LIFE CYCLE ASSESSMENT METHODS FOR BUILDINGS

LIFE CYCLE OF BUILDING

Annex 31

Energy-Related Environmental Impact of Buildings

International Energy Agency

Energy Conservation in Buildings and Community Systems Programme

ANNEX 31

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THE SPECIAL CASE OF LCA FOR BUILDINGS

Life Cycle Assessment (LCA)[1] is a technique for assessing the environmental aspects and potential impacts associated with a product. The LCA method entails compiling an inventory of relevant inputs and outputs for a clearly defined system; and then evaluating the potential environmental impacts associated with those inputs and outputs. Results are interpreted in the context of the study objectives.

LCA studies environmental aspects and potential impacts throughout a product's life – from raw material acquisition through production, use and disposal. Figure 1 illustrates this flow of materials from nature, to nature, through the course of a building's life.

Generally considered are impacts on resource use, human health and on the ecological consequences associated with the input and output flows of the analysed system. The LCA method is not the only approach to analysing the impact of material goods on their environment, but it is probably the most comprehensive.

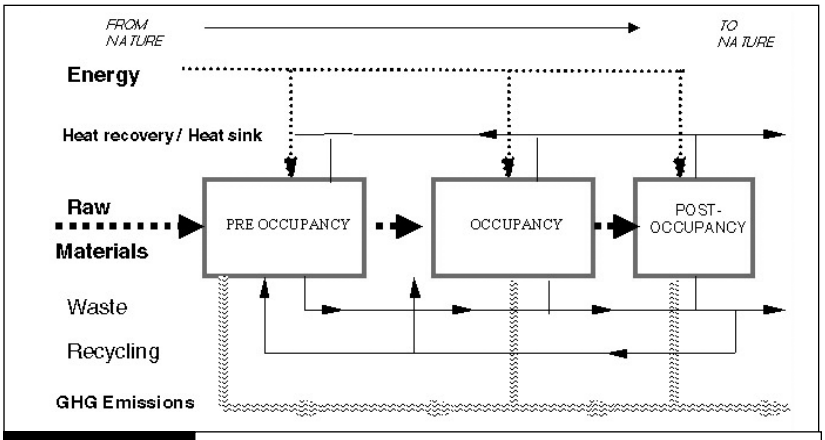


Figure 1 *Life Cycle Assessment for Buildings*

LCA methods can be directly applied to the building sector – building products, single buildings and groups of buildings. However buildings are exceptional products and have many characteristics that serve to complicate or frustrate the application of standard LCA methods. More specifically, buildings are difficult to assess because:

- the life expectancy of a building is both long and unknown, this causes imprecision. For example, the energy sources or the energy efficiency may change, thus predictions of environmental loadings cannot be precise;
- buildings are site specific and many of the impacts are local – something not normally considered in LCA;
- buildings and their components / products are heterogeneous in their composition. Therefore much data is needed and the associated product manufacturing processes can vary greatly from one site to another;
- the building life cycle includes specific phases - construction, use and demolition - which have variable consequences on the environment. For example, in the use phase, the behaviour of the users and of the services operators or facilities managers have a significant influence on energy consumption.

[1] LCA is to a large extent specified and defined by SETAC (Fava et al, 1990) (Consoli et al, 1993), CML (Heijungs et al, 1992), the Nordic Guidelines on Life Cycle Assessment (Lindfors et al, 1995) and ISO 14000 (ISO, 1997). A more recent compilation and introduction to the methodology can be found in (Jensen, 1997).

- a building is highly multi-functional, which makes it difficult to choose an appropriate functional unit;
- a building creates an indoor living environment, that can be assessed in terms of comfort and health. To maintain a good quality indoor environment, the building needs energy (heating, ventilation, lighting, etc.) and materials. There are therefore, strong linkages between the impacts on the exterior environment and the quality of comfort, indoor air, health and productivity; and
- buildings are closely integrated with other elements in the building environment, particularly urban infrastructure like roads, pipes, wires, green space and treatment facilities. Because building design characteristics affect the demand for these other systems, it can be highly misleading to conduct LCA on a building in isolation.

Organisation of this report

This report begins by summarising the basic LCA method, and describes how the method is generally applied to building products, single buildings and groups of buildings and infrastructure.

The second part of the report examines six problem areas encountered when LCA methods are used for buildings. Suggestions are made about how to adapt the LCA method. These LCA issues are examined in detail:

Issue 1. Setting Boundaries for Building Assessments

Issue 2. Accounting for Local Impacts

Issue 3. Use and Maintenance Scenarios and Accounting for Building Adaptability

Issue 4. The Allocation Problem

Issue 5. Accounting for Transportation Costs during Occupancy Phase

Issue 6. Analysing Groups of Buildings (Stock Aggregation)

A BASIC INTRODUCTION TO LIFE CYCLE ASSESSMENT FOR BUILDINGS

Definition and general methodology

Life Cycle Assessment (LCA) is now a well-known and internationally recognised technique, abundantly documented and framed by standards. LCA principles are generally applied when performing an environmental assessment of building products or of an entire building. The basic rationale for LCA have been described in the Annex 31 report on Environmental Frameworks.

In short, Life Cycle Assessment is a technique for assessing the environmental aspects and potential impacts associated with a product by:

- compiling an inventory of relevant inputs and outputs of a system;
- evaluating the potential environmental impacts associated with those inputs and outputs; and
- interpreting the results of the inventory and impact assessment phases in relation to the objectives of the study.

Previous applications of LCA for product evaluations have produced a fairly standard set of possible environmental effects for consideration. LCA generally incorporates indicators in three categories: consumption of scarce resources, ecosystem quality and damage to human health. Within these three categories, 10 possible outputs are shown in Figure 2.

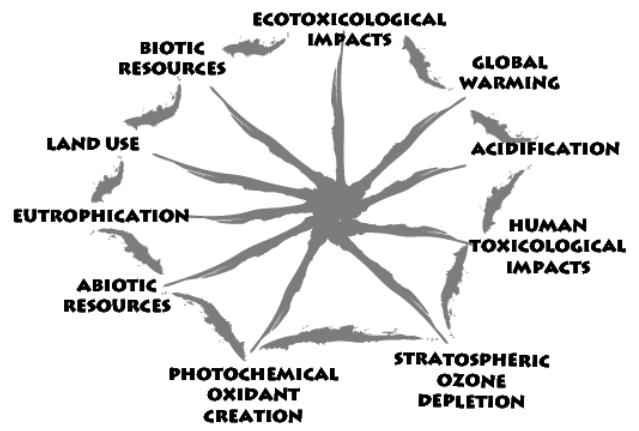


Figure 2 *Common Effects Considered in LCA*

LCA METHODOLOGY

1. Goal and Scope definition
   - Life cycle definition
   - Functional unit
   - System boundaries and data quality requirements
   - Critical review process
2. Inventory Analysis
   - Data collection
   - Refining system boundaries
   - Calculation procedures
3. Impact Assessment
   - Category definition
   - Classification
   - Characterisation
   - Weighting
4. Interpretation of Results
   - reconsider the definitions and assumptions made in the Goal and Scope definition step.

Object of an LCA

The object of an LCA is quite different from simpler approaches based on product criteria or characteristics. Not only is the product itself assessed, but included also are the production facilities and supporting systems required to produce and deliver the product and to use, maintain, deconstruct, recycle or otherwise dispose of it.

Methodology description

An LCA consists of four distinct 'methodology steps' as shown in the text box above. Successful application of these steps requires a clear identification of the product, its life cycle, the choice of technical systems to be represented in the system boundaries and statements of basic anticipations.

The term Life Cycle Inventory Analysis (LCI) is often used as the name for steps one and two of a Life Cycle Assessment.
The term Life Cycle Impact Assessment (LCIA) is often used as the name for steps one to three.

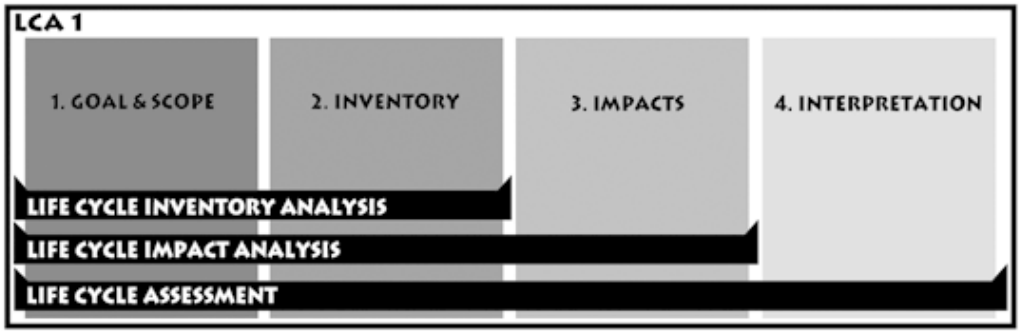


Figure 3 *Life Cycle Inventory, Analysis, and Assessment Methods*

Importance of clear basic definitions

Before starting with any data inventory for the investigated product, a set of definitions has to be made within the goal and scope definition. These basic definitions are needed:

1. for users to understand the results of the study
2. to enable a clear structure of the analysis
3. to clearly identify the object and the objective of the study.

These basic definitions have a large influence on the following steps in the assessment procedure. Meanwhile, the character of an LCA study is often iterative, as initial definitions may have to be changed, adapted and refined during the conduct of the study. Disregarding or mistreating the first steps will necessarily lead to poor quality results.

Step one – goal and scope definition

The first important step of any LCA is the definition of the Goal and Scope – including, Functional Units, System Boundaries, Data Quality Requirements, and a Critical Review Process.

These basic definitions have to be carried out carefully, as the results obtained will only be valid for those definitions. Interpretation of results in situations similar to, but varying from the preconditions of the study, may remain unsupported by the study.

Life cycle definition

The entire life cycle of the product must be included in LCA from the outset, although boundary setting may later exclude specific life stages. This means that those systems required for generating, using and disposal of the product are all relevant. This, "cradle to grave" or "cradle to cradle" approach necessitates identification of the products life cycle and of the processes participating in it. In the case of long lived products, such as a building, the definition of the product's life cycle incorporates assumptions or estimates of the:

- functional service life time
- use and maintenance scenarios
- repair and replacement of components
- major refurbishment or renovation scenarios for the building, and
- demolition and recycling scenarios

Functional units

The usefulness of a product is identified through its Functional Unit (FU), which can be expressed by various measures. It has to be clearly identified and measurable. The FU serves as a basis of comparison and as a basis for normalisation reference for the input and output flows.

The functional unit is strongly related to the "product in it's application", hence it's functionality. A useful description of the functional unit may be difficult, especially when assessing lower system levels. However in comparative studies, evaluation of different products or design solutions is valid only when the products fulfil the same functional unit.

System boundaries & data quality requirements

According to the goal and the scope of the study, boundaries identify the extent to which specific processes are included or excluded. The system boundaries define and structure the technical system under assessment. A balance is desired between practicability of the study and validity of the results.

An inventory of inflows and outflows is to be performed over all processes that lie within the system boundaries. The quality requirements for gathered data can be defined and quality indicators can be established. Data quality requirements may address aspects such as time, geographical and technology-related coverage of the included data.

Critical review process

A critical review process may serve to ensure the quality of the study. If reasonable, a reviewer or a review panel may be consulted in order to ensure that methods used are: consistent with ISO standards; scientifically and technically valid; that data is appropriate and reasonable in relation to the goal; that interpretations made reflect the limitations and the goal; that the report is transparent and consistent.

Step two – inventory analysis

Inventory Analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The Inventory Analysis step consists of data collection and the refining of system boundaries. Decisions are made about allocation[2] of energy and material flows. Data is reviewed to ensure it is valid for the specific system under study. System boundaries are refined, in consideration of the defined scope of the study. Data handling is restricted only to inputs and outputs that are significant to the goal of the study.

This refining process may involve exclusion of life cycle stages or subsystems and material flows in case of insignificance; it may also involve the inclusion of unusual unit processes in cases where they appear to generate significant impacts.

Inventory data is to be related to reference flows for each unit process in order to quantify and normalise input and output to the studied functional unit. Data will then be aggregated in order to result in an input-output table for the studied product or service. Depending on the goal and scope of the study, interpretation may be drawn directly from these data via:

- checklists that verify whether certain substances or emissions are to be found in the tables,

[2] For a description of "allocation" processes, refer to the Environmental Framework

- criteria evaluation, where key data are assessed or specially promoted and interpreted,
- indicator approach, where data contributing to certain key aspects are used to represent a first estimation of the actual environmental impact, or they may constitute input to the following Impact Assessment step.

Step three – impact assessment

The Impact Assessment step can be subdivided into four sub-steps:

1. category definition,
2. classification,
3. characterization, and
4. weighting.

Category definition

The aim is to provide guidance for selecting and defining the environmental categories addressed by the study. The selection should be rather complete and shall not avoid or disguise environmental issues or concerns. The selection of categories should be consistent with the goal and scope of the study.

Classification

The classification step is performed to assign inventory input and output data to the defined impact categories. It is a qualitative step based on scientific analysis or an understanding of the relevant environmental processes. Eventually all the relevant inventory data are assigned to potential environmental impacts, in so-called "impact categories". Classification is regarded as the minimum step of Impact Assessment. In some cases, no further impact assessment is necessary prior to interpreting results.

Characterisation

For each impact category, the relative importance of the contributing substances can be modelled and quantified. This relative importance, or impact potential, is expressed relative to norm or reference substance. Essentially the impacts are converted to a proxy using an equivalency factor.

The characterisation step necessitates the ability to model the categories in terms of standardised indicators. The chosen indicator is used to represent the overall change or loading in the category. Equivalency factors do not yet exist for all impact categories.

The result of the characterisation step is the expression of contributions to impact categories in terms of equivalent amounts of emitted reference substance for each impact category.

Weighting

For ease and clarity of decision-making, it is sometimes useful to further combine impact categories. This is accomplished by means of weighting – a process that ranks categories according to their relative importance to each other, and assigns numerical values to represent degrees of significance. Weighting often involves ethical or societal value judgements rather than scientific information. Weighting factors for such aggregation may be based on:

- Proxy methods
- Monetarisation
- Environmental state indicators
- Environmental political goals

Many approaches are used for weighting impacts, including intuition. A difficulty arises due to the arbitrariness of weighting numbers, since changes in weights can swamp efforts to ensure precision in the values to be rated. Allocating a weighting factor beyond two significant figures is almost certainly unrealistic. This, in turn, indicates that there is little to be gained by determining the value of other data beyond two significant figures also.

Weighting is especially helpful when attempting to reduce LCA to a single "score" for environmental impact, and then make overall comparisons between alternative buildings or designs. Without doubt this is of value to the actor who has neither the time nor the interest to get involved in details. However, within that very simplification lies the weakness of weighting, - namely that it can overly isolate the actor from the reality represented by much of the detail. For example, it is important for users to understand the potential for emission of greenhouse gases during the in-use phase relative to other phases, and to comprehend the significance of transportation energy in relation to the location of a building. Obscuring such information may ultimately be a disservice to the decision-makers.

Step four – interpretation of LCA results

In earlier LCA definitions, the final step of an LCA was called "improvement assessment". With varying intention in the application of LCA, from hot spot analysis in product development to comparative studies of alternative products, such improvement assessment is often not relevant. Consequently, the step has been replaced by an "interpretation of results".

Interpretation of results will incorporate an identification of significant environmental issues, an evaluation of the underlying study and the generated information and is intended to lead to conclusions and recommendations. The interpretation procedures should be evaluated for completeness, sensitivity and consistency. Any interpretation of results has to reconsider the definitions established during Goal and Scope setting.

ISSUE 1: SETTING SYSTEM BOUNDARIES

System boundaries define what is included, and excluded, as part of LCA. Boundaries can be established in all areas:

- **Life cycle stages** (e.g. extraction of resources, fabrication, transportation, construction)
- **Geographic scale** (e.g. Assemblies, Building, Site, Development Infrastructure, Urban Infrastructure)
- **Resources** (e.g. fossil fuels, plastics, steel, concrete)
- **Groups of concern** (e.g. Society, future generations, businesses, other nations)
- **Impacts of concern** (e.g. Human health, Biodiversity, Resource Depletion)

Ultimately the system boundaries must relate closely to the intended use of the tool, (this is explained in more detail within the Annex 31 report on Decision-Making Frameworks). System boundaries also need to reflect a reasonable compromise between the validity of the results and the practicability of obtaining them.

Setting system boundaries for buildings is critical to achieving valid and comparable results. A system boundary has the effect of limiting specific resource flows and emissions included in the assessment. These flows and emissions are the sources of impacts, and through cause and effect chains they ultimately establish the LCA results. Indeed, comparative studies implementing different LCA tools show that most of the variations observed in the results come from differences within the limits of the system - differences that were not always clear at the outset.

Rules of Thumb for Boundary Setting

Consensus on where to draw boundaries for building-related LCA is unlikely to emerge. Generally some rules of thumb are used to assist in boundary setting:

- some sources can be excluded simply because the associated flows are negligible to the final results,
- some desirable aspects of assessment may not actually be feasible, which is why some sources are excluded,
- non-negligible flows associated with some sources are sometimes poorly known (lack of reliable models, or uncontrolled variables such as the transport mode of occupants) and thus tool developers prefer to exclude the flows so that the more controlled environmental effects of the variants studied can be more favourably revealed,
- when decision-makers dealing with a building are unable to modify some causes of impact, these are often excluded from the assessment,
- some processes can be considered as being external to the life cycle of the building as they belong to other systems (e.g.: the final disposal of some wastes),
- the cost of the assessment should also be taken into account, as it increases in proportion to the exhaustiveness of sources; in some applications, a limit to the cost of the assessment is a criterion which can cause the limits of the system to be restricted.

In any event, if a source leads to non-negligible flows, if reliable calculations of flows are available, and if decision-makers can affect this source, it would be a mistake not to include it in the system.

Especially problematic sources for LCA include occupant behaviour in the use phase, transportation inputs, and the processes (and related flows) linked to the infrastructure of the building (in particular the water supply, sewage, and solid waste processing). These sources emphasise the fact that a building is a sort of active “process” during the use phase, and that a building is only one dependant element within a broader and more complex urban system.

Describing Functional Units for Buildings

A delicate question is the choice of a "functional unit", a common standard value in which the results will be expressed. A functional unit refers to one or more functions of the object to be assessed, and to duration of utilisation. In the case of a building, this choice is not simple. There is no single and ideal answer, particularly because a building is multi-functional, and a choice must be made according to the objectives of the study (comparison of two buildings of different size, variants of a single building, etc.).

The functional unit of indicators varies according to the intended utilisation of the tool: for a comparison between buildings, a ratio per sq. m. or cu. m. is probably the most informative,

and a currently used solution without being really satisfactory; to assess a dwelling unit and its variants, the functional unit defined by "the use of the dwelling unit for a period of one year" appears to be satisfactory. The definition of a functional unit can prove suitable for some impacts, resulting from an aggregation of flows, and not for others, such as comfort, for instance, which involves other types of variable.

Describing System Boundaries

While it is frequently difficult to define a functional unit in clear terms for buildings, it may be simpler to define the system boundaries. The issues of which life cycle stages to include, and which resources, are relatively straightforward, although the trade-offs are sometimes difficult to assess. However a more difficult task is establishing the social and economic processes that should be included in the building LCA. A useful technique for establishing social and economic boundaries is to start from a ”socio-economic whole system“, and use the system model to establish the LCA boundaries. Figure 4 illustrates such a socio-economic model. Each element within the model provides a convenient guide for initial boundary setting.

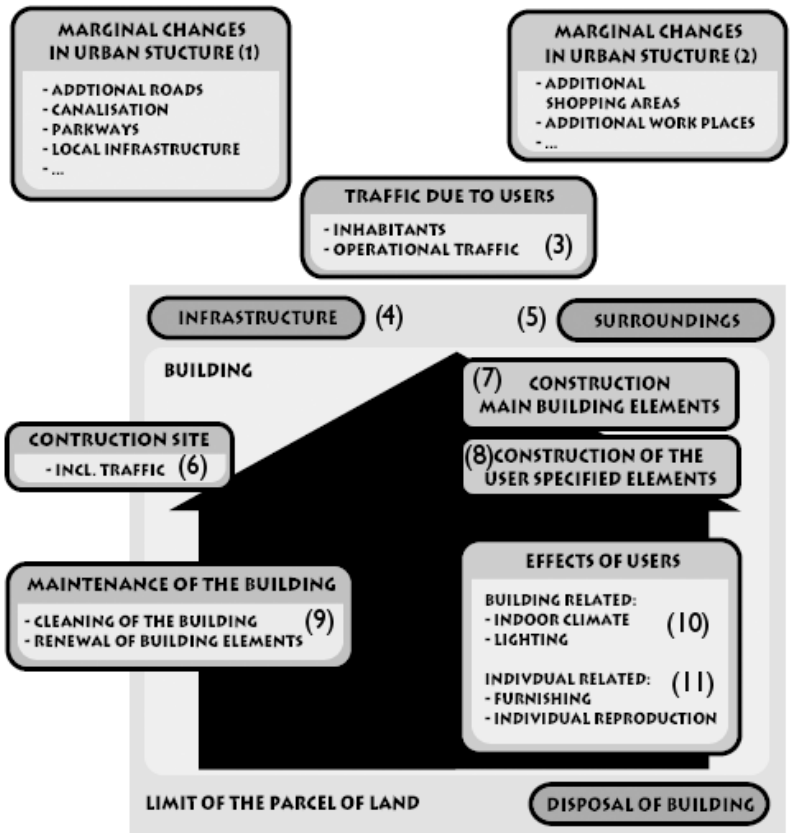


Figure 4 *The Socio-economic model for Establishing System Boundaries*

The boundary setting process should reflect the type of LCA assessment. For example, comparing two different buildings may require more inclusive boundaries than comparing alternative technology for the same building project. Table 1 examines which of the subsystems in Figure 4 are appropriate for inclusion in the LCA, depending upon the type of question that is being addressed.

Question	Functional Unit	System Boundaries		
		Sub-system	Included in Assessment?	Rationale
1. What is the preferred level of functionality for a building?	Net-revenue	1	eventually	if the project is big enough to cause changes: yes if not: no
		2	eventually	see above
		3	no	if the two variants show big differences in this aspect: yes
		4, 5, 6, 7	yes	
		8	no	can not be influenced by the investor
		9, 10	yes	
		11	no	can not be influenced by the investor
		12	yes	
2. Which one of two buildings performing the same function is ecologically better?	Pae[3] * year, at quality standard x	1, 2, 3	no	not in question
		4, 5, 6, 7, 8, 9, 10	yes	
		11	no	not in question
		12	yes	
3. Renovation or demolishing and reconstruction of a new building?	m^2 EBF[4] * year at quality standard x	1,2,3	no	not relevant
		4,5,6,7	yes	
		8	no	not in question
		9,10	yes	
		11	no	not in question
		12	yes	
4. How can buildings be considered in LCA's of other applications?	housing: m^2 EBF * year	1,2,3	no	part of the main LCA
	industry: m^3 * year	4,5,6,7	yes	
		8	no	part of the main LCA
		9	yes	
		10,11	no	part of the main LCA
		12	yes	
5. How can an early change of the original function of a building be considered in LCA?	Use of the theoretical lifetime of the building provokes some forgotten impacts that will not appear in any of the performed LCA's. A correct methodological approach would be treating it like a closed-loop recycling.			

Table 1 *System boundaries appropriate for a range of LCA assessment*

[3] Pae= Person-Equivalents: Number of persons theoretically able to live in the building
[4] EBF= Energiebezugsfläche: area of energy consumption

Sensitivity and uncertainty analysis
Inevitably, the input data used for the assessment and in the background assumptions will be subject to uncertainties. Some of these will be significant in terms of the accuracy of the outputs, whilst others will have little impact.

LCA methods can be distinguished in terms of both uncertainty and variability (Huijbregts, 1998). Uncertainty is categorised as 1) parameter uncertainty, 2) model uncertainty and 3) uncertainty due to choices. Variability covers: 4) spatial variability, 5) temporal variability and 6) variability between objects and sources.

A sensitivity analysis can be performed as part of the boundary setting process. The results can identify which subsystems have the most influence on the overall result. The results can also be used to simplify data collection and analysis for specific subsystems, without compromising the robustness and practicality of the analysis. Sensitivity analysis, when used skilfully, can dramatically reduce the scope of LCA, and the corresponding quantities of data and work needed to arrive at a robust assessment of impacts.

ISSUE 2: ACCOUNTING FOR LOCAL IMPACTS

Buildings are unusual and difficult products for LCA because many of the environmental impacts are locally specific. Site-specific environmental impacts of concern include at least four categories:

i. **Neighbourhood Impacts** (e.g. micro-climate, glare, solar access, wind patterns);
ii. **Indoor Environment** (e.g. Indoor Air Quality and Indoor Environmental Quality);
iii. **Local Ecology** (e.g. ecologically sensitive areas, connected green spaces,); and
iv. **Local Infrastructure** (e.g. carrying capacity of transportation system, water supply).

Traditional LCA does not address local impacts of this type. Instead, all the loadings are aggregated, and thus impacts can only be calculated at the regional or global scale. In order to adapt LCA to buildings, the site-specific impacts must be either excluded from the assessment (by boundary setting), or separately inventoried and classified.

Site Specific impacts are of concern to many actors, and can help to provide a much more balanced view of the building performance. They also involve processes that are quite different that the more traditional LCA impacts. This implies a more extensive data collection exercise.

Modelling of site performance is becoming much more common. However this is usually restricted to indoor environmental quality, and to natural ventilation and lighting potential. The interaction between a building and the local environment, in terms of noise, glare and other factors, is much more difficult to model and typically beyond the capacity of LCA practitioners.

As communities strive for green infrastructure and sustainable urban systems, the impact of building design on the local environment will become more significant. Well-designed buildings can benefit the community by contributing to the industrial ecology and by functioning as part of the neighbourhood infrastructure (generating power, treating wastes, collecting water and so on). Understanding such interactions is a necessary step in assessing lifecycle environmental impacts for a specific building design. Since models and tools are currently unable to predict most of these site-specific impacts, LCA methods cannot adapt to meet such needs. The best alternative may be to combine LCA with more passive and qualitative evaluation tools.

ISSUE 3: USE AND MAINTENANCE SCENARIOS AND ASSESSING BUILDING ADAPTABILITY

Unlike most other products, buildings are occupied for long periods and their 'use' phase can be more significant to the environment than all other phases combined. The issue for LCA applications is how best to characterise the use phase. Scenarios are needed to define the role of occupant behaviour. Other scenarios are needed to indicate how the building will survive – maintenance cycles, repair and replacement schedules, renovation and refurbishment of interior spaces by occupants. Especially important to building performance and longevity are assumptions about how efficiently the building will adapt to changing expectations, changing uses, and the introduction of new technologies. (Many buildings are vacated or demolished long before their useful life due to a lack of adaptability.) Creating usage scenarios is thus critical to assessing the true long term performance of a given design or product or system.

Unfortunately the high degree of uncertainty about the use phase makes it extremely difficult to develop credible scenarios. We know that the situation is unlikely to remain static – change is inevitable and the pace of change is trending greater. It is important to give credit to buildings that are designed in ways that extend their useful lifetime, and use materials and space efficiently. How is this accomplished as part of LCA?

Characterising Buildings according to Adaptability

Adaptability refers to the capacity of buildings to accommodate substantial change. Over a building's lifetime, change is inevitable, in both the social, economic and physical surroundings and in the needs and expectations of the occupants. All other things being equal, a building that is more adaptable will be utilized more efficiently and stay in service longer, because it can respond to changes at a lower cost than one that does not have adaptable features. A longer and more efficient service life for the building may, in turn, translate into improved environmental performance over its life cycle.

The concept of adaptability can be broken down into a number of simple strategies that are familiar to most designers:

- flexibility, i.e. allows for minor shifts in space planning;
- convertibility, i.e. allows for changes in use within the building; and
- expandability, i.e. facilitates additions to the space in a building.

In practice, these strategies can be achieved through changes in design, and through the use of alternative materials and technologies.

Adaptability is closely related to – but different from – two other design strategies that attempt to enhance long-term environmental performance:

- Durability: selecting materials, assemblies and systems that require less maintenance, repair and replacement. Since durability extends the useful lifetime of materials and technology in a building, it is complimentary to adaptability.
- Design for Disassembly: making it easier to take products and assemblies apart so that their constituent elements can more easily be reused or recycled. Designing for disassembly can reduce the costs and environmental impact associated with adapting buildings to new uses. It is also possible to reduce overall environmental costs by purposely designing a building for a shorter life, and for easier disassembly and reuse of components and materials – as is the case with many temporary exhibition halls.

All three strategies are important to consider when establishing scenarios for the use phase of a building.

The Importance of Designing Adaptable Buidings

As the world faces resource scarcities and ecological crises, a concern for the adaptability of buildings is especially relevant. The existing building stock represents the largest financial, physical and cultural asset in the industrialized world. A sustainable society is not possible until this key resource can be managed sustainably.

Urban areas everywhere are experiencing problems related to poor use of buildings, and high flows of energy and materials through the building stock. Demolition rates are rising, and due to the artificially low costs of landfill disposal and incineration, much of the solid waste is not being recycled. The average lifespan of Tokyo office buildings constructed during the 1960's was under 20 years. In Germany, of the 60% of buildings that survived WW2, only 15% remain standing today.[5]

Kohler[6] summarizes a number of trends found in the German building stock, which also speak to the increased relevance of adaptable stocks:

- New construction levels steadily decreasing;
- Refurbishment activities surpassing new construction;
- Large numbers of old buildings (warehouses, industry) sitting empty;
- Growing numbers of new, highly-equipped office buildings, for lease (resulting from over production and corporate downsizing and outsourcing);
- Flows of basic materials into the stock –for new construction and renovation – exceeding the solid waste flows by 4 to 10 times, (which indicates that the building sector is still a major consumer of natural resources).

While these specific trends may not yet apply to all other countries, the conclusion is clear and universal: increasingly buildings need to be designed for long-term adaptability.

[5] CMHC Building Adaptability: A View from the Future, Fanis Grammenos, Peter Russell

[6] Kohler, N., Schwaiger, B, Sustainable Management of Buildings and Building Stocks, Proceedings of the Green Building Challenge, CIB, Vancouver, 1998

Addressing Adaptability in LCA

If adaptability is to be a design concept that can be measured and addressed in LCA scenarios, it must be possible to properly distinguish those features of new buildings that will significantly increase their capacity for change. This is difficult.

Part of the problem is that few buildings exist today that have been intentionally designed for adaptability, and put to the test of time. Traditionally many designers and owners have preferred to work from the assumption that their buildings will never experience significant change. But even when the inevitability of change is fully appreciated, the marketplace offers little incentive for developers and owners to invest in long-term adaptability. The initial developer who invests in a more adaptable building structure is unlikely to ever realize the economic benefits. For these reasons there are few older buildings purposefully designed for adaptability, and thus little evidence that adaptability is an effective design principle for improving environmental performance.

A more fundamental obstacle is the difficulty in accurately predicting future requirements for buildings. While it is definitely possible to identify features of existing buildings that have enhanced their capacity to adapt, it is in no way certain that such features will function similarly in the future. The type of changes that will occur in the 21st century may be wholly unlike what has occurred in the past. The computer revolution has only just begun, the nature of work is changing, and even the climate is changing. We are almost certain to experience major environmental disasters and large movements of peoples. Even the pace of change may be significantly greater in the next few decades. In truth, the future is largely unknowable when forecasting over the 50+ year life of buildings.

Consider for example a designer from 35 years ago, who may have tried to make a new, 1960s building intrinsically more adaptable. Would the designer have had the foresight to facilitate such changes as removal of asbestos insulation from all the pipes and ducts? Extra ventilation for computer rooms? Larger window areas? Increased plug loads? Installation of natural gas, district heating pipes, or PV panels? Relocating the fresh air intakes to avoid toxic street pollution? Much higher occupancies? Greater expectations for comfort and environmental control?

Probably none of these changes were predictable. In fact long-term forecasts are notoriously inaccurate. This high degree of uncertainty undermines the present value of any potential benefits from adaptable building designs.

How Might Adaptability Improve Environmental Performance

Unless a building is capable of responding to changing circumstances it is vulnerable to becoming poorly utilized, prematurely obsolete and unable to accommodate new, more efficient technologies. The combined impact of such failures may be to increase resource use within the building sector by 20 to 30%. Depending upon the additional investment required to achieve adaptable designs and materials, it should be possible to significantly improve the environmental performance of the world's buildings in at least three ways, as outlined below.

1. More efficient use of space - Adaptable buildings are likely to use the same amount of space and materials more efficiently, on average, over their entire life. For example, increased flexibility of spaces might mean that it is easy for occupants to use floor area more effectively as their needs change, or as their business (or family) expands. Convertibility may allow

basements, attics, hallways, storage areas, roofs and entrances to be used for other purposes, as new needs arise. Expandability may allow the building to accommodate much higher densities with the same footprint and infrastructure. If such adaptations create even small improvements in space utilization over the lifecycle of buildings, the impact on resource use can still be significant. For example, if the average lifetime space utilization is 10% improved, and all buildings are similarly designed for adaptability, then the world needs 10% fewer buildings.

2. Increased Longevity - Adaptability is also a strategy for extending the total lifetime of buildings. Most buildings are destroyed due to technological obsolesce, not structural deterioration. Adaptability can therefore extend lifetimes without imposing any of the significant environmental impacts associated with all the one-time investments in the building structure and infrastructure. Consider, for example, the embodied energy in reinforced concrete – probably the single greatest pollutant source in a typical commercial building. Or consider the other long lasting elements of a building like wood, metal, glass and landscaping materials. Or consider the energy used in construction, demolition, and haulage and disposal of earth, materials and waste. If adaptable designs can extend the average lifetime of buildings by 10%, (and possibly much more), then we can similarly reduce the total world investment in replacing these long-lasting elements of the building stock. The most environmentally benign building is the one that does not have to be built.

3. Improved Operating Performance - Adaptability can also mean easier changeovers as new technology becomes available. Thus adaptable buildings benefit from technological innovation sooner and at lower cost. The average efficiency of many technologies used in buildings – like lighting and ventilation systems - has more than doubled over the past 10 years. Many other technologies, like combustion heating systems and electrical motors, have improved at least 20%. If a building has features that allow easier adoption of new, efficient technology, it is reasonable to assume an increase in average lifetime operating efficiency of 10% or more. This in turn would reduce the total environmental impact of operating the world's buildings by 10% – a very significant improvement.

Quantifying the Effect of Adaptable Design on Environmental Impact

There appears to have been no effort yet made to use LCA to directly link adaptability with environmental loading. Generally it is assumed that the improved use of space, and longevity, translate into a proportional improvement in all the environmental loadings associated with building operation and material use and disposal.

A paper by Larsson[7] examines adaptable office buildings, and assumes that the environmental benefits are largely related to two factors: the annualized reduction in embodied and replacement energy, and the annualized reduction in solid waste generation from renovation and demolition. Using data from research studies that document the quantities of embodied energy and demolition energy used by office buildings[8 9], Larsson estimates an equivalent reduction in two categories of environmental loadings:

- ~15% reduction in air emissions, and
- ~15% reduction in demolition solid waste.

[7] Larsson, Nils K., Sustainable Dvelopment and Open Building, Presentation to CIB TG26, Brighton UK, 1999,
[8] Environmental Research Group, School of Architecture, UBC, Life-Cycle Energy Use in Office Buildings, 1994
[9] M. Gordon Engineering, Demolition Energy Analysis of Office Building Structural Systems, 1997

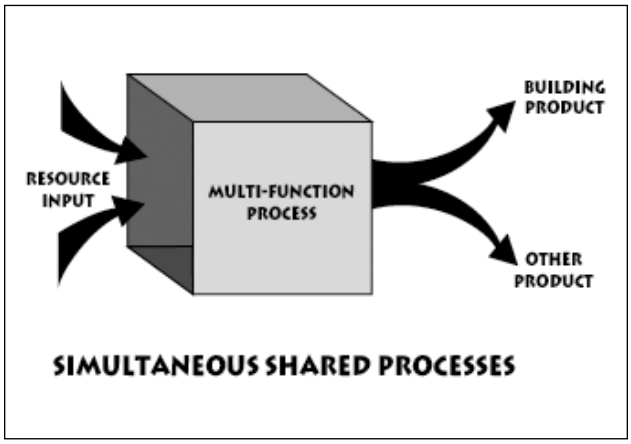
No estimate was made of the potential impacts of using office space more efficiently. Based upon the research to date, and the uncertainties described above, the issue of adaptability for buildings is not resolved at present. Usage scenarios for buildings are too simplistic at present, and reduce the validity of LCA results. Methods for defining and measuring the durability, reusability and overall adaptability of buildings need to be developed and validated. For a more detailed examination of these issues, refer to the Annex 31 Report on Assessing Buildings for Adaptability in the Annex 31 Background Reports.

ISSUE 4: THE ALLOCATION PROBLEM

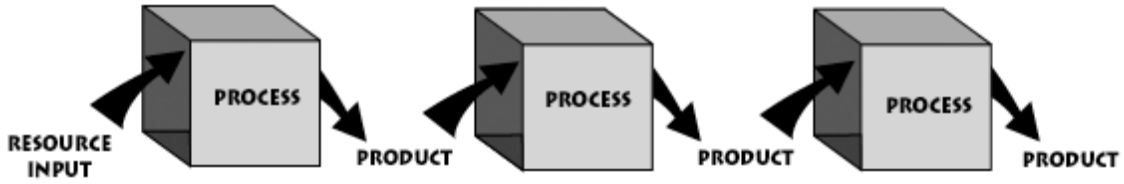
Background on the Need of Allocation

The need for allocation occurs mainly in two distinct situations:

1. **The process in question delivers more than one useful product** also called "multi functional process". In fact, most processes included within typical LCA system boundaries contribute to the production of more than one product. Under such conditions, allocation procedures are required to determine which inputs and outputs of the multifunctional system are attributable to the one product or service under assessment. For example, information may be available on the overall energy required in a factory producing metal products for the automobile industry and also a particular line of metal products used in buildings. However, there may be no records that discriminate between the amounts of energy required for the auto products and the building products. One of the many ways to allocate the energy would be to apportion the total energy use to each product on the basis of weight. Whatever allocation procedure is used, the object is to ensure that products receive their fair share of the environmental interventions originating from the shared processes.



2. **The process in question is part of recycling loops.** In other words, the multifunction process delivers more than one useful product, succeeding each other in time. For example, the metal produced by the metal factory may contain 50% recycled scrap iron, with correspondingly less environmental loadings. And once the metal has been used in the house, it may be destined for re-use in another building at least once, and then returned to the scrap iron pile for recycling into auto parts. Allocation procedures are needed to fairly allocate the environmental loads from mining, transportation, industrial processes and so on amongst these successive products.



SEQUENTIAL SHARED PROCESSES

In Life Cycle Assessment, allocation is performed within the Life Cycle Inventory Analysis. Various allocation procedures[10] have been established and are available for reference. In the case of non-LCA assessment methods, allocation is often dealt with in a non-explicit manner, e.g. by offering certain bonuses or credits in the case of use of recycled materials, or in the case of use of recyclable materials.

Generally, allocation procedures[11] for any product, including a building and its elements, can be based on:

- Technical / Natural Causality
- Physical Quantities, e.g. mass, volume or energy content
- Economic Value
- Social Causality, and
- Arbitrary Numbers

Existing LCA standards do not identify the allocation method to be used. Instead the allocation procedures are to be chosen by the practitioner. This is to be done carefully and transparently as well as with consideration of the goal and scope definition, as the results of the assessment can be significantly influenced by the choice of method. Whatever procedures are adopted, they need to fulfil a set of key requirements[12]:

1. Based on effect oriented causalities
2. Acceptable to the users of the LCA results
3. Easy to apply
4. Designed with internal logic
5. Avoiding double accounting
6. Feasible at a low level of information
7. Giving incentives for production and use of secondary raw materials

[10] Frischknecht 1997
[11] Lindfors et al, 1995
[12] Ekvall & Tillman, 1997 and Klöpffer, 1996

Life Cycle Allocation over Building Lifetimes

Allocation for buildings is complicated by the large time spans encountered in the lifetime of buildings. Scenarios need to be adopted for establishing the quantities, costs and impacts of recycling products at various times over the next 60 years or more. The longevity of building products (here: buildings) requires specific guidelines regarding credits for recycling at extended future dates. The goal is to develop a protocol that fairly allocates the loads, while at the same time encouraging planning and design decisions that facilitate greater recycling potential at the end of the use period.

In life cycle analyses of non-durable consumer goods, the opinion is sometimes held that with the development of a "total cost" of resources and energy, a reclaimable portion can and should be calculated based on reuse or thermal value at the end of the life cycle. This protocol results in a calculation of initial, operating and disposal costs with a reclaimable portion. While such allocation protocols may be appropriate for non-durable consumer goods it may be unwise to transfer the approach to highly durable goods like buildings. The result can be neglect of space and time. The longevity of buildings means that, effectively, recycling may have negligible affect on the environmental impacts of concern today. In particular, the real and time-dependent energy and material streams cannot be equated. Scarcity, ecological carrying capacity, energy mixes and other factors are certain to change radically, and cannot be controlled and discounted in a similar fashion to monetary cost streams.

Options for How to Deal with Recycled Materials

Three distinct possibilities may be considered when dealing with long-term recycling potential:

1. **Exclude** - Establish system boundaries so that recycling at the end of the life or use phase is completely excluded from the life cycle analysis of buildings.
2. **Relieve Disposal Costs** - The recycling effect is seen as "local relief" in the disposal costs. Materials that are recycled do not need to be disposed of and are therefore not a burden to landfills nor have the resulting environmental impact.
3. **Conditional Global relief at future date** - The recycling effect is taken into account firstly as a relief on disposal costs, and secondly as time-dependent "global relief". The global relief is credited only at the point in time when the event is scheduled to occur, and only if the estimated impact of the recycling processes does not exceed the impact of manufacturing a new product.

Calculation of Recycling Potential

The development of a "recycling potential" indicator is necessary in order to evaluate building products and provide relief. Such a unit would improve the validity of LCA results, and educate decision-makers about the characteristics of buildings, which contribute to reuse and recycling ("Design for Disassembly").

Recycling is never an automatic occurrence. Rather the extent of recycling is dependent upon the available technology and the demand for recycled products at the time of demolition and disposal. However, the planning and design work is influenced by any recycling potential that can be realized within the LCA. From this perspective, the priority is best given to changing behaviour today, despite uncertainties, and to maximising opportunities in the future.

Defining "potential recyclability" is not easy. Assumptions are needed about technical capacity, and whether assumed cost/benefit ratios are prudent. In general, it is prudent to assume that recycling will be cost effective if the technologies available today already show a favourable cost benefit analysis.

Incorporating the Benefits of Recycling at Appropriate Times in the Life Cycle
Whatever the effect of the recycling process, it can and must be seen in a time-dependent manner. The following points in time and period of time are relevant:

- The point in time the material was produced
- The point in time of construction
- The period of time of use (period of repair)
- The period of time of use of demolition and disposal

MATERIAL PRODUCTION
Two possibilities exist for incorporating recycling potential during material production:

1. Use average consumption of resources and energy and in this way incorporate the recycling component in inventory analysis. For example, in steel production the use of scrap metal is already a part of inventory analysis.
2. Treat recycled material as a separate category of input, and create an inventory analysis that reflects the changes in environmental impact.

Recycling effects, which occur in the production process in a closed system at the manufacturer, have a direct effect in the inventory analysis and can only be determined in process analyses.

CONSTRUCTION
Leftover materials from the construction of a building can be introduced into recycling processes. Normally, the amounts are insignificant. The reuse of packaging, scaffolding, etc. is considered in that only a percentage of the energy and material stream as well as the resulting environmental impact (similar to a write-off) is assigned to the individual object which results from the average number of uses/cycles.

REPAIR
The problem of the consideration of recycling effects during repair is methodically identical to the phase demolition/disposal and is only different in its period of time.

DEMOLITION/DISPOSAL
If recycling potential is high, it is possible to assume that building products will actually be used after the end of the use period. However the recycling effect of buildings constructed today is only effective in the future. Therefore, the benefits cannot be credited against consumption today.

Creation of Requirements for the Establishment of Recycling Potential

Scenarios in the inventory analysis of individual buildings can address the potential recycling effects. The impacts from increased recycling include, firstly, reduced landfill volume at the end of the use period. This in turn can generate benefits such as reduced emissions, improved land use, and so on.

Secondly, the recycling potential can be translated into reduced costs in raw materials and energy, as well as resulting environmental impacts. This can generate "relief' by transferring part of the loading to sequential users of the product. Such effects are time dependant, and cannot be credited against resource consumption occurring prior to the time of recycling.

Assessing the Recycling Potential for Buildings Stocks

In contrast to individual buildings there is also value in addressing recycling when assessing groups of buildings, over a point in time-dependent analysis reference year. From an economic standpoint it is possible to calculate, for a specific reference year, the effects of a recycled building stock against the costs of a new building stock. In either case, the LCA method is a useful tool if it can help to predict the average annual energy and material flow into and out of the entire stock year by year. This type of information can help to guide the choices made about investing in enhancing the recycling potential of buildings.

ISSUE 5: ACCOUNTING FOR BUILDING-RELATED TRANSPORTATION

The Importance of Building Related Transportation in LCA

Transportation is a process that needs to be inventoried at each stage in a building's life cycle. Typically, the loadings from transportation are calculated separately from other processes. Transportation energy, for example, would include the energy consumed by:

- transport of raw materials,
- transport of fabricated materials,
- distribution of building materials from warehouse to building sites,
- transport of construction workers and maintenance crews, and
- transport of disposed materials at the end of their lifetime.

Energy used for all this transportation can be very significant. Often transportation impacts are the most variable input for a product, and serve to differentiate the higher and lower impact options. Often transportation is the single greatest energy account, as is the case for buildings in their construction phase.

A major difficulty with LCA for buildings is determining how best to account for transportation during the use phase. Occupant behaviour is difficult to predict, and transportation scenarios are complex. Types and amounts of occupant transportation are dependant upon many factors unrelated to building design or occupancy. And it is difficult to correlate design and management decisions with quantifiable changes in the amounts of occupant transportation. It depends on the system boundaries and objective of the study if this is included in LCA for buildings.

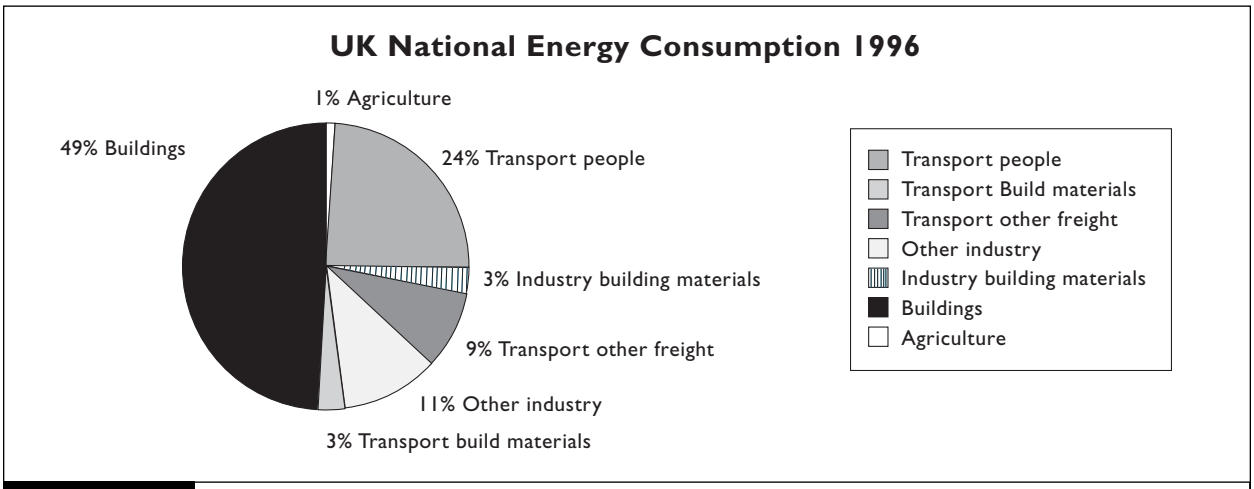


Figure 5 *The energy consumption in the UK.*

Assessing the Significance of Occupant Transportation

Throughout Europe, about 50% of national energy consumption is due to the operation of buildings, and a further 25% is used to move people between buildings. Figure 5 illustrates the very significant impact of transportation on energy consumption for the UK.

Whereas building operational energy is falling due to advances in energy efficient design and new technologies, transport energy is predicted to rise by 4% per annum.

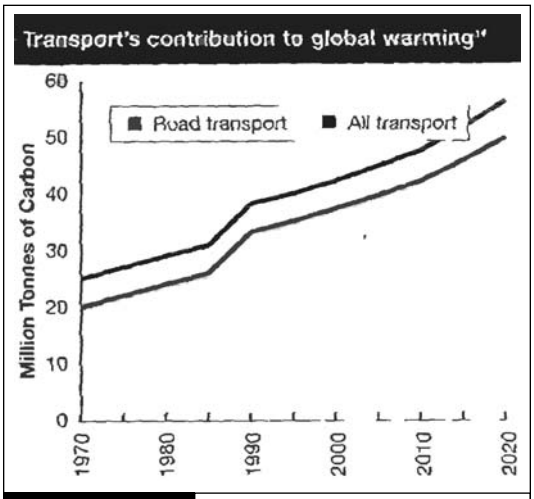


Figure 6 *The contribution of UK's transport to global warming*

In the UK, as with all other developed and urbanised countries, the car is the dominant mode of transport. Figure 6 highlights the contribution of UK's transport to global warming and shows that road transport accounts for 80% of the total carbon produced by transport. The Confederation of British Industry (CBI) has put the cost of congestion to the British economy at approximately £15 billion (EUR 22.5 billion) every year. Transport to and from a workplace can cause environmental impacts as large as those for operating the building. Hence, the transport related environmental consequences of location and the potential for savings are substantial.

Telecommuting

The way we work is changing rapidly. Our presence in a particular location is no longer essential. For a great many tasks using computers and advanced technology enables us to conduct our work from almost anywhere. Teletrips and telecommuting now comprise about 18% of all work in the USA today. LCA methods currently are unable to predict the impact of such changes, even though they are primarily determined by building design and management.

The Importance and Relationship of the Location of a Building

The location of buildings can have a major influence on transport patterns, and particularly on the use of the single occupancy automobiles for commuting and business travel. Location refers to such factors as distance to work and home, distance to amenities, access to public transit and cycle routes, distance to convenience stores, schools and services.

Figure 7 shows the total energy breakdown for two office buildings in the UK. The breakdown for these buildings emphasises the importance of access to transit. The Medlock St. building is actually significantly closer to employee homes, and average travel distances were much shorter. However the lack of access to transit has produced almost twice the energy consumption. In the Medlock St. building, the transportation energy actually exceeds all other energy accounts.

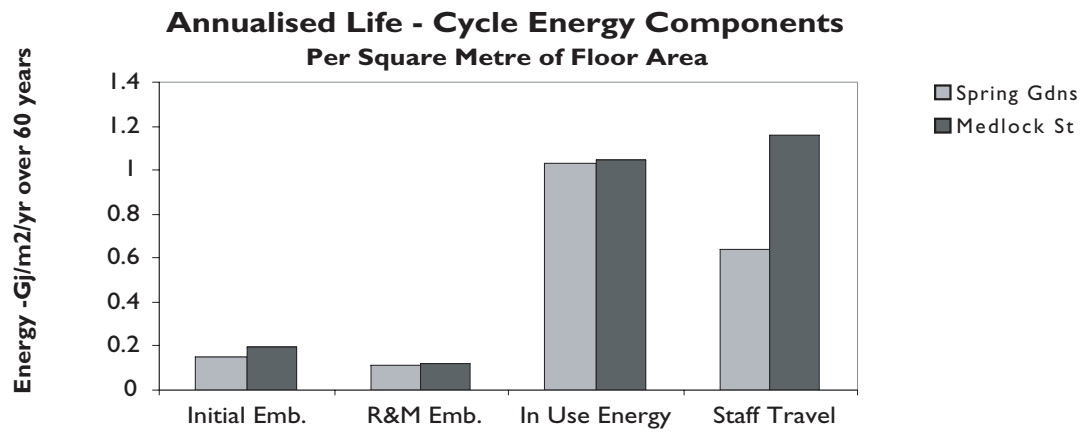


Figure 7 *Energy Components From Two British Council Offices*

Benchmarks for transport emissions related to location

Benchmarks for transport have already been incorporated into the Building Research Establishment Environmental Assessment Method (BREEAM). The table below provides benchmarks of good and typical performance for transport emissions related to a building's location.

Location	Energy (return) GJ/person/day	CO2 emitted (return) KgCO2/person/day	NOx emitted (return) gNOx/person/day	VOC's emitted (return) gVOC/person/day	CO emitted (return) gCO/person/day	SO2 emitted (return) gSO2/person/day
Capital City -						
Good Practice	0.03	3.8	53	17	52	43
Typical Practice	0.05	5.4	75	25	93	55
Major City						
Good Practice	0.06	5.1	44	27	212	22
Typical Practice	0.09	7.8	70	39	284	40
Rural / Out of town						
Typical Practice	0.1	7.9	50	40	354	13

Table 2 *Benchmarks of good and typical practice within various locations*

The benchmarks show the transport related energy and emissions on a per person basis from 3 typical building locations. The emissions are broken down within the locations into good and typical practice. They can be used to assess the transport related environmental impacts of staff commuting to buildings in a capital city, a major city and an out of town or rural location. They are especially useful when planners, designers and operators of buildings choose to set targets for commuting.

Benefits from Addressing Reductions in Transportation

Three types of benefits can motivate an assessment of occupant transportation:

1. A need to optimise financial returns from office portfolios and to maximise office space utilisation. This is an everyday problem that many organisations face. High land and rental costs together with half - empty buildings are forcing organisations to utilise their buildings more efficiently. In many large cities a quarter of office- based organisations have unoccupied space in their building. Relocation to a building with higher rental costs can also pose a similar problem.
2. Improving and maximising business efficiency and customer service is a concern for many organisations that have witnessed a decline in their performance caused by transport issues.
3. Concern for the environment and the community is a major issue for many businesses and local authorities. Forecasts of increasing traffic and problems with congested roads have driven organisations to produce counter measures. Within local authorities, it is seen as being vitally important to set a good example to the community that they serve.

Transportation-Oriented Design

LCA methods need to be adapted if inventories are to include the very significant flows of energy and material associated with occupant transportation. The ideal approach is to develop scenarios for modelling transportation, based on characteristics of the region, building design features and management policies. Such modelling would need to be calibrated on many actual buildings to ensure validity. The net impact of such assessment would be emphasis of the benefits of Transportation Oriented Design (TOD) and along with management programs that encourage alternatives to single occupancy vehicles. Some of the key components of TOD are summarised below:

- Live – work spaces in housing
- Mixed-use buildings with easy access to stores, day care, etc.
- People-friendly streetscapes (Safety Through Environmental Design)
- Safe and convenient access to transit and pathways
- Covered traffic-free entrances
- Safe and convenient bike storage, with lockers and showers, and
- A reduction in the number of car parking spaces.

Workplace innovations

Innovations in the organisation and design of workplaces can greatly impact the amount of commuting transportation. Examples include:

- Teleworking,
- Flex work,
- Hot-desking and other alternative working practices,
- Car pools and ride sharing,
- Parking fees and rebates and other policies can discourage use of single occupancy vehicles for commuting.

Optimising the location of a Building

Optimising a building location can improve access by staff and customers. Developments within easy access to integrated transport systems will encourage staff and visitors to leave their cars at home. Relocation of part or all of an organisation to areas served by good transport infrastructure can also encourage new travel patterns.

ISSUE 6: ANALYSING GROUPS OF BUILDINGS (STOCK AGGREGATION)

Stock Aggregation refers to the process of evaluating the performance of a building stock using LCA results from components of the stock. For example, total energy use by a stock of buildings can be estimated by adding up the energy estimates for all the individual buildings within the stock. Or for less effort, a subset of representative buildings can be analysed using LCA methods, and the results then factored in proportion to the total number of such buildings in the stock.

Stock Aggregation methods can contribute to decision-making in two ways:

1. by assisting designers of individual buildings to understand how their design choices might affect – or be affected by - the overall stock performance, and
2. by providing planners and policy-makers at varying scales (local to national) with a richer, more powerful database on building costs, energy and resource use, and environmental effects.

Because Stock Aggregation begins with the analysis of individual buildings, it is referred to as a 'bottom up' approach. Any performance issues that can be analysed and assessed at the 'bottom' – for an individual building or specific technology - can be aggregated upwards and used to evaluate the performance of a building stock.

Stock Aggregation is frequently the best method available for analysing stock performance for several reasons:

1. Energy and resource flows are a function of dynamic relationships between a building's shell, and its constituent equipment, systems and operations. By first using the dynamic micro-models created for use at the building or end use level, and then aggregating upwards, one can observe, analyse and resolve energy use and environmental performance with greater accuracy.

2. Much of the energy and environmental impact associated with buildings is related to the full lifecycle of buildings – including material production and demolition. Only by aggregating data based on LCA methods is it possible to accurately estimate the impacts of the stock.
3. The detailed and precise structure of a bottom-up database can facilitate the identification of sensitive variables that may be especially important to the overall performance. By changing such variables, it is possible to forecast the results of specific scenarios, and to prepare substantive arguments for particular building designs and policies.

The scale of Stock Aggregation can vary, from a small housing stock within a single project, all the way to national building stocks for the residential, commercial, and institutional sectors. The base data and the results can be nested from neighbourhood to community to region to nation, - while preserving the same data structure and detail. Partial stocks can be aggregated, consisting of sets of private or publicly owned buildings.

It is possible to aggregate and analyse the performance of a building stock in the present year, or at any time in the past, depending upon data availability. Profiles can be created for specific years, showing the breakdown of energy and resource use by each end-use (e.g. heating, cooling, lighting, equipment) and by each building type (e.g. office, school, apartment, retail).

Trends can be established by comparing performance of the stock over a number of years. Benchmarks can be created by comparing individual buildings with other buildings or with the average performance results for related groups of buildings. One building stock can be compared with another.

Stock Aggregation can be used to estimate performance of building stocks in the future, if assumptions are made about the growth and turnover rates within a stock, and the adoption rates for new technologies. Forecasts for energy, water and land use, and for generation of solid and liquid wastes, can be compared with the current and planned capacity limits for the surrounding infrastructure. Environmental loadings originating with the stock can be compared with the ecological carrying capacity of the surrounding air sheds, watersheds, and land base.

How Stock Aggregation Methods Improve Building Performance

Stock Aggregation methods are of value to energy analysts, building scientists, statisticians and practically anyone involved with planning urban development and promoting environmentally friendly technologies. Table 3 provides examples of user groups and typical queries suitable for Stock Aggregation methods.

In general, Stock Aggregation can be used to:

- Highlight areas where substantial potential exists for improvement in resource use and economic efficiency;
- Allow for quick "what-if?" analysis;
- Allow policy makers to optimise regulations and market incentives to achieve specific targets;

- Analyse how policies in one area, like energy security, or housing affordability, can affect other impacts from buildings, like air pollution, or energy demand; and
- Develop priorities for research and development.

It is possible to communicate the results of Stock Aggregation using the same data presentation techniques used for describing the performance of individual buildings. The same performance criteria can describe one building or many, except in cases where impacts are definitely site specific. Stock performance can be presented using a number of common graphical methods such as trend lines, profiles that breakdown the performance of the stock at a point in time, and forecasts of that project and how each part of the stock might change over typical 5, 10 and 15-year planning horizons.

Classes of Users and Responsibilities	Example Query
Policy Analysts • Local Agenda 21 • Regional Growth • National • European Union • International Energy Agency	"What kinds of building technologies are needed in order to meet greenhouse gas emission targets?"
Planners • Site Development • Infrastructure investment • Technology Promotion and Development	"What is the potential for a district energy system?"
Private Sector • Large Corporations • Specialty Businesses	"What is the expected market size for window replacements?"
Utilities • Electric / Gas • Water / Sanitary • Telecommunications	"What is the expected peak demand for houses in the planned neighbourhood?"

Table 3 *User Groups and Example Applications*

Applying LCA Methods at a Range of Scales

The appropriate spatial scale for Stock Aggregation will depend upon the areas of influence and control for the decision-makers involved, and the type of questions they want answered. As shown in Figure 8, the planning horizon tends to lengthen as the spatial area increases from local to national scales.

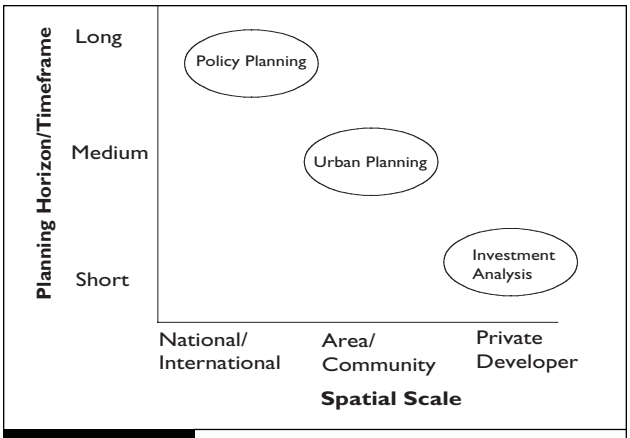


Figure 8 *Spacial Scale and Planning Horizons*

Stock Aggregation is suitable for spatially dispersed sets of buildings. For example government agencies responsible for public buildings may have developed extensive databases on their buildings, wherever they are located. A number of such agencies are now beginning to batch process all their buildings through energy analysis tools like DOE 2.1. Spatially dispersed sets are more difficult to model due to the greater variety of infrastructure systems and environments.

National Applications

In most countries, the main responsibility for energy and environmental policy is at the national level, and it is here that the greatest benefits of Stock Aggregation are usually experienced. The building stock represents the largest financial, physical and cultural capital of industrial societies, and stock aggregation can help to manage this basic resource more sustainably. Most recently national plans to meet Kyoto targets for greenhouse gas reductions have required a number of countries to create a detailed database on their building stock, and to use energy modelling tools on representative buildings.

Utility Applications

Stock Aggregation methods may be appropriate for utilities that want to better analyse their customer base. Traditionally utilities have estimated demand for services by using simple coefficients for each customer type, based upon past performance. For example, if population is expected to grow, a utility planner will use a standard demand factor for each household. This type of top-down analysis doesn't provide insight into the impacts of new technologies, or changes in economic base. Nor can the utility planner investigate potential for offsetting demand through load management programs, or through services that improve conservation and efficiency. With the emerging market for greenhouse gas offsets, and the increased competition in the energy sector, utilities can benefit from a deeper understanding of their customer demands.

Stock Aggregation offers utilities a more sophisticated and accurate means for:

- local area load management;
- long term load forecasting;
- capacity constraint analysis;
- investment planning;
- business expansion (new territories, and new building-related services);
- integrated resource planning (with optimisation of supply and demand options); and,
- monitoring impacts of policy and programs.

Community Applications

In the future, Stock Aggregation may be especially suitable for towns and cities that are trying to manage the impacts of growth, or prepare building regulations and guidelines that help the community meet its environmental goals. Stock Aggregation can be especially effective at the local level because:

- physical resource scarcities and ecological constraints often vary greatly from one locality to the next, and may necessitate locally appropriate building designs and policies;
- differences in the pace and direction of structural changes in the local economy may vary from one community to another;
- different population growth rates at the local level will affect the significance of building energy and resource use;
- cost and adequacy of municipal and utility infrastructure may vary with different building designs and geographic locations. For example, regional energy supplies may be sufficient for meeting the needs of a growing building stock, but power availability may be limited at the local level due to limited wire capacity, voltage, transformers, and rights-of-way.
- A local database on buildings, with bottom-up forecasts, can empower local citizenry and provide a rational basis for democratic environmental policy development.

Fostering A Tiered Approach to LCA Applications

One of the benefits of applying Stock Aggregation at the level of individual communities, is that it becomes possible to create a tiered approach, in which results are first aggregated at a local level (i.e. block, neighborhood or municipality), and then further aggregated to create regional or national statistics. Synergy may be achieved, since the same database can be created and managed for different purposes, at lower cost for all parties.

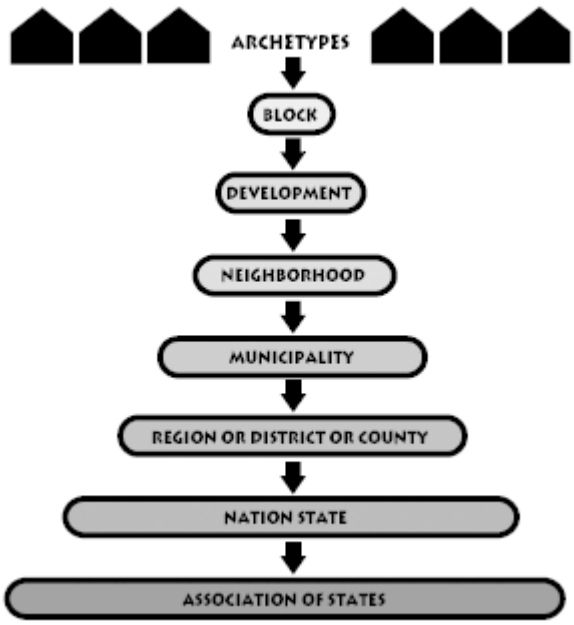


Figure 9 *A Tiered Structure for Building Stock Databases*

How Stock Aggregation Can Influence Building Design Decisions

Although not currently practiced, it is conceivable that building designers could use Stock Aggregation to assist in their design work. Several benefits are suggested:

AVOIDING THE RISK AND COST OF OVERLOADING THE LOCAL INFRASTRUCTURE
Ideally the capacity constraints of infrastructure need to be understood before the best choice of technology can be made for a specific building. For example, if the energy supply system is operating near capacity, it makes sense to avoid technologies that increase peak demands on the system, even if they appear to be the least cost option for the individual building. By considering the aggregate impacts of design decisions, the building designer achieves three benefits:

- the building can be marketed as more sustainable and more locally appropriate;
- permission to build may be easier to obtain from the local authorities; and,
- the building owner will be less exposed to the risk of disruptions in service, or sudden increases in taxes, fees, or other costs.

CREATING OPPORTUNITIES FOR COOPERATIVE INVESTMENTS BETWEEN BUILDING OWNERS OR DEVELOPERS
Stock Aggregation can also be used to justify new business ventures by determining the break-even scenarios, and the life cycle returns on collaborative investments. For example, a threshold number of buildings or level of service is necessary before a developer or planner can justify investing in district energy storage or supply. Stock Aggregation can be used to assess if and when this threshold demand is likely to exist. This type of analysis is especially valuable with larger building developments, where developers are increasingly likely to realize financial returns from on-site infrastructure.

PROVIDING CLEAR, RIGOROUS ARGUMENTS FOR SOCIALLY RESPONSIBLE DECISIONS
Stock Aggregation can be used to show how individual design decisions influence the overall ability of a community to achieve specific goals. This makes it easier for developers and others to satisfy regulations from a performance basis, rather than requiring prescriptive regulations and red tape in order to ensure compliance. Performance modelling is particularly warranted for demonstrating sustainable communities that may want to exploit the added market value or goodwill for ecologically sensitive urban development.

Coping with Data Complexity and Lack of Data

Historically, the single greatest obstacle to evaluating buildings within their urban context has been access to data on the composition and condition of the stock, and the relationship between buildings and the surrounding infrastructure. It is beyond the capacity of the average design professional to collect data on the carrying capacity, costs and environmental impacts of the urban infrastructure that makes their building function. Each location is different, and even urban planners, utility engineers and economists do not have a good understanding of how changes in demand for building services correspond to long-term infrastructure costs and resource requirements.

Once a community database is organized and entered, it can be used with modelling and Stock Aggregation tools to profile the performance of the city for the key energy and resource flows, and for the associated costs and emissions. For practicality, a building stock database must be designed for easy updates and additions, and to interface with Geographic Information Systems. Once operational, a database can be used to provide environmental reporting on the stock, providing planners and public with regular feedback on performance of specific neighbourhoods, or the city and region as a whole.

Data Collection Methods

LCA methods can easily be frustrated by lack of data, or by data that is inappropriate for the spatial boundaries, time periods and types of technology under study. These type of data problems are especially common when analysing building stocks. Techniques for coordinating data collection and accessibility, database management and maintenance, and upgrading data quality, are presented in the Annex 31 Background Report on Stock Aggregation.

How to Analyze and Simplify a Building Stock Database

All Stock Aggregation methods attempt to calculate total energy and resource statistics by analysing empirical data on buildings and infrastructure. Methods vary in terms of how much empirical data is used, and the techniques used to convert empirical data into energy and resource quantities and impacts.

At one extreme it is possible to avoid sampling of the stock by collecting measured data for every energy and resource service, in every building. Each building can then be modelled, as necessary to better describe the nature of the resource consumption, and then the values can be totalled to arrive at a Stock Aggregation. Such a data-intensive approach is usually too expensive and time consuming for any but the smallest building stocks.

At the other extreme it is possible to represent the entire building stock using only a handful of representative buildings, each of which is modelled and analysed as if it were an actual building. The proxies or building archetypes are used to estimate the characteristics of an entire population.

Between these two extremes are various compromises between quantity of data and the ease of data base management and scenario forecasting.

Using Reference Buildings for each Building Category

To simplify the process of Stock Aggregation, it is usually worthwhile to create separate databases of reference buildings for each category of building within the stock. These reference buildings can be thoroughly and accurately described, and selected to represent the full spectrum of features and sizes within the category. The reference databases can be monitored and updated as required. Reference buildings avoid problems from poor data quality. They also greatly simply the process of analysing a stock, since the number of reference buildings needed for statistical modelling may be only a small fraction of the total stock.

A particularly useful feature of reference buildings is that they can be summarized in different ways for different sorts of analysis and modelling. The range of diversity within the stock is maintained, which is not the case if only a single, statistically averaged composite building represents each category within the stock.

Another advantage to creating reference-building databases is that they can be open-ended, and absorb additional buildings, as the data becomes available. It may even be possible to provide mechanisms by which building inspectors and private contractors can contribute data sets on an on-going basis, in exchange for analytical information or rating values on each building they contribute.

Creating Archetypes for each Building Category

An archetype is a statistical composite of the features found within a category of buildings in the stock. Archetypes are always more complex than actual buildings since they include bits of many different materials, technological systems, and energy and water sources.

Depending on the focus of the investigation, archetypes can be normalized as a building (or household) for the residential stock, and as one square meter of typical floor area for the commercial/institutional stock.

Archetypes are especially important in Stock Aggregation, because they make it possible to easily describe and analyse the stock, and create new scenarios. The amount of simplification involves careful trade-offs. It is possible to create a single, highly complex building archetype to reflect the entire stock of residential buildings, for example. However such a large amalgamation of building types is rarely useful, since the benefits of dynamic modelling are lost. At the same time it is beneficial to minimize the number of archetypes in order to facilitate scenario planning. It is much easier to change assumptions for just 20 representative buildings than for 50 or 100.

Normally separate archetypes are created to reflect the different use categories for buildings, and the fixed long-term differences in the stock. For example, differences in age, attachment type, and foundations are fixed variables used for residential archetypes, and can be easily identified from national statistics.

Stock Aggregation with archetypes involves two steps:

1. Sub-totalling by multiplying the results from each archetype by the number of buildings or by the floor area it represents, and
2. Totalling the sub-totals for each archetype to arrive at a Stock Aggregation.

Archetypes can be created from:

- expert opinion,
- top-down statistics on characteristics of the stock,
- an empirical database of the entire stock of buildings, or
- an empirical database of well-classified reference buildings.

Using an empirical database of reference buildings is the usually the most reliable method. It may be necessary to use the same referenced buildings for creating several archetypes, depending upon the scope of modelling and analysis. An archetype for energy modelling may not be suitable for analyzing the flow of physical materials or water through the stock.

Sometimes an extensive empirical database is available that describes the physical features of the stock, and can thus be used to create archetypes. The data must be sufficiently detailed to generate the specificity needed for any models that will be applied to each archetype.

Empirical data can also be used to directly estimate the energy and resource flows for archetypes. For example, programs like PRISM and FASER can be used to convert energy billing data into base thermal loads for space conditioning and domestic hot water.

More commonly the empirical databases suffer from poor data quality, and are inappropriate for establishing energy and physical resource flows. Empirical data typically needs to be corrected for incorrectly categorized energy, and for inappropriate levels of aggregation. For example, many large older homes may have accessory suites, yet these suites may be unofficial, and overlooked by statistical data. Or energy billing data may have been averaged over the year. Or buildings with natural gas heating equipment may also incorporate extensive amounts of supplementary electrical resistance heating.

Once archetypes are defined, they can be used in combination with micro-models and utility records to derive specific and accurate estimates of energy and physical resource flows. It is possible to combine in one archetypal building different fuels, envelope types, and fractions of mechanical systems in ways that would never be possible in reality. As long as the completed archetype is capable of being modelled and analyzed as if it were a real building, it can effectively represent a known class of building types.

The variations between archetypes must reflect the opportunities available for managing the stock. For example, older buildings have different turnover rates, and quite different conservation options, than do newer buildings. Combining the two age groups into one archetype can make it difficult to see how policies might become more effective by targeting just one of these age groups. Also, cost benefit calculations can be distorted by combining many expensive small opportunities with a few large, profitable opportunities.

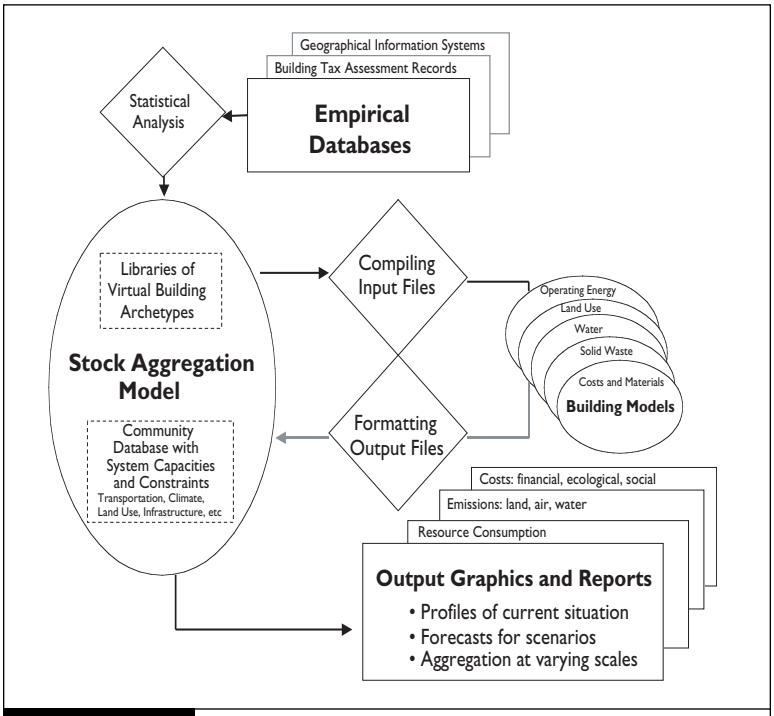


Figure 10 *Schematic of Stock Aggregation Model*

One useful principle to apply when creating archetypes is to analyze which parts of buildings are most amenable to change. As a rule of thumb, features or characteristics of buildings that are unlikely to change over time, and that have little influence over potential improvements to other features of the building, can be combined together into a single average value without much loss in functionality for the database. Examples of such immutable features are lot size, orientation, and location of rooms. Conversely, those features that are influential in determining how building energy use might change over time should be used to differentiate the archetypes. Examples are building age and attachment type.

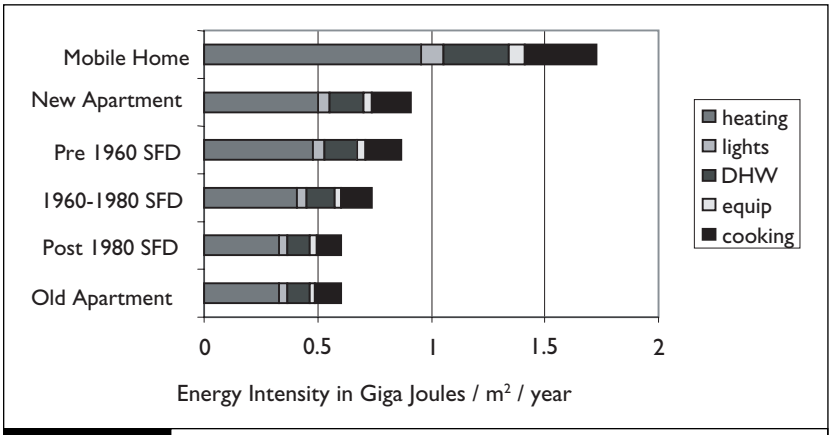


Figure 11 *Energy Consumption by End User for Different Archetypes*

In other cases it is not so much the analysis that differentiates archetypes from individual buildings, but the data collection and inputting requirements. A restaurant, for example, may contain specialized equipment and the archetype must permit such equipment to be included and modelled.

If survey data is being used to define archetypes, then the numbers of archetypes may need to reflect the quantity of data available. For example, the descriptions of the archetype must be based upon a large enough sample to calculate the degree of accuracy that is desired (e.g. "accurate to plus or minus 3.2% 19 times out of 29).

In general, the object is to create a discrete number of unique archetypes that reflect the entire stock under analysis, within the constraints of the data available. To achieve flexibility in forecasting resource use, it is usually necessary to create 30 to 50 archetypes, to represent any given building stock. Within each archetype, there may be multiple "generations" or age categories. Even more archetypes may be required if the forecasting incorporates the possibility for highly innovative new building types or renovation concepts. As a rule of thumb, the shorter the forecast timeframe, the smaller the number of archetypes necessary to model the stock. Often 5 or 10 percent of the stock is so unusual that it cannot be easily represented by the standard archetypes. However including these exceptional building types in a "catch-all" archetype does not normally introduce significant error, since they are a small fraction of the total, and their consumption is constant over time.

It is possible to cut the stock different ways, creating different sets of archetypes for analysing different aspects of energy use. For example, the entire building stock could be represented by 10 archetypes for the purpose of calculating transportation energy, by 30 archetypes for thermal energy, and by 5 archetypes for lighting. However the numbers of each archetype will change over time, due to turnover, renovation and new construction. This complicates calculations.

Another useful approach is to create a small series of "templates" or (primary archetypes) for modelling purposes, and then split each of these templates into a number of variants (or secondary archetypes) for calculating resource flows and costs over time. This hybrid approach is sometimes used for saving time in cases where complex simulations are needed to estimate impacts. By modelling a few templates, instead of the many archetypes, the results can simply be transferred to the archetypes within each class of template.

Archetypes must include, at a minimum, the building sectors that are present in the area of study, or that will be present during the period to be forecasted. It is sometimes useful to create separate archetypes for rural and urban locations, due to the large differences in resource use. Practicality, data availability, and the capabilities of the modelling personnel will ultimately limit the numbers of archetypes.

Infrastructure costs and resource flows

In this context infrastructure refers to all of the community systems that are required by a building by virtue of its technology and location. This includes roads, pipes and wires, generating plants, sewage treatment facilities, landfills and so on. Portions of the energy and resource costs associated with each of these systems can be allocated to reference buildings, or to archetypes, in proportion to their share of the total usage.

Each part of the infrastructure needs to be defined and described in terms of average and marginal costs, resource consumption and emissions per unit of service. Each building can then be allocated a portion of these infrastructure costs, with the percentage allocation reflecting the actual breakdown for that category of building. A more intensive overview of methods and applications can be found in the Annex 31 Background Report on Stock Aggregation.