	5.89	4.03
Waste Heat in Gigajoules (GJ)[2]	64.14	47.18	32.18
Sewage (incl. storm water) in Kilolitres (KL)[3]	80	80	80
Construction & Demolition (C&D) Waste in Tonnes (T)[4]	0.96	0.57	0.38
Household Waste in Tonnes (T)[5]	0.63	0.56	0.49

From this data three groupings of cities emerge: the American and Australian cities which were the most car dependent, European cities which are in the middle and use fuel at about a third of the first group; and Asian and Latin American cities with the least car dependence and least fuel use.

As each city has a mixture of three urban fabrics what this suggests is that the first group are dominated by automobile city urban fabric, the second group by transit city urban fabric and the third by walking city urban fabric.

Although this work has been broadly discussed in the literature some criticisms such as Höjer and Mattsson (2000) rightly identify that there are additional factors required if the causal relationship between density and car use is to hold – it is possible to deliver high density automobile fabric if the conditions for transit or walking are not provided, however, the results are often suboptimal with regard to sustainability and livability (Thomson et al., 2016). Indeed it is precisely the opportunities that population density offers to meet thresholds to support more sustainable infrastructure (e.g., transit ridership, catchments for service provision, housing density to allow short infrastructure lengths to support distributed utilities etc.) that enable higher density urban fabric to be more sustainable. Höjer and Mattsson's (2000) observation of the need for these additional factors is echoed by others such as Hall (2013) who observes that the more holistic and integrated the approach to urban planning the greater the opportunity for a good outcome.

3.2. Basic raw materials

Basic raw materials (BRM) are the sand, clay and stone that form the foundation for building construction. They literally are built into the fabric of a city.

Basic raw material studies are rare (e.g. Hendriks and Petersen, 2000). Recent data collected by the Curtin Sustainability Policy Institute (CUSP) and Arup (Gardner and Newman, 2013) on Perth enables us to see the significant variations that can be observed in urban metabolism across different parts of the city. The normal quantities of material that went into construction in three parts of the city were examined: central/inner which is very similar to the old walking city; middle suburbs which are similar to the transit city; and outer/fringe suburbs that are the automobile city.

The variations across the city can be demonstrated graphically in Fig. 3 and the data are shown in Table 2 below. The variations are huge (due to the amount of fabric required in construction) and are even greater when the factor of technologically innovative construction techniques is applied. In Fig. 3, the area of the circles represents the proportional volume of basic raw materials required for new building types per person. In the Perth case study the BAU automobile urban fabric requires about almost twice as much basic raw materials (288 t/person) compared to walking urban fabric (147 t/person).

3.3. Metabolism of the three urban fabrics

The full urban metabolism of the three urban fabric samples in Perth is set out in Table 2, which shows resource input variations between urban form types, and Table 3, which shows waste output variations between urban form types, (Gardner and Newman, 2013). These data show the variations in energy, water, land, food, and basic raw materials in the three areas of the city as well as the wastes produced from this. There are very different metabolism flows in the three different fabrics. Inputs such are significantly reduced in the denser walking and transit urban fabric compared to automobile fabric for example:

- Transport fuel per capita usage is more than halved in walking urban fabric compared to automobile urban fabric,
- Water use is significantly less – this is largely a function of not having to irrigate large garden areas in Perth's hot and dry summers
- Land consumption is over 3.5 times less per capita substantially reducing urban encroachment upon surrounding agricultural land and valuable ecological areas (South Western Australia where Perth is located is a global biodiversity hotspot)
- Basic raw materials are roughly half.

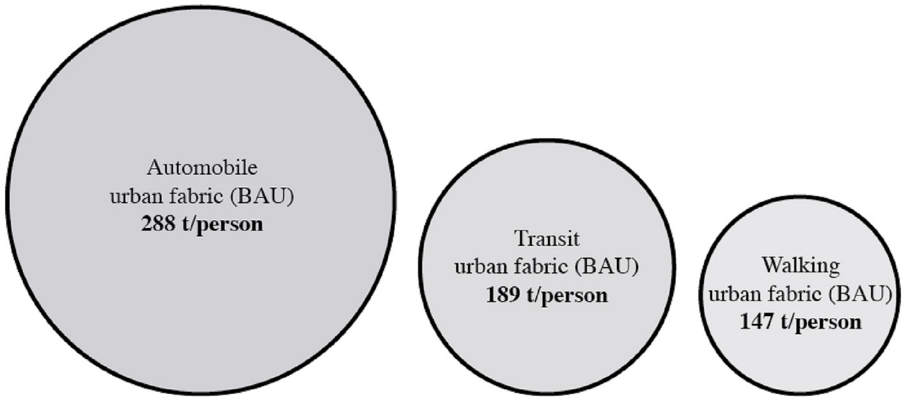

Fig. 3. Perth's basic raw material demand in terms of three urban fabrics.

Source: Gardner and Newman (2013)

The high basic raw material demand in BAU automobile urban fabric is due to both the additional material used in low density dwellings, for example the provision of a double garage but also the additional infrastructure required to service those plots both on the plot such as fill and driveways and off the plot such as additional length of infrastructure (e.g., roads or pipes) to service fewer dwellings for the same length (e.g., ten times the road length is required to service dwellings at 10 persons/ha (a common density for automobile fabrics) versus 100 person/ha (a common density for walking fabric).

Similar efficiencies in terms of outputs were seen in the denser walking and transit urban fabrics as shown in Table 3, particularly in terms of greenhouse gas (GHG) and waste heat; and construction and household waste.

The fundamental structural difference in the three urban fabrics dominates the differences between the three kinds of urban systems.

3.4. Optimizing urban fabrics

An additional layer of analysis captured in Table 4 (inputs) and Table 5 (outputs) demonstrates the considerable urban metabolism improvements if Technological and Construction Innovation (TCI) is introduced. The greatest gains being found in the reduction of basic raw materials (BRM) and construction and development (C&D) waste through the introduction of efficiency measures such as prefabricated building techniques. As Fig. 4 illustrates per capita requirements of walking urban fabric with TCI can be reduced to around 15 t/capita, almost twenty times as efficient as BAU automobile fabric (288 t/capita) in the same city (Gardner and Newman, 2013, p. 22).

4. Using urban fabric to reduce and regenerate urban metabolism

4.1. Town planning implications

Modernist urban planning is almost universally applied to cities and creates predominantly an automobile city set of fabric areas and fabric qualities, with their associated metabolism. Overcoming the dominance of this paradigm will be required to shift the current trajectory away from planetary boundary transgressions outlined by Steffen et al. (2011). More sustainable patterns of urbanization are also the subject of the United Nation's new urban agenda (2016).

This transition has begun to occur as the world is witnessing 'peak car' and a dramatic growth in transit and walking city fabric (Newman and Kenworthy, 2015). The new era appears to be shifting away from automobile urban fabric this is largely a function of economics. The walking city enables greater face-to-face interaction and this function has been recognized as increasingly significant for the growing economic functions associated with the knowledge economy, the creative economy and the services economy (Florida, 2002; Hall, 1999; Newton, 1991). This demands that we have a more coherent set of planning norms that can more easily accommodate a reduction in metabolism and improved livability associated with less automobile urban fabric. The town planning system is however going to need to change away from its statutory regulations on densities, car parking, mixed use and other key regulations that end up producing automobile urban fabric.

Wherever possible when planning for greenfield and brownfield urban areas automobile fabric should be minimized in favor of higher density transit and walking fabric so as to maximize resource efficiency for the more difficult urban components such as transport fuel, solid waste and building materials.

In addition new developments should seek infrastructure synergies at the energy, water and waste nexus (GIZ and ICLEI, 2014), such integration of utilities can optimize efficiency between each through an industrial ecology.

How then do we begin to practice town planning based on the theory of urban fabrics to advance the regenerative city concept? How do planners manage cities in this rapidly changing set of factors outlined above and where the 20th century modernist certainties about automobile urban fabric are now losing their appeal? Transitioning to sustainable urban forms that support an efficient circular urban metabolism will require a combination of the right urban fabric, infrastructure integration, and technology as outlined below.

4.2. Designing urban fabric to optimize urban metabolism

At any stage in a city's history the patterns of land use can be changed and the building opportunities can be taken to enable a regenerative approach.

If cities are shaped by their transportation systems which in turn have a major impact upon urban metabolism then the most important policy and planning direction to reduce the ecological footprint for the city is to restrict the development of automobile urban fabric in favor of transit and walking fabric. However, when redeveloping existing urban areas it will be necessary to carefully co-ordinate land use intensity concurrently with the imposition of new transportation systems over the urban fabric or else this mismatch will render them largely dysfunctional.

Creating new, or regenerating old, urban areas for sustainability requires first a consideration of the transport mode and building

Table 4
Resource input variations between urban form types due to technology and construction innovation (see Appendix A for table assumptions).

INPUT (Per Person Per Year)	Automobile Urban Fabric	Transit Urban Fabric	Walking Urban Fabric
Resources			
Fuel in Megajoules (MJ)[1]	50000	35000	20000
Power in Megajoules (MJ) [2]	4620	4620	4620
Gas in Megajoules (MJ) [2]	2450	2450	2450
Total Energy in Gigajoules (GJ)[2]	57.07	57.07	57.07
Water in Kilolitres (Kl)[2]	70	70	70
Food in Kilograms (kg)[3]	451	451	451
Land in Metres Squared (m^2)[4]	547	547	547
Urban Footprint in Hectares (ha)[5]	2.22	2.22	2.22
Basic Raw Materials (BRM) for New Building Types Per Person[6]			
BRM 1) Sand in Tonnes (T)	56	22	5.7
BRM 2) Limestone in Tonnes (T)	34	13.2	3.4
BRM 3) Clay in Tonnes (T)	22	8.7	2.3
BRM 4) Rock in Tonnes (T)	33	13	3.3
Total BRM in Tonnes (T)	145	57	15

Table 5
Waste output variations between urban form types due to technology and construction innovation (see Appendix B for table assumptions).

OUTPUT (Per Person Per Year)	Automobile Urban Fabric	Transit Urban Fabric	Walking Urban Fabric
Waste			
Greenhouse Gas (Fuel, Power & Gas) in Tonnes (T)[1]	7.13	4.98	2.95
Waste Heat in Gigajoules (GJ)[2]	57.07	39.90	23.65
Sewage (incl. storm water) in Kilolitres (KL)[3]	80	80	80
Construction & Demolition (C&D) Waste in Tonnes (T)[4]	0.29	0.22	0.18
Household Waste in Tonnes (T)[5]	0.63	0.56	0.49

typologies as these shape and define the urban fabric. An integrated approach offers greater opportunities for optimization of urban metabolism (Bunning et al., 2013; GIZ and ICLEI, 2014; Newman, 1999; Newton et al., 2012a).

An individual building can be optimized in terms of its metabolism however development needs to address at least the neighborhood or precinct scale to benefit from the additional opportunities for optimization offered by urban fabric and district utility and community services. Integrated precinct design has the potential to deliver transitional, decentralized, sustainable neighborhoods that cumulatively work toward delivering a regenerative (or at least more sustainable) city. The precinct is the ideal scale to trial innovative processes and technologies, successful prototypes can in turn inform urban policies or guide institutionalized financial incentives to ultimately mainstream the type of sustainable urbanism needed to reduce the ecological footprint of cities through the optimization of their urban metabolism.

The potential to create regenerative opportunities are significantly improved if a center or sub-center are the fundamental urban fabric that is being regenerated.

But particular strategies will still be needed for each component of urban footprint to collectively reduce its urban metabolism and work toward the delivery of a regenerative city. For example:

1. Energy can become regenerative if the fuel used to build and operate buildings and build and run transport, is renewable and greater than is actually being consumed by the city and can be used to help power and fuel the surrounding bioregion. This is likely highly energy efficient buildings and maximizing the available sites to create renewable energy from sun, wind and geothermal sources to power electric systems in buildings and transport as well as renewably-powered gas (Droege, 2008; Newman and Kenworthy, 2015),
2. Water can become regenerative if there is a big emphasis on water efficiency as well as collecting rain water and ground water, and recycling waste water and any excess is used to help regenerate aquifers and water bodies in the bioregion. This can be done with current technologies,
3. Biodiversity can become regenerative if it is built into every part of the urban fabric. Such biophilic urbanism approaches will need to enable green roofs, green walls and water sensitive design to create more habitat opportunities than existed prior (Beatley, 2009; Kellert et al., 2011; Newman, 2014; Newman and Matan, 2013). While this is not possible when urban development encroaches upon intact ecosystems, is can occur where urban development or expansion is into degraded agricultural or urban land. The greening of degraded urban land is a common theme in best practice urban regeneration for example where hardscape such as roads can be retrofitted or surface parking redeveloped and revegetated (Dunham-Jones and Williamson, 2008; Gehl and Rogers, 2013; Newton et al., 2012b). Bioregional needs in biodiversity can be assisted by the city with its different structural habitats and intensive human power (e.g., gardening and remnant urban habitat conservation),
4. Waste can be reduced to very small amounts but not regenerated unless very large amounts of energy are used due to thermodynamic limitations. However the return of carbon, phosphorus, nitrogen and other trace elements to surrounding soils in the bioregion can be done through recycling. Nutrient recycling can also provide rich growing mediums for urban agriculture (Newman and Jennings, 2008),
5. Materials can be significantly reduced if new technologies in building materials and construction techniques (such as modular off-site construction) can be used and recycling is optimized; however thermodynamic limits mean that productive material outputs can never be greater than material inputs unlike water and energy (Gardner and Newman, 2013).

The transformation of automobile fabric would appear to offer the greatest opportunities for sustainability improvements. This is good news for the cities of the USA, Australia and Canada with their high ecological footprint but also large areas of automobile fabric that may be regenerated. This is not to say there is no place for automobile fabric in cities as lower density automobile fabric does offer some advantages in particular:

- Greater privacy,
- Space for private gardens, including deep rooted planting for trees,
- Opportunities to incorporate ecosystem services such as biodiversity habitats, carbon sequestration and urban agriculture.

However, the aggregate benefits to a city, and its surrounding hinterland, are increased with the higher population density of transit and walking urban fabric because they offer:

- Viable catchments to meet business cases for improved public transport, distributed utilities, and greater service, job and retail density,
- Greater proximity to services, shops and jobs to reduce vehicle kilometers travelled and to support a vibrant walking and cycling community,
- Reduced embodied energy through lower material requirements e.g., shared walls, or shorter infrastructure lengths with much lower per capita cost,
- Reduced encroachment upon adjoining productive land or valuable ecosystems.

In addition to optimizing urban fabric, a regenerative design overlay can further drive down the ecological footprint of an area. An integrated approach to the provision of urban systems, and monitoring by an urban metabolism analysis, can offer city makers a powerful tool for further environmental gains and build a powerful narrative of positive change. Regenerative design considerations might include:

- Urban applications of industrial ecology, e.g. seeking synergies between, and productive uses for, solid and liquid waste which might be used to create biogas or fertilizer for urban food production,
- Technology and construction innovation to reduce material inputs and improve building performance e.g. prefabrication,
- Substitution of centralized (and usually hydrocarbon powered) energy, water and waste management systems with distributed infrastructure e.g. solar photovoltaics, trigeneration, water sensitive urban design, grey water, black water and nutrient harvesting,
- Seeking to understand and enhance the bioregional qualities of the subject urban area and reflecting this in the built form and public space, as opposed to the conventional practice of homogenous application of Modernist planning principles that have facilitated the global spread of automobile urban fabric.

5. Conclusions

Given that human populations are rapidly urbanizing, the city provides a great opportunity for (re)designing urban fabric to reduce ecological footprint.

The continued degradation of the ecosphere requires a city planning response that goes beyond the maintenance of material flow equilibrium, rather it warrants a regenerative design approach to actively build natural capital.

This paper demonstrates that city planning decisions are highly influential in delivering sustainable cities because different urban fabrics have different urban metabolisms. This is most convincingly demonstrated in the Perth case study that clearly shows the significant advantages in terms of resource efficiency that walking and transit fabric offer over automobile fabric in most resource and waste issues of urban metabolism. The Perth case study indicates that the basic raw material demand of walking fabric with a technology and construction innovation (e.g., application of regenerative design principles) has the potential to improve urban efficiencies almost twenty times over the conventional automobile urban fabric in the same city.

However, additional studies that compare the urban metabolism of different parts of other cities would be beneficial, as would governance mechanisms for implementation. Never the less the size of the differences in urban metabolism with urban fabric suggests that cities can indeed make major contributions to ecosphere functioning.

The (re)design of a city's urban fabric to reduce ecological footprint, has the potential to offer regional solutions that address several grand challenges of this generation, including

- climate change through reduced energy use,
- resource scarcity through more efficient material use,
- reduced rates of biodiversity loss and encroachment upon rural land through compact city footprints.

An Urban Metabolism approach supported by material flow analysis provides a powerful tool for monitoring cities but if different urban fabrics are made a focus of urban policy then the potential to create regenerative change becomes possible to imagine.

Collectively these opportunities can be taken to create a more regenerative city in terms of reversing its footprint from large to small to negative. However it cannot be done unless the economic and social generators from the site are simultaneously being achieved. The articulation of a regenerative city vision provides a clear and positive direction for the application of urban metabolism models, however, as with all visions its implementation will be dependent upon strong leadership and alignment of key actors, institutions and business models around this vision, particularly how the statutory planning system can include and assess low metabolism urban fabric in its system.

The combination of these potential urban metabolism improvements – optimizing urban fabric, overlaying regenerative design and introducing biophilic urbanism – would help mitigate climate change and biodiversity loss in urban areas – addressing the core planetary boundaries.

Appendix A. – INPUT ASSUMPTIONS

Assumptions–Table 2 (BAU)

1) Fuel per capita by suburb is provided by Chandra (2006) and the predictive model by Trubka et al. (2010) confirms the general variation from inner to outer.
2) Power Gas and Water were provided by Perth's utilities. The power variations with Urban Form are not clear so were left the same between types. Gas is used mostly for heating and was put at 60% for multiunit/smaller dwellings. Gas use will decrease in greyfields and brownfields due to reduced heating requirements for multi/smaller dwellings. The assumed reduction is 60% for both greyfields (transit fabric) and brownfields (walking fabric). Water varies with size of garden and is considered to reduce to 60% in small blocks and to 50% with multistorey buildings.
3) Food consumption per person per year is calculated from National Nutrition Survey Foods Eaten Australia 1995 Compiled by the Australian Bureau of Statistics and the Department of Health and Aged Care. Figures for select foods (meat including fish, cereal including cereal dishes, fruit and veg and milk products) added for 25–44 age categories. Foods separated into meat and non-meat categories. Total values attained then divided by 1000 to get daily kg intake. This is in turn multiplied by 365 to get yearly kg intake per person. The rounded figures are 70 kg per person per year intake of meat and 381 kg per person per

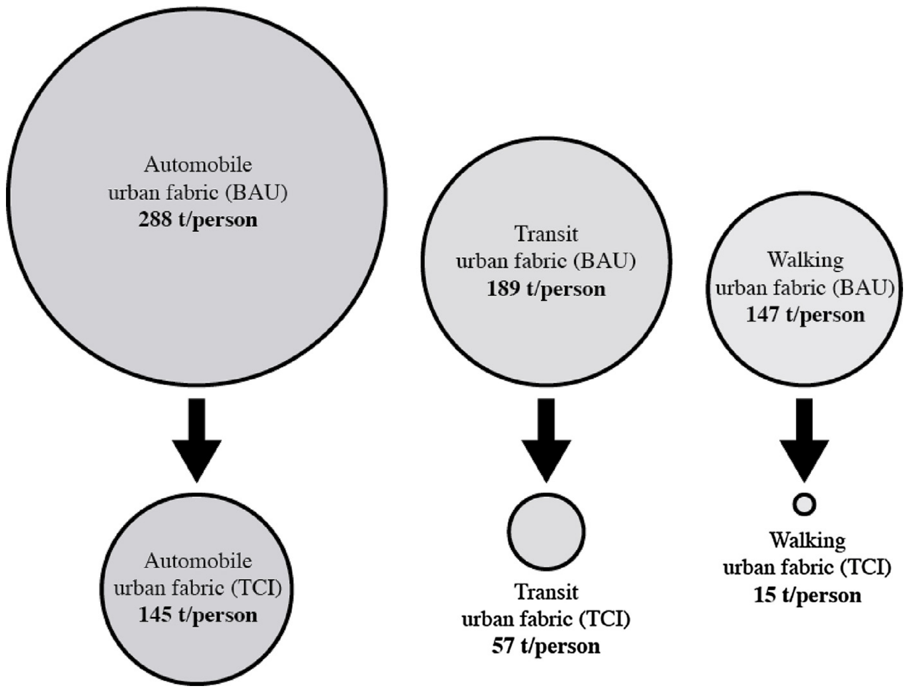

Fig. 4. Perth's basic raw material demand in terms of three urban fabrics plus Technology and Construction Innovation (TCI) Adapted from: Gardner and Newman (2013).

year intake of selected non meat products. This added together gives a total figure of 451 kg per person per year food intake. It was assumed that the amount of food consumed by the individual on a yearly basis would not change between urban form types.

4) Land Size was acquired from an Urban Development Institute of Australia (UDIA) Blog (See http://blog.udiawa.com.au/article/increased-appetite-for-smaller-lots (accessed May 7th)), which identified the median lot size as being 419 m^2 as of June 2012. This figure was multiplied by 3 to include other urban land like roads & commercial space associated with each dwelling. Lot sizes will become increasingly diminished for Middle and Inner redevelopment areas so lot sizes of 150 m^2 and 80 m^2 (x3) where chosen as suitably representative samples.
5) Urban footprint calculated using following factors obtained from (Wackernagel and Rees, 1998)
   a) Energy: 100 GJ produced per ha.
   b) Water: 233 KL produced per hectare.
   c) Land: ha of urban land as in 4 above.
   d) Food: Used Canadian per Person yearly requirement 1.30 ha/capita.

The urban footprint is then calculated by dividing the three urban forms energy, water, landscape and food input values by their equivalent factors and then adding the results together.

6) Original BRM Figures obtained from (CCI 2007), Table 10, adjusted due to occupancy levels of outer 2.3, middle 2.1 and inner 1.8. The data provided was for single detached dwellings and multi- unit dwellings. (60% less). The anticipated inner development is reduced to 40% due to smaller units. Thus assumed consumption of materials was 60% for Middle and 40% for inner.

Assumptions–Table 4 (TCI)

Assumptions as above except where noted below

1. Fuel per capita, water, food and land – No change from BAU as the forme of the city is not changed by TCI and hence no change from BAU.
2. Power and gas – assume use of off-site construction with reductions of 50% greenfields (automobile fabric), 60% greyfields (transit fabric) and 70% brownfields (walking fabric) due to design precision, energy efficient materials, construction and control (Wong and Tang, 2012)
3. Basic raw materials – sand, limestone, clay and rock – assume use of off-site construction with reductions of 60% greenfields (automobile fabric), 70% greyfields (transit fabric) and 90% brownfields (walking fabric) due to design precision enabling exact amounts of materials, and shared walls in higher densities (Wiedmann and Barrett, 2007).

Appendix B. – OUTPUT ASSUMPTIONS

Assumptions–Tables 3

1. Energy (Fuel, Power & Gas) conversio into Greenhouse Gases (GHG) defined as being by a factor of 0.125 t (T) of CO2 per Gigajoule (GJ) of Energy.
2. Waste Heat output has been calculated as being equal to total energy input.
3. Sewage Discharge Per person per year figure of 80KL derived from NSW government document, (See http://www.dlg.nsw.gov.au/dlg/dlghome/documents/information/section5.pdf (accessed 7th May 2015)) which provided daily per person average of between 150 and 300 l. Figure rounded to 200 l per person then multiplied by 365 (no days in year) and then divided by 1000 (converting litres to kilolitres). 73 KL figure obtained then rounded to 80 KL to give rounded even figure.
4. Construction and Demolition (C&D) waste combined and sourced from the W.A. Governments Feb 2003 Summary Report of Waste to Landfill Perth Metro Region (See http://www.wasteauthority.wa.gov.au/media/files/documents/wastelfsummary.pdf. ((accessed 7th May 2015) Used Total Waste Stream for Building and Demolition figure for 2000/2001

period of 1243,584 t (T) and divided it by 2001 ABS Census Population figure of 1, 302, 126 (See http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/4A775DD1B80BEB3CCA256C6000033701/$File/20305_2001.pdf (accessed 7th May 2015)), for Perth-Mandurah region. Middle and Inner suburbs were reduced according to estimations of reduced expected C&D waste generation.

5. Household waste was calculated in the same way but due to expected reductions in garden waste between three Urban Forms (Outer most & Inner Least). The Summary report indicated on page 21 that 20.9% of Household (termed municipal in doc), waste is garden waste, so middle and inner suburbs where reduced accordingly. This reduction was impacted by the difference in average occupancy between greenfields (automobile fabric) (2.3), greyfields (transit fabric) (2.1) and brownfields (walking fabric) (1.8).

Assumptions Table 5 (TCI)

Assumptions as above except where noted below:

1. GHG, waste heat, sewage – No change from BAU as the form of the city is not changed by TCI and hence no change from BAU.
2. Construction and demolition (C&D) waste – For all urban fabrics assumes use of off-site construction reduces construction waste by 70% due to processes and ease of recycling on-site factory. Assumes no demolition in outer greenfields (automobile fabric) areas; greyfields (transit fabric) assumes deconstructing or recycling rather than demolition with a 50% reduction of demolition waste; brownfields (walking fabric) assumes deconstructing or recycling rather than demolition with a 50% reduction of demolition waste. DataSource: Crough, D (2013) Unitised Building Australia, Property Council of Australia, Density Wars conference.
3. Household waste – expected reduction factor applied to census data. Data source: Government of Western Australia, Waste Management Board, Summary Report of Waste to Landfill: Perth Metropolitan Region (1 July 1998–20 June 2002), February 2003, pg 16. Australian Bureau of Statistics, 2001 Census of Population and Housing: Perth A Social Atlas, October 2002, pg 1.

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