OPEN ACCESS

The 4th World Sustainability Forum
1 - 30 November 2014

http://www.sciforum.net/conference/wsf-4

World Sustainability Forum 2014 – Conference Proceedings Paper

Material Flow Analysis (MFA) for Liveable Cities

Dexter V.L. Hunt [1,]* Joanne M. Leach, Susan, E. Lee, Chris Bouch, Peter Braithwaite and Christopher D.F. Rogers [1]

[1] School of Civil Engineering, College of Engineering and Physical Sciences, University of Birmingham, Birmingham, B152TT, UK.
E-Mails: huntd@bham.ac.uk (D.V.L.H); c.d.f.rogers@bham.ac.uk (C.D.F.R.); j.leach@bham.ac.uk (J.M.L); ; s.e.lee@bham.ac.uk (S.E.L); c.bouch@bham.ac.uk (C.B.); p.braithwaite@bham.ac.uk (P.B.)

* Author to whom correspondence should be addressed; Tel.: +44-121-414-5148; Fax: +44-121-414-3675

Received: 2nd September 2014/ Accepted: 29th October 2014/ Published: 03 November 2014

Abstract: Well-functioning ‘liveable’ cities should be sustainable and their consumption of natural resources and production of waste must fit within the capacities of the local, regional and global ecosystems. It is increasingly becoming suggested that an Urban Metabolism (UM), approach could help city decision-makers (e.g. planners) take account of numerous critical influencing factors related to the inward outward flow(s) of natural resources (e.g. food, water and energy) and accumulation of waste. The paper identifies the precursory step for any UM study (Mass Flow Analysis - MFA) and applies it to a case study (Birmingham, UK) in order to show how it could contribute to the measurement, assessment and understanding of liveability, defined as 80% reduction in carbon (from 1990 levels); resource secure (an ethos of One planet living); with maintained or enhanced wellbeing. By provided focus upon an individual resource stream (i.e. water) at multiple scales (city to individual) it is shown that MFA can be used as a starting point to develop realistic and radical engineering solutions. However further work is required for it to be truly reflective of broader aspects of urban liveability.

Keywords: Urban Metabolism, Energy, Water.

---

1. Introduction

Well-functioning 'liveable' cities, both now and in the future, are dependent upon numerous critical influencing factors, including: the inward movement of natural resources (for example, food, water and energy) in sufficient quantities to meet demand; and, effective mechanisms for disposal of waste. They must, however, be sustainable and their consumption of natural resources and production of waste must fit within the capacities of the local, regional and global ecosystems [1] and operate in the same way as many natural systems do. Sustainability, however, is a logistically complex goal to achieve, and urban planners must consider many influencing factors and constraints, not least significant growth in urban populations (94% of the UK population is expected to live in cities by 2050 [2], and reduction in global availability of resources per capita. There are undoubtedly issues of governance, carbon intensity and wellbeing that must be addressed both now and in the future; therefore barriers to achieving planning goals must be identified and transformative solutions developed to overcome them [3,4]. Clearly a framework is required to help planners identify, develop and assess such sustainability interventions.

Based upon its growing contribution to sustainable urban development issues [5,6], this paper explores the feasibility of creating a framework, based on techniques developed in, and borrowed from, the field of urban metabolism field. Urban Metabolism is a modern anthropogenic metabolism global analysis tool considering linear throughput of biological systems [7,8] or in much simpler language it is used to analyse the *resource inputs* and *waste outputs* of a system [4,5]. The first author to use the term 'Metabolism' of cities was Abel Wolman in 1965 [9] and since then the approach has been developed by a few academics for analysing single or multiple flows into and out of nations and cities. Such an approach has rarely, if ever, been used in policy development for city planning in the UK and yet we believe it could hold the potential to enhance and enlighten decision-making therein.

The research work presented here is drawn from 'Liveable Cities' http://liveablecities.org.uk/, a 5 year (2012-2017), UK Research Council (Engineering and Physical Sciences Research Council - EPSRC)-funded programme which aims to transform the engineering of cities to deliver global and societal wellbeing within the context of low carbon living and resource security. In so doing it seeks to develop realistic and radical engineering solutions that demonstrate the concept of an alternative future' that meet the following criteria:

1. 80% reduction in carbon (from 1990 levels);
2. Resource secure (an ethos of One planet living);
3. Maintaining or enhancing wellbeing.

The underlying six-step methodology is outlined in Section 2 with results being presented in Section 3 then discussed in Section 4. Conclusions are subsequently drawn in Section 5.

2.0. Methodology:

The methodology adopted within this paper consists of four clear steps as shown. A fuller description can be found in the respective referenced sections.

(1) Identify and classify existing urban metabolism studies (focussing on UK) (Section 2.1);
(2) Identify the precursory methodology for UM studies (Section 2.2);
(3) Apply precursory methodology to a city (Birmingham, UK) at multiple scales (Section 3);
(4) Discuss methodology based on outcomes (Section 4).

2.1. Step 1: Identify and classify existing urban metabolism studies (focusing on UK).

The first step within the methodology was to undertake an extensive literature review with the aim of identifying and classifying UM studies conducted over the last 15 years with a focus toward highlighting those undertaken for the UK. Approximately 150 relevant UM studies were considered and the following key elements were identified.

a) Location(s) adopted
b) Key flow(s) considered
c) Time period(s) covered
d) Methodology / tool(s) adopted
e) Data source(s) used

With respect to the above, 34 countries had been considered with >50 cities being analysed in some form or other. The breakdown by region is shown in Figure 1. In total some 22 studies were identified for the UK undertaken at various scales (Table 1); 12 at national, 4 at regional (e.g. North West, South West, etc.), 6 at city (e.g. Manchester, Liverpool, York, London (x3) and Birmingham) and 1 at development scale (i.e. Bedzed, Sutton).

The most commonly considered resource(s) in the UK studies were materials (i.e. timber, metals, aggregates etc.) followed by energy and waste (Figure 2). The least commonly considered were products, followed by food then water. The earliest time considered was 1937 and the longest time span considered was 60 yrs. The most recent UM study by Arup in 2006 using IRM (Integrated Resource Modelling) was of the Thames Gateway.

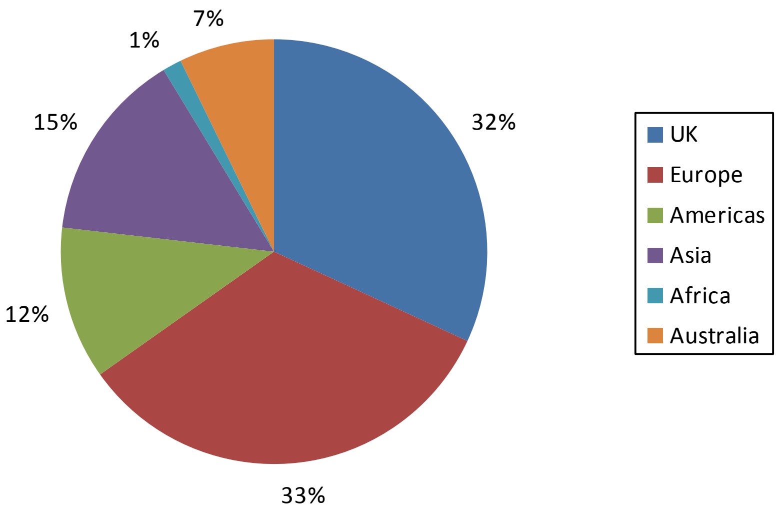

Figure 1. Breakdown of regions considered in UM studies.

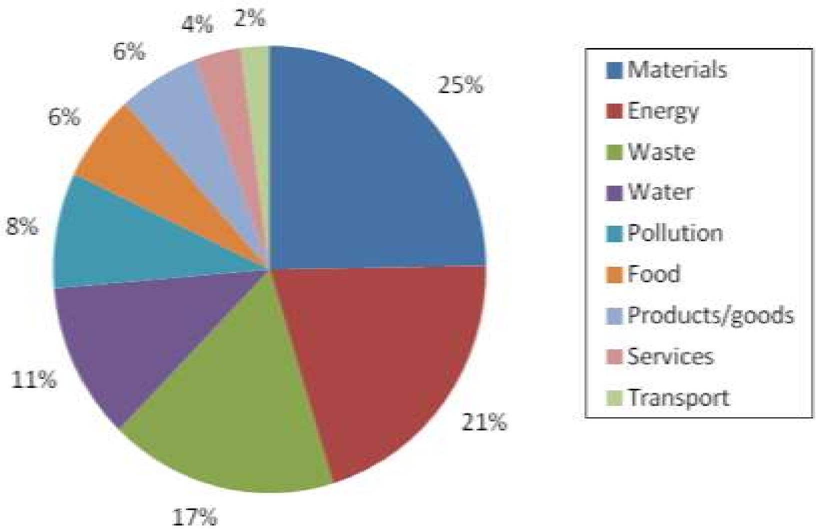

Figure 2. Breakdown of resources considered in Urban Metabolsim studies.

The various tools and methodologies adopted across the UK studies seem (on the whole) to be variations on three approaches: MFA (Table 2), LCA (Table 3) and Foot-printing (Table 4) with everything else being techniques for working with or accounting for data (Table 5). The most comprehensive datasets for the EU15 (the European Union member countries prior to the accession of ten candidate countries on the 1st of May 2004) were compiled by Eurostat [10,11,12,13] and OECD's Inventories of Country Activities [14,15,16].

Table 1. Urban metabolism studies undertaken for the UK in the last 15 years
(Resources refer to CO_2, Energy, Materials, Waste, Food, Water, Land use, Transport and Tourism)

Region(s)	**Year**	**Assessment(s)**	**Tools (see Table 2)**	**Data sources (see Table 3)**	**Reference(s)**
Wales – *Cardiff*	2004	Resources	MFA, EF	ONS, FAO, BGS, Welsh Executive	[17,18, 19]
Scotland - *Angus, Aberdeen, Dundee, Edinburgh, Glasgow, Inverness*	2002, 2003, 2004	Resources, Land use, Transport, Tourism	MFA, EF	ONS, FAO, BGS, SEPA, Scottish Executive	[21,22,23]
UK	1937-1997	Biomass, mineral materials, fossil materials	MFA-BIF	Dti, BGS, Forestry Commission, Agriculture statistics, Input output tables	[24]
UK	1970-1999	Resources	EMFA	ONS, PRODCOM, EUROSTAT,	[25]
UK	1970-2000	Resources	MFA	ONS, PRODCOM, EUROSTAT,	[26]
UK	2000	Resources	PIOT	ONS, PRODCOM, EUROSTAT,	[27]
UK	2001	Iron, Steel, Aluminium	MFA-BIF	ONS, EUROSTAT	[28]
UK - *60 UK Cities*	2006	Resources	EF	-	[29]
UK	1996-2003	Resources	MFA (Eurostat)	ONS, EUROSTAT	[30]
UK	1997-2004	Resources	MFA-BIF	ONS, PRODCOM, EUROSTAT,	[31,32]
UK	2002	Resources	FLAT	ONS, PRODCOM, EUROSTAT,	[33]
UK – *10 regions*	2004	Resources	MFA, EF,	REAP v1	[34]
UK	2004	Resources	MRIO	ONS, PRODCOM, EUROSTAT,	[35]
UK	2005	Material and Fossil Fuel	MFA (RCN, DMC_{fossil})	ONS, Defra	[36]
UK, Manchester	2002	Resources	-	-	[37]
UK, Manchester – *Merseyside*	2003	Transport	MFA, EF	-	[38]
UK, Liverpool	2000	Resources	EFA	-	[20]
UK, SW England	2001	Resources, Land use, Transport, Tourism	MFA, EF	ONS, FAO, BGS	[39]
UK, NW England	1999-2000	Construction Minerals	MFA	-	[40,41]
UK, York	2001	Resources, Land use, Transport, Tourism	MFA, EF	-	[42]
UK, Greater London	2000	Direct energy, Materials, Food, Waste	MFA, EF	-	[43]
UK, London	2001		EFA, ES, MFA	-	[44]
UK, Thames Gateway	2006	Resources	IRM	-	[45]
UK, Birmingham	2004	Ecological Footprint, Carbon footprint Greenhouse gas footprint	EF CF REAP v2	ONS, DfT, AEA Environment, Local Authority data, ACORN, CACI, BERR, Global Footprint Network	[46,47,48]
UK, Bedzed, Sutton,	2001	Construction materials	LCA, EP	-	[49]

Table 2. UM Analysis methodologies / tools applied at UK levels: Footprinting

Methodology	Description	Tools	Reference(s)
EF Ecological Footprint	Designed as a readily comprehended indicator of the sustainability of the human economy vis-a`-vis the Earth's remaining 'natural' capacity to supply resources (sometimes considered equivalent to the planet's terrestrial 'carrying capacity'). The Sustainable Process Index (SPI) is an engineering tool for ecological evaluation and a member of the ecological footprint family based upon the calculation of the total land area required by any process, technology, or other economic activity to sustainably provide natural material and energy resource flows and maintain waste assimilation or "sink" services. Ecological footprints have been calculated for more than 140 countries and can be found in the NFA (National Footprint Accounts).	**REAP v1 and v2** (Resources and Energy Analysis Programme) www.sei.se/reap. **SPIonExcel** tool http://spionexcel.tugraz.at/	[34,50,51,52,53,54,55,56]
CF Carbon Footprint	A measure of the total amount of carbon dioxide (CO2) and methane (CH4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent(CO2e) using the relevant 100-year global warming potential (GWP100)	**ISO 14067** (CF - Carbon footprint)	[57,58]
WF Water Footprint	The total volume (Litres) of freshwater used to produce the goods and services consumed by a defined consumer group (i.e. individual, family, village, city, province state or nation).	**ISO 14046** (WF - Water footprint)	[59]
EM Environmental Management	Used to assess the eco-efficiency of product systems. A term coined by the World Business Council for Sustainable Development (WBCSD) in 1992, it measures the ratio of added value to environmental impact.	**ISO 14045**	[60,61]
ES Environmental Space	The primary function of environmental space (ES) is to quantify or track sustainable development by comparing resource demands with available 'environmental space' (closely linked to notions of 'carrying capacity') or the upper and lower physical boundaries of the Earth's supply of environmental services that are available and can be appropriated sustainably by humans.		[61,62]

Table 3. UM Analysis methodologies / tools applied at UK levels: LCA

Methodology	Description	Tools	Reference(s)
LCA Lifecycle Assessment/ Lifecycle Inventory	An environmental management tool for identifying (and comparing) the whole lifecycle, or cradle-to-grave, environmental impacts of the creation, marketing, transport and distribution, operation, and disposal of specific human artefacts. LCA strives for completeness with as many substances as possible. MFA provides an inventory for LCA for an individual component (e.g. concrete or steel frames) or a complete product (e.g. an automobile).	**ISO 14040:2006, ISO 14044:2006** **ISO 14047:2012, ISO14049:2012** **EIME V3.0, EIOLCA** tool, **Environmental Impact Estimator** V3.0.2, **Ecoinvent waste disposal inventory tools** v1.0, **ReCiPe**, **Lime2, USEtox, ILCD, IMPACTworld** **WRATE** (Waste and Resource Assessment)[3] **WRAP** (tool for tracing EEEE appliances)	[61,63,64,65,66,67,68,69,70,71, 72]
MIPS Material Intensity per Unit Service	Involves the identification of a single mass-based measure of the total, life-cycle-wide (or cradle-to-grave) primary material and energy requirement of environmentally significant economic output in the form of specific products (e.g. coffee, orange juice) forms of infrastructure or service delivery.	**Gabi V5** www.gabi-software.com/uk-ireland/index/ developed to include economic, environmental and social metrics. **Umberto V5** http://www.umberto.de/en/	[61, 73,74]
EP Environmental Profiling	The Environmental Profiling methodology is a standardised method derived and used within the UK for identifying and assessing the environmental effects associated with building materials over their lifecycle - that is their extraction, processing, use and maintenance and their eventual disposal. The approach is not dissimilar to the Lifecycle Assessment (LCA) approach excepting the extension of the approach to use dimensionless unifying values for impacts (using stakeholder derived weightings) called 'Ecopoints'	**BRE - Environmental Profiling** **BRE - Green Guide to Specification** **BRE- Eco-points**	[75]

Table 4. UM Analysis methodologies / tools applied at UK levels: MFA

Methodology	Description	Tools	Reference(s)
MFA Material Flow Analysis (See Section 3)	Developed by Paul Brunner (Vienna University of Technology, Austria). **'**Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time'. Sometimes referred to as RFA (Resource Flow Analysis,) EMFA (Energy and Material Flow Analysis), MEFA Material and Energy Flow accounting) or EW-MFA (Economy-Wide material Flow Analysis). Based on system approach and mass balance. In essence this is a book keeping approach to what stays and leaves the anthroposphere. MFA is a suitable forecasting tool for long-term trends in material use and has been used within Industrial symbiosis. Only flows that cross the system boundary are counted, not the flows within the boundary (referred to as 'stocks'). MFA strives for transparency and manageability with a limited number of substances.	**EUROSTAT** **IRM** (Integrated Resource Modelling – developed by ARUP to track energy and material flows in order to reduce environmental impacts). Main data sources for inputs are **PIOT** (Table 5) **NAMEA**	[8,10,11,12,13,76,77,78,79,80,81,82,83]
EFA Energy Flow Accounting	Energy Flow Accounting (EFA) aims at the establishment of a complete balance of energy inputs, internal transformations, and energy outputs of a society or of a defined socioeconomic component in a way that is compatible with MFA. In essence it is a measure of human appropriation to nature.	See MFA tools	[84,85,86,87]
SFA Substance Flow Analysis	Focuses on material flows of just one, chemically defined substance (e.g. nitrogen and phosphorous, chromium, mercury, lead and other heavy metals, carbon, water, and organochlorine compounds), or a limited group of such substances through the metabolism of a relatively extensive, predefined geographic region.	**STAN** subSTance flow ANalysis. **STAN 1.1.3** free tool (developed in Vienna)	[61]
MFA-BIF Material Flow Analysis - Bulk Internal Flow	Developed as material flow balance models that focus on both material inputs and output flows and stock accumulations, induced by the entire societal metabolism of a given region**.**		[10,11,12,13,61,88,89,90]
MFA Company-Level	Material Flow Accounting aspects in company-wide or plant-based "gate-to-gate" analyses such as materials bookkeeping, eco-balance reports, and material-based eco-auditing.		[91]
MMFA Mathematical Mass Flow Analysis	Process-based MFA studies (as above) deliver indicator values for a system's characteristics (e.g. recycling rates), performance (e.g. resource efficiency, rates of resource depletion) and impacts (e.g. range of available resource deposits or landfill capacities).MMFA applies a mathematical formulation and modelling where poor data availability occurs.	**SIMBOX**	[92,93]

Table 5. UM Analysis methodologies / tools applied at UK levels: Accounting techniques

Methodology	Description	Tools	Reference(s)
IO Input / Output	Input Output tables were developed by Leontief for economic analysis in the 1930s. The tables connect goods, production processes, deliveries and demand in a stationary and dynamic way through a network of flows of goods and provisions. The tables include emissions and wastes and are incorporated into both MFA and LCA.	**COMPASS** **GLODYM**	[8, 94, 95]
PIOT Physical Input-Output Tables	National-level analysis that extends the conventional input-output methodology and classifications to incorporate environmental resource and waste output "sectors" to provide measures of the physical flow of materials and goods within the economic system and between the economic system and the natural environment	-	[8, 61; 96,97]
TMRO Total Material Requirement and Output	Total Material Requirement and Output is a material flow accounting approach that quantifies the physical exchange of aggregated material flows between national economies and the environment**.**	[1]**S.Draw** (Sankey diagrams) [2]**e!Sankey** [3]**Umberto 5**	[61, 98,99,100]
IRM Integrated Resource Modelling	IRM processes resource inputs and provides quantitative values for a set of key performance indicators (e.g. energy consumption or total greenhouse gas emissions) that have been defined within a framework set to appraise the sustainability of the whole design.	**SUNtool** calculates flows	[101]

Table 6 provides an indicative list of data sources that are generically applicable to the UK. This abundance of accessible UK / Europe data may go some way toward explaining why there appears to be an urban metabolism research bias shown in Figure 1.

Table 6. Principal primary data sources applicable to material flows in UK cities

Product/ emission	Frequency	Source	Coverage
Aggregates, minerals	Annual *(1970 to present)*	British Geological Survey (BGS) UK minerals Yearbook, Office for National Statistics (ONS)	UK, Regions
Air emissions	Annual	National Environment Technology Centre (NETCEN)	UK, Regions
Arable, livestock	Annual	Defra, Food and Agriculture Organisation (FAO)	UK, Regions
Energy	Annual	Department of Environment for Climate Change (DECC)	UK, Regions
Food	Annual	ONS and Defra	
Forestry	Annual	Forestry Commission (FC)	UK, Regions
Industrial purchases	Annual	Office for National Statistics (ONS)	UK, Regions (sorted also by products)
Oil, gas, coal	Annual	Department of Trade and Industry (DTI)	UK, field, mine
PRODCOM (commercial sales by product)	Annual	Office for National Statistics (ONS) UK manufacturers sales by product (PRODCOM) – Accessed through ONS or Eurostat.	Product level
Traded goods	Monthly	Her Majesty's Customs and Excise (HMCE)	UK
Water abstraction and leakage	Annual	Environment Agency (EA), local water providers (e.g. Severn Trent Water for Birmingham), OFWAT ((The Water Services Regulation Authority)	UK, Region, Company areas, District Metering (DMA)
Waste (i): municipal solid waste, commercial waste	Annual	Local Authorities(LA's)	UK, Regions
Waste(ii): commercial	Annual	Environment Agency (EA), Defra	UK, Regions

2.2 Step 2: Identifying precursory methodology for Urban Metabolism (UM) studies

Of the international studies reviewed within this paper the most widely adopted (~50%), at a range of scales, was Material Flow Analysis (MFA) or variations thereof (Table 4). The approach appeared to be the fundamental building block for all Urban Metabolism (UM) studies, the results of which could be fed into either a footprint or Life cycle analysis. As such we term this our precursory methodology. Before applying it the paper provides some more historical context is provided with an outline of the methodological principles upon which it has been based.

2.2.1 Methodological Principles of MFA

The basic principle of Material Flow Analysis (MFA) is not new, being first postulated by Greek philosophers more than 2000 years ago as the conservation of matter (i.e. input must equal output). This principle can be applied to a person (and was, by Santorio Santorio from 1561-1636), or for management of resources, wastes and the environment in such diverse fields as medicine, chemistry, economics, engineering and life sciences [8,98,99]. MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time that connects sources, pathways and intermediate as well as the final sinks of a material [8]. Over the last three decades MFA has developed considerably becoming increasingly refined and precise [5,8,78,79,98,99,102,103,104,105]. In principle there are four main objectives [8,31]:

(1) Reduce the complexity of the system as far as possible;
(2) Assess the relevant flows and stocks in quantitative terms, observing sensitivities and uncertainties;
(3) Present results about flows and stocks of a system in a reproducible, understandable, and transparent way;
(4) Use the results as a base for the management of resources, the environment and wastes.

3. STEP 3: Application of Precursory Methodological approach

Having now identified the precursory methodology this paper investigates the way(s) in which MFA can contribute (or not) to the measurement, assessment and understanding of 'liveability', as previously defined, and identification of realistic and radical engineering solutions. This includes a 'drill down' procedure at opposite ends of the spectrum, i.e. from city scale of (Section 3.1), where MFA is increasingly being adopted, to an individual end-use scale (Section 3.3) where MFA application within the literature is less apparent.

3.1. City scale application, Birmingham: UK

By using Birmingham, UK, as an example (Figure 3) and applying a relevant set of flow metrics at city scale quantification of what passes into and out of the cities' political boundary can be identified using datasets from Table 3 [106]. Following a traditional MFA approach everything is weight-based (i.e. tonnes) and considers yearly contributions through the city and annual stock taking in this way undoubtedly provides simplification of what is actually quite complex.

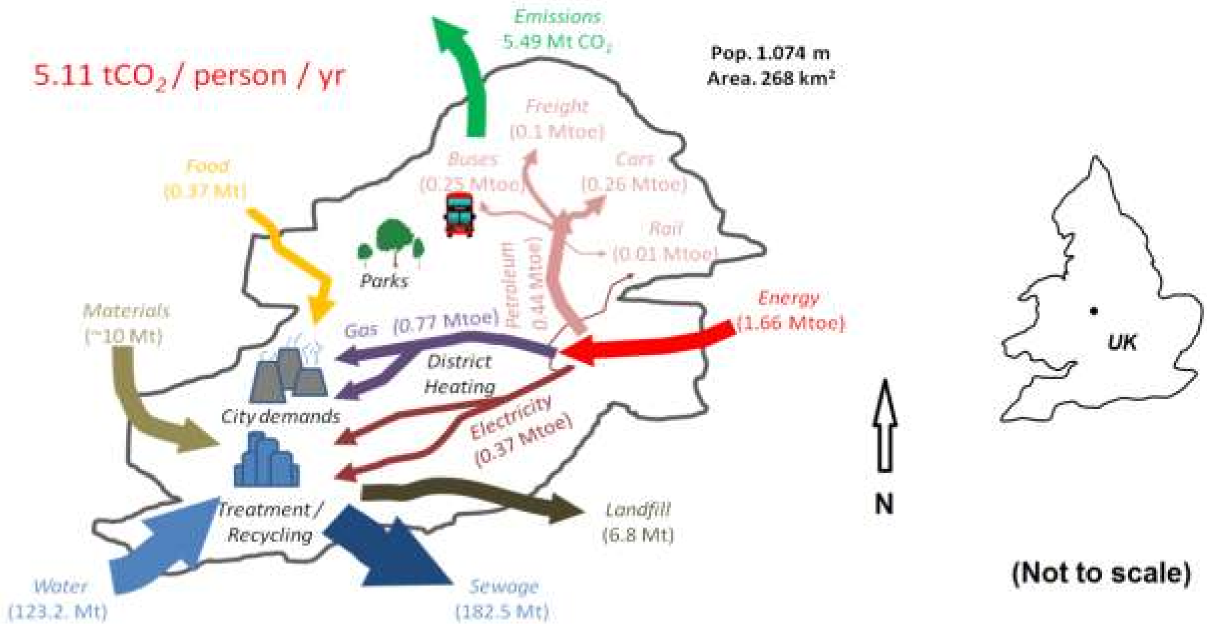

Figure 3. MFA for the city of Birmingham (UK) in 2011/2012

Whilst we have adopted comparable units throughout, the question might be posed regarding what units and quantification should be used in order to convey the messages clearly to decision-makers? The unifying internationally agreed metric for environmental impacts is typically geared toward carbon emissions and if we were to consider only the direct carbon emissions from energy consumption at city scale for Birmingham in 2013 these would be 5493 kt/yr (5.11 tonnes CO_2/capita), showing a reduction by 20% on 1990 levels [106].

3.2. City scale – water

In figure 4 the flow model is refined to see what new incites become apparent. The more detailed data analysis, albeit still at a very course level, provides a focus on water. We chose this due to its dominance (in mass terms) in material flows [102]. From the MFA analysis of Birmingham water dominated other flows - by a factor of 74:1 (when compared to the energy – the next highest flow). Moreover, when consulting the literature it appeared that except for a handful of MFA water studies this research area was currently under-represented both globally and within the UK [107,108,109,110,]. Moreover it was not being totally accounted for in traditional nationally-applied MFA, particularly with respect to the total amount of material used in an economy, i.e. Domestic Material Consumption – DMC [112]. The Sankey diagram approach was chosen for representing the material flow of water in Birmingham where arrows are sized according to their magnitude. This provides a contrasting visual representation (to Figure 3) for water volumes being used within the city. This extra layering of information is useful and required because it provides a necessary baseline for city water provisioning (i.e. supply, demand and disposal) by sector in Birmingham. For example, it identifies the water sector as a low contributor to city carbon emissions and the domestic sector as a significant user of water resources. In addition it highlights that more water is lost through leakage than used by the non-domestic sector (i.e. industry and commercial sectors) and this is certainly a scale at which potentially transformative interventions start to become clearer. In terms of leakage reduction and prevention, perhaps improved asset management tools are required [113] or alternative ways to plan for, place and house utilities below ground [114,115]. With this increased level of refinement it becomes more apparent where water is coming from, where the water is going to, however it still does not provide information on the individual or the high levels of variability that exist in water supply volumes and the delicate balancing act that is required to ensure demands from domestic and non-domestic end-users are met day-in and day-out. [Although the study by Kowalski et al. (2011) provides a useful review of non-domestic flows and consumption of freshwater for the UK [116] and is a good place to start such an analysis from.]

Unfortunately an MFA analysis as shown in Figure 4 excludes the physical connectivity provided for by a networked infrastructure system that links demand nodes with supply sources nor does it make apparent the geospatial limitations or opportunities for new water and its supply-disposal streams [117]. However, the results of such an MFA approach can be used to inform this type of requirement when used in parallel.

Identifying where water sources are located and what water supply boundaries exist (and therefore with whom the environmental impact responsibility is associated) is particularly important in this respect for both resource security and local provisioning. Birmingham is a particularly interesting case because in 1896 water scarcity issues led to the majority of the city's water being sourced from outside its physical city boundary (from the Elan Valley Reservoir in Wales) and at 73 miles this resides well beyond what might be considered its' hinterland. The shows that granularity of information is required.

Local contextual meaning is required in order that multiple MFA datasets can be layered interrogated and interpreted correctly [117]. This is important for making existing connections and dependencies explicit whilst identifying interconnectivity and associated nexus issues, for example between vital supply streams which include water, food and energy [118,119,120] that are critical to the liveability of a city and yet so often overlooked.

A detailed, city-scale MFA should form part of any sustainable resource efficiency process where localised resource loops can be identified and formed within a range of sectors (i.e. not just industrial) and across a range of scales. City-scale MFA provides the basis of flows from which such ideas can be explored.

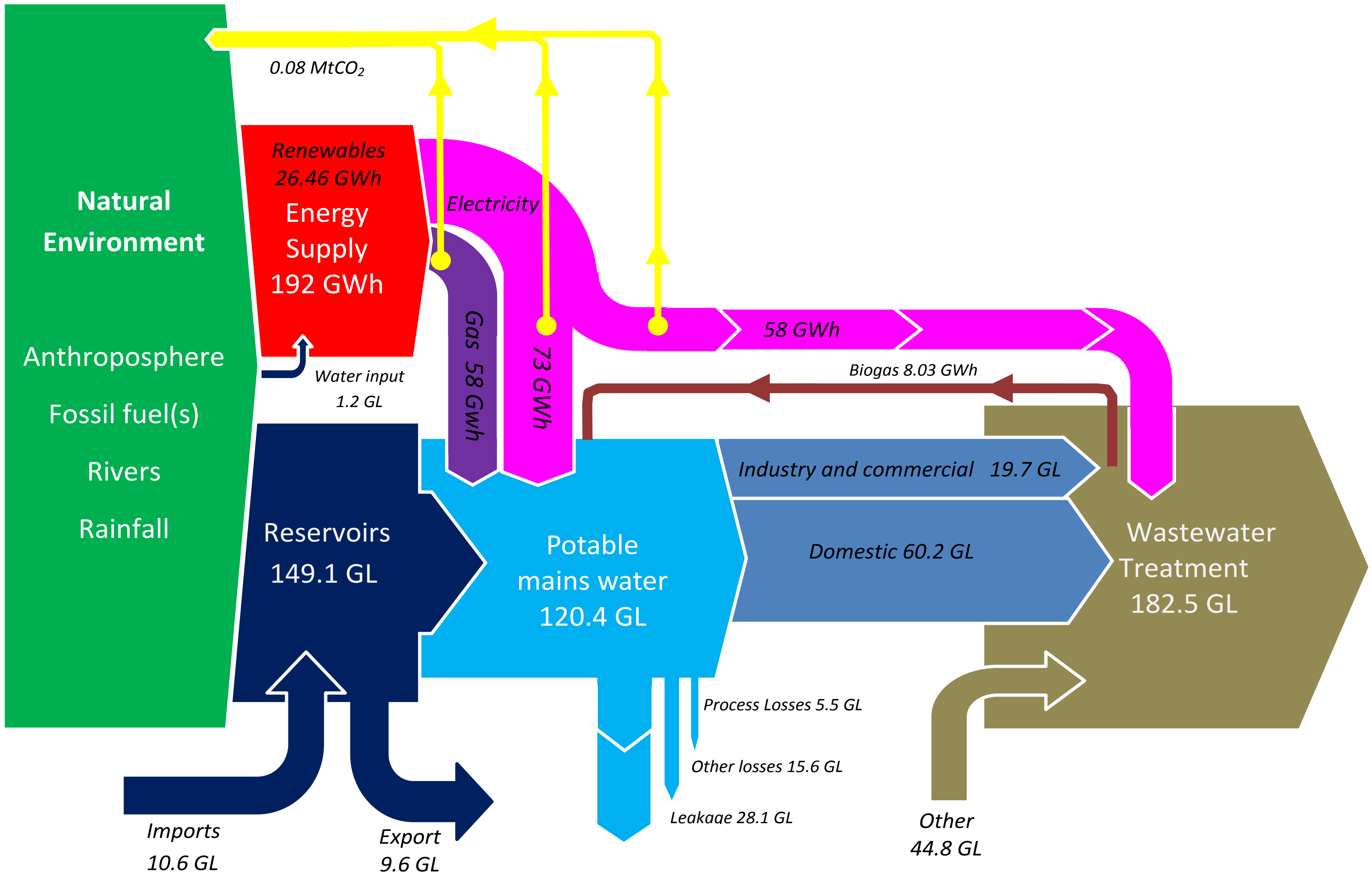

Figure 4. Water (and associated energy) flows for Birmingham in 2011 (embodied water excluded)

3.3. End-user scale: domestic water

By scaling down to a single domestic end-user in the highest demand sector (Figure 5) much finer levels of detail can be achieved with respect to improving liveability. End-user scale as with all other scales requires assumptions to be made in order to establish representative baseline resource flows. Hence a flow metric of litres per person per day (l/p/day) has been chosen for each water end-use. This metric along with leakage (mentioned earlier) is a key measure of efficiency within Urban Metabolism analyses [121]. The quantities of flow are drawn from previous work [122]. Assignment of carbon emissions (in this case only for cleaning mains water supplies and sewage) are made in order that carbon-critical use(s) within the domestic sector (i.e. showering) are made explicit. A metric of kg per person per year has been chosen (kg/CO_2/yr).

In this example carbon is calculated considering water cleaning and transport only, the additional carbon costs associated with water heating (i.e. an energy flow), which occurs in all uses except water closet (WC, toilet) flushing, have been omitted. This shows the importance of boundary setting within analyses and once again highlights the importance for decision-makers, or those interpreting MFA figures, to identify interconnectivity and (inter)dependency issues.

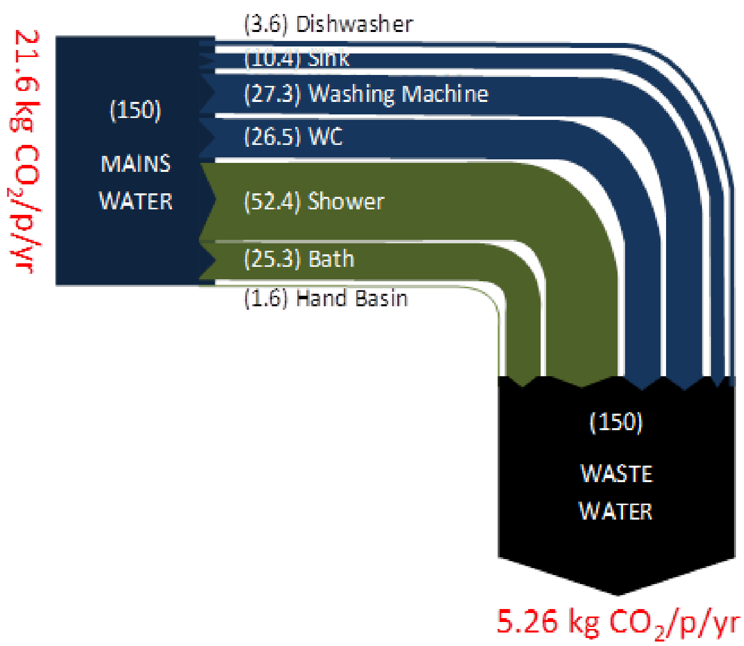

Figure 5. MFA showing daily resource use (l/p/day) and yearly carbon emissions.

When a whole range of water flows are considered within the household boundary (Figure 6) potential areas for saving water resources whilst reducing carbon emissions become clearer. For example, Figure 6 shows the impact of by flushing toilets with rainwater harvested from rooftops – Rainwater Harvesting (RWH). The added benefits here are reduced pluvial run-off and reduced mains water use [123]. For the Material Flow Analysis to be robust the daily changes in stored water volumes and residual storage capacities need to be measured [123]. A policy intervention might seek to make household water users responsible for the water that falls within their boundaries. This is particularly so for rooftops where continued growth in city centre pluvial run-off due in part to increases in paved over front gardens for parking, frequently overburdens existing storm water systems [123].

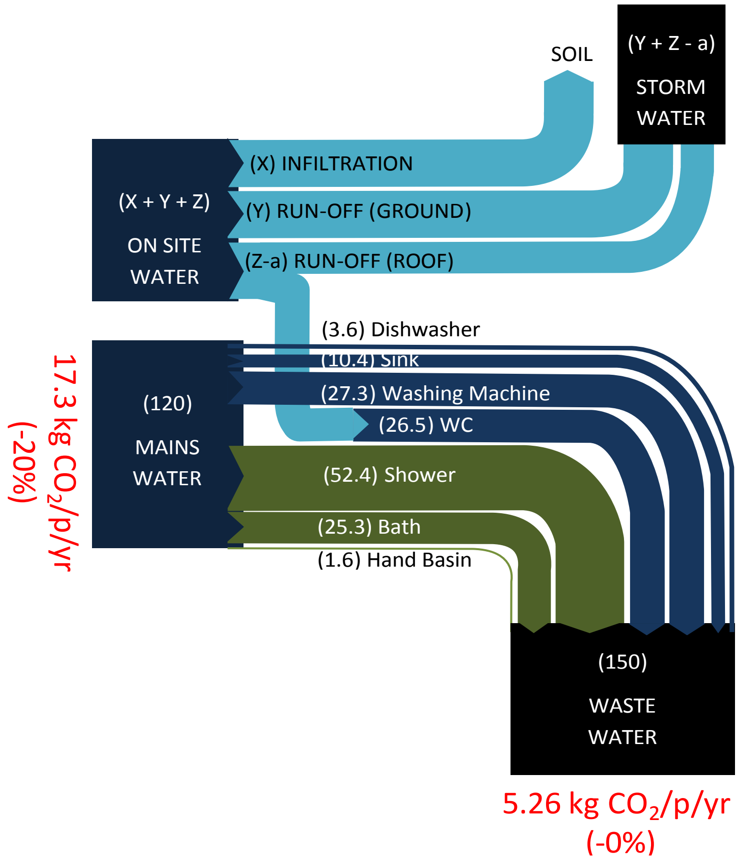

Figure 6. Impact of RWH on daily resource use (l/person/day) and yearly carbon emissions

An alternative transformative intervention would be the re-use of greywater (GW) from showers - Figure 7 shows this for a single-end user. By extending this philosophy to other city water users the potential for symbiosis, not just industrial (as is typically linked with Urban Metabolism, [124,125]) can be explored. Figure 8 shows the impacts on resource use and carbon emissions when interconnecting water use and recycling in offices and domestic dwellings. The advantage in this case is that the water-using lifestyle of the end user has not been impacted with any of these options.

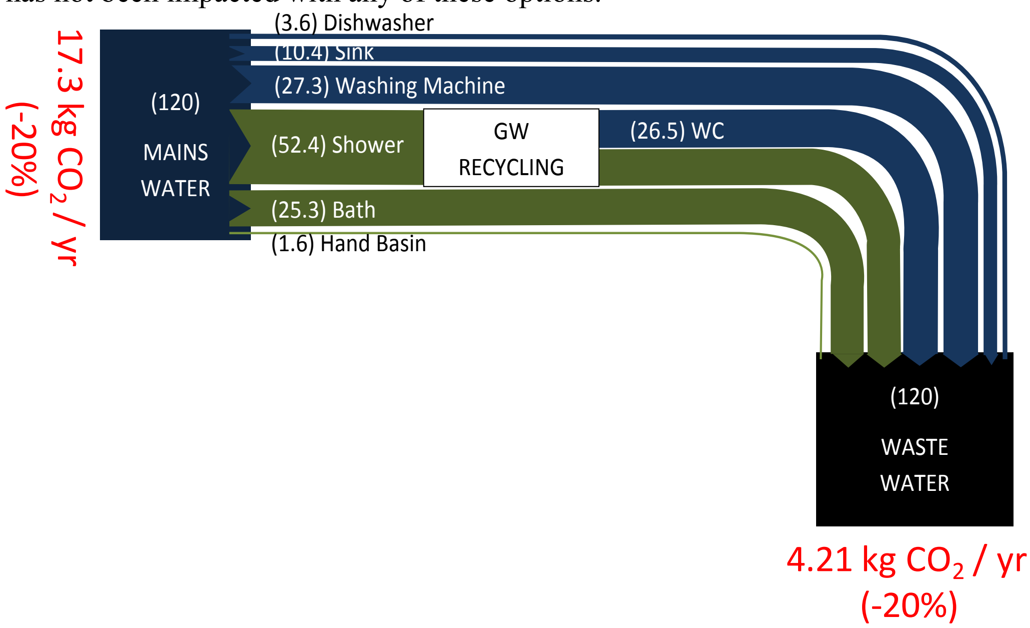

Figure 7. Impact of GW supplies on daily resource use (l/person/day) and yearly carbon emissions

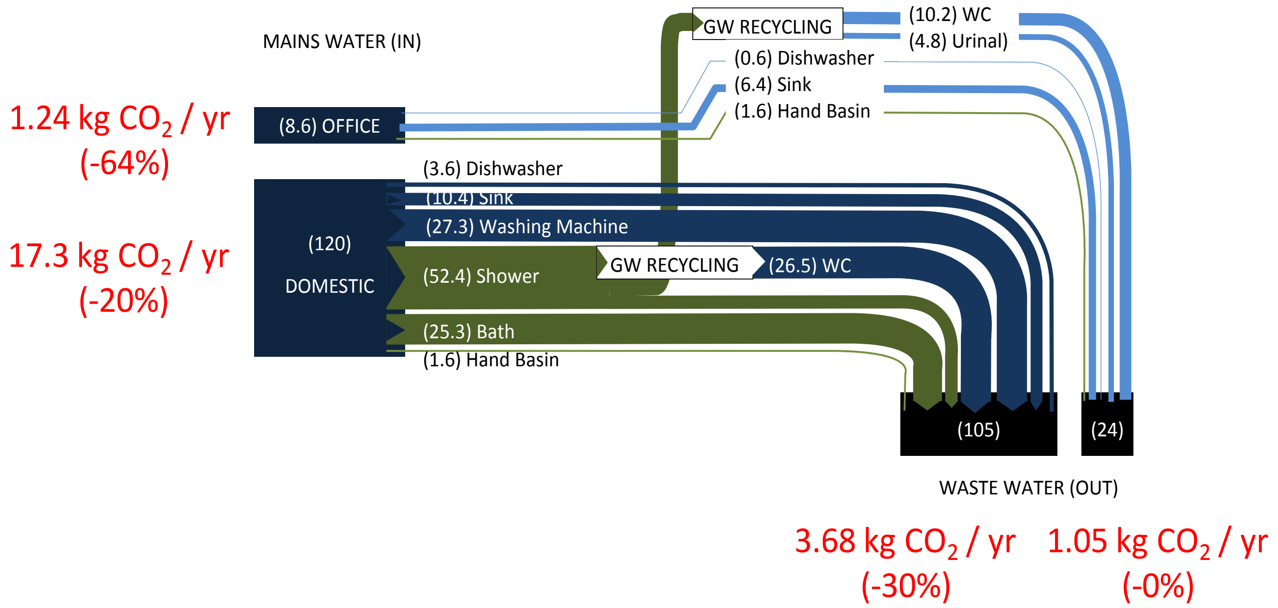

Figure 8. Impact of interconnections on daily resource use (l/person/day) and yearly carbon emissions

In addition, the wastewater production has been reduced, thereby increasing future local infrastructure capacity. However, to truly reflect how 'liveability' is or could be impacted other considerations would be required. For example, by exploring: long-term acceptability based on cost, reliability, responsibility etc; influence of additional carbon costs, i.e. a full carbon footprint related to new localised infrastructure provision [126]; additional embodied and virtual water [110]; and calculation of an overall water footprint [127]. This is particularly true when these transformative solutions are scaled-up. MFA is undoubtedly the precursory step to allow this to happen effectively. Scaling-up to apply MFA at the District Metering Area (DMA) level would provide a logical crucial linking thread between what happens at the individual household scale and what happens at city scale. However, one hurdle to overcome, which is well recognised within the literature, is confidentiality of water data [103,104,105] and issues of accountability.

3.4. Single end-use: Domestic water

The supply interventions proposed in the previous section are unlikely in isolation to achieve the liveability aim of 'resource security', indicating that a combination of supply-side and demand-side interventions are required to achieve the best decrease in water use. In order to achieve a reduction in water demand it is necessary to explore the key influences at play according to a hierarchy of key drivers. This is more easily illustrated when considering a single end-use, for example showering drawn from the previous domestic Sankey flow model (Figure 5).

To get the best out of an MFA analysis at this scale a different approach to the sankey diagram is required. Hunt et al. (2013) suggests that the two key driving influences here are user behaviour (a social driver) and technological efficiency (a technology driver) [128]. [N.B. it is not suggested that the two are completely divorced (e.g. technologies may inadvertently influence user behaviour and vice versa), moreover they operate in a field of influence pushed and pulled by other external influences such as economics and policy]. By utilising a possibility space (Figure 9) a range of water reduction strategies and resulting flows can be assessed.

The possibility space provides three options to reach a specified reduction in water flows: (1) improve technological efficiency alone (i.e. a water efficient shower), (2) adopt a step change in user behaviour alone (i.e. a much shorter showers) or (3) a combination of each.

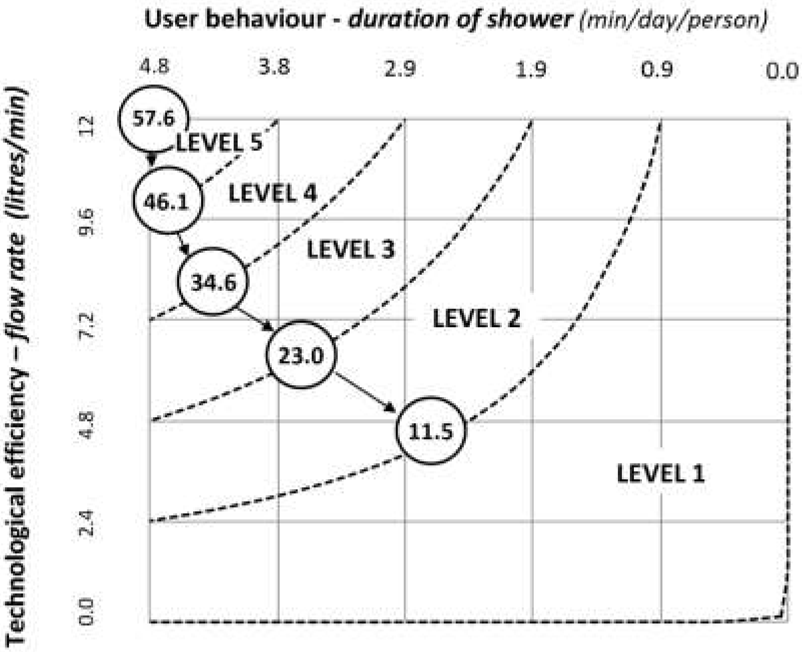

Figure 9. Reducing flows (per person) and carbon emissions during showering [126]

The current 'average' use (57.6 litres / shower) is shown in the top left hand corner and a contour is shown for each 20% reduction in flow from this starting point. At this scale it is much easier to investigate water demand reduction options and explore its impact on quality of life because it relates directly to the individual, something that is more difficult to determine at larger scales. The possibility space allows for interrogation of domestic flow reduction strategies and can be used for water (as shown) but also energy (forthcoming publication).

Through thinking about the linkages with key drivers of change and asking whether they can push or be pulled by the choices that are made the MFA analyses are both more informative and useful. For example, what will it cost the user to invest in more efficient technologies? How much water and carbon will it save? Do they deliver the expected user experience? What should water resources cost to effect a change in behaviour [129]? What policies need to be put in place to ensure change? Instigating technical change (e.g. installing a low-flow shower) is perhaps easier to tackle than behaviour change [126]. Although the starting point may simply be to make people more aware of what they use compared to what they could use, and perhaps a band rating for water would help here [129]. The richness of this approach and a band rating option is that together they allow for the subtle differences between wants and needs to be made explicit, or perhaps as suggested by emerging findings from the POLFREE project, sufficiency vs efficiency to be explored [130]. These are key threads to true urban liveability with regards to 80% carbon reduction, resource security and wellbeing.

Figure 9 could easily be adopted for Water Closet (WC, toilet) use and in this case the technological intervention would seek to significantly reduce flushing volumes. In essence this simplified framework helps engineers to ask questions (e.g. do we really need to add water to urine and/or solid waste in WC systems?) and seek innovative solutions (e.g. waterless urinals and composting toilets) or approaches (e.g.

reduced flush frequency during the day) which can then be scaled-up. In each case the carbon and resource use and cost can be assessed and mapped back onto the water flows in order to assess overall household liveability implications.

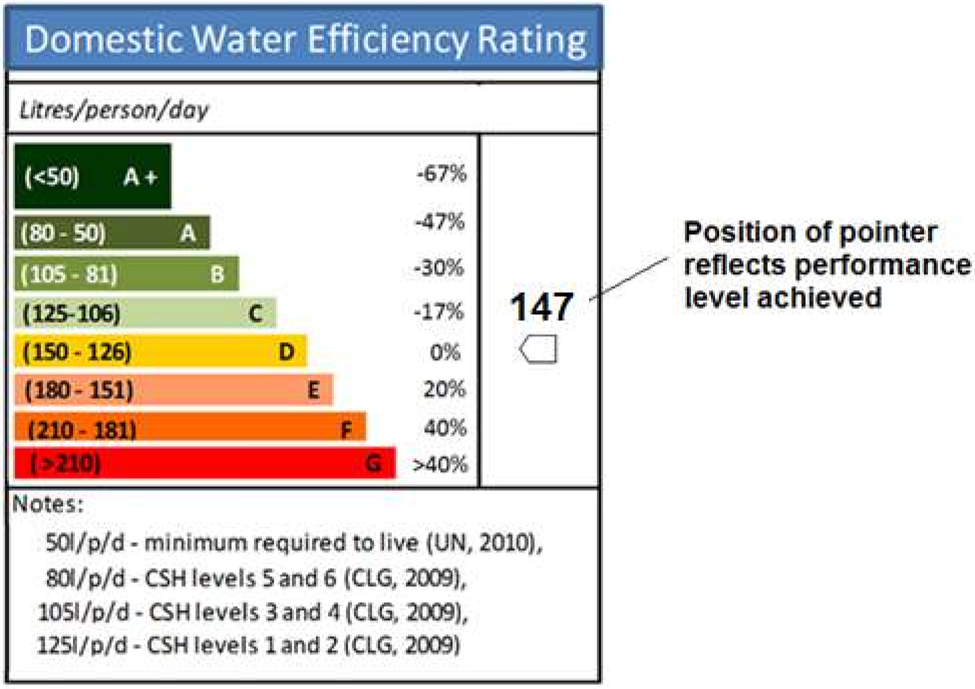

Figure 9. Band rating an individuals' domestic water use (Hunt and Rogers, 2014)

4. Discussion

This paper has proposed the use of an Urban Metabolism approach with a focus toward MFA as the precursory methodology to assess the impacts of transformative engineering solutions designed to improve the future liveability of cities (defined as maintaining or enhancing wellbeing whilst improving resource security (i.e. moving toward one planet living) and reducing carbon (achieving 80% reduction on 1990 levels by 2050)). In this discussion section we pose two questions about MFA:

Q1. What shortfalls to MFA (in approach and application) exist that could undermine its usefulness in achieving 'liveable' cities? (Section 4.1)
Q2. Is MFA alone sufficient to produce change? (Section 4.2)

4.1 What shortfalls to MFA (in approach and application) exist that could undermine its usefulness in achieving 'liveable' cities?

The purpose of MFA analyses outlined in this paper was to convey clear messages on material flows within our cities that ultimately could be used to invoke change and spark ideas to improve the liveability. An extensive review of the Urban Metabolism literature highlighted numerous MFA studies on the UK. However, the most glaring shortfall was in the lack of regional 'urban scale' studies, a situation highlighted previously by Barles [5]. This was accompanied by a lack of cross-sectional studies, multiple city comparators and time series studies [131,132].

Many studies suffered from being 'over precise' and 'over quantified' invoking the questions (in the face of uncertainty) of what level of precision is possible [133] and in order to make decisions what levels are actually required?. This is important when considering difficult to obtain data related to food, electricity and water consumption that often requires proxy data [20]. This is important, because if policy decisions are to be based purely on (MFA) input-output models [134] where high degrees of uncertainty will result in calculated econometric responses (and we contest also environmental and societal responses), this uncertainty would ultimately undermine MFA's usefulness as a city analysis tool within an overarching UM city planning framework. Therefore there are strong arguments for making data sets more robust or alternatively more useful and accessible through adoption of simpler or, let us say, less precision-focussed models [135]. MFA at city scale is looking at city level data sets, which are necessarily estimates and should be seen as "macro-data" rather than precise design data – therefore the law of diminishing returns applies. For example, within the literature MFA at this scale appeared very much to be about 'stock taking' and typically considered only what happens over a complete year, so it does not include daily or even monthly temporal changes which can significantly impact upon city design quality and ultimately liveability. For instance, times when water supplies are abundant (not least through localised rainfall) or significantly diminished. This "micro-data" would require strings of input output (IO) tables, targeted data analysis and translation/interpretation to convey key messages to stakeholders. Ultimately if transformative solutions for reducing carbon, increasing resource security and wellbeing are to be successful there must be a requirement to simulate and evaluate existing as well as future flow scenarios [21,22,23,136,137], so as to test solutions to ensure they are sufficiently robust and resilient to future changes [138,139].

4.2. Is MFA alone sufficient to produce change?

MFA undoubtedly allows for more meaningful synthesis of data sets in order that we can truly understand 'liveable' cities. Moreover it does reveal sufficient levels of detail to make it more obvious where changes (interventions) can be made in order to limit resource use whilst reducing carbon emissions. However, there are three important aspects that need to be addressed so that the methodology can work effectively and produce city changes for the better.

Firstly, it can be argued that MFA (in isolation) does not give a true picture of the impact to the environment of meeting city demands, this requires per capita carbon footprints (this includes emissions from housing, transport, food, consumer items, public/private services, capital investment and others). Whilst this cannot be gained directly from MFA analysis flows, the results calculated therein can inform a much broader EF analysis which includes carbon foot printing - the most widely recognized measure(s) for environmental sustainability [140]. [For example, the carbon footprint for Birmingham is been estimated to be 10.78 tonnes CO_2/capita [29]. This translates into a land requirement of 5.22 gha to support the consumption of each Birmingham resident or 2.9 planets to support the city, ranking it 17th out of 60 UK cities [29]. These should be combined with water footprinting and LCA in order that tangible performance outputs can be easily translated to decision-makers and compared between cities. What is of most interest here is that when considering the mini-Stern review for energy in Birmingham it was clearly shown that the highest percentage of carbon savings could only be made at the national level, e.g. pricing, national grid, etc [141]. Therefore it is not inappropriate to assume this may also be the case for other areas, such as water, transport and food. Perhaps then MFA at National/international scale might also be considered so as to provide a broader picture.

Secondly from analysing the literature and applying MFA at multiple scales it becomes apparent that MFA does not yet go far enough in terms of other more organic qualities which reflect how a city functions. This is a shortfall first noted by Newman (1999) who suggested that the methodological approach should be broadened to include dimensions related to the dynamics of settlement (e.g. built environment, economic priorities, cultural priorities, infrastructure provision, ecology and ecosystem services) and urban living (e.g. Health, employment, income, education, housing, leisure activities, accessibility, urban design quality and community) [1]. This shortfall is well known within the Industrial Ecology community and awareness is growing that the effect(s) on flows of social dimensions and stakeholders, each with different profiles and priorities, need to be considered [124]. This is particularly true for 'wellbeing' where a better understanding is gained from considering the users (i.e. individual end-use scale MFA).

Lastly, the fact that growth in material turnover (or flows) in our cities is closely associated with economic progress [8] presents a significant barrier to resource reduction within the liveability umbrella. There is also a suggestion that if we are to better prepare our cities for the future we cannot ignore the causal relationships that exist in our between economically motivated human behaviour and resource-driven consumption [142].

6.0 Conclusions

In this paper MFA was shown to be a precursory step to any UM city analysis. When subsequently applied at a range of scales (i.e. city to individual) the paper provided a focus toward an underrepresented sector (i.e. water) that dominates city movement in terms of its actual mass. By applying MFA, albeit at a superficial level, at increasing levels of detail a greater understanding of water flows was achieved. This leads directly to identification of interventions at varying scales that aim to: decrease mains water consumption; decrease carbon flows and increase resource security (without eroding wellbeing). The visual interpretation of the 'stock-taking' information for stakeholders and decision-makers must be conveyed clearly if they are to aid decision-making. A variety of approaches have been used herein but perhaps more are required. This paper has shown that MFA is most effective and therefore has greatest potential for improving future liveability of cities when applied at a range of scales (i.e. city to household), each of which reveals different layers of granularity of city living and each of which requires very different transformative solutions (whether it be technical, economic, political or social). When parallel streams are considered interconnectivity issues (water / energy / food nexus) and the potential for loop closing (e.g. water re-use/recycling) can be highlighted. MFA should not be used in isolation, it is a precursory tool within a toolkit and in order to represent the broader impacts of city it requires footprint analyses (carbon and water), LCA and a deeper understanding of issues related to city dynamics. Aspects of infrastructure provisioning and issues of temporal changes cannot be ignored as an excess (or lack of) flows during the year can lead to key liveability issues for end-users. When considering an individual user and a single water use cognisance of flows is still important, however it has been shown that supplementary approaches to MFA, such as a Futures Framework are required in order to start and unpick wellbeing issues.

Acknowledgements

The authors wish to thank the Engineering and Physical Sciences Research Council for their support under the *Liveable Cities* (EP/J017698) Programme Grant.

Author Contributions

Dexter V.L. Hunt undertook the main body of the research within this paper. Contributions from all co-authors provided critical judgement on the research being undertaken.

Conflict of Interest

The authors declare no conflict of interest.

References and Notes

1. Newman, P.W.G. (1999) Sustainability and cities: extending the metabolism model, *Landscape and Urban Planning* **44,** 219-226
2. UN (2012) World Population Prospects: The 2012 Revision http://esa.un.org/unpd/wpp/unpp/panel_population.htm
3. Lombardi DR, Leach JM, Rogers CDF, Barber A, Boyko CT, Brown J, Bryson J, Butler D, Caputo S, Caserio M, Coles R, Cooper R, Farmani R, Gaterell M, Hale J, Hales C, Hewitt CN, Hunt D.V.L, Jancovic L, Jefferson I, Mackenzie AR, Memon FA, Phenix-Walker R, Pugh TAM, Sadler JP, Weingaertner C, Whyatt JD. (2012) *Designing Resilient Cities: A Guide to Good Practice: (EP103)*, IHS BRE Press
4. Ferrao, P. and Fernandez, J.E. (2013) Sustainable Urban Metabolism. The MIT Press, Cambridge, London England. 260 pages.
5. Barles, S. (2010). Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues, *Journal of Environmental Planning and Management*, 53: 4, 439 — 455
6. Kennedy, C.A. and Hoornweg, D., (2012), Mainstreaming urban metabolism. Column in Sustainable Urban Systems special issue. *Journal of Industrial Ecology*, 16 (6), 780-782.
7. Baccini, P. and P. Brunner. (1991). Metabolism of the anthroposphere. Berlin: Springer-Verlag.
8. Brunner, P.H. and Rechberger, H. (2004). Practical Handbook of Material Flow Analysis. CRC Press, Boca Raton, Florida.
9. Wolman, A., 1965, The Metabolism of Cities, Scientific America, **213**, 3, pp179-190, Nature Publishing Group, New York, United States of America
10. Eurostat. (2001a). Economy-wide material flow accounts and derived indicators: A methodological guide. In *European Commission, Eurostat theme 2: Economy and finance.* Luxembourg: Office for Official Publications of the European Communities.

11. Eurostat. (2001b). Material use indicators for the European Union, 1980-1997. In *European Commission, Eurostat theme 2: Economy and finance.* Luxembourg: Office for Official Publications of the European Communities. 110 pages.
12. Eurostat (2002). Material use in the European union 1980-2000. Indicators and analysis. Luxembourg, Eurostat Office for Official Publications of the European Communities
13. Eurostat. (2009). Economy Wide Material Flow Accounts: Compilation Guidelines for reporting to the 2009 Eurostat questionnaire. Version 01 – June 2009 http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/documents/Eurostat%20MFA%20compilation%20guide%20for%202009%20reporting.pdf
14. OECD (2008a) Measuring Material Flows and Resource Productivity. Volume I: Inventory of Country Activities. Organisation for Economic Co-operation and Development (OECD), Paris, France, 164 pages
15. OECD (2008b) Measuring Material Flows and Resource Productivity. Volume II: The Accounting Framework. Organisation for Economic Co-operation and Development (OECD), Paris, France, 107 pages
16. OECD (2008c) Measuring Material Flows and Resource Productivity. Volume III: Inventory of Country Activities. Organisation for Economic Co-operation and Development (OECD), Paris, France, 107 pages.
17. WWF (2005a). Cardiff's Ecological Footprint. Cardiff County Council, Wales.
18. WWF (2005b). Reducing Cardiff's Ecological Footprint. A resource accounting tool for sustainable consumption. Cardiff County Council, Cardiff, Wales. 183 pages
19. Collins, A., Flynn, A. and Netherwood, A. (2005). Reducing Cardiff's Ecological Footprint, Cardiff.
20. Barrett, J. and Scott, A. (2001). An Ecological footprint of Liverpool: Developing sustainable scenarios. 121 pages.
21. Best Foot Forward, (2003). *An ecological footprint analysis of Angus, Scotland*, Angus. Available at: http://www.angus.gov.uk/sustainability/pdfs/AngusEcologicalFootprintFinalDraft.pdf.
22. Best Foot Forward, (2002). *Five Cities Footprint: Estimating the Ecological Footprint of Aberdeen, Dundee, Edinburgh, Glasgow, and Inverness*, Oxford.
23. Vergoulas, G., Lewis, K., and Jenkin, N. (2003) An ecological footprint of Angus, Scotland. Best Foot Forward, Oxford, UK.
24. Schandl, H., Schulz, N. (2000). Using Material Flow Accounting to operationalise the concept of Society's Metabolism. A preliminary MFA for the United Kingdom for the period of 1937-1997. ISER Working Paper. No. 2000-3. University of Essex, Colchester.
25. Bringezu, S and Helmut, S. (2001). Total Material Resource Flows of the United Kingdom. Wuppertal: Wuppertal Institute for Climate, Environment, Energy. A study undertaken for DEFRA (Department for Environment, Food & Rural Affairs)', London: DEFRA

26. Sheerin C (2002) UK Material Flow Accounting. Economic Trends No. 583, pp 53–61. Available at http//: www.statistics.gov.uk/cci/article.asp?id=140
27. Linstead, C. and Ekins, P. (2001), Mass balance UK. Mapping UK resource and material flows. Royal Society for Nature Conservation.
28. Dahlström, K., Ekins, P., Heb, J., Davis, J. and Clift R. (2004) Iron, Steel and Aluminium in the UK: Material Flows and their Economic Dimensions. Executive Summary Report, April, Policy Studies Institute (PSI), 38 pages.
29. Calcott, A. and Bull, J. (2007) Ecological Footprint of British Residents. A publication for World Wildlife Fund (WWF). 40 pages.
30. ONS (2005) UK Material Flow Review. Office for National Statistics. London, 99 pages.
31. Wiedmann, T., Minx, J., Barrett, J. Vanner, R. and Ekins, P. (2006). Sustainable Consumption and Production - Development of an Evidence Base: Resource Flows. Stockholm Environment Institute (SEI) and Policy Studies Institute (PSI)
32. Wiedmann, T., Minx, J.C., Barrett, J. and Wackernagel, M., (2006) Allocating Ecological Footprints to Household Consumption Activities by Using Input-Output Analysis, Ecological Economics **56**(1): 28-48.
33. Barrett, J. and Simmons, C. (2003). An Ecological Footprint of the UK: Providing a Tool to Measure the Sustainability of Local Authorities, 81 pages.
34. Barrett J, Ravetz J & Bond S (2006) Counting Consumption: CO2 emissions, material flows and ecological footprint of the UK by region and devolved country: Godalming, WWF-UK
35. Carbon Trust, 2011. *International Carbon Flows*, London. Available at: https://www.carbontrust.com/media/38075/ctc795-international-carbon-flows-global-flows.pdf
36. Papathanasopoulou, E. and Jackson, E. (2010) The UKs fossil Resource Consumption between 1968 and 2000. Journal of Industrial Ecology, **14**(2), 354-370
37. Douglas, I., Rob Hodgson, R. and Lawson, N. (2002) Industry environment and health through 200 yrs in Manchester. Ecological Economics **41** 235–255
38. Barrett, J. and Scott, A. (2003). The Application of the Ecological Footprint: A case of passenger transport in Merseyside, Local Environment: The International Journal of Justice and Sustainability, 8:2, 167-183 [Accessed April 15, 2014].
39. Best Foot Forward (2005) Stepping Forward: A resource flow and ecological footprint analysis of the SW of England. 34 pages
40. McEvoy D., J. Ravetz and Handley, J. (2001). 4 sight: Resource flow audit for sustainability. A framework strategy for the North West, Centre for Urban and Regional Ecology, University of Manchester.
41. McEvoy D., J. Ravetz and Handley, J. (2008). Managing the Flow of Construction Minerals in the NorthWest Region of England: A Mass Balance Approach. *Journal of Industrial Ecology,* 8(3),121-140

42. Barrett, J., Vallack, H., Jones, A., Haq, G., (2002). A Material Flow Analysis and Ecological Footprint of York. Technical Report. Stockholm Environment Institute, Stockholm, Sweden.
43. CIWM (2002). *A resource flow and ecological footprint analysis of Greater London*. Chartered Institute of Wastes Management London: Best Foot Forward.
44. GLA (2003) London's Ecological Footprint. Greater London Authority, London, UK 32 pages.
45. Nates, M. and Bartlett, J. (2008). Feasibility study to examine making the Thames Gateway a low carbon/carbon neutral development area. Department for Communities and local Government (DCLG), London, 166 pages.
46. SEI (2007) An Introduction to the Resources and Energy Analysis program http://www.fcrn.org.uk/sites/default/files/REAP_UK_Methodology.pdf
47. SEI (2008a) Environmental Accounting for People and Places: Fact Sheet Stockholm Environmental Institute http://sei-international.org/mediamanager/documents/Publications/ Climate/reap.pdf
48. SEI (2008b) REAP v2 Experimental release data for Birmingham: 15-10-08. Published by SEI, Stockholm.
49. Lazarus (2002) Bed:ZED Toolkit Part 1. A guide to construction materials for carbon neutral dvelopments http://www.oneplanetcommunities.org/wp-content/uploads/2010/03/BedZED-Toolkit-Part-1-Materials-Report-screen.pdf
50. European Commission (2008). Potential of the Ecological Footprint for monitoring environmental impacts from natural resource use Analysis of the potential of the Ecological Footprint and related assessment tools for use in the EU's Thematic Strategy on the Sustainable Use of Natural Resources2008. http://www.ec.europa.eu/environment/natres/pdf/footprint.pdf
51. Barrett, J., Birch, R., Cherrett, N. and Simmons, C. (2004) An Analysis of the Policy and Educational Application of the Ecological Footprint. Technical Report. Stockholm Environment Institute, Stockholm, Sweden, 39 pages.
52. Hertwich, E.G. and Peters, G.P. (2009). Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.*, 43 (16), pp 6414–6420
53. Krotscheck, C. and Narodoslawsky. M. (1996). The sustainable process index: A new dimension in ecological evaluation. *Ecological Engineering* 6: 241–258.
54. Collins, A. and Flynn, A., (2007). Engaging with the Ecological Footprint as a Decision-Making Tool: Process and Responses. *Local Environment*, 12(3), pp.295–312.
55. Wackernagel, M. and Rees, W. (1996). Our ecological footprint: Reducing human impact on the earth. Gabriola Island, BC: New Society Publishers.
56. Monfreda, C., Wackernagel, M., Deumling, D., 2004. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity accounts. Land Use Policy 21, 231 – 246
57. Wright, L.; Kemp, S.; Williams, I. (2011). Carbon footprinting': towards a universally accepted definition. *Carbon Management* **2** (1): 61–72.

58. ISO (2013) Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication (ISO/TS 14067:2013), International Organisation for Standardisation (ISO), Geneva, 52 pages.
59. ISO (2014) ISO14046:2014. Environmental Management: Water Footprint,: Principles, requirements and Guidelines, International Organisation for Standardisation (ISO), Geneva
60. Huppes, G., and Mansanobu, I. (2007). Quantified eco-efficiency: An introduction with applications. (Vol. 22). Springer London, UK.
61. Daniels, P.L. and Moore, S (2012) Approaches for Quantifying the Metabolism of Physical Economies Part I: Methodological Overview. Journal of Industrial Ecology **5** (4) 69-93
62. Opschoor, J.B. and Reijnders, L. (1991) Towards sustainable Development Indicators. *In search of Indicators of Sustainable Development*. Environment and management Volume 1. 7 -27
63. Maclean, H. and Lave. L, (1998). Life-cycle of an automobile. *Environmental Science and Technology* 32(13): 322A–328A.
64. Jonsson, A, T. Bjorklund, and A.M. Tillman. (1998). LCA of concrete and steel frames. *International Journal of Life Cycle Assessment* 3(4): 216–224.
65. ISO (2006a) Environmental Management- Life Cycle Assessment – Principles and Framework (ISO 14040:2006) International Organisation for Standardisation (ISO), Geneva, 20 pages
66. ISO (2006b) Requirements and Guidelines (ISO 14044:2006), International Organisation for Standardisation (ISO), Geneva, 46 pages.
67. ISO (2012b) Environmental management -- Life cycle assessment -- Illustrative examples on how to apply ISO 14044 to impact assessment situations (ISO/TR 14047:2012), International Organisation for Standardisation (ISO), Geneva, 85 pages.
68. ISO (2012b) Environmental management -- Life cycle assessment -- Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis (ISO/TR 14049), International Organisation for Standardisation (ISO), Geneva, 48 pages.
69. Saouter, R. and van Hoof. G. (2002). A database for the life-cycle assessment of Proctor and Gamble laundry detergents. *International Journal of Life Cycle Assessment* 7(2): 103–114.
70. WRAP tools http://www.wrap.org.uk/content/model-market-flows-electrical-products
71. WRAP (2011) Market Flows of Electronic Products & WEEE Materials, 13 pages.
72. WRAP (2012) Electrical product material composition, Waste and Resource Action Programme. Banbury, Oxford. 9 pages
73. Lehmann, H. and F. Schmidt-Bleek. (1993). Material flows from a systematical point of view. *Fresenius Environmental Bulletin* 2: 413–418.
74. Ritthoff, M., Rohn, H. and Liedtke, C. (2003). Calculating MIPS – Resource productivity of products and services http://www.wupperinst.org/uploads/tx_wibeitrag/ws27e.pdf
75. BRE (2008) Global Methodology for Environmental Profiles of Construction Products. SD6050. British Research Establishment, Watford, UK.106 pages

76. Brunner, P. H. (2002), Beyond Materials Flow Analysis. Journal of Industrial Ecology, 6: 8–10.
77. Cencic, O. and Rechberger, H. (2008) Material Flow Analysis with Software STAN. Journal of Environmental Engineering and Management, **18**, 3.
78. Fischer-Kowalski, M. and Hüttler, W. (1998). Society's Metabolism. The Intellectual History of Materials Flow Analysis, Part I, 1860-1970. *Journal of Industrial Ecology* **2** (1), 61-78.
79. Fischer-Kowalski, M and Hüttler, W. (1999). Society's Metabolism. The Intellectual History of Materials Flow Analysis. Part II, 1970-1998. *Journal of Industrial Ecology* **2** (4), 107-136.
80. Luks, F. and Hammer, M. (2003). Material Flow Analysis, Discourse Analysis and the Rhetorics of (Ecological) Economics. SERI Working Paper. 32 pages. http://seri.at/publications/other-working-papers/2009/09/20/material-flow-analysis-discourse-analysis-and-the-rhetorics-of-ecological-economics/
81. Hinterberger, F., Giljum, S. and Hammer, M. (2003). Material Flow Accounting and Analysis (MFA) – A valuable tool for analyses of society-nature interrelationships. Entry prepared for the Internet Encyclopedia of Ecological Economics. 19 pages http://www.isecoeco.org/pdf/material.pdf [Accessed 30/04/2014]
82. Barles, S. (2007). A material flow analysis of Paris and its region. Paper presented at the International Conference CISBAT.
83. Barles, S. (2009). Urban metabolism of Paris and its region. *Journal of Industrial Ecology, 13*(6), 898-913.
84. Haberl, H., Erb, K.H., Krausmann, F., Loibl, W., Schulz, N., Weisz, H., (2001). Changes in ecosystem processes induced by land use: human appropriation of net primary production and its influence on standing crop in Austria. *Global Biogeochemical Cycles* 15 (4), 929–942.
85. Haberl H, Fischer-Kowalski M, Krausmann F, Weisz H, Winiwarter V., (2004). Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy* 21, 199-213
86. Krausmann, F. and Haberl, H, (2002). The process of industrialisation from the perspective of energetic metabolism, socio-economic energy flows in Austria 1830-1995. Ecological Economics 41 (2) 177-201
87. Schandl, H., Grunbuhel, C.M., Haberl, H. and Weisz, H. (2002). Handbook of Physical Accounting measuring bio-physical dimensions of socio-economic activities. Social Ecology Working paper. 81 pages.
88. Huttler, W., Payer, H. and Schandl, H. (1997). *National material flow analysis for Austria 1992: Society's metabolism and sustainable development.* Schriftenreihe des IFF-Soziale O kologie, Vol. 45. Klagenfurt, Vienna: Institut fur Interdisziplinare Forschung und Fortbildung, Abeitlung Soziale Okologie.

89. Bringezu, S. (2000). History and overview of material flow analysis. Paper presented to the OECD Special Session on Material Flow Accounting, 30th Meeting of the Working Group on the State of the Environment. 24 October, Organisation for Economic Cooperation and Development, Paris.

90. Hendriks, C., Obernosterer, R., Muller, D., Kytzia, S., Baccini P. & Brunner, P.H. (2000). Material Flow Analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss Lowlands. *Local Environment,* **5**(3), 311–328.

91. Diener, D.L. Tillman, A.M. and Harris, S. (2013), Lessons Learned from Conducting a Company-level, Downstream MFA. Re-engineering Manufacturing for Sustainability, 559-564

92. Baccini, P. and H.-P. Bader (1996). Regionaler Stoffhaushalt: Erfassung, Bewertung und Steuerung. Heidelberg Berlin Oxford, Spektrum Akademischer Verlag.

93. Streicher-Porte, Bader, H., Scheidegger, R. and Kytzia, S. (2007). Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies. *Clean Techn Environ Policy* **9**, 325–345

94. Hendrickson, C., Horvath, A., Joshi S. and Lave L.B. (1998). Economic Input-Output Models for Environmental Life Cycle Analysis, *Environmental Science & Technology*, April, 184-191.

95. Meyer, B., Uno, K. (1999). COMPASS - Ein globales Energie-Wirtschaftsmodell. ifo Studien 4, 703 719.

96. Gravgard Pederson, O. (1998). Physical input-output tables for Denmark. Copenhagen: Statistics Denmark.

97. Stahmer, C., M. Kuhn, and N. Braun. (1997). *Physical input-output tables for Germany, 1990.* Report prepared for DG XI and Eurostat. Luxembourg: Eurostat Directorate B, Unit B6.

98. Bringezu, S., Schütz, H. and Moll, S. (2002) Towards Sustainable Resource Management in the European Union. Wupertal Papers. 50 pages

99. Bringezu, S., Fischer-Kowalski, M., Kleijn, R. and Palm, V. (1997). Regional and national Material Flow Accounting: From paradigm to practice of sustainability. *Proceedings of the ConAccount workshop* 21-23 January, 1997, Leiden, The Netherlands

100. Matthews, E., Amann, C., Bringezu, S., Fischer-Kowalski, M., Hüttler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schütz, H., van der Voet, E. and Weisz, H. (2000). The Weight of Nations. Material Outflows from Industrial Economies. Washington D.C.: World Resources Institute.

101. Page, J; Grange, N; KirkpatrickN. (2008) The Integrated Resource Management (IRM) model – a guidance tool for sustainable urban design PLEA 2008 – 25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October 2008 http://plea-arch.org/ARCHIVE/2008/content/papers/oral/PLEA_FinalPaper_ref_506.pdf

102. Kleijn, R. (2001) Adding It All Up The Sense and Non-Sense of Bulk-MFA. Journal of Industrial Ecology, **4**(2). 7-8

103. Hammer, M., Hubacek, K. (2002). Material flows and economic development. Material flow analysis of the Hungarian economy. Interim Report. No. 02-057. International Institute for Applied Systems Analysis (IIASA), Laxenburg.

104. Hammer, M., Giljum, S., Bargigli, S. and Hinterberger, F. (2003). Material flow analysis on the regional level: questions, problems, solutions. NEDS Working Paper. No. 2, Hamburg

105. Hammer and Giljum (2006) Material flow analysis of Hamburg Vienna and Leipzig (in German). SERI Working Paper. 94 pages.

106. Lee, S.E., Leach, J.M., Hunt, D.V.L., Rose, K and Rogers, D.D.F. (2013) A City Analysis Methodology to elucidate Urban Challenges: Energy and material flows of Birmingham. Liveable Cities Conference, 21st October, Birmingham, UK. 6 pages.

107. Chambers, N., Griffitihs, P., Lewis, K. and Jenkin, N. (2004). *Scotland's Footprint: A resource flow and ecological footprint analysis of Scotland*, Oxford: Viridis. Available at: http://www.scotlands-footprint.com/downloads/Full Report.pdf.

108. Kane, M. and Erickson, J.D. (2007). Urban Metabolism and Payment for Ecosystem Services: History and Policy Analysis of the New York City Water Supply, in Jon D. Erickson, Frank Messner, Irene Ring (ed.) *Ecological Economics of Sustainable Watershed Management (Advances in the Economics of Environmental Resources, Volume 7)*, Emerald Group Publishing Limited, pp.307-328

109. Thériault, J., Laroche, A.-M., 2009. Evaluation of the urban hydrologic metabolism of the Greater Moncton region, New Brunswick. *Canadian Water Resources Journal* **34**(3), 255-268.

110. Kenway, S., Gregory, A. and McMahon. J. (2011) Urban Water Mass Balance Analysis. *Journal of Industrial Ecology,* 15(5), pages 693–706

111. Venkatesh G. and Brattebø, H. (2011). Analysis of chemicals and energy consumption in water and wastewater treatment, as cost components: Case study of Oslo, Norway, *Urban Water,* **8**(3) 189-202

112. Hass, J. and Popescu, C. (2011). Economy-wide material flows: European countries required more materials between 2000 and 2007. Eurostat publication. European Community. 8 pages

113. Shah, J., Jefferson, I. and Hunt, D.V.L. (2014) Resilience Assessment for Geotechnical Infrastructure Assets. *Proc. Institute of Civil Engineers*: *Asset Management,* http://dx.doi.org/10.1680/iasma.14.00007

114. Rogers, C. D. F and Hunt, D. V. L. (2006). Sustainable Utility Infrastructure via Multi-Utility Tunnels, *In proceedings of the Canadian Society of Civil Engineering 2006 conference*, Towards a sustainable future, Calgary, May 23rd 2006, Paper CT-001.

115. Hunt, D.V.L., Nash, D. and Rogers, C.D.F (2014). Sustainable utility placement via multi utility tunnels. *Special issue of Tunnelling and Underground Space Technology.* 39, 15-26

116. Kowalski, M., Waylen, C., Clist, S., Wilcox, S., Lynn, S. and Garrow, D. (2011). Freshwater availability and use in the United Kingdom. Banbury: WRAP. 123 pages

117. Makana, L.O., Jefferson, I., Hunt, D.V.L., and Rogers C.D.F. (2014). 3D Geospatial Visualization of Underground Space to Enhance Geo-governance. *Geocongress 2014.* pp. 3455-3464

118. Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Dolf Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. and Yumkella, K. (2011) Considering the energy, water and food nexus: Towards an integrated modelling approach. Energy Policy, 39: (12): 7896-7906.

119. De Laurentiis, V., Hunt, D.V.L., and Rogers C.D.F. (2014) Food security challenges: influences of an energy/water/food nexus. *Proceedings of the 4th World Sustain. Forum*, 1-30 November 2014. Sciforum Electronic Conference Series, Vol. 4, 2014.

120. Hoff, H. (2011) Understanding the Nexus - Background Paper for the Bonn2011

121. Kennedy, C. Ibrahim, N., Stewart, I., Facchini, A. and Mele, R. (2014). An urban metabolism survey design for megacities. Working Paper 2/2014, Enel Foundation, Rome, Italy. 40 pages

122. Hunt, D.V.L., Lombardi, D.R., Farmani, F., Jefferson, I., Memon, F.A., Butler, D. and Rogers, C.D.F. (2012b) Urban Futures and the code for sustainable homes *Institution of Civil Engineers Engineering Sustainability*. 165 (1), 37–58

123. Hunt D.V.L. and Rogers C.D.F. (2014) Rainwater harvesting: Trade-offs between pluvial flood risk alleviation and mains water resource savings *Proceedings of the 4th World Sustain. Forum*, 1-30 November 2014. Sciforum Electronic Conference Series, Vol. 4, 2014.

124. Boons F. and Howard-Grenville, J. (2009) The social embeddedness of industrial ecology Cheltenham [u.a.] : Edward Elgar, ISBN 978-184-720-782-1. - 2009, p. 273-281.

125. Clift, R. (2013) System Approaches: Life cycle assessment and industrial ecology. Chapter 17, pp.385-416 in : *Pollution: Causes, Effects and Control 5th ed.* (Ed. G. Harrison), Royal Society of Chemistry, London.

126. Zadeh, S.M., Hunt, D.V.L., Lombardi, D. R., and Rogers C.D.F. (2014). Carbon costing for mixed-use greywater recycling systems. *Proc. Institute of Civil Engineers*: *Water Management,* 1-15 http://dx.doi.org/10.1680/wama.12.00093

127. Feng, K; Hubacek, K; Minx, J; Siu, Y; Chapagain, A; Yu, Y; Guan, D; Barrett, J. (2011). Spatially Explicit Analysis of Water Footprints in the UK. *Water* 3, no. 1: 47-63.

128. Hunt, D.V.L., Rogers, C.D.F. and Jefferson, I. (2013). Scenarios analysis through a futures performance framework. Special themed issue of Earth Systems Engineering within *Engineering Sustainability* 166 (5), 258-271.

129. Hunt, D.V.L. and Rogers, C.D.F. (2014) A Benchmarking system for Domestic Water Use. *Sustainability,* 6, 2993-3018; http://doi:10.3390/su6052993

130. Ekins (2014) Updates on the European funded project "Policy Options for a Resource Efficient Economy (POLFREE)", including publications, dissemination activities and ongoing research. http://us5.campaign-archive2.com/?u=b0b49001d0568fd41fbba5c22&id=b9dfe1765b

131. Kennedy, C.A., Cuddihy, J. and Engel Yan, J., (2007). The changing metabolism of cities. *Journal of Industrial Ecology*, 11 (2), 43-59.

132. Kennedy, C., Steinberger, J., Gasson, B., Hillman, T., Havránek, M. Hansen, Y., Pataki, D., Phdungsilp, A., Ramaswami, A., Villalba Mendez, G., (2009), Greenhouse gas emissions from global cities. *Environmental Science and Technology*, 43, 7297-7302
133. Rechberger, H., Cencic, O., and Fruhwirth, R. (2014) Uncertainty in Material Flow Analysis. Journal of Industrial Ecology Volume 18, Issue 2, pages 159–160.
134. Keirstead, J. (2014). Fit for Purpose? Rethinking Modelling of Industrial Ecology. Journal of Industrial Ecology, **18**(2) 161-163
135. Grimm, V., E. Revilla, U. Berger, F. Jeltsch, W. M. Mooij, S. F. Railsback, H. -H. Thulke, J. Weiner, T. Wiegand, and D. L. DeAngelis. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science* 310 (5750): 987-991.
136. Hinterberger, F., Omann, I., Stocker, A. (2002). Employment and Environment in a Sustainable Europe. Empirica 29, 113-130.
137. Spangenberg, J., Omann, I., Hinterberger, F. (2002). Sustainable growth criteria. Minimum benchmarks and scenarios for employment and the environment. Ecological Economics 42, 429-443.
138. Lombardi DR, Leach JM, Rogers CDF, Barber A, Boyko CT, Brown J, Bryson J, Butler D, Caputo S, Caserio M, Coles R, Cooper R, Farmani R, Gaterell M, Hale J, Hales C, Hewitt CN, Hunt D.V.L, Jancovic L, Jefferson I, Mackenzie AR, Memon FA, Phenix-Walker R, Pugh TAM, Sadler JP, Weingaertner C, Whyatt JD. (2012) *Designing Resilient Cities: A Guide to Good Practice: (EP103)*, IHS BRE Press
139. Hunt, D.V.L.; Lombardi, D.R.; Atkinson, S.; Barber, A.; Barnes, M.; Boyko, C.T.; Brown, J.; Bryson, J.; Butler, D.; Caputo, S.; Caserio, M.; Coles, R.; Farmani, R.; Gaterell, M.; Hale, J.; Hayes, C.; Hewitt, C.N.; Jankovic, L.; Jefferson, I.; Mackenzie, A.R.; Memon, F.A..; Whyatt, D.; Weingaertner, C.and Rogers, C.D.F.; (2012a). Scenario Archetypes: Converging rather than Diverging Themes. In *Sustainability 4* (4), 740-772
140. Chang, Ma H.W. and Cui, G (2012) Ecological Footprint Model Using the Support Vector Machine Technique. PLoS ONE 7(2)
141. Gouldson, A, Kerr, N., Topi, C., Dawkins, E., Kuylenstierna, J. and Pearce, R. (2013) The Economics of Low Carbon Cities A Mini-Stern Review for Birmingham and the Wider Urban Area - Preliminary Findings. Centre for Low Carbon Futures, Leeds, UK. 56 pages.
142. Kytzia, S., Faist, M. and Baccini, P. (2004). Economically-extended – MFA: A material Flow Approach for a better understanding of Food Production Chain. *Journal for Cleaner production.* **12**(8/10), 877-889.