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Environmental sustainability assessment of urban systems applying coupled urban metabolism and life cycle assessment



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Short summary

The necessity of assessing and addressing the environmental sustainability of urban systems is becoming increasingly relevant due to growing urbanization across the globe, higher consumption in urban systems and related competition for finite resource stocks. In this study we present how fused urban metabolism (UM) and life cycle assessment (LCA) can be applied to assess the sustainability of urban system, taking into account up- and downstream activities directly or indirectly linked to the metabolism of urban systems. Further we apply the fused UM-LCA approach to assess the absolute environmental sustainability of large urban systems by relating the environmental sustainability performance of urban systems with global environmental burden boundaries quantifying pollution thresholds beyond which performance of global ecosystems services may be detrimentally affected.

Keywords: Urban metabolism, life cycle assessment, UM-LCA, planetary boundaries

1. Introduction

Urban metabolism (UM) has over the last 4 decades served as a credible means to assess the environmental performance of urban systems, however its purest form, 1st generation UM, only provides the magnitudes of non-standardized material and energy flows making it difficult to provide meaningful comparative analysis of the environmental performance of different cities. Independently over the last 3 decades energy has been implemented as a 2nd generation UM analysis model by systems ecologists. However, due to its complex thermodynamic origin, the energy based UM models are opaque and are at a disadvantage to communicate results to the public and policy makers alike. In the present study we introduce 3rd generation UM, relying on the coupling of UM and full-scale (i.e. complete indicator set) life cycle assessment (LCA), the UM-LCA fusion approach.

The UM-LCA coupling was tested out on existing UM studies covering 5 major urban areas [1]. The results of this UM-LCA application study clearly underline that the UM-LCA coupling facilitates comparison across cities, mainly due to the ISO standardized LCA framework. Further the study by [1] reveals that the major sustainability burdens of cities are not related to the impacts within the cities but occur up- and downstream of the cities showing that the major impacts are embedded within the provision of energy and goods for consumption in the cities and the waste and goods excreted by the cities. Furthermore, the representation of an urban environmental loading with common indicators (e.g. global warming potential, particulate matter formation, etc)[1] appeared to improve communication of UM-LCA results over earlier UM methods.

Application of LCA for relation of product system impacts and planetary boundaries as suggested by [2] is still in its infancy [3] but the available data suggests that LCA can serve as a means to address the absolute sustainability of product systems and hence urban systems that consume those products. In this presentation we therefore propose a UM-LCA framework to assess the

absolute sustainability of urban systems, relating the climate burdens of the 5 urban systems assessed in [1] to the planetary climate boundaries suggested by [2] as a cursory example.

Cities as they currently function are simply not sustainable into the future. They are heavily reliant on other cities and beyond to provide material and energy resources, and dispose of waste [4]. In the process of this material and energy metabolism, cities interrupt the cyclical material flows of the biosphere and transfer them to the predominantly linear material flows in the technosphere (taking resources from the biosphere and returning them as waste to incompatible receiving areas) [5]. Cities take useful materials and largely relegate them to the landfill or the incinerator, which would not pose an issue if not for the fact that many of the planet's resources are finite, and that humanity is consuming them at an ever increasing rate as both the global economy and population grow [6]. Additionally, cities being the centres of economic growth [7] play an important role in the scale and direction of material flows [8]. Concurrently with their resource consumption cities are also disproportionately large producers of many forms of pollution [9]. Pollution problems in cities vary from the local to the global in their impacts. For instance the industrialization of Manchester 200 years ago has left contaminated soil and waterways that the city is still grappling with today [10]. In a global sense, cities are estimated to contribute upwards of 70% of greenhouse gas (GHG) emissions to the atmosphere [11]. Compounding these issues is the increasingly globalized economy, whereby the consumption of goods in a city in one part of the world can lead to negative local environmental implications across the planet at the point of extraction and processing [12], while at the other end of the consumption train, the exportation of waste to emerging economies, such as electronic waste, has become increasingly common in recent decades [13].

Urban areas are overwhelmingly absorbing population growth around the world through both domestic and international migrations [14]. Urban environmental pressures will increase parallel to the growth of the planet's urban population if current environmental trends continue, with an approximated 70% of the humanity expected to reside in urban environments by 2050, up from roughly 50% in 2008 [15]. The bulk of this rural to urban migration is going to occur in the transition economies, which will place increased pressures on an already stressed planetary ecosystem as new urbanites attempt to attain the same standards of living (and consumption) in line with the developed world [6]. Cities, the hyper-concentrated centres of human activity [16] represent both the problem and solution to global sustainability. Cities not only pose a looming environmental challenge, but they also represent areas where technological innovation and behavioural shifts can be implemented on large populations. In essence, an economy of scale with regards to the effects of sustainable policy can theoretically be achieved, as these policies can target large populations in condensed spaces. The predicted growth in urban population has additional benefits in that it will allow for sustainable urban development (SUD) policy to be implemented from the ground up, as the city grows. This provides the opportunity for planners in the developing world to avoid the difficulties of "technological lock-in" – whereby the socio-techno-economic systems support the use of an unsustainable technology to the point that it is difficult to displace [17]. Because of all of these reasons, SUD is not only important, but imperative, particularly in a world where estimated planetary boundaries for pollution and resource extraction are quickly being met [3]. Cities represent the battleground for the future sustainability of society.

2. Methodology

In this study we, based on the results presented by [1], illustrate how fusion of the Life Cycle Assessment (LCA) framework and the UM methodology can provide a more complete description of the environmental impact profiles of 5 major case cities and how the fused UM-LCA methodology addresses some of the existing issues in UM practices. Further, we illustrate how the results obtained applying the fused UM-LCA methodology can be used to relate the environmental sustainability performance of cities to the planetary boundaries as those presented by [2].

2.1 Case cities

For the application of the fused UM-LCA methodology presented here, 5 case cities were chosen. The case cities are all major capitals and presented in table 1.

Table 1: Characteristics of the 5 case cities to which the fused UM-LCA methodology is applied during the years modelled.

City	Population (millions)	Population Density (inhabitants/km ²)	GDP (billions Year 2000 USD)
Beijing (2006)	17.1	1016	85.2
Cape Town (1997)	3.0	1239	18.9
Hong Kong (1997)	6.6	6480	169
London (2000)	7.4	4978	211
Toronto (1999)	5.07	858	160

2.2 Urban metabolism

Urban Metabolism (UM) is becoming an increasingly popular framework, due to its novel aim of providing a complete measure the environmental loading incurred by the total sum of city's activities. Though UM has only come into vogue in the past decade, it is one of the oldest tools for quantifying the environmental impacts of urban areas [18]. UM is gaining greater traction with policy makers around the world and is being considered a serious methodology for municipalities to track their sustainability. UM was developed in the 1960s, whereby a city was viewed as analogous to an organism in that it requires flows of material and energy inputs to sustain functions and grow, while at the same time generating waste as a by-product [19]. Much like an organism, this process of consuming matter and energy to sustain life functions in a city, is termed the city's metabolism. The concept is very much akin to material flow accounting (MFA), but performed on the scale of the urban agglomeration. Astonishingly, the principles of the UM method in the original paper have seen little advancement in the convening 45 years. An enlargement in the number of flows included have been made, and the accounting methods have been updated to reflect agreed upon standard methods [20] but essentially, the method has remained primarily focused accounting the annual direct mass and energy flows through a city. The field of UM has not remained completely static since its development. A second school of UM studies which integrates Odum's thermodynamic concept of emergy (a method that accounts for the embedded solar energy in material and energy flows) emerged in the 1970s [21]. The UM method has waxed and waned in popularity since its introduction, but it has seen a resurgence in popularity, mainly from a school of researchers based in China who primarily use it as a tool for assessing the SUD of Chinese cities. Another indirect development of the UM method has been the birth of the Ecological Footprint (EF) framework. This framework is very similar to UM in that it quantifies the flows of material into a city over a year, however it differs from the MFA method in that it converts these flows from mass to the global hectare [22]. Though originally intended for use on national accounts, it has been routinely applied to cities, and can be considered an unofficial extension of the UM method. Because the core of UM studies are firmly rooted in the concept of capturing only direct mass flows, they remain unable to fully assess SUD.

One failure is that by only accounting for masses directly consumed by the city, current UM studies neglect those masses utilized in processes upstream necessary to provide the direct mass flows consumed [8]. Secondly, mass flows are incommensurate with environmental loading, and therefore do not form a proper basis for assessing the environmental sustainability of a city [23]. Shortcomings in the current UM framework highlight the need for methodological advancements that can both, capture the upstream flows not being quantified now, and transform the quantified masses into indicators that better represent their environmental loading. Capturing upstream flows has been addressed to an extent by the emergy and EF assessment methods. However, this success remains limited in the amount of upstream flows these methods can account for and the limited number of downstream pollutants they model [22, 24]. Additionally, the esoteric concept of emergy is difficult to convey to both policy makers and the public, limiting its practical application to SUD. Thus, major methodological gaps remain in the UM tool, and complimentary improvements are necessitated to bring it to the level that it can be applied to properly quantify SUD. Moreover, if

the goal of UM is to provide indicators to properly inform SUD policy decisions, then current deficiencies must be addressed, otherwise by providing incomplete or erroneous results UM risks being of little utility to policy makers, or worse, counteractive to SUD. Given the importance of SUD and its potential contribution to overall global sustainable development, it is necessary to quantify the environmental loading of cities [14]. UM can contribute to this end, but as outlined above, the method is currently immature.

Urban metabolism has been described as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and elimination of waste” [25]. In essence, urban metabolism uses analogies from biology to liken a city to an organism. Thus, cities are perceived as entities requiring resources in the form of metabolic fluxes that are required to maintain human activities and provide for growth [26]. Accordingly, urban metabolism is focused on quantifying flows of materials and energy into cities, and the resulting wastes out of cities. The flows of materials through societies have been an interest of economists and philosophers (eg. Marx and Malthus) since the 19th century [27], the concept was not crystallized to the scale of the city until 1965 by Wolman as outlined in his seminal work that studied a hypothetical American city of 1 million inhabitants [19]. Though crude in its formulation, this study provided the framework of all future urban metabolic studies. In the three decades following the publication of Wolman’s study, only a dozen or so urban metabolism projects were completed, however since the mid-1990s the field has seen a renaissance as a topic of renewed research by a number of engineers, systems ecologists and environmental scientists [8].

2.3 Life Cycle Assessment

‘LCA is a methodology for assessment of the environmental effects of a product or service throughout all stages of its life. Potential impacts are gauged quantitatively, and the perspective can be holistic – from ‘cradle to grave’ – depending on the assessor’s goals [28]. LCA developed over a two-decade period due in part to the economic interest of large corporations to realize greater material efficiencies in production processes [29] or to assist decision making of clearly defined product end goals [28]. It was not until the publication of the Centrum Milieukunde Lieden (CML) LCA handbook in 1992 that a worldwide standardization of the science began to take shape.

By providing quantification of the resource use and release of pollutants to the environment LCA can be applied to [30]:

- Finding where material and energy optimizations can be made along a life cycle
- Identifying phases in a life cycle that are environmentally problematic
- Comparing and choosing between existing and new product/service designs
- Benchmarking the environmental impacts of a product or services

As the science has become increasingly regimented, it has also proliferated in the scope of its application. LCA is now a popular choice of environmental assessment tool for a wide range of decision makers including academics, private firms, NGOs and policy makers [31]. The framework of LCA remains a work in progress as the field continues to harmonize. A major step in this direction was the establishment of an international standard [32]. Guidelines for the practice of LCA have also been released to compliment the ISO standard, most recently the International Reference Life Cycle Data Reference System [33] or the earlier work of others [30]. Additionally on the international level, projects by the United Nations Environmental Program (UNEP) and the Society of Toxicology and Chemistry (SETAC) aim to further build consensus in the field [31]. LCA consists of four separate phases intended to track the impacts of a product or process from raw material extraction to disposal: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation [33]. LCA is an iterative process that relies on communication between the phases and updating of information in accordance with the goals and data requirements set out for the process.

The LCA based comparison of products and services, works by assessing the flows associated with a functional unit. This is the process or service that must be fulfilled (eg. hold 500 mL of liquid, or transport a person 1000 km in a day, etc.). Thus, all calculations are related to the impacts

required to fulfil the functional unit.

2.4 Life Cycle Impact Assessment (LCIA)

Contrary to the UM methodology, the LCA methodology does not stop at the mass, direct material and energy exchanges with the environment. The flow results obtained in the LCI step can via an impact assessment methodology and accompanying characterization models be converted in to potential environmental impacts or damages. Results from a full LCA including the LCIA step are typically provided as predicted/potential environmental impacts resulting from the flows needed to fulfil the functional unit. These flows can be communicated as midpoint impacts which characterize predicted impacts in terms of specific environmental indicators (eg. global warming potential, terrestrial ecotoxicity, etc.). A second option is the use of endpoint indicators that are aggregations of midpoint impacts. Endpoint impacts communicate predicted effects of the system in of more general environmental and health issues (eg. ecosystem quality, damage to human health, etc.) [28].

The conversion of the flows, quantified in the LCI, to potential impacts is impact assessment methodology specific. In present study we apply one of the most recent and widely acknowledged methodologies, the ReCiPe methodology, see fig. 1 and [34]. LCA is a malleable framework in that optional steps can, as presented in fig. 1, be applied. These include converting predicted midpoint impacts to endpoints, normalizing predicted impacts to a reference quantity, or weighting and aggregating impacts to create a single score. As such, LCA can be tailored by practitioners to suit their needs, including providing information to support SUD policy development.

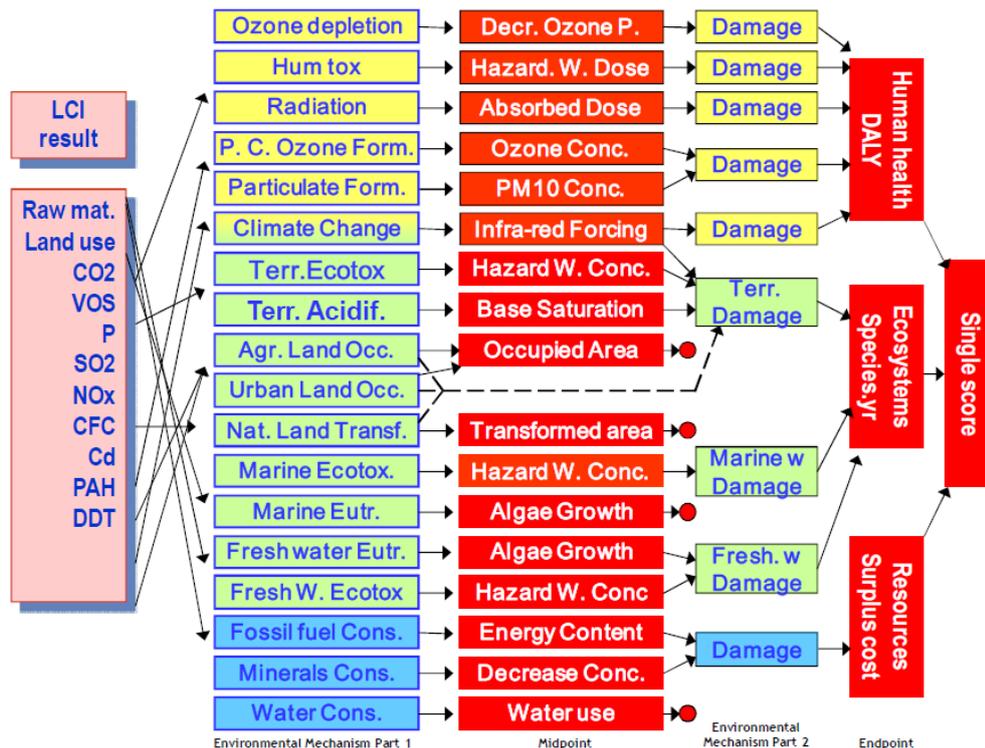


Fig. 1: The ReCiPe framework. From [34].

2.5 Fused urban metabolism and life cycle assessment (UM-LCA)

LCA is a widely applied QSA tool and the coupling of UM and LCA to most LCA practitioners seems obvious, thus, an LCA literature review was done to judge the novelty of the fused UM-LCA approach. Ensuring that LCA practitioners have not already covered this project in another form provides confidence that this study will not only be novel, but also provide an improvement to the field of UM. From reviews of previous LCA literature there appear to be only two papers which

attempted to assess the built environment with a full LCA. A study [36] of high and low density housing in Toronto using an economic input-output LCA, this case was limited in the sense that it only performed a carbon accounting of building materials, transport energy and operational energy inputs. The other study of study interest is the aforementioned 3rd Generation UM by [36] on Finnish cities. Both previous studies depart from the current one at hand in a number of key dimensions. Firstly, in both cases the LCA was focused on carbon and energy accounting, not applying all of the potential LCIA (i.e. multiple impact categories), as will be done here. Moreover, the Toronto study only looked at hypothetical “built forms”, thus primarily serving as a conceptual model as opposed to an assessment of an existing urban system. Hence the coupling of UM and LCA presented here applying a full set of LCIA impact indicators is new and has never been performed before on existing urban environments.

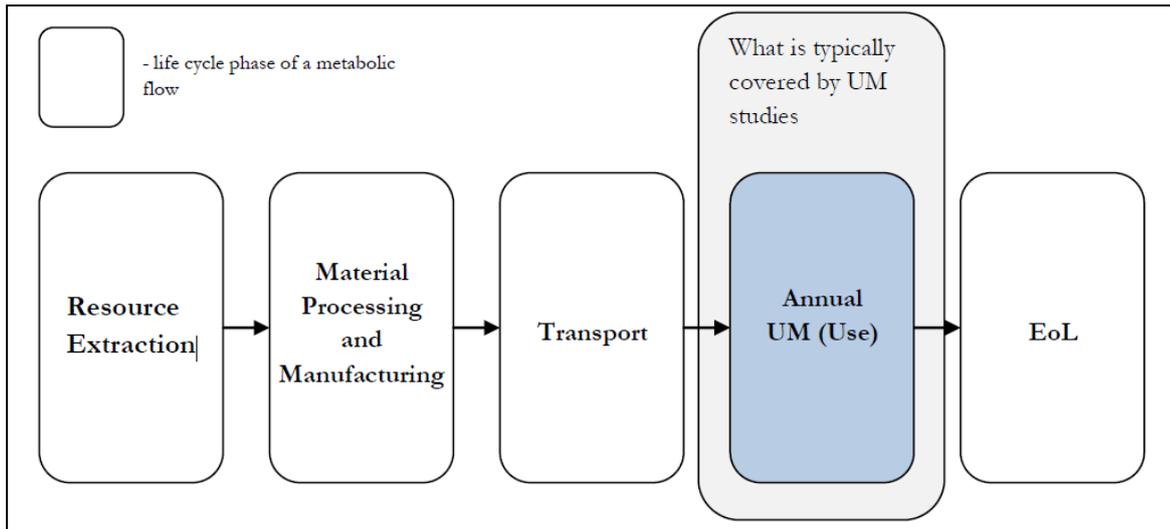


Fig. 2: Comparison of the UM and the UM-LCA coverage. From [1].

2.6 Planetary boundaries

The planetary boundaries as defined by [2] quantifies for a range of earth-system processes/impact categories, thresholds or rather planetary boundaries below which ecosystem services as we know them can be maintained, the boundaries quantified by [2] are listed in table 2. Since many subsystems of the earth react non-linearly or even abruptly, exceeding the planetary boundaries can according to [2] lead to bifurcations of some earth sub-systems such as e.g. the monsoon system shifts permanently into a new state with deleterious or even disastrous consequences for humanity. In the study at hand we solely try to relate the results obtained on the 5 case cities to the planetary boundary for climate change. The planetary boundaries for climate are presented in table 2. keys are listed in table. 3

Table 2: Planetary boundary for climate change in atmospheric CO₂ concentration and radiative forcing change. From [2].

Earth-system process	Comment	Proposed boundary	2009 status
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5

The planetary climate change boundary as presented in table 2 provides an absolute measure for sustainable life on planet earth in terms of global warming. Hence if humanity according to [2] can

maintain atmospheric carbon dioxide concentration below 350 ppm, the Earth should not experience abrupt changes in its sub-systems and hence avoid potential environmental disasters. The issue is that humanity already has transgressed the 350 ppm CO₂-eq. boundary and the question is hence how to get below this boundary again and avoid potential disaster. According to [37], there should be a 75 % chance to get below the climate change boundary again if the predicted 2050 global greenhouse gas (GHG) emissions are cut by 60 % compared to the global 1990 GHG emissions implying an atmospheric peak concentration of GHG gasses in the atmosphere of 470 ppm CO₂-eq between 2010 and 2020. According to [37] should the global 2050 GHG emissions amount to app. 4 GtC-eq/year (equalling 14,4 GtCO₂-eq/year).

Combining the data from [2] and [37] hence provides us with absolute sustainability measures in the form of global CO₂ “boundary quotas” for sustainable life in 2050. The boundary quotas can be calculated according to various allocation keys and thereby provide political angle specific SUD measure for climate change. In this study we apply two CO₂ quota allocation keys; an egalitarian (E) key allocating the CO₂ quota equally based on population number (i.e. each person receives same share) and an individualist (I) allocation key allocating the CO₂ according to GDP (i.e. the higher the GDP the higher the city quota). For a more thorough introduction to political perspective specific sustainability analysis, please see [34]. The CO₂ sub-quotas allocated according to the two

Table 3: Planetary boundary based and city specific 2050 CO₂ quotas, allocated according to an egalitarian (E) and individualist (I) allocation key. Allocation keys based on data from table 1, a global population in 2000 of 6.188 billion people [38] and a world GDP in 2000 of 32,334 billion US \$ [38].

City	CO ₂ quota (E) MtCO ₂ -eq/year	CO ₂ quota (I) MtCO ₂ -eq/year
Beijing	40.2	37.9
Cape Town	7.2	8.4
Hong Kong	15.6	75.3
London	17.4	94.0
Toronto	11.9	71.3

3. Results

Applying the fused UM-LCA the impact potentials normalized per capita were initially calculated in order to compare the city performances across a variety of impact categories, thereby facilitating the comparison of the environmental burdens related with the metabolisms (i.e. consumptions and excretions) of each of the cities covered by our study.

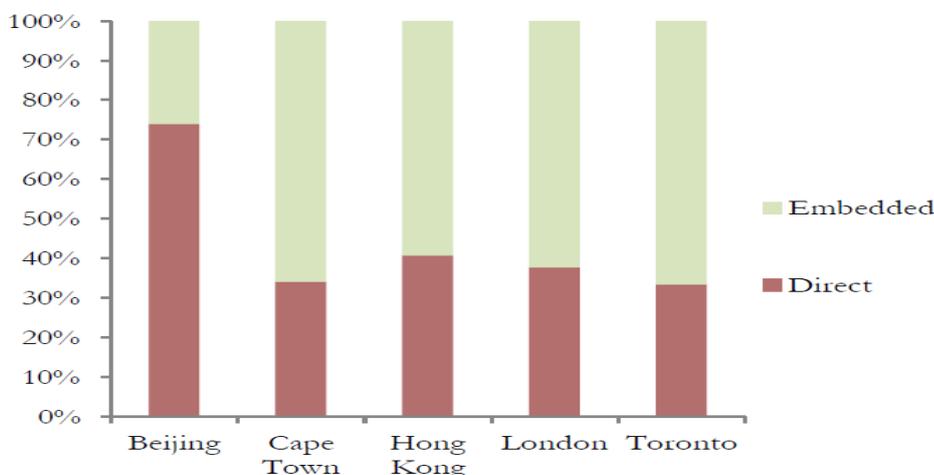


Fig. 3: Proportions of the mass flows covered by conventional UM (direct) as well as the fused UM-

LCA approach and mass flows solely covered by the fused UM-LCA approach (embedded).

The fraction of potential impacts covered by the conventional UM approach compared to the fused approach (please see fig. 2) can be visualized by the fraction of mass flow occurring within the urban area (direct) and up- or downstream of the urban area (embedded) as presented in fig. 3.

Applying the fused UM-LCA methodology allows, due its process based nature, for quite detailed analysis of the origin of potential impacts, fig. 4 illustrates this point by highlight the activities contributing the most to impact profile of the city.

Table 4: Midpoint impacts for the 5 case cities. PMF = Particular Matter Formation, POF = Photochemical Oxidant Formation and pr. = per resident. Highest value within each midpoint impact is marked in bold

Midpoint Impact	Beijing	Cape Town	Hong Kong	London	Toronto
Agricultural land occupation [m2a/pr.]	1700	1500	2200	3300	2700
Contribution to GWP [t CO2-eq/pr.]	17.1	11.2	10.2	12.2	18.0
Fossil depletion [t oil eq/pr.]	4.8	2.3	3.1	3.6	4.9
Freshwater ecotoxicity [kg 1,4-DB eq/pr.]	170	62	31	36	43
Freshwater eutrophication [kg P eq/pr.]	0.88	0.33	0.35	0.29	0.51
Human toxicity [t 1,4-DB eq/pr.]	1.9	1.0	0.8	0.4	0.6
Marine ecotoxicity [kg 1,4-DB eq/pr.]	134	42	672	19	22
Marine eutrophication [kg N-Equiv./pr.]	26	13	20	12	18
Metal depletion [t Fe eq/pr.]	8.2	0.4	0.7	0.7	0.8
Natural land transformation [m2/pr.]	2.33	1.42	2.83	2.02	2.86
Ozone depletion [g CFC-11 eq/pr.]	0.83	0.36	0.42	2.78	1.39
PMF [kg PM10 eq/pr.]	42	18	18	11	16
POF [kg NMVOC/pr.]	60	29	42	25	34
Terrestrial acidification [kg SO2 eq/pr.]	106	56	54	34	54
Terrestrial ecotoxicity [kg 1,4-DB eq/pr.]	5.2	5.0	5.3	2.3	4.5
Urban land occupation [m2a/pr.]	355	206	349	217	408
Water depletion [m3/pr.]	22900	9400	8400	10600	114900

Based on the annual GHG emissions from the 5 cities and the planetary boundary determined CO2 quotas presented in table 3, the GHG emission reductions needed by 2050 can be calculated.

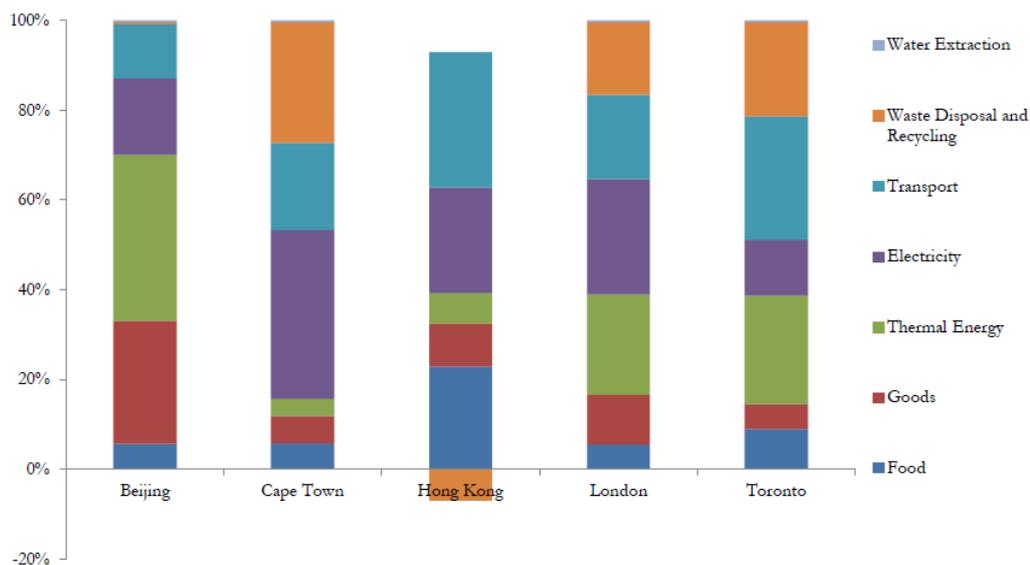


Fig. 4: GHG emission hot spot analysis of the 5 case cities.

The annual GHG emissions and needed emission reduction for the 5 case cities are presented in table 5.

Table 5: GHG emissions reductions quantified by the planetary boundary for climate change quantified by [2] applying the fused UM-LCA approach and two sets of political perspective determined CO₂ emission quotas allocation.

	Beijing	Cape Town	Hong Kong	London	Toronto
Contribution to GWP [Mt CO ₂ -eq/year]	291.9	34.1	67.5	90.3	91.3
Emission reduction needed by 2050 - egalitarian allocation of CO ₂ boundary quotas (%)	86.2	79.0	76.9	80.7	86.9
Emission reduction needed by 2050 - individualist allocation of CO ₂ boundary quotas (%)	87.0	75.3	-11.5	-4.1	21.9

4. Discussion

The application of UM and LCA in combination to assess and quantify the environmental burdens of urban systems appears, as presented above, promising. One major issue relating to the comparison of urban environments is the question of whether the comparison is following the basic LCA requirements and hence if the assessment is based on comparison of the same functional unit. The services provided by the 5 cities compared in this study are basically seen as the same since the essential services the cities delivers to the citizens are the same (i.e. provision of an urban system), the quality of this service however differs tremendously across the compared the cities, which cannot be accounted for by the UM nor the UM-LCA approach.

Comparing UM studies is difficult due to the non-standardized manner in which UM studies are performed. The lack of an "UM standard" clearly introduces a considerable source of comparison error, since the UM assessors are given a large "artistic freedom" to e.g. include and exclude flows contributing to an urban metabolism. A similar problem has been encountered in LCA. In order to ensure that LCA studies are comparable an ISO standard on the general LCA framework was published in 1996 [39], thereby laying the basic validation criteria for the any LCA, and thereby providing standardized guidance on e.g. goal and scope definition, inventory analysis (i.e. analysis of exchanges between technosphere and ecosphere), impact assessment and interpretation of assessment results.

Fusing the UM and the LCA methodology may seem as a further complication of the assessment of urban systems. The midpoint results presented in table 4 on the other hand reveals that by combining the two methodologies, midpoint impact indicators facilitate comparison of assessment results across the cities. Since one of the major deficiencies of the MFA based UM approach is the problems relating to the comparison of various forms of mass flows (e.g. comparison of steel and concrete flows). At the same time we find that the midpoint impact indicators presented in table 4, are generally easier to communicate than emergy based UM results since it is possible for people, with some guidance to relate to the individual impact categories. Hence fusing UM and LCA facilitates inter-city and inter-study comparisons of results and further enhances the communication of the assessment results compared to emergy based UM results.

Applying the fused UM-LCA approach ensures a holistic approach, by taking into account the up- and downstream exchanges between the urban system and the ecosphere, and hence facilitates the coverage of the complete system. This approach decreases the likelihood of burden shifting by shifting, whereby environmental burdens from direct to embedded flows (i.e. moving environmental burdensome processes up- or downstream as illustrated in fig. 2, by e.g. moving concrete production upstream and hence out of the urban system). As presented in fig. 3 are the majority of ecosphere-technosphere exchanges related to cities metabolisms located up or downstream of the urban system and hence outside the scope the conventional UM framework.

The process nature of the LCA part of the fused approach facilitates, as presented in fig. 4, easy in-depth analysis of the assessment results and streamlined identification of the activities contributing most to the pallet of impact categories included in any given study applying a LCIA methodology. As presented in fig. 4 can the varying importance of problematic processes such as e.g. energy provision be tracked across the impact profiles of the cities.

Accounting for the environmental burdens of large complex socio-technical systems such as nations, cities or large companies may in some instances require discounting/cut-off of impacts being passed on up- or downstream to the final consumers who may reside in geographically disparate regions. The problem relating to the standardization of accounting for “trading of environmental burdens” has, primarily based on the carbon accounting trends, is not new and has been dealt with in LCA, most recently by the European Commission [40]. Hence standardized approaches for allocating environmental burden trading are already implementable in LCA context and hence these standard approaches could easily be applied to the fused UM-LCA approach, thereby providing guidance with how to deal with this difficulty.

In the present study it was chosen to assess the cities applying mid-point indicators. Comparing cities across the 17 impact indicators is as is evident from table 4 a complex task. Absolute ranking of cities based on the 17 impact categories included in present study is impossible, without weighing the individual impact categories. The ReCiPe methodology includes, as presented in fig. 2, two additional impact assessment steps, endpoint assessment (i.e. quantifying the damage caused by the exchanges between the technosphere and ecosphere) and single score assessment (i.e. aggregating the mid-point impacts via the end-points to single scores), see fig. 1 and [34]. Despite the fact that single scores are related to some subjective interpretation of impact category prioritisation (and related uncertainty), it does allow for comparative ranking of cities in terms of environmental sustainability.

On the other hand, single-score based assessments allow for comparison of the impact assessment result with absolute sustainability measures such as the planetary boundaries presented by [2]. Comparison of the UM-LCA results of the cities with absolute sustainability indicators provides an initial quantification of the sustainability of the case cities relative to environmental tipping points, and hence, the limits of the environmental loads that these urban areas can place on the ecosystem before they become incommensurate with the populations or economic activity they support. However, as presented in table 5, it remains to be seen whether the allocation of absolute sustainability measures allow for various more or less true/objective depictions of the environmental sustainability performance of urban systems. Judging from the egalitarian perspective, the data in table 5 indicates that, for the case cites, avoiding crossing the planetary boundary is related with considerable effort (77-87 % reduction of GHG emissions) however also that this goal in term of CO₂ emission reduction seems plausible for all cities. Moreover, the need for some cities (Beijing, Cape Town and Toronto) to reduce GHG emissions based on the Individualist approach, shows that their economies are sub-optimized for environmental performance.

5. Conclusions and comments

The UM methodology has a number of research needs that until now have been largely discussed but not addressed; a narrow scope not addressing up- and downstream impacts of a cities metabolism and inter-city and inter-study incomparability of different mass and energy flows. Combining UM and LCA seems to attenuate these weaknesses by introducing a holistic scope and ensuring inter-city and inter-study via standardized sets of impact indicators.

The fused UM-LCA approach further allows for comparison with planetary boundaries and evaluation of cities performance relative to the earth carrying capacity in terms of environmental deterioration/pollution.

Present study had to be based on more or less fragmented data sets and the fused UM-LCA approach hence needs further validation.

6. References

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