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Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs

Martin Erlandsson[a,*], Mathias Borg[b]

[a] *IVL Swedish Environmental Research Institute, Stockholm SE-100 31, Sweden*
[b] *Department of Building Sciences, KTH (Royal Institute of Technology), Stockholm 100 44, Sweden*

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Abstract

Environmental improvement in the building sector will be crucial for the societies ecological sustainability development. Life-cycle assessment (LCA) is one of the well-known tools used ad hoc for ecological sustainable development. In the implementation of a generic LCA methodology applicable on constructions, the most complex abstraction level for the functional output will focus on the building operation usefulness, which regards services rather than construction properties. Furthermore, constructions or parts of it can be regarded as a streamlined application of an LCA methodology operating on the more complex service building level. A number of significant characteristics valid for a generic LCA methodology for buildings have been put forward and then checked in accordance with "today's practice", represented by five different LCA concepts utilised for buildings. On this basis, current practice but also development needs have been identified on the following themes; service coverage, life-cycle definition, time dependence (coverage), life-cycle inventory and life-cycle impact assessment.

Keywords: LCA; Buildings and constructions; Sequential life-cycle thinking; Methodologies; Services; Functional unit

1. Introduction—the building sector and LCA

The building material industry, energy and water use of the households and the more-or-less permanent occupation of land are building, construction and operation services-related factors that constitute a dominant part of the total environmental impact caused by society. The building sector, including housing, constitutes 30–40% of the society's total energy demand [1] and approximately 44% of the total material use [2]. Consequently, the building sector has to be prioritised to be able to reach a sustainable society within a reasonable period of time. This is essential, especially when the long service life of constructions and the pace of research and development within the building sector is considered which make it time consuming to implement the necessary changes to improve the environmental performance of the building sector.

Life cycle assessment (LCA) is applicable on all system levels in the building sector. Two major approaches of LCA for construction applications can be lined out, a *bottom up approach* focusing on building material selection, etc. and a top *down approach* that consider the entire building as a starting point for further improvements. In the first case, if the operation phase shall be included, the environmental impact from the operation phase has to be estimated in relation to a generic context and then distributed down to the building material or the building component level [3]. Examples of applications of LCA in the building sector are single material producers working with environmentally sound product development [4], environmental declarations based on LCA, e.g. EPD [5] and ISO 14025 [6], and implemented in different environmental reporting and management systems, e.g. EMAS [7] and ISO 14000 [8]. LCA can also be implemented to cover an evaluation of an entire sector and has been utilised by the Swedish building sector [2,9] to describe the impacts and possible improvements in relation the Swedish environmental quality goals [10,11] (Fig. 1).

The use of LCA, in the way described above, identifies a need to describe different aspects of concern to be able to execute accurate assessments of the

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[*] Corresponding author. Fax: +46-8-598-563-90.
E-mail address: martin.erlandsson@ivl.se (M. Erlandsson).

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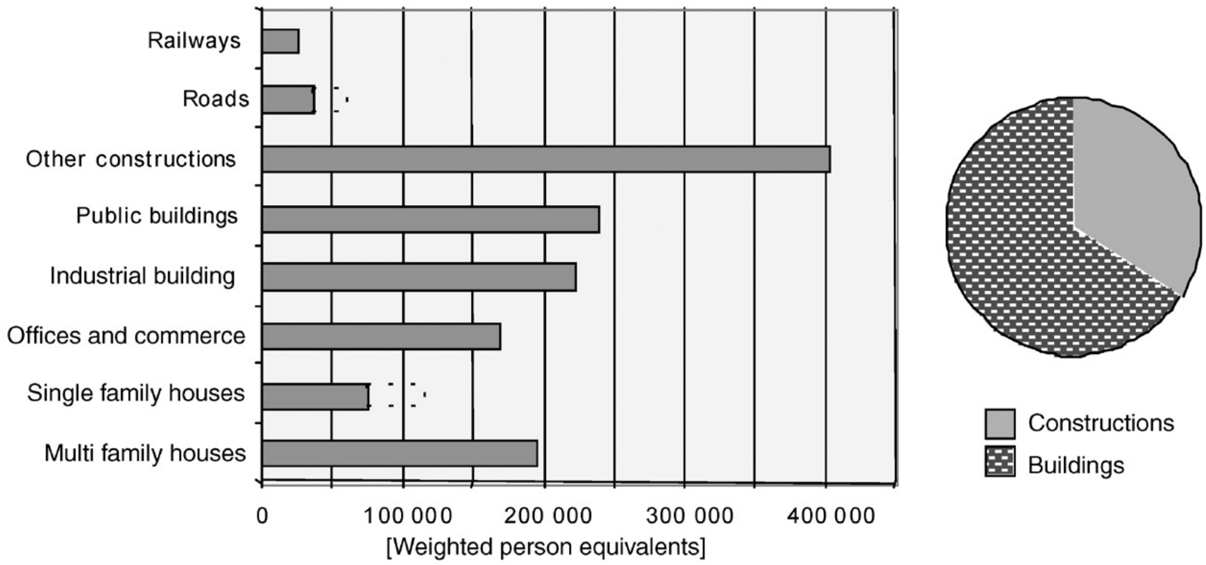


Fig. 1. Swedish yearly integrated environmental impact (1998 and 1999), divided into a number of building and constructions types. The pie illustrates the share from constructions versus buildings related activities, including raw material production, maintenance, transportation, etc. The dotted staples indicate precarious background information from many small privet property owners [11].

environmental impacts associated with the physical building, its utilisation and aspects related to adjacent external systems. LCA has, in this matter, been identified as a strong tool that has the opportunity to be a scientifically established method for generation of the necessary decision support. This kind of decision support is needed to be able to reach the goal of a sustainable society, which a resource efficient building sector with a improved environmental performance is a part of.

2. Scope

The scope of this article is, primarily, to describe specific and significant methodology problems with, and the development needs related to, a generally applicable LCA methodology for buildings and constructions. This generally applicable methodology for buildings and constructions should include both the physical constructions and the use of it, i.e. operation services. The scope is to elaborate different abstraction levels applicable on buildings and constructions, in order to define the highest level of complexity valid for a generic LCA methodology. In other words, assessment of more well-defined products like a physical construction or parts of it can be regarded as a streamlined application of an LCA methodology applicable on the superior service level. As recognised by the SETAC working group "LCA in Building and Construction" [12] a congruent line of argument can be presented to motivate why *buildings* should be preferred as staring point rather than *constructions* for which the utilisation often can be easier to define. This fact is also utilised in this paper, why the denotation building below also can be valid for constructions. Similar problems that can be identified for buildings can also be recognised for other products that constitute long-lived systems. The article will answer the following questions:

- What methodological application specific characteristics can be identified as important in order to establish a general and flexible LCA methodology applicable on buildings?
- What is the practice of today concerning LCA methodology for buildings in relation to the characteristics defined above?
- In order to improve current LCA practice; what development areas can be suggested based on the practice of today?

The problems specific to buildings and constructions are basically originating in the following characteristics:

- The functional output has to be regarded as a service rather than a product.
- The system behind the services (as well as the environment context associated with it) is dynamic.
- The provided service has a defined service life, while utilised building facilities, building products, etc. have their own life cycles and service lives.
- Actions taken in the building sector also affect other sectors, not only on the margin, which makes margin markets an area of special interest.
- In the ordinary design process, different aspects are put forward as performance requirements. This application of LCA emphasises the need to improve the utilisation in practice to be able to assess functions.

A number of LCA tools with a clearly described methodology and that currently are in use, have been identified in order to evaluate the practice of today regarding generic LCA methodology for buildings. For this purpose, a second valid selection criterion is that they should be known from scientific journals or international conferences. This fact implies that we have not included methods that are still under development, methods that are not published in the way described above or LCA methodologies utilised in different case studies. Furthermore, the tools are chosen based on an aspiration towards including global trends regarding feasible LCA methodology approaches for the building sector. These selection criterions resulted in the following tools and or methodologies to describe the current practice:

- ATHENA Sustainable Materials Institute, "ATHENA^{TM}",
- BRE, "Envest",
- IVAM, "Eco-Quantum 3",
- SBI, "BEAT 2000",
- US EPA, "BEES".

It should be noticed that there are other compilations of LCA-based tools for building and construction published that include several other tools, which has been found to be outside the scope of this article due to different restrictions in their usability and scope or based on the absence of adequate documentation. Examples of extensive inventories of several different types of environmental tools with, in most cases, some relation to LCA methodology and utilised for the building sector can be found in [13,14].

Theses five tools are designed for use at different building levels. It is not a homogeneous group while they differ in scope, approach and practicability for whole building assessments, if they are at all useful for whole building assessment and assessment on the level above the building level, i.e. provided service. The difference in approach between the tools/methodologies listed above is that the majority of the tools are developed based on a bottom up approach, i.e. a combination of building materials and components sums up to a building. This even though they are designed to consider the whole building including energy demand, etc. The only tool that is based on a top down approach is the Envest tool, which is a tool explicitly developed for use in the design phase of a building project. The starting point of the assessment in Envest is to choose the shape of the building and then gradually work your way down through the construction to the choice of materials in the frame and infill walls etc. The BEES tool differs in usefulness for whole building assessments, while it is designed for decision support in material choice situations. This distinction between the tools studied in this article is supported by e.g. the classification of tools made by the ATHENA^{TM} Sustainable Materials Institute [15], i.e. that ATHENA^{TM}, Eco-Quantum and Envest are level 2 tool (whole building decision support tools) while BEES is a level 1 tool (Product comparison tools). BEAT 2000 is not mentioned in the by ATHENA introduced assessment tool classification system, but the characteristics and intended use of BEAT 2000 is similar to ATHENA^{TM}, Eco-Quantum and Envest.

The LCA methodologies used in the tools are described separately in available LCA-methodology reports for four of the tools; ATHENA^{TM}—"Research Guidelines" [16], Envest—"BRE methodology for environmental profiles of construction materials, components and buildings" [17–19], BEAT 2000—"Miljødatablade for bygningsdele" [20], BEES—"BEES 2.0 Building for Environmental and Economic Sustainability—Technical Manual and User Guide" [21], while there is no methodology report available for the fifth tool, Eco-Quantum.

The use of the LCA methodology to design comparative scoring system for the building sector is not in the scope of this paper for the following reason. In an evaluation of a building the building will have to compete with itself, i.e. each building is restricted to a location and to object related conditions that put restrictions on possible designs, constructions and material choices. The goal is, thus, to make the best choices, in each case, based on the context that the building will be situated in. The use of a scoring system to benchmark different buildings, or the use of buildings, based on predefined and generic environmental performance requirements is not regarded as adequate, since the building and operation context then must be made independent of the actual context, which theoretically is impossible. For example, the environmental performance of a building is not only dependent on the geographical location based on energy use considerations, but also due to requirements on the design of the foundation and logistic context. This imposes that it is necessary to have flexible methodology approaches when the environmental performance of constructions and operations are to be assessed. The use of the LCA methodology to design comparative scoring system for the building sector is not in the scope of this paper and will, therefore, not be discussed further.

3. Considerations valid for a flexible LCA methodology

3.1. A construction including a sequential life time and integrated service system

LCA for buildings is often performed as a linear life cycle including life-cycle phases such as construction, operation (including maintenance), ending with a demolition and waste treatment phase. This kind of linear thinking is not valid for most buildings in reality and will not be applicable for rebuilding in particular, since this life-cycle phase, i.e. rebuilding, then automatically will not be included. Therefore, in this paper *sequential life-cycle* thinking is introduced. The sequential life-cycle of a physical construction can be divided in different activities such as construction, maintenance, rebuilding, extension, operation and "end-of-life scenarios" e.g. including demolition and material recycling,

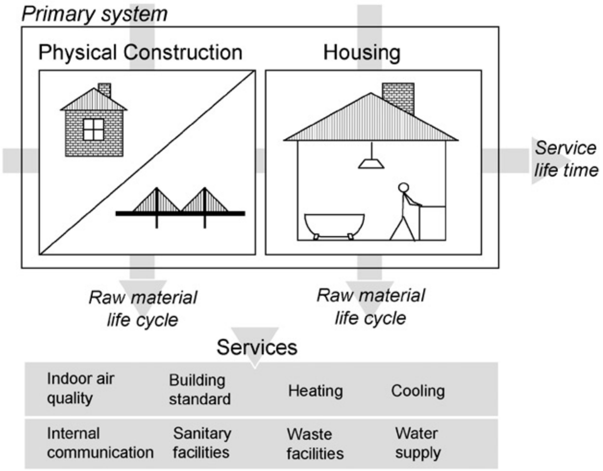


Fig. 2. The studied primary system with the functional output defined as services—rather than products. Two life-cycles approach are valid for the physical building and related operation namely the over all service lifetime and the life-cycle for utilised activities indicated as "raw material life-cycle" in the figure.

while operation can more or less be compared to a continuous process. The basis behind the sequential life-cycle approach is that the different life-cycle phases should be treated separately in the life-cycle inventory analyses. Depending on the actual boundary conditions it is then possible to add up the sufficient life-cycle phases corresponding to the goal and scope definition. However, for benchmarking it could always be argued that a normative linear life-cycle always should be presented to illustrate what happens if a linear life-cycle should be valid. The sequential life-cycle modelling and boundary setting allow the practitioner to add the life-cycle phases that are found convenient and necessary in respect to the goal and scope definition in the particular case study. Consequently concerning rebuilding, etc., the existing construction parts such as the bearing building frame optionally can be regards as a sunk cost, which is found adequate for e.g. rebuilding [22].

To make a flexible modelling structure available for construction services a *primary system* is introduced, constituted by two subsystems equal to the *physical construction* and with the construction related housing or in more generally terms *operation*, see Fig. 2. This is essential for two reasons:

- Performance requirements and building services can often be grouped in these two major issues. In an LCA it should be possible to consider the construction (consisting of building elements), building products and finally building and auxiliary materials (solvents, etc.) separately.
- The main part of the environmental impacts associated with the physical construction is often known while the characteristics of future operation usually are determined by assumptions. Normative scenarios can always be established for future events, at least for comparative assertions, while "known" potential impacts are not negotiable.

The primary system is defined by the *services* that are included and considered in each LCA case study and according to LCA terminology *services* will be included in the functional unit [23]. The analysed systems for both the physical construction and operation include related up and down stream activities. Examples of related up and down stream activities in the case of operation systems are heating, ventilation and water supply. When houses, offices, service buildings, etc. are considered, it will be hard to make a sharp distinction between which environmental impacts that originate in the characteristics of the analysed building and which originate in the behaviour of the users of the building. This kind of aspects is not needed to take into account if the functional unit is based on the building service level rather than the physical building itself. The operation included here is "building related operation", which means that the environmental performance of an activity must be influenced by the utilisation of the building or dependent on the design of the building. A consequence of this definition of operation is that e.g. the transportation of tenants to and from a building and other facilities are not included in the operation service, since it is not related to the utilisation of the building as such or effected by the design of the construction. In other concepts, as in the REGENER project, the transportation of tenants are assumed to be a part of a building service and will then give a significant contribution to the overall impact [24–26]. However, this kind of environmental assessment is preferably considered in urban planning.

3.2. The starting point for evaluation

A building is usually produced with a defined final utilisation in mind. Since both the building and its utilisation will change over the time, the integrated products must be regarded as a dynamic system with potentially different functional outputs over time. The physical structure of a building, however, can often be regarded as a simple product in relation to the service that the building satisfies in the society. The problem is to define a functional unit that covers the building as a dynamic system, including all services that the building provides. For example, the service that a construction provides is the function of housing, for which it will always exist a demand. An LCA in this context should cover the performance functional demand for housing that the building shall fulfil, rather than the physical building in itself as a separate entity. This alternative viewpoint makes it logic to distinguish between two approaches to apply LCA for buildings and operation, described below and in Fig. 3:

- *Alternative product evaluation* (*APE*). This approach corresponds to the original application of LCA described in ISO 14040 [23], which means that the quantified functional outputs of a product system (or service) is described

Alternative Product Evaluation:

$$\underset{\textit{(varies)}}{\text{Environmental profile}} = \frac{\text{Environmental impact } \textit{(varies)}}{\text{Functional outputs } \textit{(fix/starting point)}}$$

Environmental Function Demand:

$$\underset{\textit{(fix/starting point)}}{\text{Environmental profile}} = \frac{\text{Environmental impact } \textit{(varies)}}{\text{Functional outputs } \textit{(varies)}}$$

Fig. 3. Two different approaches utilised to apply LCA for buildings and constructions.

by a functional unit that works as a fix reference unit. Different products that satisfy the defined functional unit are then evaluated regarding their environmental performance.

- *Environmental functional demand* (*EFD*). This approach is based on a quota decided in advance that is equal to a acceptable environmental impact divided by the function output. A number of such, in advance decided, quotas are then set up as goals and as such constitute the starting point for the assessment procedure. Different technical solutions that satisfy the quota are then identified, refereed to as inventory profile or environmental profile (if the characterised figures are utilised).

The intended application and benefit of the two approaches is illustrated by the following statements representing the questions that the two approaches can satisfy:

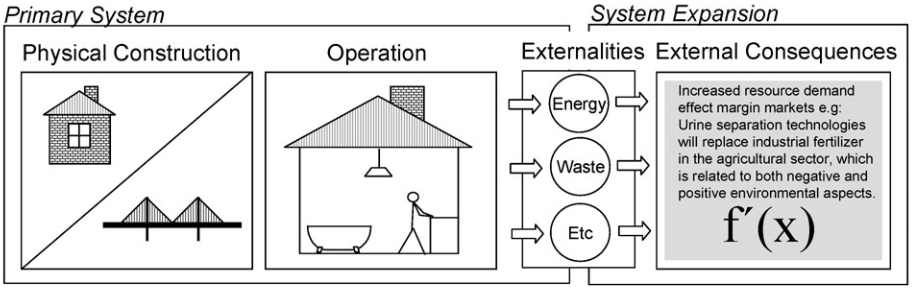
- EPE—What is the environmental impact associated with the activity of driving different vehicles 1 km carrying 1 tonne of gods?
- EFD—What vehicles can be utilised for carrying 1 tonne of gods 1 km if the acceptable environmental consequence is restricted to a certain environmental impact?

The EFD approach is developed in an ongoing project "Environmental functional demands for ecological sustainable buildings and housing" [11], as an alternative solution to be able to implement LCA in the building sector. The benefit with EFD approach is that it can be used parallel with other functional demands for other design aspects already applied in the design process such as fire safety and indoor air quality. The concept results in a smaller need for a weighting method in that respect that all functional demands shall be reached and different EFDs do not need to be compared. Furthermore, EFD concerning the same building service can in its most simplified form be given as a one-dimensional criteria or indicator, but the system is designed with the possibility to expand this criteria by introducing an environmental profile (i.e. a characterised inventory profile). This characteristic of the EFD system can be illustrated with an example for energy conservation for domestic dwellings built between 1961 and 1970. An EFD of 38 $\mathrm{kWh/m^2}$ in energy demand for heating corresponds to a sustainable building requirement in Sweden [22] and an alternative to this one-dimensional parameter is the use of an environmental profile per square meter living area as an EFD. Hence, the building service is anticipated to satisfy this multi-parameter goal, rather than a simple physical indicator, this could promote technical developments and will reduce the risk for sub-optimisations. Furthermore, the EFD approach has the advantage that environmental problems can be addressed by defining an EFD for each service, which makes it possible to establish a common "language" between different actors in the building sector that apply normative decision support systems.

The APE approach for definition of a functional unit for buildings is congruent with the view on functional unit for buildings presented in the SETAC Report "LCA in building and construction" [12]. This way of introducing LCA for buildings and constructions imply that the functional outputs are given as a fixed values and that they are the starting point of a comparison, see Fig. 3. In the SETAC report there are a series of examples of "building performance characteristics" presented that correspond to "system deliverables" in Fig. 3. These building performance characteristics should be used to be able to assess the true functional equivalence of buildings and constructions over the expected service life of a building or a construction and the choice of characteristics are dependent on the goal of the study. Examples of proposed characteristics, in this paper called services, are conformity, location, indoor conditions, service life and deterioration risks, adaptability, safety and comfort.

3.3. *Interconnections and its prospective effects*

The building sector cannot be regarded as an autonomous subsystem without interconnections to the rest of society. The building sector is essential as a foundation of society and interconnects with almost all other sectors and functions of society. This implies that assessments of buildings and other constructions or building sector related activities could not always be treated as a marginal change problem without consequences on the demand for new technologies in adjacent sectors such as the energy sector. Thus, e.g. the energy sector has to be included in a study due to the fact that it is affected by changes in the building sector. The energy sector is defined as a *foreground process* [27,28]. LCA, however, can handle both *retrospective assessments*, e.g. assessments of existing constructions, and *prospective assessments*, e.g. assessments of alternative constructions in the design phase including systems affected by the design such as the energy sector [29]. In a generic LCA methodology for buildings, system expansion must be regarded as an optional choice to study marginal effects on externalities e.g. increased electricity supply. A comparison between a *retrospective* and a



Increased resource demand effect margin markets e.g: Urine separation technologies will replace industrial fertilizer in the agricultural sector, which is related to both negative and positive environmental aspects.

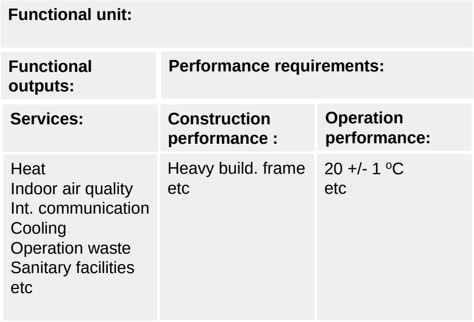
Fig. 4. The conceptual approach utilised to describe the construction and operation function, divided in a primary system and an optional system expansion.

prospective assessment gives that a *prospective* assessment, including marginal technologies, gives additional information in order to put attention on and minimise the potential risk for sub optimisation in the studied primary system. Therefore, when analysing buildings, it has been found convenient to define a *primary system* that covers the subsystem equal to the *physical construction* and the utilisation of the construction and facilities related to it, referred to as the subsystem *operation* in Fig. 4.

The services all together will then in each case study correspond to the system boundaries valid for the *primary system*, which corresponds to "foreground system", or "*foreground process*" as mentioned above [27,28,30], in that sense that the influence of design, tenant behaviour and externalities is very central for the over all studied construction and operation function. Therefore, as an optional choice for a service related to the primary system, it is always possible to work with the concept of *prospective assessment* in order to evaluate external consequences caused by a changed behaviour in the building sector regarding other systems such as energy supply or wastewater handling. Prospective assessment, in this application, is an interesting tool to apply to services that affect the margin market [31]. This in combination with system expansion will in this case give additional information on "what will happens if ..." a material or energy flow increase or decrease on the market. Therefore, the functional unit for construction and operation primarily is defined by a primary system and an assessment of its potential effects on margin markets, which have as a consequence that the services included in these systems also have to be defined in the functional unit.

3.4. A holistic functional unit with optional entries

Both operation and the construction services included in an assessment will constitute the actual so-called functional unit in each LCA applied to construction and operation. Since the precise goal and scope cannot be generally established in a generic LCA methodology it will not be adequate to select and established a generic functional unit covering the actual services of interest. Instead it is suggested that all opportunities, which reasonably can be addressed, for the functional unit of concern should be listed. This list can then form a menu of adequate services that together constitutes the actual functional unit of the studied system (Fig. 5).



Functional unit:		
Functional outputs:	**Performance requirements:**	
Services:	**Construction performance :**	**Operation performance:**
Heat Indoor air quality Int. communication Cooling Operation waste Sanitary facilities etc	Heavy build. frame etc	20 +/- 1 ºC etc

Fig. 5. Terminology and important parts related to the system deliverables. Functional unit, functional outputs and performance are terminology found in ISO 14040.

The structure and schematic entities of the concept of the functional unit as described in this article are illustrated in Fig. 4. The difference compared to the ISO 14040 [23,32–34] series is that the word service is preferred before product due to the fact that the word service better covers the functional output from a building. A more precise definition of the performance requirements valid for a specific design process and the selection of the same based on the functional unit is found convenient to be dealt with by specialists, e.g. designers [12]. This indicates that the framework for the functional unit can be defined on a higher level than the product level by specifying the selected services. If the purpose is to set up a reference unit then the performance requirements have to be more measurable and the definition has to be narrower.

3.5. Introduction of characteristics valid for constructions and operation services

In order to characterise different LCA concepts utilised for buildings, a number of different building related topics, that can be considered, have to be introduced, see Table 1. The goal is to find out how far the development and implementation of LCA for buildings has come so far. The Topics in Table 1 are based on the authors' perception

Table 1
Different topics used to characterise different LCA systems applicable for buildings

Decision supported by	Sub groups	Topics
Scope	Building life-cycle phases and status	Definition of the buildings life-cycle phases Assessment of a new building Assessment of a existing building Assessment of an activity, i.e. rebuilding, extension, demolition.
	Services coverage	Water consumption and use Waste water system Heating and cooling system Ventilation system Building maintenance, i.e. durability aspects Plot operation and maintenance Building related choice versus user-related impact.
	Time dependence (coverage)	Average of today's practice Time dependence affecting LCI Time dependence affecting LCIA
Methodology	Inventory	Allocation procedure for processes Handling of material recycling (i.e. open-loop recycling, boundary setting between products). Sunk costs Scenario modelling Time dependence (i.e. data for future processes) Procedure obtaining specific or generic data Procedure for dealing with data gaps
	Impact assessment	Indoor air quality, IAQ Time dependence Spatial difference Geographical difference Impact categories Conservation of resources Valuation methods

of which topics that would be adequate to find in an ideal LCA concept for buildings, rather than what is expected to be found. Therefore, Table 1 also reflects which areas that could be subjects of further research.

4. Today practice based on characterisation of five generic LCA approaches

A questionnaire based on the topics of interest presented in Table 1 were presented to the originators of the five tools, i.e. ATHENA^{TM}, Envest, Eco-Quantum 3, BEAT 2000, BEES. The results from the questionnaire have been analysed by the authors and a selection of the results of this analysis and comments to the results are presented below for the four principal topic groups: Service coverage, Time dependence (coverage), Inventory related considerations, LC impact assessment related considerations. In Appendix A there is a compilation of the five questionnaires.

4.1. Service coverage

4.1.1. Definition of the assessment context level

If the starting point for an evaluation is the service that the building or construction satisfies, the building services related to housing and construction will constitute the highest assessment context level. In respect to traditional practising of LCA for building or constructions the physical building is often the focus in the assessment [12] and different user-related services are more or less added as add-on part LCAs. The current LCA practice for building is related to different facilities which imply to define a service as *heating* (connected to the heating system) [24–26], rather than to define an indoor *operative temperature*, which can cover a integrated system manly restricted to heating, cooling, ventilation and the building design. The way to describe the service performance has to be decided by the common praxis on each building market and not determined by the LCA methodology and is therefore not

Table 2
Environmental impact assessment level and example of substructure, improvement strategy and other related tools (besides LCA)

Context level	Example of substructure	Improvement strategy	Other related tools
Urban planning	Building, communication, recreation etc. facilities.	Sustainability technology development	Strategically environmental impact assessment
Building services	Operation and physical construction	Function design	LCA, Eco-Efficiency
Building constructions	Building parts (e.g. foundation, facade, etc.)	Product redesign	LCA, Design for environment.
Building elements	Building materials and manly factions (e.g. windows, doors)		
Building materials	Manly factions (e.g. insulation material)	Cleaner production	Environmental impact assessment

discussed in this paper. However, the LCA tools type 2 (see Scope above) have more or less included the following building-related services or facilities; water supply, wastewater handling, heating and cooling system, ventilation system, building maintenance, i.e. durability aspects, operation waste handling systems, building plot operation and maintenance. The two exceptions on the list given above are wastewater handling and building plot operation and maintenance. Wastewater treatment is only included in Eco-Quantum and building site operation is not included in any of the LCA tools. Hence, the building is the starting point for assessment with the currently analysed tools, the system boundary settings are given by the physical building. It can therefore in practice seem adequate not to include the topics of wastewater handling and building plot operation and maintenance. Nevertheless, it seems more stringent to, in the first place, define a generic boundary setting valid for a functional unit based on the service that the building is intended to satisfy and then, as a consequence of this, define what will be accounted for in the system. The suggested generic definition of a holistic building service, that is to be included in the functional unit for a building or construction service, is (as already mentioned) defined as

> The activities included here are addressed as all "building related operations or services", which means that the environmental performance of an activity must be influenced by the utilisation of the building or dependent on the design of the building.

On the basis of this holistic building service definition it is obvious that all building functions listed above, except building plot operation and maintenance, will be covered by this definition. The suggested definition could therefore be regarded as a de facto standard. It is already mentioned that the transportation of tenants to and from a building or other facilities is not included in the building service, in relation to the presented definition, since transportation is not related to the utilisation of the building as such or effected by the design of the construction. Building plot operation and maintenance can hardly be said be a part of the building and consequently is not be affected by the building design. It can, however, be noticed that real estate, including building plot operation and maintenance, is accounted for in the Swedish Environmental Stressor Profile [35]. On the other hand, the scope of the Swedish Environmental Stressor Profile LCA model is not restricted to the building itself. It takes also urban planning into account. With other words, it is possible to constitute a further assessment context level valid for urban planning. The definition valid for building service will then easily be rearranged by changing the word "building-related service" with "urban planning-elated service". Dependent on the context level, different system boundaries will be valid, as illustrated in Table 2.

4.1.2. *Definition of the building life-cycle*

In respect to reality, rebuilding should to be included in the "life-cycle thinking" of a building, in one way or another, if a generic LCA model covering the current situation shall be the goal. The preferred life-cycle approach in the software and methodology practises in the investigated type 2 LCA models designed to perform an LCA are utilised according to a predefined linear life-cycle, typically given on terms of; raw material extraction, manufacturing, on-site construction, operation (including maintenance) and end-of-life/demolition. A generic approach valid for rebuilding is not found in any of the investigated LCA tools/methodologies. It is, however, noticed that the LCA tools/methodologies are designed to be able to always handle any building-related activity. This fact is also valid for rebuilding, why rebuilding as a single activity could be assessed in the established models. The purpose of a life-cycle thinking for a single activity will however not

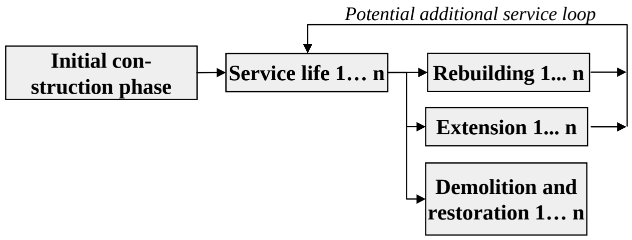


Fig. 6. General description of a buildings life-cycle including a number of potential service life, referred to as life time No. 1 to *n*.

be clear. A life-cycle covering rebuilding, operation and demolition could fulfil the same purpose as the normative commonly defined "traditional" linear life-cycle thinking for a "new" building. Since the investigated type 2 LCA models are using the physical building as the restricting factor to define the life-cycle, general pre-established life-cycle durations of 50–75 years are used as default. This methodological choice will be adequate if the purpose is to carry out an assessment on the building context level, but when the building service is utilised and the object of the assessment, the life time or duration of the service itself should be utilised to define the starting point and end point of the life-cycle. Hence, the building service can in one way be regarded as continuous, i.e. we will always need a place to live. This implies that the service can be specified in time. For instance, office buildings in central city areas have a short service life-cycle, frequent rebuilding will take place (e.g. every 3–6 years). To be able to perform an assessment of rebuilding, a set of requirements that the building services should fulfil must be handled in the design phase. An LCA, performed for the building function, will be in line with the arguments put forward for a more generic application of LCA, refereed to as life-cycle management [36]. It must therefore, be the conclusion that the adoption of building service as a context level can be a way to handle rebuilding in a sufficient way, but no such generic applicable LCA methodologies have been found in the literature.

The sequential life-cycle thinking, described earlier in this paper, is the way rebuilding can be handled today, i.e. by just adding another building service life-cycle phase to the already establish list above (see Fig. 6).

4.2. Time dependence (coverage)

The questionnaire, based on the topics presented above, reveals that the tools analysed in this paper are utilised to handle the time dependence and time coverage in some way. The results of the questionnaire are presented in Appendix A. The majority of the tools have the possibility to take all the activities and life-cycle phases, which can be considered, into account. There seems, however, to be a difference in the interpretation of the concept of time coverage. The time coverage is linked to activities and life-cycle phases in the sense that several of the activities and life-cycle phases that ought to be considered, especially when buildings, constructions and building services are concerned, take place in a distant future due to the long service lives of buildings, see Fig. 7.

All of the tools are designed to handle all life-cycle phases that are of interest based on the intended application. BEES do not handle the usage phase in the same way as the other tools due to the fact that it is not intended as a whole building assessment tool but rather a decision support tool in material choice situations. A majority of the tools is, according to the questionnaire, utilised to handle future processes. This can, however, be questioned for some of the tools when available methodology reports are consulted. Some of the tools have the same databases as a source of information and they have interpreted the time coverage of these databases differently.

A general impression is that it is considered that supplying marginal, average and best-available technology LCI data satisfies the intention to cover the time dependence of LCA studies of buildings. This can, however, be insufficient if there is no possibility to build scenarios, which consider technical development that can change the studied system and the context of the studied system over time. This is especially important for long-lived products as buildings, which can have a service life of about 100 years. There is a significant difference in the average environmental load per year due to, among other things, the anticipated pace of development in the energy sector towards renewable energy sources over the long service life of buildings [37]. This implies that it is not sufficient to only consider best-available technology at present but also to allow different technology development scenarios over time.

None of the tools, based on the questionnaires, have the possibility to take the time dependence of impacts into account, i.e. LCIA data for the environmental context of future environmental loads is not included. Further information regarding the LCIA methodologies applied in the studied LCA tools and methodologies is presented in "LC impact assessment related considerations" below.

Both of the above-described time-dependent aspects that could, and probably should, be addressed by tools designed for the buildings are dependent on a willingness from the designers of the tools to make assumptions regarding the future. Without these assumptions or the possibility for the user to incorporate their own scenarios, and thus introducing large uncertainties, these tools will not be able to take the time dependence of the assessments into account.

4.3. Inventory-related considerations

There are four different approaches towards dealing with allocation in the case of recycling and in the case of unit processes that have multiple input and output flows, and the allocation problem in general, represented in the studied tools and methodologies, see Table 3. Three of the tools have incorporated or proposed a specific allocation

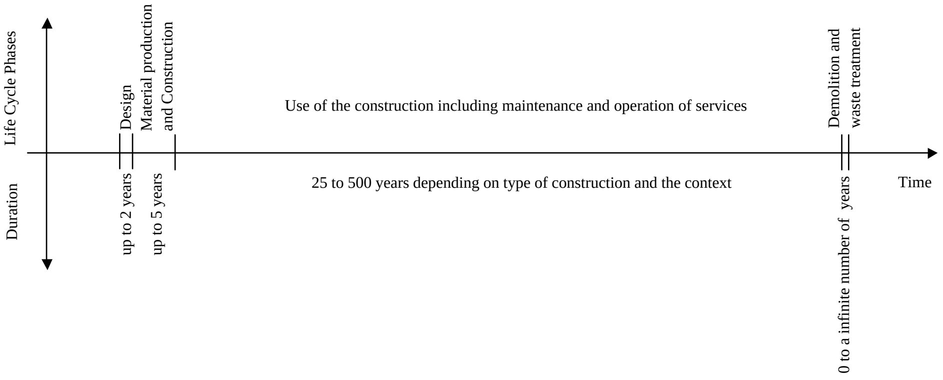


Fig. 7. Different life-cycle phases and their duration and place in time.

Table 3
Characterisation of allocation procedures implemented or recommended in the five studied tools

Allocation procedure valid for	Material recycling (open loop recycling)	Future material recycling (open loop recycling)	Multi in or output at a unit process.	Allocation of reuse when multiple service live are included.
ATHENA^{TM}	CSA procedure (cut-off)	As present	Mass	Not specified
Envest	Economic value	As present[a]	Economic value	Not specified
Eco-Quantum 3	Economic value based cut-off	As present[a]	Economic value	Not specified
BEAT 2000	Users choice	Users choice	Users choice	Not specified
BEES	Not specified	Not specified	Not specified	Not specified

[a]Future economical values could be utilised but are not implemented in the methodologies/tools.

procedure, in the tool or in the methodological report associated with the tool, that ought to be used according the designers of the tools in at least one of the two allocation situations mentioned above.

Two of the tools have not specified any specific procedure. One of the tools has chosen to let the user of the tool decide how the allocation, if needed, should be performed and the other tool have not made any comment regarding allocation, neither in the questionnaire nor in the referred methodology report. In the BEAT 2000 tool, which has given the user of the tool the opportunity to choose the type of allocation that the user finds suitable, the recommended allocation procedure is to use a traditional cut-off allocation in the case of recycling. This is motivated by the long service life of buildings and building products and that most building products are subjects of “low-level recycling”. The second tool that does not specifically specify a preferred allocation procedure is the BEES tool. It is, however, stated in the Technical Manual that a majority of the data used is data from Ecobalance database.

The tools that have specified a specific allocation procedure, i.e. ATHENA^{TM}, Eco-Quantum and Envest, have in two cases, Eco-Quantum and Envest, chosen the same basis for allocation in both the case of recycling and in the case of unit processes that have multiple input and output flows and the basis is economic value. The Envest tool allocation procedures based on economic value are comprehensively described in the BRE Methodology. The procedures applied in Eco-Quantum cannot be found in a methodology report but are briefly described in the questionnaire and the multiple input and output flow allocation is described as economic allocation and the procedure for recycling is described as a cut-off based on economically based cut-off criteria. The approach to allocation is somewhat different in the ATHENA^{TM} tool. The multiple input and output flow procedure is a mass-based allocation, but the allocation on mass basis is supposed to be applied only when it is not possible to divide the studied unit process to avoid allocation. Allocation in the case of recycling is also different compared to the other tools in this survey and the procedure incorporated is basically in accordance with the Canadian Standards Association (CSA) guidelines for life-cycle assessment [38]. The procedure is a set of principles that should be applied in certain situations. The first option is to allocate based on the actual mass flows between product #1 and product #2, which requires that both production system #1 and #2 are known. If this approach is not feasible three arbitrary methods are proposed presented in order of complexity. The first option is to allocate based on the percentage of the two products produced, the second is based on the principle that the avoided disposal can be allocated to the product being recycled and the third is based on an even distribution (50/50 allocation).

The use of environmental sunk costs, on the analogy of economical sunk costs in life-cycle cost assessment (LCC), as a cut-off when performing assessments of buildings and constructions seems not to be common among the studied tools. The use of environmental sunk costs could be a feasible approach to handle the problems occurring when assessments of rebuilding is performed, i.e. how the existing building and its original environmental loads are handled when the building (during it's service life) is rebuilt or altered in a way that it can be said that the building enters a new life-cycle or life time [39] with in the total life-cycle of the building or service.

Scenario modelling is another topic that, like environmental sunk costs, is not commonly handled methodologically in the five studied tools and if it is handled it is mostly a predefined scenario that is applied and which is not user influenced. The Envest tool applies "current practice" which, according to the methodology report [15], is predefined scenarios for energy, maintenance, transports, etc. and predefined service lives for different materials and components. The user of the tool can, however, influence the choice of service life for the assessed building. The tool undergoes continuous development and a possibility to influence the demolition and disposal scenarios has been incorporated into the BRE methodology [18].

The questionnaire and the questions regarding data quality show that there are two approaches represented on how to collect data and how to handle data gaps. The data used in the tools is either generic data, in this case typical UK (Envest), or company specific (ATHENA^{TM}) or variations on the theme like the BEES tool that aims at using US average data or the BEAT 2000 and the Eco-quantum tools that use both types of data. Data gaps are handled differently in the different tools. Envest uses best estimates to deal with data gaps; BEAT 2000 recommends data gaps just to be left as gaps, Eco-quantum does not recommend any specific action while ATHENA^{TM} and BEES handles known data gaps by collecting more data to fill known data gaps. The data gaps in ATHENA^{TM} and BEES are probably left as gaps until the new data is collected, i.e. generic data is not used to temporarily fill the gaps.

4.4. LC impact assessment-related considerations

An attempt to define and establish the current best available practice concerning characterisation factors was the objective of the recently finished SETAC project, the SETAC working group on life-cycle impact assessment. The resulting document of the project is not jet published. An older version is available [40], which discusses general issues valid for impact assessment in LCA. Regarding impact assessment, specific questions valid for buildings have been investigated in the evaluated methods, namely handling of the following issues:

- resource depletion and different impact categories;
- site specific or site-dependant data including spatial difference;
- time dependence for characterisation factors, e.g. background conditions such as a concentration of NO_x; VOC a significant substance valid for the characterisation model for photochemical ozone formation;
- indoor air quality;
- valuation/weighting method.

The impact categories included regarding different impact categories and resource depletion in the different LCA models investigated, are summarised in Table 4.

It is noticed that the building indoor air is not taken into account in LCA in general. This conclusion is also valid for European risk assessment software EUSES [44], and consequently not included in its implementation in LCA as suggested by CML called EUSES LCA [45]. Among the studied tools/methods only BEES has included indoor air quality in the impact assessment as an impact category, but it is stated that there is little scientific consensus about the relative contribution of different emissions to indoor air performance. The magnitude of impact on the indoor air quality is, in the absence of equivalence factors, measured as the total of the VOCs emitted by a product [21].

The development of site specific or site deponent characterisation factor is still under development in LCA in general and is so far not adopted in any of the investigated LCA models for buildings. Hence, buildings are long lived and the environmental impact occurs to a great extent during the usage phase. It implies that there is a possibility to take different parameters that affect the categorisation factors into account. This is of course only valid for such characterisation models that are "effect oriented" and not based on inherent properties. In relation to site-dependence, it can be argued that to capture the changing of different background conditions over time, and which are affecting characterisation factors, is more difficult in LCIA than to capture the influence of site-dependent parameters [46]. All of the studied LCA models include a valuation method that is briefly described in Table 5.

Since the use of valuation methods is restricted in ISO 14042 [34], it should be acceptable for the end user of the system and software to receive a recommendation regarding what this kind of aggregated data could be and/or could not be used for. This information is, however, lacking in the methodology reports for the tools: ATHENA^{TM}, Envest, BEAT 2000, Eco-Quantum but is mentioned in the BEES 2.0 Technical Manual. We assume that this is also the case for the related software, i.e. there are no comments in the tool regarding the use of the results

Table 4
Implemented impact categories or category indicators in five LCA building methodologies. Different non-endpoint oriented impact categories or category indicators such as embodied energy, waste, transport, etc. have been left out

Characterisation factors in	Resource depletion	Climate change, acidification, photochemical ozone formation, stratospheric ozone depletion	Human and ecological toxicity	Bio diversity
ATHENA 1.2	Yes, via recycling Scenarios	Only climate change included	Water and air toxicity (in development)	Yes, “ecological carrying capacity”[a]
Envest	Classified and Characterised for fossil fuel depletion and minerals used	Mainly CML 92[b]	CML 92	No
Eco-Quantum 3	Yes, CML 92[b]	CML 92	CML 92	No
BEAT 2000	UMIP[c]	UMIP	UMIP	No
BEES 2.0	Yes[d]	Yes[d]	Yes, including indoor air quality[d]	No

[a] Ref. [41].
[b] Ref. [42].
[c] Ref. [43].
[d] Ref. [43].

Table 5
Characterisation of normalisation or valuation method in r five LCA building methodologies

Implemented characterisation factors in	Normalisation available?	Normalisation basis	Valuation available?	Value choice	Background information available on valuation
ATHENA 1.2	No	—	Yes, but only for resource use (“weighted resource use”)	Expert panel, based on environmental issues	[41,47]
Envest	Yes, one	UK citizen	Yes, “Ecopoints”	Expert panel, based on environmental economical and and social issues.	[19]
Eco-Quantum 3	Yes, one	A reference building	No		Not available
BEAT 2000	Yes, one	Average world citizen	Yes, the EDIP method	Political goals and a time reference to scarcity for resources	[43]
BEES 2.0	No	—	Yes, one valuation method including two optional or mixed time perspectives	Panel verbal importance ranking using the AHP-method, concerning environment current and/or future consequences	[21]

generated with the tool, except for Envest that have information regarding use of the results in the help function of the tool, when it is used for executing assessments of different kind.

5. Conclusions and discussion

The following conclusions and discussion are based on the considerations valid for a generic LCA methodology for buildings, which are identified and presented in this article. Today's practice for different, on the market available, LCA tools is then investigated and further evaluated in relation to a number of issues valid for LCA methodology applied on buildings (see Table 1). The main conclusions from this work are that:

- The building controlled utility services level is identified to constitute the highest level of complexity valid for LCA applications for buildings.
- The other abstraction levels valid for buildings can then be derived as a subset from the building service level. The other complexity levels are the building construction level, the building element level and building material level.
- A potential user guidance for methodology and value choices (in the goal and scope definition) can be established for a flexible LCA methodology applied on buildings if methodology choices are available as a menu. The menu allows optional entries that are decided by the end user's value choices and actual scope in each case study.
- The issues high lighted in Table 1 can be used as basis for a menu as the previously proposed. This menu can then guide the LCA practitioner to make the correct choices, i.e. by putting forward leading questions in a dialogue using the technique from knowledge-based systems.
- Another component that could be necessary to establish a flexible LCA methodology covering different life-cycle approaches is the concept of sequential life-cycle thinking. Depending on the actual boundary conditions it is then possible to add up the sufficient life-cycle phases corresponding to the goal and scope definition.
- According to the today's practice on LCA methodology for buildings (in accordance with the five evaluated LCA methods) time dependence and scenario handling are portly handled, which implies that further development is needed in this field if the building service life shall be adequately assessed.

5.1. Building abstraction level

A building is preferably defined based on physical building properties according to the SETAC report "LCA in building and construction" [12]. With this preference it is adequate to use different physical building properties to define the functional unit, which is the common approach among the five evaluated tools. This interpretation and approach to assessment of buildings is correct if the actual building controlled utility services are not included in the scope of the LCA. If this is the case, the building related functions in a user perspective, and its properties, must be included and considered by the functional unit, see Fig. 4. The conclusion, that the service level is identified to constitute the highest level of complexity valid for LCA applications for buildings, will significantly change the building context abstraction level with the purpose to use the building service to define the functional unit, rather than the physical building itself. The functional output of a building defined as a service can be regarded as continues and the service must thus be specified in time. Altogether this improvement of the application of LCA (assessment of services) has to be further developed, but it covers, in a more accurate way, the actually market demand valid for buildings. This implies to two different configuration alternatives representing the building context and where none of them, by definition, is more correct than the other, but the choice is dependent on what is asked for in the goal and scope definition and thus only one correct choice remains. The two different configuration alternatives representing the building context are *the physical building structure* versus *building controlled utility services*. The meaning of *building controlled utility services* takes into account the (here found and identified) over all de facto definition of building service, that states that a building related activity included must be influenced by the utilisation of the building or dependent on the design of the building.

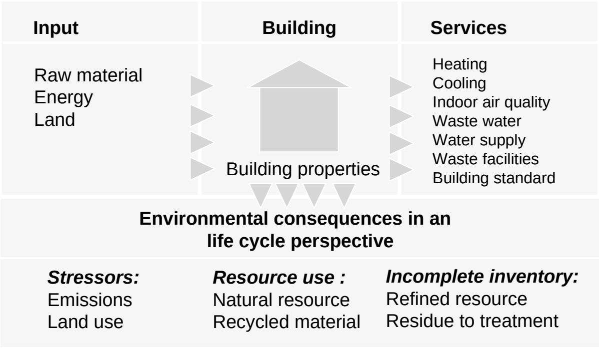


Fig. 8. Two different configuration alternatives representing the building context (defined in the functional unit), refereed to as the two focus zones; the physical building structure versus building controlled utility services.

One way to illustrate the two different applications is to compare the functional unit for a building. One part of the functional unit of a building could be the building property: energy supply need specified according to the transmission loss method, e.g. 150 $\mathrm{kWh/m^2}$, see Fig. 4. This building property is measurable and just like an U-value not dependent on e.g. the indoor temperature and cumulated yearly required degree hours. Following the actual tenants behaviours do not influence the LCA result, which prove that this specification is valid to be utilised for a functional unit definition for a buildings in terms of the physical building context. However, if the building context level takes the tenants into account, different building services are the zone of focus, see Fig. 8. In this example, the building heating could be specified as an operative temperature. To obtain and assess a required operative temperature the tenants, building material properties, buildings structure heating and cooling system, etc. affect the final result. On this building context level it will not be adequate to separate building related versus user-related environmental impact, as they both constitute the building context level. This problem is most valid if the more narrowly defined applications of LCA on buildings, where the zone of focus is aimed at the physical building structure [48]. Consequently, if a building is assessed on a physical building context level the studied system can appear as a static system, but if the very same system is assessed from the building controlled utility services the system will clearly turn out as dynamic system.

5.2. User guidance for methodology and value choices

It is up to the final LCA user to decide what consideration that should be accounted for to reflect the entities of the object-oriented system. This is achieved by an inventory of the environmental considerations that the end user provides by expressing the type of decision support that the LCA is supposed to deliver. This will guide the LCA-practitioner regarding what must be included in the LCA to satisfy the end users needs and thus be reflected in the functional unit. Based on the general assumption that all construction projects are unique and that LCAs performed with the proposed definition of the functional unit is based on the services that the construction is supposed to satisfy makes each LCA study unique and consequently not directly comparable.

The list of topics that the questionnaire was based on can be considered as a part of the results of this paper. The list given in Table 1 can be regarded as a menu and can be of help as a checklist to be able to identify the issues that are appropriate to consider to include and consequently to look for when choosing a methodological approach when performing an LCA in the context of buildings. A potential user guidance for methodology and value choices (in the scope and goal definition) can be establish for a flexible LCA methodology applied on buildings if methodology choices are regarding such a menu. The menu approach allows optional entries that are decided by the end user's value choices and actual scope in each case study. Issues highlighted in Table 1 can be used as basic start for such a menu. This developed menu can then guide the LCA practitioner to make the correct choices, i.e. by put forward leading questions in a dialogue using the technique from knowledge-based systems.

The concept of sequential life-cycle thinking is introduced to allow the practitioner to add the life-cycle phases that are found convenient and necessary in respect to the goal and scope definition in the particular case study. The sequential life-cycle of a physical construction can be divided in different activities such as construction, rebuilding, extension, operation and "end-of-life scenarios" e.g. including demolition and material recycling, while operation can more or less be compared to a continuous process.

The primary system is defined by the services that are included and considered in each LCA case study and according to LCA terminology services will be included in the functional unit. The analysed systems for both the physical construction and operation include related up and down stream activities. When housing, offices, service buildings, etc. are considered, it will be hard to make a sharp distinction between which environmental impacts that originate in the characteristics of the analysed building and which originate in the behaviour of the users of the building. This kind of aspects is possible to take into account if the functional unit is based on the service of housing rather than the building itself, or more generally speaking, based on operation.

5.3. Time dependence and scenario handling

The topic of scenario modelling seems not to be a prioritised area of concern among the five studied tools/methodologies, but if it is assumed that utility services are the starting point of our assessment and the function that is to be described consequently is a part of a dynamic system, then will the demand of and the requirement on the scenarios deployed be more extensive than in the case of a apparently static system based on the physical building. Scenario modelling can include one or more of the topics: replacement rate of various materials and products, service life definition and estimation, risk of substitution or changes in the demand for the provided service, estimation of sunk costs, etc. All parts of the scenario modelling have to be in relation to the over arching goal of maintaining the services that the studied system provides and not only be related to the physical building.

There are some obstacles to overcome in the strive towards adapting a more dynamic approach to assessments of objects of the building sector and which can be identified by comparing today's practice, as it appears in the five studied tool, with the proposed approach. For example, economically based cut-off criteria are not consistent with a desire of using environmental sunk costs as the economic cut-off usually is based on a zero value point in the life-cycle of the building/service, which will not occur if it is assumed that there is a economical sunk cost that can be assigned to the studied object. The problem can in this case be that the zero value point can only be found in the end of the complete service life, i.e. when the decision of demolition is taken. This even though the object still theoretically can be assigned a value that is based on the value of the in the construction incorporated materials and components and not the value of the aggregated materials and components, i.e. the construction/building.

Table 6

Topic/question	ATHENA	Envest	Eco-Quantum 3	BEAT 2000	BEES
Are a fix number of buildings life-cycle phases defined?	√ Extraction, manufacturing, on-site construction, occupancy and end of life	√ (Built in)	√ The total chain is part of the determination method divided in three phases: production, use and waste handling	√ Construction, maintenance, operation and demolition	√ Raw materials acquisition, manufacturing, transportation, use, end of life
Is assessment of new buildings included?	√ Either at a conceptual stage or from architectural and structural drawings	√	√	√	(√) Building PRODUCTS, not entire buildings
Is assessment of an existing building included?	√ Building is reverse engineered from drawings	(√) Can be used for that purpose	×	× BEAT 2000 can be used for assessment of both new and existing buildings, but no examples of existing buildings are included	(√) Building PRODUCTS, not entire buildings
Is assessment of an activity, i.e. rebuilding, extension, demolition included?	√ All results can be viewed by life-cycle stage	× Not explicitly, could be	√	× See above	(√) Building PRODUCTS, not entire buildings
Are the following services included and briefly how?				All the below-mentioned services can be included, but at present some are left out due to missing data	
Water supply	×	√ Benchmark-econ 19 guide	√ All effects: LCA data	×	× BEES only covers products, not entire buildings and its systems
Wastewater handling system	×	×	√ All effects: LCA data	×	×
Heating and Cooling system	√ User must enter energy use and type from external energy simulation programme	√ Benchmark-econ 19 guide	√ Dutch EPC calculation method all LCA effects	√ Energy use and emissions	×
Ventilation system		√ Benchmark-econ 19 guide	√ Idem	√ Energy use and emission	×
Building maintenance, i.e. durability aspects	√ Preset defaults are called upon to replace various building elements over the building's stipulated life	√ Defaults inbuilt	√ Periodic maintenance all effects	√ Replacement of materials or building elements with a lifetime shorter than the building	√ Product repairs and replacements over a 50-year use phase are included in both the LCA and the life-cycle costing evaluation

Table 6 (*continued*)

Topic/question	ATHENA	Envest	Eco-Quantum 3	BEAT 2000	BEES
Operation waste handling systems	×	×	√ Only data of current situation and waste scenarios	×	×
Plot operation and maintenance[a]	×	?	?	×	× Not sure what you mean by this question
It is possible to separate between building-related choice versus user related impact?	√ Occupancy effects are separately reported from the embodied effects of the building	√ Operational and embodied are separate	√		? Not sure what you mean by this question
Is today's practice utilised for LCI and LCIA data for all activities in the building scenario? If no, answer the two following questions	?	√		√	√
Is time dependence affecting LCI included (i.e. additional data for future processes)?	√ LCI database supports various technologies		×		
Time dependence affecting LCIA. Is time dependence affecting LCIA included (i.e. additional data for future environmental context i.e. increased No_x concentration concerning photochemical ozone formation)?	×		×		
Describe allocation procedure for a process	Mass basis. We attempt to break apart individual unit processes or machine centres to minimize the use of allocation	See BRE environmental profiles methodology	Economic allocation method	The tool does not perform allocations—this is done by the user who enters the data—e.g. combined electricity and district heating production is not entered as one process, but as two separate processes, where the user performs the allocation ones and for all	BEES 2.0 Technical Manual Sections 2.1.1. and 2.1.2

Table 6 (*continued*)

Topic/question	ATHENA	Envest	Eco-Quantum 3	BEAT 2000	BEES
Describe allocation procedure for handling of material recycling (i.e. open loop recycling, boundary setting between products)	See Section 5.5 of attached protocol for steel recycling	See BRE environmental profiles methodology	Input and output cut by economic allocation rules	Again individual, but usually (because of the very long lifetime of buildings, and because reuse is often “low-level-reuse” i.e. bricks crushed and used as sand/stone) all environmental impacts from the production of a material is allocated to the first user.	BEES 2.0 Technical Manual Sections 2.1.1 and 2.1.2
Is environmental sunk costs (compare with LCC) allowed as cut off[b]	×	?	×	?	BEES 2.0 Technical Manual Sections 2.1.1 and 2.1.2
Describe procedure for scenario-modelling[c]	?	Current practice		?	A limited number of parameters may be set by user
Specify procedure obtaining or choice for specific or generic LCI data	Generally we do not use secondary LCI information. All LCIs are completed by industry experts using our LCI protocol in tandem with direct industry participation	Generic only	√/× Both generic and company specific LCA profiles are available	Most of the building materials used in the Danish building industry is produced in Denmark. In these cases we (SBI) have collected product specific data from most the actual producers. For other products data from literature are used	BEES 2.0 Technical Manual Section 2.1.2
Specify procedure for dealing with data gaps		Best estimates	×	They are simply left out	BEES 2.0 Technical Manual Section 2.1.2
Are the following topics included and how?[c]					
Indoor air quality, IAQ	×	×	×	×	√ BEES 2.0 Technical Manual Section 2.1.3
Time dependence	√ Building life span dictates replacement and maintenance scenarios	×	×	×	× Not sure what you mean by this question
Spatial difference	×	×	×	×	× Not sure what You mean by this question

Table 6 (*continued*)

Topic/question	ATHENA	Envest	Eco-Quantum 3	BEAT 2000	BEES
Geographical difference	√ All LCIs reflect regional technology differences, electricity grids and transportation modes and distances	√ UK average data based on appropriate transport distances, mode, grid mix, etc.	×	×	× US average
Impact categories	√ Use six impact indicators primarily characterization with some valuation measures	√, some CML and some BRE	√ CML 11	?	√ BEES 2.0 Technical Manual Section 2.1.3
Conservation of resources	√ Via recycling modeling	×	√	√ Consumption of non-renewable resources are included in the environmental profile	√ BEES 2.0 Technical Manual Section 2.1.3
Valuation methods	√ Valuation scenario used to compare and contrast the impacts of extracting disparate resources	√ Ecopoints (BRE Digest 446)	√ To 4 and 1 score	√ UMIP-method (it is not "hard coded" into the tool (and can therefore be changed by the user))	√ BEES 2.0 Technical Manuarl Section 2.1.4

[a] The topic of real estate maintenance seems to be a topic that is not commonly handled by LCA tools for the construction sector according to the questionnaire. The case could, however, be that real-estate maintenance is not the proper designation for the activities of gardening, maintenance of roads and walkways, playgrounds, patios, etc. We have, therefore, excluded the topic of real estate maintenance from the result presentation.

[b] The question is in this case if it is possible to assign the object under studied a environmental sunk cost (residual environmental value) that can be subtracted from total environmental cost obtained in the assessment in analogy with life-cycle cost methodology. The use of environmental sunk cost (residual environmental value) as a cut-off could be a feasible way of avoiding the problem of allocation between different phases of a constructions total life-cycle.

[c] Procedures for scenario modelling seem not to be commonly incorporated in the studied LCA tools, or it might be the case that scenario modelling is not a procedure that should be included in an LCA tool. Instead it might be more feasible to ask if the tools are utilised to give the user the possibility to change the parameters that are associated with life-cycle scenarios, replacement rate of various materials and products, service life definition and estimation, risk of substitution or changes in the demand for the provided service, estimation of sunk costs, etc.

This reasoning leads to the identification of another difficulty i.e. the choice of basis for the estimation of the service life of the different entities that constitute the service providing system (e.g. economic or technical service life) and the choice has to be based on a wider perspective including other decision supporting information as e.g. LCC studies.

Appendix A.

This is a compilation of the results of the questionnaires based on the topics in Table 1 and which where sent to representatives for the five tools. In the Table below, √ represents a positive answer, i.e. the topic is handled by the tool, and × represents a negative answer, i.e. the tool does not handle the topic (Table 6).

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