# Chapter 28
# LCA of Buildings and the Built Environment

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**Abstract** How we design human settlements has a profound influence on society's environmental pressures. This chapter explores the current state of LCA applied to two scales of human settlements; individual buildings and the built environment, where the built environment is understood as a collection of autonomous buildings along with the infrastructure and human activity between those buildings. The application of LCA to buildings has seen growing interest in recent years, partly as a result of the increased application of environmental certification to buildings. General findings are that the use stage of the building tends to dominate environmental impacts, though as buildings become increasingly energy efficient, life cycle impacts shift towards other stages. LCA of built environments has been a useful supplement to mass-based urban environmental assessments, highlighting the importance of embodied environmental impacts in imported goods and showing interesting trade-offs between dense urban living and the greater purchasing power of wealthy urbanites. LCAs of human settlements also face difficult challenges; the long use stage (often decades) introduces high uncertainty regarding the end-of-life stage; evolving electrical mixes throughout the use stage; gaps in consumption data at the city level. This chapter endeavours to elucidate the strengths, research needs and methodological shortcomings of LCA as applied to buildings and the built environment, showing that they can act as complimentary tools to help society's shift towards a sustainable future.

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## 28.1 Introduction

Settlements are comprised of buildings along with the spaces and infrastructure between them, the design of which strongly influences the environmental performance of the overall system. A settlement is no mere assemblage of buildings, but an interplay of buildings, infrastructure, space, environment and institutions that help shape the behaviour of residents and visitors alike, and by proxy, their consumptive regimes and environmental impacts. In understanding the environmental pressures of how we construct the places we inhabit, research has focused on two units of analysis: the individual *building* and the *built environment* (assessments at the nation-state and planetary level notwithstanding). The building is an independent structure that provides shelter from the elements to facilitate one or multiple human activities (living, manufacturing, trading, etc.) The built environment is an umbrella term for the buildings, infrastructure and the human activity between buildings (e.g. mobility, leisure, etc.), ranging from the rural to the urban, the latter of which will be the focus of discussion in this chapter since cities now house more than half of humanity and a much larger share of economic activity (Kennedy et al. 2015). Figure 28.1 illustrates the difference between the two systems.

In terms of the scale of this resource use and environmental degradation, the contributions of buildings and the built environment to global totals are significant. According to UNEP's Sustainable Buildings and Climate Initiative, buildings account for 40% of global energy use, 38% of global greenhouse gas emissions and 40% of the solid waste streams in developed countries (UNEP 2012). When moving up to the city, the impacts are larger: an estimated 70% of greenhouse gas emissions and over 66% of global electricity use eminate from urban activites (Fragkias et al. 2013). Cities are also the drivers of global material consumption, typically in a linear fashion, that pulls resources from their hinterlands and beyond for use within the city and then disposal outside the city, disrupting bio-geochemcial ecological cycles. Nutrient use is a salient example of this, whereby the nutrients incorporated in food are exhaust to local waterways through human waste, which has become the single largest source of nutrient emissions to surface waters globally since the 1940s (Morée et al. 2013).

### *28.1.1 Buildings and the Built Environment: Crucial Differences*

Of concern is that the environmental impacts from buildings and the built environment show little sign of abating: gross global energy and material consumption continue to grow for both the building sector and cities in lockstep with urbanisation and economic development. LCA has a role to play in informing future designs of buildings and urban environments during the transition towards a sustainable future, helping ensure that the benefits of economic growth do not

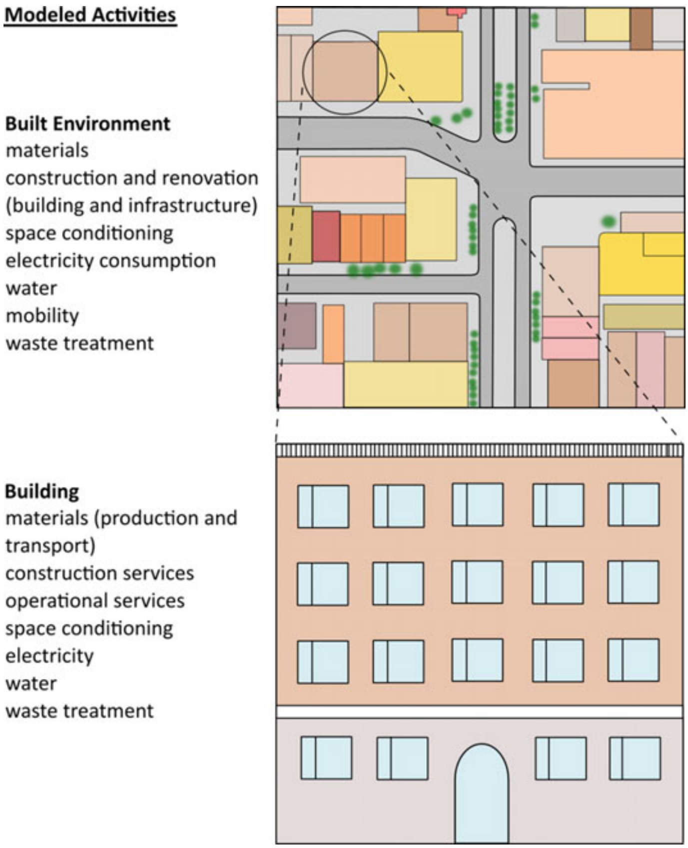


**Fig. 28.1** Juxtaposition of the built environment (*top*) and a single building (*bottom*) incorporated within the dense urban fabric

undermine global ecosystems functioning. LCAs of buildings and the built environment are not identical in methodology and have distinct framings of the systems they assess:

1. Scale: Building LCAs focus on a single building or building type and attempt to model this to a *high* degree of accuracy. Built environment LCAs model an agglomeration of buildings (neighbourhood, city, conurbation) and attempt to model this to a *reasonable* degree of accuracy.
2. Temporal Scope: Building LCAs focus on the entire lifetime of a building, typically decadal. LCAs of the built environment take a snapshot of the material, energy demands and waste generation of the study system over a short period, typically a calendar year.
3. LCI Method and Data: Building LCA strives for accuracy and concerns itself with minutia (exact masses and lifetimes of building components, precise construction techniques, etc.) preferably with buildings specific data.

**Table 28.1** Rough outline of the differences between the application of LCA to buildings and the built environment

| Assessment type | Scale assessed | Temporal scope | LCI components | LCI data |
|---|---|---|---|---|
| Building | Single building or building type | Building service life (decades) | Materials, energy consumption patterns, water usage, construction methods, disposal technologies | Site tailored |
| Built environment | Neighbourhood, city, conurbation | Single year | Major categories of consumption: construction aggregates, metals, plastics, food, wood, fuels (transport and heating), water, electricity, waste generation (solid, liquid and gas) | Expenditure surveys, census data, waste statistics, industry reports |

Built environment LCAs are more interested in capturing general trends in a city's environmental loading (construction aggregates, metals, transport fuels, etc.) based off of coarser data sets (waste statistics, household consumption surveys, census data, etc.)

4. LCA Method: Building LCA is predominantly done using process-based LCA. Input–output LCA is equally as popular as process-based LCA in assessing built environments.

Table 28.1 provides a general overview of these methodological disparities.

### *28.1.2 Complimentary Methods to Inform the Design of Human Settlements*

The differences between the two applications of LCA do not stop at methods but also their strengths. A simple example illustrates this clearly. Imagine a new neighbourhood comprised of extremely energy efficient homes built at a great distance from areas of recreation, work and shopping, and that this neighborhood lacks viable public transit options, necessitating personal vehicle use for most errands. Now imagine a dense city with reliable transit and nearby amenities that negate the need for significant automobile use, but that the building stock is comprised predominantly of old and energy-inefficient buildings in a continental clime (hot summers, cold winters). Which system would you guess is sustainable? An LCA of the buildings in both situations would identify the first situation as superior. But, if we scaled our assessment up to the built environment (both neighbourhoods), we would find that neither is preferable since both hypotheticals rely on large energy imports to the system that are very likely fossil fuel based (transport for the first, the latter for space conditioning).

This does not mean that the neighbourhood scale LCA is superior, since such an LCA would only be able to identify the major drivers of the impacts (transport and building energy), but is far too coarse to propose specific design interventions to rectify these sub-optimisations. Informing the design of sustainable human settlements requires a multifaceted LCA approach, leveraging both the detail-oriented building perspective and the broader built environment viewpoint. The goal of the chapter is to show how LCA can be applied to these complementary scales of the human settlement in order to help aid in the societal shift towards a sustainable future. Both *buildings* and the *built environment* will be discussed in sequence to convey the methodological considerations when performing LCA on these systems, summarise major findings in the use of LCA on buildings and built environments, and finally impart the reader with the skills to differentiate between more and less rigorous applications of LCA to these systems.

## 28.2 LCA of Buildings

Since the oil crises in the 1970s, a major concern within building design and operation has been to limit the need for operational energy and hence the need for oil-based heating and electricity. Increasing regulatory requirements on the energy performance of buildings has taken the building design to ever more complex levels where additional materials and technologies are used in order to reduce the energy consumed in operating the building and in servicing the needs of the users. This development of buildings towards increasingly complicated products coupled with the attribute of relatively long product service lives makes LCA an obvious part of the environmental evaluation of buildings.

LCAs within the application area of buildings are mainly used to compare different choices of shape, design or material at a single building level. Either the comparison is made with the potential impacts of alternative design solutions or the results are evaluated against a benchmark performance of the specific type of building and use. A more holistic LCA methodology applied to buildings has received increasing interest over the past decade, also following an increasing focus on life cycle thinking, development of building sustainability certification systems (e.g. BREEAM, DGNB) and the parallel development of standards and LCA methodology in general. For instance, the ISO/TC 59 SC 17 and the European CEN/TC 350 standards series on sustainability assessment of buildings and constructions provide harmonised approaches for structuring and evaluating environmental impacts of a building's life cycle.

Even though harmonised approaches to structuring and calculating building LCAs exist, horizontal comparison of the environmental impacts of one building with those of another building is difficult. This is due to the uniqueness of the service provided by each assessed building, reflecting a vast range of specific requirements including:

- Building type (e.g. office, multifamily residential)
- Site and location specific requirements (e.g. relation to surrounding built environment)
- Technical requirements (e.g. thermal transmittance of building envelope)
- User/owner specific requirements (e.g. low maintenance, adaptability of design, aesthetics).

Although most building LCAs are performed in the later stages of the design or even as the building is finished, there is a general agreement within the sector of the need for developing measures to include LCA-based decisions in the earlier stages of the building design. As opposed to the as-build accounting of impacts, intervention in the early design stage can change the actual physical design of the building in order to improve the environmental efficiency of the building. However, regardless of the temporal focal point for assessing the environmental sustainability of buildings, a range of subjects related to system boundaries and study set-up are still not harmonised in the building LCA practice. This is further explained in the following sections.

### *28.2.1 The Building Life Cycle Stages*

The life cycle stages of buildings are generally divided into three main stages of pre-use, use and after-use. Within these three main stages, additional substages as illustrated in Table 28.2 are often specified depending on the study.

**Table 28.2** Main life cycle stages and substages of these seen in building LCA studies

| Main life cycle stages | Substages seen in building LCA studies |
|---|---|
| Pre-use | Extraction of raw materials<br>Transport to manufacturing<br>Manufacturing<br>Transport to retailer<br>Transport to building site<br>Construction site activities<br>Construction worker's transport |
| Use | Use (e.g. emissions from installed materials)<br>Maintenance<br>Repair<br>Replacement<br>Refurbishment<br>Energy demand for building operation<br>Use specific energy demand<br>Water consumption |
| After-use | Demolition<br>Waste processing<br>Disposal<br>Next product system/recycling potential |

The use stage of the building spans the expected service life of the building, i.e. the assumed number of years in operation. In practice, but often without further justifications, 50–80 years is habitually used as reference study period in assessments, even though the physical structure of an average building has the potential to last longer. Still, 50–80 years is a substantial amount of time in which annual impacts from energy and material consumption are added to the total results of a building's LCA. Thus, the use stage has traditionally contributed considerably to the calculated life cycle impacts, for instance, by 95% primary energy consumption in a 2003 study of a Michigan university campus with a service life of 75 years (Scheuer et al. 2003). Correspondingly, in a 1996 study of a generic office building with a service life of 50 years, the use stage contributed with 80 and 90% of the life cycle energy in the locations Vancouver and Toronto, respectively (Cole and Kernan 1996).

However, the continuous effort in reducing the operating energy in buildings has led to a change in the role of life cycle stages, subsystems and materials in LCAs of recent low-energy buildings, where embodied impacts then are gaining importance (Ramesh et al. 2010). An important consideration in the analyses of use stage impacts from energy consumption versus embodied impacts from building materials lies in the system boundaries set for each study. Specifically, whether the user-related electric requirement—the plug load—(for cooking, cleaning, entertainment etc.) is included or excluded. This share of electricity consumption may cause impacts of the same magnitude as the impacts from a low-energy building's operational energy consumption (heating, ventilation, etc.) and can thus be a prominent contributor to the overall potential impacts from a building.

### *28.2.2 System Boundaries of the Building Life Cycle*

The system boundaries of a building life cycle are important to the assessment at two distinct levels:

- The primary level is the boundary of the life cycle stages and substages included or excluded from the assessment, for instance; is the maintenance of the building components included?
- The secondary level is the boundary of the life cycle inventories included or excluded within each assessed life cycle stage, for instance; is the detergent for the window cleaning included in the maintenance stage or is it only the biennial layer of paint?

Although the boundaries at both levels should be established in accordance with the goal and scope of the assessment, simplifications without further explications can be seen in many case studies.

#### 28.2.2.1 Next Product System: An Additional Life Cycle Stage?

The influence on results of an additional life cycle stage within the scope can be seen in a study by Thormark (2002), where an—at this point—additional life cycle stage, the recycling potential, is evaluated in the context of low-energy row-houses with assumed service lives of 50 years. The recycling potential expresses how much of the embodied energy and natural resources used in a building or a building element could, through reuse or recycling, be made usable in the next product system after demolition of the building in which the materials were originally installed. What can be made usable in the next product system is then deducted from the impacts of the building system under scope. Results showed that 37–42% of the embodied energy could be recovered through recycling and that the recycling potential was about 15% of the total energy use during an assumed lifetime of 50 years (Thormark 2002).

Calculating the recycling potential is but one approach of several to deal with recyclable materials in the building system. Other approaches referred to in building LCA studies include the ‘second allocation method’, whereby the recycling of materials benefits the building profile only by a reduction in waste generation (Scheuer et al. 2003) or the ‘cut-off approach’ (see Frischknecht 2010) whereby the product system is cut off at the point in time where the recyclable items cease to be waste, i.e. when it regains a market value. Thus, the life cycle stages at the building after-life, the waste processing and the recycling of materials, are potentially influential to the LCA results obtained, although to a very varying degree depending on the allocation approaches used in the specific study (see more about allocation in Chap. 8).

#### 28.2.2.2 Simplifications of Life Cycle Stages and LCI Input

A Swiss study by Kellenberger and Althaus (2009) explored the potential impacts of different building components and at different levels of simplifications often seen in building LCAs, both regarding life cycle stages and the inventoried materials used for the construction. Results showed that for all studied components the additional materials play an important role with up to 30% of the total impacts from a component. For heavier materials, the transport process had quite a high impact (>10% of total impact from component), but the installation process for the components and the cutting waste could be neglected as they influenced results to a minor degree.

The above-mentioned study on simplifications furthermore confirms what is highlighted in several studies; that with the contemporary low-energy buildings there is no single element or life cycle stage certain to dominate the impact results of a building LCA. On the contrary, different life cycle stages and material scopes can prove important at different variations of building design and geographical preconditions. Specific goal and scope definitions of a study can justify simplifications of life cycle stages and inventory, but it is important to be aware of potentially misleading results if simplifications are conducted without further reasons in a building LCA study.

#### 28.2.2.3 Scenario Evaluation

The very long service life of buildings sets the studies apart from many other LCA applications. Because the use stage of the building is so long, the life cycle impacts from the use stage and the after-use stage are very much depending on the defined scenarios, e.g. for maintenance frequencies or the annual heating demand in the building. However, applying scenario testing as part of sensitivity analyses of studies is not that common within the field; the exception being scenarios for the technologies behind the energy provided for the use stage. In this regard, several studies can be found that evaluate the sensitivity of results to the geographical and technological scope of the electricity production. For instance, assessing a Norwegian building, the generated impact results will prove much different depending on whether the national mix (primarily hydro power), the Nordic mix (where nuclear- and coal-based CHP technologies influence to a larger degree) or the European mix (dominated by fossil fuel-based technologies) is used.

A few studies also evaluate the temporal scope of the energy production, i.e. how will the technologies change in the course of the building service life? This is relevant because the annual energy used is assumed constant for the building service life of 50–80 years, but the technologies providing this annual input of energy cannot be static as the energy system in fact does change. Depending on the purpose of the building LCA study, there is thus reason in evaluating the dynamics of the system.

#### 28.2.2.4 Impact Categories Assessed

An additional aspect of comprehensiveness lies within the scope of the impact categories assessed in the building LCAs (see more about impact assessment in Chap. 10). The prevailing focus on energy within the building sector is reflected in the early generation of environmental assessments of buildings, where the (primary) energy consumption is the single most used indicator (Khasree et al. 2009). The inherent connection between the materials used in the building construction and the capability of the installed materials to reduce the energy consumed, means that energy balances of buildings remains a prevalent topic of the sectoral LCAs. The exclusive focus on energy performance does not capture the full extent of resource uses and problematic emissions also generated by the building sector. Hence, a more complete set of indicators must be applied to ensure comprehensiveness of the assessment. Furthermore, as the energy consumed in the use stage of new building diminishes due to improved building envelopes, the embodied impacts of the buildings become apparent. Table 28.3 sums up a general picture of the assessed impacts categories found in building LCA studies.

**Table 28.3** Impact categories seen in building LCA studies

| Often included categories | Less frequently included categories | Rarely included categories |
|---|---|---|
| Primary energy demand<br>Global warming | Acidification<br>Eutrophication<br>Photochemical ozone creation<br>Ozone depletion<br>Resource depletions | Ionising radiation<br>Toxicity (human/ecosystem)<br>Land transformation<br>Land occupations |

A study by Heinonen et al. (2016) also points to this relevant issue of lack of comprehensiveness in assessed impact categories. However, on a European scale at least, explanations can be found on this current state of the art of assessed impacts, namely in the fact that within the framework of the European standards for Environmental Product Declarations (EPDs) of building materials (EN 15804), a predefined set of indicators is established. The set corresponds with the CML methodology plus additional resource use and waste generation categories. As building material EPDs form the basis of many building specific LCAs, this scope of impact categories from a material level is transferred to the building level. In this sense, the sectoral application and standards development affects the practice of conducted building LCAs, also at the scientific level.

### *28.2.3 Notable Studies*

Having outlined the general areas of application related and methodological attention points of the building scale LCA, this section and Table 28.4 briefly introduce a range of notable studies highlighting selected aspects of relevance in the practice and development of building LCA.

Methodological issues of building LCA highlighted in the studies in Table 28.4 concern the use of dynamic modelling of the important use stage of the building (see Collinge et al. 2013) as well as the previously mentioned significance of simplifications at system level, input level and indicator level. The two different modelling approaches of input–output-based LCA (see Chap. 14) and process-based LCA modelling seem in general to be applied at the different levels of national building sector scale and single building scale, respectively. Nässén et al. (2007) discusses difference in results from applying the two different approaches to the production stage of buildings.

Future application of building scale LCA may well continue its importance in the post-construction evaluation of certified buildings although the application to early stage design (see Basbagill et al. 2012) remains an important area of development in order to identify environmentally preferable design solutions before construction takes place. Furthermore, incorporation of the financial and social aspects of building construction alongside the environmental assessment (Ostermeyer et al. 2013) will have a profound relevance to the decision takers in the

**Table 28.4** Selected building LCA studies highlighting different aspects of methodological and application issues

| Study | Aspect | Highlights |
|---|---|---|
| Nässén et al. (2007) | IO-LCA of buildings versus process-based LCA | Energy use (GJ/$m^2$) of relevant sectoral processes such as transport, construction activities and service sectors may be grossly underestimated in process-based LCA of buildings |
| Kellenberger and Althaus (2009) | Relevance of simplifications in LCA building components | How typical simplifications of LCI and life cycle stages may have significant relevance to LCA results depending on component type |
| Blengini and Di Carlo (2010) | Significance of impacts from life cycle stages in a low-energy building | How embodied impacts from the pre-use and maintenance of the building supersedes the operating energy in majority of assessed mid-point impact categories in a current low-energy building |
| Basbagill et al. (2012) | Application of LCA to early building design | Introduces a method enabling designers to understand the relative global warming potential implications of building component decisions |
| Collinge et al. (2013) | Dynamic modelling | Use stage scenario testing by dynamic modelling of characterisation factors and electricity mixes |
| Ostermeyer et al. (2013) | LCA coupled with life cycle costing (LCC) and social LCA (SLCA) in a refurbishment project | The study introduces a Pareto-optimisation approach to refurbishment activities of residential buildings and highlights the need for further development of SLCA to be included as evaluation of the sustainability of building activities |
| Heinonen et al. (2016) | Simplifications of LCIA categories included in assessment | Based on a case study: how only eight of 17 mid-point categories of the ReCiPe methodology correlates to the GWP which is oftentimes used in studies as the single environmental indicator |

construction process. This may hold true especially for the vast body of western post-war buildings ripe for refurbishment actions, because these existing buildings are already deeply defined within a site-specific social and economic context that needs to be taken into account when a change in design and functionality is regarded.

## 28.3 LCA of Built Environment

The quest to understand the environmental impacts of cities was initially an inwardly focused effort to improve conditions for the working poor that had amassed in recently industrialised cities around the world in the nineteenth century. John Snow's study of an 1854 cholera outbreak in London linked the infectious disease to contaminated drinking water, providing partial impetuous for the study of water and waste flows in the city and the development of the city's modern sewage system and drinking water network (McLeod 2000). This type of urban self-assessment was championed by the reform-urbanism movement at the turn of the twentieth century, which fought the pernicious effects of poor air, water and waste management in cities, eventually formalising into the sanitisation standards and modern land-use planning enshrined in modern cities.

It was not until the 1960s that the attention shifted from a public health focus to an environmental focus. In addition to the question, 'how is the environment in the city affecting the inhabitants?', researchers began to ask, 'how is the city, as a whole, interfering with the functioning of the environment?' Widely acknowledged as the first researcher to explicitly address this question was Abel Wolman's study 'The metabolism of cities' (1965). Wolman's study estimated the fluxes of materials and energy consumed by and the air pollution from an 'average' US city of one million inhabitants. This 'urban metabolism', measured as the material, energy and waste treatment demands of a city, is exactly synonymous with the LCI components considered as part of an LCA of the built environment that were introduced in Sect. 28.1.1. This part of the chapter will show how quantifying the primarily mass-based urban metabolism can be used as starting point of a full LCA of the built environment, contrast this with methodologies of LCAs of the built environment and highlight some of the recent developments in this field.

### *28.3.1 From Urban Metabolism to LCA of the Built Environment*

Kennedy et al. (2007) suggest a definition of urban metabolism as: 'the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste'. Since Wolman's (1965) paper, the number of studies of various cities' urban metabolisms is in the dozens and could very well over 100 (Decker et al. 2000; Kennedy et al. 2007, 2010; Zhang 2013; Stewart et al. 2014). The majority of these studies have been undertaken in the past two decades and have been performed by researchers in the field of industrial ecology. Industrial ecology is itself a diverse research field of the environmental implications of socio-technical systems in general, and this wide scope is mirrored in different methodologies that have been employed to assess urban metabolism: ecological footprint, eMergy (energy memory), carbon footprint, material flow analysis (MFA), etc.

It is the MFA of urban metabolism that is most relevant to our discussion, since it yields results in terms of mass flows through the study area, which can be interpreted as an LCI of the built environment and readily fed into the LCA framework for environmental profiling. MFA of an urban metabolism is akin to a material balance of an urban system, with the exception that non-mass flows such as electricity are often included as well, with accounting almost invariably performed over the period of a year. Kennedy (2012) provided a formalised mathematical description of how MFA would ideally be applied to a built environment, accounting for fluxes of materials through the study area, material additions to stock and waste generation. Though no consensus exists regarding what types of flows need to be included in an MFA of a built environment to adequately characterise a city's environmental footprint, Table 28.5 outlines the material and energy flows to be accounted if one is to make a comprehensive assessment of the metabolic, as adopted from Kennedy and Hoornweg (2012). These material and energy flows seek parsimony between the need to be sensitive to current data limitations, whilst capturing important activities driving environmental impacts and resource consumption.

**Table 28.5** Comprehensive list of material and energy flows that a holistic LCA of a built environment would account for

| *Inflows* | *Outflows* |
|---|---|
| Biomass (t and J) | Waste emissions (t) |
| Food | Gases |
| Wood | Solid |
| Fossil fuel (t and J) | Wastewater |
| Transport | Heat (J) |
| Space conditioning/industrial | Substances (t) |
| Electricity (kWh) | Produced goods (t) |
| Natural energy (J) | |
| Water (t) | *Stocks* (*inflows that do not exit system within assessment period*) |
| Drinking (surface and groundwater) | Infrastructure/buildings (t) |
| Precipitation | Construction aggregates |
| Substances (t) | Metals |
| E.g. salts, degreasers, etc. | Wood |
| Produced goods (t) | Other materials |
| | Other (machinery, durable) (t) |
| *Production* (*inflows to technosphere generated within urban territory*) | Metals |
| Biomass (t and J) | Plastics |
| Minerals (t) | Other materials |
| Energy (J) | Substances (t) |

Typical units of measure are indicated in square brackets. Adopted from (Kennedy and Hoornweg 2012)

It is often the case that there is little information about the material flows in and out of a city, and it is thus rare to find a study that has this level of completeness in accounting a city's urban metabolism. It is far more likely for studies to cobble together disparate data sources to build an MFA inventory. This is typically done in two ways; bottom-up (or 'activity-based') using basic data on economic activity and demographics to estimate flows (e.g. number of housing construction starts in a year times the average amount of concrete in a house to estimate concrete demands of a city's construction sector) (Kennedy et al. 2007) or top-down using regional trade data to balance production, imports and exports to gauge a city's demand (Rosado et al. 2014). Moreover, many of the flows of key materials in terms of embodied environmental impacts and future resource scarcity (plastics, rare earth metals) are embedded within electronics and other consumer goods, for which data is scarce.

In assessing the sustainability of the built environment, MFA has proven to be invaluable in exposing the extent to which cities continue to rely on unsustainable, non-renewable resource regimes to fuel their daily metabolism and growth. MFA studies have also illuminated one of the most pernicious aspects of modern cities; their linear metabolism that uses the urban hinterland and beyond as a source for both essential imports and waste assimilation, whilst recycling only marginal amounts of total inputs (Kalmykova et al.'s 2012). Nonetheless, MFA is not without its shortcomings. Most salient is the limitation of using mass as a proxy for environmental impacts. An obvious example of this is the way that high 'biomass' flows in MFA studies are almost always considered sustainable, despite the fact that the food flows lumped into this biomass category are some of the largest drivers of land-use change, greenhouse gas emissions and threats to biodiversity at the global level. Next is that most MFA studies only estimate direct mass and energy demands of a city, eschewing the 'ecological rucksack' of indirect mass and embodied energy, which can account for more than 50% of a system's burdens (Goldstein et al. 2013), as shown in Fig. 28.2 which highlights the embodied mass and energy aspects of five different cities. Lastly, when MFAs consider pollutant loading in terms of GHGs, they tend to include scope 1 (direct combustion within city limits) and scope 2 (imported electricity) impacts, ignoring the significant impacts embodied within imported goods.

### *28.3.2 Linking MFA to LCA*

Coupling MFA with LCA is a natural solution to the methodological shortcomings of MFA focused studies in order to provide a more holistic assessment of the environmental performance of built environments. LCA of the built environment only requires a change of perception, whereby the MFA is viewed as the LCI for the *use stage* of a city's annual demands (see Chap. 9). In this line of thinking, the MFA morphs into a crucial part of the process. With the MFA viewed in this

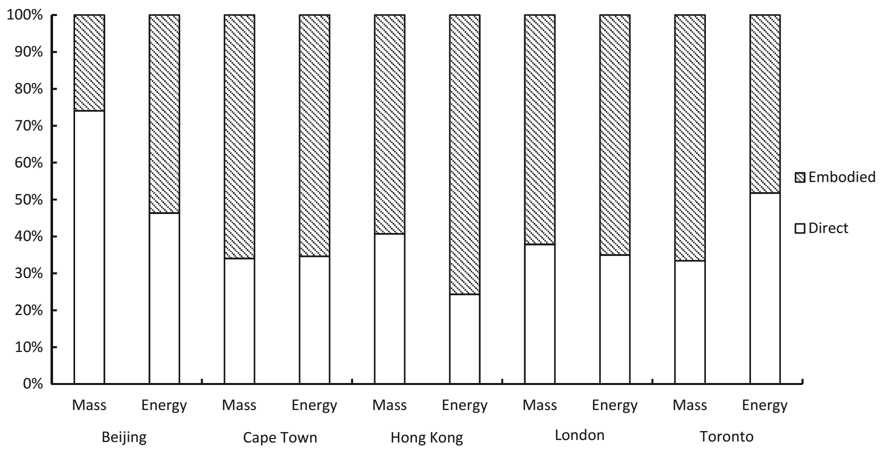


**Fig. 28.2** Relative importance of embodied mass and energy impacts in LCAs of five cities. The direct mass and energy represent what is traditionally captured in MFA studies. Note Beijing's lower embodied mass, a result of the frenetic construction activity in the city and the resulting concrete and aggregate flows. *Source* Goldstein et al. (2013)

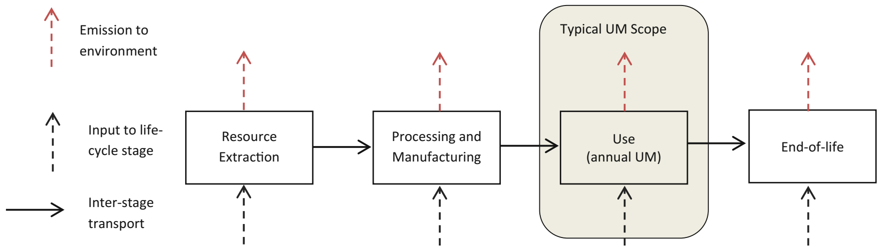


**Fig. 28.3** Fusing MFA with LCA: urban metabolism (UM) is taken as the use stage of the metabolic flows, with supporting upstream production and downstream waste management activities built around this. *Source* Goldstein et al. (2013)

complimentary manner, it is easy to imagine building the other life cycle stages up- and downstream of the use stage characterised by the MFA (LCI) of the built environment, which can then be modelled using traditional LCA methods. Impacts from consumption occurring within the city, such as fuel combustion or electricity, can also be modelled using the same principle; where the assessor's job is to identify the most representative processes and align them with the demands of the study region. Figure 28.3 illustrates this.

Due to the durability of many of the goods consumed by cities, it is challenging to accurately model the end-of-life phase of these goods. Rosado et al. (2014) developed a method to account for the lifetimes of goods imported into the Lisbon region, which could theoretically be employed in the framework described here, but the proposed method can obviate the uncertainties in future recycling rates and evolving waste treatment technologies. To sidestep this issue, one could ignore the disposal phase of the durable goods used in the built environment and only include the impacts from waste treatment performed in the study region over the assessment period, though this has the double issue of underestimating impacts due to waste treatment in the future, whilst simultaneously ignoring the fact that many goods with substantial embodied impacts may be recycled at end of life (structural steel, aluminium, glass and maybe someday, precious metals in electronics). There is no right or wrong method here, but transparency in communicating the method chosen and its shortcomings is paramount.

Another methodological consideration is that the level of detail of the MFA is normally very coarse. The LCI for the use stage typically consists of bulk categories of goods such as 'steel', 'aluminium' and 'wood', which the assessor then has to turn into a life cycle. This means that generic material production processes in an LCA database usually employed in modeling ignoring more detailed processes related to manufacturing of specific goods (forming, assembly, etc.). Moreover, transport is also difficult to come by, meaning that one is either left excluding it from the assessment, or using international trade data to make informed judgements about plausible sources of materials imported into a city. Considering the uncertainties regarding specific types of goods consumed and sources of those goods, it might be defensible to omit these from assessments of the built environment, since assembly and transport are often not the dominant sources of environmental impacts in the life cycles of many products

#### 28.3.2.1 The Functional Unit: What are We Actually Assessing?

One essential aspect of the LCA is the functional unit (see Chap. 8 on scope definition for more information about the functional unit). In an LCA of the built environment, what are we assessing exactly? Because built environments do not perform any one function, and many of the functions performed are impossible to quantify (foster community, facilitate cultural exchange, build institutional capacity), developing a functional unit moves from a methodological necessity to an esoteric philosophical exercise in semantics, and has been largely avoided in urban scale LCAs. Notwithstanding, since LCA is ostensibly to be used either for benchmarking or to decision-support between urban design alternatives, a common basis of assessment should be used to facilitate appraisals. This typically takes the form of taking gross impact potentials for the built environment and normalising these to the per-capita level, since this will at least show the environmental intensity of providing for the metabolic activities of the average denizen

### 28.3.3 Process-Based and Input–Output LCA of the Built Environment

Both process and input–output (IO) LCA have been applied to the built environment, with IO methods figuring most prominently in urban LCA literature. For a detailed description of IO-LCA, the reader can refer to Chap. 14 of this book.

Section 28.3.1 largely outlined what could be considered a process-based approach to assessing the built environment with LCA: determine the direct material demands of the study region and include the embodied impacts up- and downstream, as well as relevant impacts during the use stage. The reason that the process-based method has seen less application is that the general tenor amongst urban sustainability researchers has been that in order for LCAs of the built environments to be as complete as possible, an IO-LCA or hybrid-LCA approach should be employed (Chester et al. 2012). This rationale is absolutely justified; if data for final demand is available, inputting this into the IO-LCA framework yields a more complete inventory and accounting of environmental impacts. Moreover, if multiregion-IO methodology is used, then trade interdependencies between the study region and other economies can be ascertained. Another advantage of the IO-LCA method is that it provides a true demand-side analysis of a built environment, accounting for the environmental burdens of the study area's final demands. Process-based assessment has the shortcoming of not allocating fuels and electricity used in the production of goods manufactured in the study region but ultimately exported to the final consumer, meaning that some of the burdens for these exported goods are incorrectly ascribed to the producing city.

IO-LCA of the built environment faces numerous methodological challenges. Much like the process-based approach, data availability is a challenge, this time in terms of getting final consumption data (in terms of final expenditures) at the subnational level, which means that IO-LCAs of built environments are often built from scaled national-level data (consumer household expenditure surveys have been used in a US context to scale down to the sub-urban level). Moreover, the IO tables are also at the national level, ignoring the regional industry interdependencies, though advances in multi-scale IO models may be able to overcome this (Bachmann et al. 2014). Though comprehensive in terms of value-chain coverage, the number of substances ($\sim 100$) covered by IO-LCA are meagre in comparison to the process approach (over 1000), meaning that until now IO-LCA on the built environment has primarily focused on accounting GHGs (arguably meaning that these were not full multi-criteria LCAs as per ISO standards). Moreover, the IO-LCA method is not compatible with existing LCIA methods, missing out on the indicator sets and communicative power of these tools. IO-LCA is caught in a permanent present tense, whereby it models the impacts of present final-demands, ignoring life cycle stages beyond production and use.

The story is that process-based and IO-LCAs of the built environment are not incompatible, but have different strengths that the assessor should leverage depending on available data and study aims. Process-based LCA is best applied when the benefits of the LCIA methodologies are wanted and/or detail beyond the level of the economic sector is wanted. IO is optimised for inventory completeness.

### *28.3.4 Opportunities and Challenges*

The application of LCA to the built environment is new and evolving, but there are already a number of exciting envisioned uses for this tool. Most obvious is the use of LCA as an environmental screening tool to identify weak-points in the environmental performance of a neighbourhood, city or conurbation, and as a benchmarking method to assess longitudinal environmental performance related to policy changes or growth in a study area. LCAs of the built environment have been able to identify important characteristics of relating the environmental impacts of a study region to the urban form, economic development, population dynamics and local climate. Table 28.6 shows the effects of various urban attributes on the environmental performance of the built environments, pinpointing where policy interventions might be best applied.

LCA of the built environment can also be used for scenario analysis, testing out the environmental efficacy of urban design interventions (i.e. how would the environmental performance of a city change if large-scale food production were employed or if a certain type of built form was pursued?) or policies (how would GHG emissions change with implementation of a congestion charge?).

LCA of the built environment also provides exciting opportunities to explore other aspects of their environmental performance. *Nexus interactions* are one such area, whereby single metabolic activities that drive environmental impacts on multiple fronts, and therefore, that driver acts at the *nexus* of the drivers. Increase in private motor vehicle usage is one such metabolic driver that sits at the nexus of

**Table 28.6** Findings of LCA applied to the built environment

| Study region attribute | Typical effect on urban environmental performance |
|---|---|
| Low population density | Impact potentials from mobility take on increased importance (Heinonen et al. 2011) |
| Climate variability (hot summers, cold winters) | Impacts from space conditioning take on increased importance (Goldstein et al. 2013) |
| High population growth rate or economic development | Impacts from capital formation (building and infrastructure construction) take on increased importance (Goldstein et al. 2013) |
| Low population growth rate | Impacts from household consumption takes on increased importance (Goldstein et al. 2013) |
| High disposable income | Impacts from household consumption takes on increased importance (Heinonen et al. 2011) |
| Compromised waste management system | Local impacts take on increased relevance (Goldstein et al. 2013) |

non-renewable resource use (fossil fuels and metals), GHG emissions (combustion) and the embodied impacts of construction aggregate use (new road construction). LCA can play a role in quantifying the collinearity of these impacts through urban design. Another interesting prospective use of LCA at the scale of the built environment is to quantify *boundary effects* at the border of a city or region, such as impacts from waste expelled into neighbouring geographic regions and fluxes across the system boundary (e.g. through traffic). LCA could predict the severity of environmental disruption from these types of boundary effects and highlight both the benefits and burdens of adjacent human settlements.

Challenges also abound in the application of LCA to the built environment. Data shortcomings cannot be overstressed. Often environmental assessments at the scale of the built environment rely on data from other sources that are used as a proxy for material and energy demands at the neighbourhood, city or regional level. The use of 'big data' to develop more representative consumption profiles could increase the robustness of LCAs of the built environment, and provide finer scaled assessments in terms, both spatially and demographically. Another area of improvement would be the current 'black box' nature of LCA-based assessments, which ignores the way that interactions between subsystems within the built environment generate the study system's emergent metabolism. The 'black-box' perspective results in static models unable to capture non-linear behavior, reducing their predictive power. Combining the environmental auditing power of LCA with other dynamic modelling tools such as system dynamics (Tam et al. 2014) in the urban realm would enhance the applicability of LCA in the urban realm and justify its place at the table when considering urban design or policy interventions.

An emerging approach to the LCA of the built environment is 'territorial LCA'; the application of LCA framework to mixed rural–urban systems (Loiseau et al. 2014). The method is closely aligned with those of this chapter with the noteworthy divergence that the territorial LCA method focuses on land uses and programmes as a method for describing functional units, providing a new perspective to overcome the ambiguity or lack of functional unit in previous LCAs of the built environment. Loiseau et al. have already applied this method to regions along the coastline of Southern France (2013, 2014), highlighting the method's potential applicability.

### *28.3.5 Notable Studies*

We will close the dedicated discussion of LCAs of the built environment with a concise list of studies that exemplify the methods we have discussed, explored ways to overcome current methodological challenges or pushed LCA of the built environment into new exciting directions. The list is not restricted strictly to LCAs, including MFA and carbon footprint studies as well since these can be readily incorporated within the LCA framework. Table 28.7 provides an overview of selected studies. In general, LCAs and MFAs of cities have shown strong links between urbanisation and increasing per-capita material flows (Kennedy et al.

2007), and as mentioned above, assessments of the built environment have related the metabolic profiles of cities to levels of economic development, city morphology, local climate and population dynamics (Goldstein et al. 2013).

In terms of important methodological developments, Lenzen and Peters (2010) showed how multiregional IO-LCA can be applied at the scale of the urban household. Using a simpler, single region IO-LCA of Helsinki, Finland, Heinonen et al. (2011) demonstrated that dense living may reduce transport emission within the city, but increase consumption in other areas by affluent residents erased these benefits, highlighting the tension between urban morphology and wealth.

Goldstein et al.'s (2013) assessment of five cities was the first to apply a process-based approach and use the full suite of indicators available to LCA practitioners. Figure 28.4 shows how local environmental improvement with economic development (particulate matter formation) can be juxtaposed with increasing environmental pressure in private consumption (agricultural land

**Table 28.7** Details of notable studies of urban environmental performance

| Study | Method | Highlights |
|---|---|---|
| Lenzen and Peters (2010) | Multiregion IO-LCA | Applied a multiregion IO of GHGs to Sydney, Australia |
| Hillman and Ramaswami (2010) | Process-based LCA of GHGs of 8 US cities | Identified 6 key cross urban boundary activities that can be used for expedited, yet complete, GHG accounting of cities and explore boundary effects (i.e. air travel) |
| Heinonen et al. (2011) | IO-LCA of GHGs of Helsinki, Finland neighbourhoods | Dense urban living reduces per capita transport emissions, but increased wealth of inhabitants ultimately results in higher overall consumption and carbon footprint |
| Chen and Chen (2012) | GHG accounting of Vienna, Austria | Combined network analysis with GHG accounting to show interconnections between urban subsystems |
| Goldstein et al. (2013) | Process-based LCA of five cities using multiple indicators | Application of hitherto unexplored indicators at the urban level (eutrophication, ecotoxicity), linking economic development and local environmental performance |
| Tam et al. (2014) | System dynamics MFA model of Shenzhen, China construction sector | System dynamics approach to predict future C&D waste (legal and illegal) generation for different policy scenarios |
| Rosado et al. (2014) | MFA of Lisbon, Portugal | Comprehensive trade statistics used to account for over 10,000 goods used in the city and included embodied mass within goods |
| Kennedy et al. (2015) | MFA of global megacities | Identified links between urban morphology and electricity demands, and showed the super-linear scaling of urban metabolism and population |

formation). Highlighting the utility of MFA as a means of LCI development, Rosado et al.'s (2014) study of Lisbon, captured over 10,000 goods entering and exiting the urban system using trade statistic, while concurrently accounting for indirect mass flows embodied within those goods.

Hillman and Ramaswami's (2010) GHG accounting of eight US cities laid down a solid methodology to account for the majority of GHG impacts and showed and explored the boundary effects of transport across municipal borders. Chen and Chen's (2012) paper illustrated how network analysis can be used to open up the urban 'black box', elucidating how material and energy fluxes between urban subsystems influence GHG emissions in Vienna. Tam et al. (2014) combined MFA with system dynamics to assess policy scenarios on C&D waste in Shenzhen, illustrating that focusing on a single aspect of a city's metabolism can yield detailed and relevant results. Lastly, Kennedy et al.'s (2015) MFA of the worlds megacities (population > $10^7$) showed how environmental impacts scale super linearly with urbanisation, serving as a prescient reminder of the need to improve the environmental performance of the built environment as urbanization continues globally.

## 28.4 Methodological Challenges and Best Practice

Having outlined the application of LCA to buildings and the built environment, it is prudent to end with a discussion of current methodological challenges related to this type of assessment. Data, LCI components, LCA method and other noteworthy methodological aspects are discussed in sequence, and are summarised in Table 28.8.

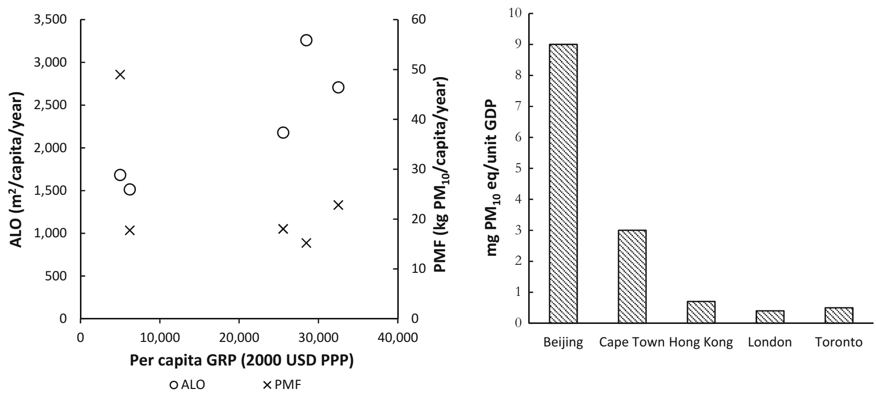


**Fig. 28.4** Per-capita agricultural land occupation (ALO) as $m^2$ $year^{-1}$ and PMF as kg particulates <10 μm $year^{-1}$ are shown on the *left*. Local air pollution issues in Beijing and Cape Town are disproportionately high relative to the amount of economic activity, particularly when the predicted impact per unit of economic activity is taken into account as shown on the *right*. Wealthier cities show a tendency to minimise air pollution while the exported environmental pressure of ALO increases with the wealth of the residents. *Source* Goldstein et al. (2013)

### 28.4.1 General Challenges

Sensitivity testing of the scenarios applied in building LCAs remains an important issue in order to evaluate the potential impacts of a building. It is especially important due to the long service life of the building for a great deal of societal and technological changes can happen within the time frame of 50–80 years. Thus, the scenarios for the use stage and the end-of-life stage should preferably be tested to ensure some sort of likelihood of the obtained results. Such a particularly long time frame also comes with a difficulty of correctly interpreting the impact scores obtained. Due to the aggregation of emissions and their characterisation with time-integrated characterisation factors, emissions and resource extractions occurring at different moments in time during 50–80 years or more are represented as if they would take place simultaneously, and affecting the same (human) generation. For most product LCA applications, which will typically have time frames in the range of 10–30 years, this is not of particular importance, but needs to be considered in this context. An additional challenge to the practice of building LCAs is for the practitioners to harmonise, if not the inclusion then at least the description of the life cycle stages accounted for. For now, it often presents a challenge to compare results of different studies because of the opacity in the explanations of included life cycle stages and processes.

Other methodological notes for LCA of the built environment include the static nature of the assessment and the black box perspective on the study system. Integration of LCA within the system dynamics framework or network analysis should be able to help overcome this, though work in this direction remains cursory. Lastly, built environments are socio-technical systems, and it should always be kept in mind that the predominantly environmental assessment provided by LCA, though linked to the system's economic and social attributes, should always be balanced against the more detailed work of social scientists, economists and political scientists who look at equity, living conditions, crime, institutions, employment, artistic and cultural practices, psycho-geography, public health and a myriad of other important aspects of life in human settlements. This last sentiment is probably truer for LCA of the built environment than any other application of LCA.

### 28.4.2 Goal and Scope

Like any LCA, looking at buildings and the built environment with this tool requires a decision between process and IO-LCA. Both process and IO have their strengths; detail and completeness, respectively. Neither is preferred, though the process-based approach does have the advantage of better compatibility with the various LCIA methodologies and related indicator suites. Relatedly, as a rule, LCAs of the built environment should use multi-indicator assessments to minimise the risk of burden shifting between environmental issues, a practice that is difficult for

**Table 28.8** Overview of the challenges of applying LCA to buildings and built environments

| | Building | | Built environment | |
|---|---|---|---|---|
| | Shortcoming(s) | Best practice | Shortcoming(s) | Best practice |
| LCI data | Lack of transparency in EPDs of building materials | Applying generic data to assessments of early design and specific data for footprinting and accounting | Local data typically absent for many metabolic activities | Use local data or adjust proxy data to local conditions |
| LCI components | Simplifications are frequently performed in studies without estimations of the impacts they might be responsible of | Including all inputs relevant to the purpose of the study | Only selected metabolic activities covered<br>Coarsely aggregated fluxes<br>Embodied impacts in imported goods ignored | Major environmental drivers (construction, mobility, building energy, food) represented<br>Fluxes should also be as disaggregated as possible<br>Imported goods should be included to avoid underestimations |
| Goal and scope | Energy use and global warming potential often the only evaluated categories | Inclusion of a comprehensive set of impact categories to avoid burden shifting | Single indicator assessment<br>Defining functional unit | Multi-indicator toolsets should be used to avoid burden shifting<br>Transparency in functional unit definition |
| General challenges | Scenarios for use/EoL stage rarely evaluated as part of sensitivity testing<br>Lack of transparency and lack of consistency in life cycle stages included in assessments<br>Lack of transparency in EPDs of building materials | When relevant according to the purpose, testing of the energy, maintenance/replacements and EoL scenarios<br>Addressing all relevant life cycle stages in relation to the purpose. Applying estimates for the stages where there is a lack of data. Describing thoroughly the processes involved in the included life cycle stages<br>Applying generic data to assessments of early design and specific data for footprinting and accounting | Static and black box models<br>Social issues largely eschewed | Combine LCA with system dynamics and/or network analysis<br>Compliment assessment with work from social scientists, public health specialists and economists |

Current best practices are highlighted to give the reader a guideline for performing LCAs and appraise the work of others

IO-LCA practitioners due to database limitations. In the future, best practice in this application area might consist of hybrid-IO-LCA that marries the best features of process and IO-LCA, though this has yet to see application. Lastly, there have been a number of GHG studies on the built environment that have focused on scope 1 (direct) and scope 2 (imported electricity) emissions (see some of the background data for the carbon disclosure project; www.cdp.net). This practice ignores GHGs embodied in imported goods and should be avoided since it can vastly underestimate the true carbon footprint related to a built environment's metabolism.

## *28.4.3 Inventory and Product System Modelling*

### 28.4.3.1 Data

Data used on building LCAs is seen at different levels of specificity, generic data describing average production impacts and product specific data relating to products from specific manufacturers (see Chap. 9 for more general information on Inventory and Product System Modelling in LCA). Generic data on building materials is found in most general LCA databases, but are limited in the sense that they cover mainly industrial products; thus a range of, e.g. biomaterials and innovative materials cannot be found. A whole category of technical components is also underrepresented in current databases. The product specific data is widely promoted as generating the most correct results when assessing a specific building. However, as the product specific data is mainly marketed in the format of EPDs, there is often a lack of consistency and transparency across the different national EPD programmes and the product category rules they each use. This affects the system boundaries and allocation methods applied in the LCA calculations. For instance, different national EPD programmes will account differently the biogenic carbon storage possible in wood products. An ongoing effort in harmonising EPD programmes and assessment methods (e.g. the European Product Environmental Footprint—PEF) will increase the possibilities of using the EPDs for studies, although the format of the EPDs continues to be 'black box' oriented, meaning that only LCIA data and not LCI data is presented in order to protect property rights of the manufacturers.

At the built environment level, a succinct lack of consumptive data at the subregional scale is a recurring theme, since trade statistics of goods/materials, food balances and household consumption surveys are normally performed at the national or regional level. Waste statistics, though normally available at the local level, are notoriously coarse in terms of disaggregating constituent flows within waste streams. Activities, such as private automobile use are also normally procured through surveys that are at best generalisations of travel patterns. This does not mean that good data is not available at the level of the built environment, but many studies rely on data from larger regions as proxies for urban metabolic activities and use coarse local level data. Jones and Kammen (2014) have shown how publicly available consumer expenditure data can be used to map carbon footprints at the neighborhood level, while commercial geo-demographic data has also been employed to move more granular assessments (Minx et al. 2013). Moreover, with the proliferation of so-called 'big data', rich data sets of real urban metabolic activities should become available to researchers in the future. Ideally, high quality, locally contextual data should be used (see Rosado et al. 2014), and this data should be disaggregated enough to capture important goods within metabolic activities (e.g. 'biomass' should be broken down into food and non-food, with the former preferably disaggregated further to meat, fruits, etc.). Where national or regional data are used as proxies, these should be made locally contextual using economic data to account for the disparity in purchasing power between the area to be assessed by LCA and the region covered by the data (this holds for process and IO-LCAs).

#### 28.4.3.2 LCI Components

There is great disparity in the way building LCAs delimit the input flows of the system under scope; the main reason for this disparity probably being the different purposes of studies. If the purpose of the study is to assess the building within a specific certification framework, the completeness of the LCI may not be warranted as long as it aligns with the guidelines of the certification scheme. In this sense, it is important to keep in mind that certification-related assessment may not strive for the absolute accuracy of LCA results, rather it aims to place the building performance within a relative benchmark system developed for the certification scheme in question. For studies detached from these or similar relative performances, the basic LCA principle of comprehensiveness naturally applies (see more about inventory analysis in Chap. 9). Transparency and exact descriptions of the materials and components included are paramount in the reporting, because even materials seemingly irrelevant to the results, for instance the fittings and fixtures, can affect certain impact categories. Thus, as no harmonised approach exists in the reporting of the LCI components, it can be difficult to interpret whether fittings may be included in the respective elements where they are installed, e.g. a wall, or if the fittings are not included in the study at all.

LCI of the built environment is usually driven by data availability. There are numerous studies that have had to reduce their scope due to lack of quality data. Best practice would be to include all of the urban metabolic activities listed in Sect. 28.3.1, but this is an optimistic assertion. One aspect to be cautious about is to ensure that the LCA broadly covers the major environmental drivers; construction, building energy, mobility and household goods (and sometimes water) to a reasonable extent, unless the assessment is explicitly focused on a particular aspect of a city's environmental performance (nutrients, mobility, etc.). As mentioned above, biomass should always be disaggregated. To simply lump all biomass together as a renewable resource since it is produced by the planets annual solar budget ignores the reality that the consumption of some food items, namely, meat and dairy, are some of the largest drivers of global environmental pressure.

## 28.5 Conclusion

To perform an LCA of a human settlement is a complex exercise. What is a clear is that parsimony between the reductionist perspective of the autonomous building and the generality of the territory should be struck in order to address the multi-scalar sustainability challenges of the buildings and their agglomerations into the built environment. At the building scale, the environmental impacts during the use stage, as a rule, dominate, though environmental burdens shift to other life cycle stages with increased building operational efficiency. For the built environment, it is typically the mobility, space conditioning and nutritional needs of the residents that drive the majority of environmental impacts, with antagonism existing between lowering building energy use in new construction and increased transport energy from dispersed nature of these developments. Recent advances in LCA at the built environment have seen the application of IO-LCA, often at a multiregional level, and models that include dynamics of the subsystems that constitute a city. Next steps in the assessment of built environments will include harnessing novel data sources provided by ubiquitous computing ('internet of things') to ameliorate data gaps and provide real time monitoring and feedback of urban environmental performance, and the use of network science and systems thinking to shed light on the inner workings of the urban 'black box'. At building level, recent advances include the standardisation of LCA calculation procedures (Khasreen et al. 2009); although the harmonised studies following this have yet to be seen on a larger scale. Further development of building LCA may be found within the area of early design stage interventions as well as more holistic approaches to evaluating the life cycle of not only new constructions but also existing constructions in relation to the social and economic preconditions.

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