Explicit consideration of time in the life cycle assessment of buildings

James Kallaos
PhD Candidate
Norwegian University of
Science & Technology
Trondheim, Norway
james.kallaos@ntnu.no

Summary

There are a limited number of true life-cycle assessments (LCAs) examining the carbon impact of structures. In these, the issue of temporal differences (differences or patterns of distribution through time) is rarely explicitly addressed. While a time-frame or horizon is typically specified, little regard is generally given to the sensitivity, or validity of application, of the chosen number, which may represent an arbitrary cut-off value or an estimation of lifetime.

Land-use change, energy use and associated emissions may have different effects depending on when during the life-cycle of the structure they occur. Most approaches simply average any impact across the lifetime (or the chosen assessment time-horizon) of the structure. Consideration of the temporal distribution of effects may lead to different results, while using the same data.

This project examines how durability and service life are treated in environmental analyses regarding sustainability of structures. The examination considers the treatment of and approaches to the handling of temporal distribution in the calculation of a life cycle carbon footprint. Current research and state of the art in the incorporation of temporal considerations into LCA are addressed and discussed.

Keywords: LCA, Buildings & constructions, Methodologies, Time, Service life

1. Introduction

During the last few decades, sustainable development and sustainability have become crucial issues globally. The terms were highlighted in 1987 in the report *Our Common Future* by the World Commission on Environment and Development, where sustainable development was defined as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]."

While sustainability is understood to encompass environmental as well as social and economic factors, it is the impending threat of global climate change that seems to be driving the agenda for action. Calls to define and implement sustainable practices are becoming more frequent and more definite as evidence of anthropogenic climate change builds. According to the Fourth Assessment of the Intergovernmental Panel on Climate Change "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations [2]."

It is becoming more and more apparent that definite action will have to be taken now in order to 'meet the needs' of the present without compromising the future. A recent report jointly produced by the European Environment Association, the Joint Research Centre, and the World Health Organization calls for "immediate action" on climate change "in order to safeguard the economy and environment of Europe and the rest of the world [3]."

Implementation of sustainability has proven less simple than definition of the goal or the problem. An important element is quantified knowledge about the effects that human activities are having on the environment.

Of human activities impacting the environment, building and construction are the cause and foundation for some of the largest impacts. The building and construction sector is not only the largest consumer of natural resources, in terms of both land use and materials extraction, but is responsible for 30-40% of primary energy use and greenhouse gas (GHG) emissions worldwide [4]. While there are many current initiatives that aim to reduce the impact of the built environment on the natural environment, the United Nations notes that "…there is still a clear lack of initiatives aiming at addressing global issues from a life-cycle perspective of the built environment [4]."

Many research and government policies in the United States and abroad regarding building energy use and environmental impact have focused mainly on operational energy consumption, and have neglected to consider other stages of the building life cycle [5-9]. Operational energy consumption is but one part of the complex system of environmental interactions that can be attributed to a building throughout its life cycle, which includes manufacturing, construction, maintenance and end-of-life.

Efficiency measures applied to building design should involve an optimization process that considers not only operational energy use, but the environmental impacts of the entire building life cycle, including energy transformation, materials use, GHG emissions, health effects, and pollution to air, water and soil. One approach to the quantification of consumption, impacts, and emissions across an entire life cycle is Life Cycle Assessment.

2. Life cycle assessment and the treatment of time

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) attempts to track all of the impacts of a product throughout its life cycle, from cradle to grave. Standard LCA utilizes a bottom up or process based approach to quantify the effect of each process along the life cycle. LCAs that attempt to assess a current situation are known as "attributional" and tend to use average data, while a "consequential" LCA would assess changes in a system from alternative scenarios, and generally utilize marginal data [10,11]. Another approach is a top down, or input-output LCA, which starts with known higher order data about energy consumption in the economy, and then attempts to disaggregate the data into smaller and smaller sectors in a large matrix. Hybrid methodologies have emerged which utilize process data for measurable quantities, and input-output data for processes that are not or cannot be directly measured.

The methodological underpinnings determining the allocation of burdens and impacts are not set in stone, but the overall process of LCA is generally governed by the standards published by the International Organization for Standardization (ISO) in ISO 14040: Environmental management -- Life cycle assessment -- Principles and framework [12], and the rest of the ISO 1404X series. Consequential, input-output and hybrid methodologies are currently not as well standardized as attributional LCA.

An LCA of a complicated product such as a building is a very data intensive process. Data quality and availability are important factors that can complicate or compromise the suitability and validity of an assessment. Adding to the complexity are temporal aspects of environmental interventions and impacts; not only is there the initial embodied energy, emissions, and the actual materials used (and wasted) in the manufacturing of the structure, but there are also those of the construction process itself, recurrent embodied energy, emissions and materials in the form of building products that are replaced, upgraded or added throughout the life of the building, and the energy, emissions and materials fate associated with the end-of-life treatment of the structure and its components [5,13]. There may also be vast differences in the efficiency of (as well as pollution and GHG emissions created by) energy generation during different stages of the building's life cycle.

2.2 Patterns of distribution through time (Temporal patterns)

There is much value to be gained from calculating and understanding the life-cycle consumption and emissions patterns of the built environment. With buildings this is especially important, as this knowledge can help inform the debate over existing buildings: namely when retrofitting, adaptive reuse, or demolishing and rebuilding are appropriate. Awareness of the patterns of distribution through time (temporal patterns) related to energy transformations and environmental emissions caused by building construction, use and demolition could lead to more informed decisions regarding building durability and preservation.

Knowledge of the effects that our current housing stock has had and is having on our environment is the first step towards taking action to minimize that impact. While currently the majority of life cycle building energy consumption likely does occur during building operational energy use [13-17], the synergism of effects from conservation measures means that may change in the future. Energy efficient buildings may incorporate more efficient appliances, increased insulation, increased thermal mass, tighter envelopes, larger overhangs, internal and external daylighting and shading devices, and on-site energy storage and generation. These products and processes have their own energy burdens, which need to be considered as trade-offs in any analysis. Efficient technologies such as those used in passive or solar houses have been shown to increase the embodied energy of a building [14,16,18,19]. If efficient buildings use less operational energy, the amplified quantity of embodied energy takes on a greater percentage of life-cycle energy consumption [13,16,20].

2.3 Explicit consideration of temporal patterns, differences, and effects

The issue of temporal differences is typically not explicitly addressed in LCAs [11] in general, nor in the limited number of true LCAs examining the sustainability of structures. While a time frame or horizon is generally specified, little regard is generally given to the sensitivity of the chosen number, which may represent an arbitrary cut-off value or an estimation of lifetime. There are however, other and possibly more important temporal considerations and effects not typically included in discussions of the LCA of buildings.

Materials and energy use, as well as environmental impacts and emissions may have different effects depending on when during the life cycle of the structure they occur. Most approaches simply average any impact across the lifetime (or the chosen assessment time-horizon) of the structure. Consideration of the temporal distribution of effects may lead to different results, while using the same data.

There are several reasons why otherwise equivalent consumption, emissions, or pressures occurring at different times or across different time scales may result in unequal physical, economic, or societal impacts. These include uncertainty, instability in consumption and production patterns and efficiencies, structural change, and the methodological basis for discounting.

Across a short time scale, both economists and natural scientists agree that most events considered should be treated similarly. It can be assumed that the world in 1 hour will still have the same material and energy demands as today, that the climate will be the same, and that human consumption patterns will remain relatively stable. For a certain finite and foreseeable time frame, these assumptions remain true. As the time horizon progresses from the relative certainty of the present, or one hour from now, to one year or 20, 50, 100, 1000 or 2000 years from now, uncertainty grows about a multitude of factors affecting the calculation of impact.

These uncertainties include knowledge of the global population in the future, technological changes regarding energy production, carbon sequestration, the future climate, and atmospheric concentrations of GHGs and other emissions. Future concentrations of GHGs affect the relative impact of each unit of gas released: gases released across different time periods will have different impacts. Future global surface temperatures may be different than today, and the feedbacks involved may create different marginal effects from GHG emissions. The global population may be drastically different than our best predictions. There also exists the possibility of catastrophic events (low probability but high impact events such as world war, thermohaline shutdown, mass migrations, etc.) causing global societal and/or environmental shifts and concomitant changes in supply and demand patterns for energy, food, and natural resources.

2.4 An example: Changes in energy

As an example of the possible effects of temporal differences on the calculation of impacts, consider the case of energy. There are vast differences in the makeup of the energy and transportation infrastructures between cities and countries, and across time. For example, only 2.5% of Norway's electricity production is provided by fuel combustion (the majority is hydropower), while in Canada this increases to 25%, and in the United States over 70% of electricity production is from fuel combustion [21].

Many countries are attempting to decarbonize their energy supply (at least relatively, per unit of energy). The US has increased the efficiency of electricity production – mainly through increased quality of fossil fuel inputs, such as a higher proportion of natural gas to coal fired power plants coming on line in recent years. Electricity production in Massachusetts, for example, emitted 20% less GHGs to produce an equivalent amount of electricity in 2005 as it did in 1990 [22].

Other countries appear to be headed in the opposite direction. Domestic electricity production in Norway, for example, has historically been provided by low carbon hydropower, but the upper limit of domestic hydropower production appears to have been reached [23]. For several years in the last decade, Norway has been a net importer of electricity [24,25] produced from a mix of sources, including coal and nuclear [24]. Marginal supplies to cover ever-increasing demand will likely continue to rely on these higher-impact imports or production of new gas-fired thermal plants [23]).

In an assessment focusing on existing buildings, temporally specific information would provide a clearer picture of the actual energy, materials, and emissions embodied in a building than the utilization of current data. Changes in the process efficiencies of both the national energy supply and the manufacture of building materials may lead to discrepancies between historical and current calculations of embodied energy [13,26,27]. Research regarding the primary fuel mix of a region can be tedious, and allocation difficult, as electricity is bought, sold, and transferred between markets at varying quantities from year to year.

3. State of the art: Explicit consideration of temporal issues

Fearnside [28] considers the issue of time preference for delayed carbon emissions, whether based on the use of discounting or limited time horizons. He brings up the point that postponement of carbon emissions until some later date through delayed activity (deforestation in the paper) is equivalent to the "permanent gains" counted for avoided emissions from fossil fuel combustion. In the case of fossil fuel combustion, he notes that delayed (displaced) emissions are treated as cascading forward, under one of three approaches: indefinitely, until the end of the chosen time horizon, or until the considered activity ceases at some fixed point in time. Fearnside goes on to consider the use and choice of an appropriate discount rate. In doing so, he further discusses the lack of equivalence between current and future emissions and their impacts. An emission creating an impact occurring at some point in time causes global warming effects that occur "from that time forward," not just at that one point in time, and a "permanent gain" is realized in the time interval created by delaying the emission.

Over ten years ago, Herrchen [29] was calling for the explicit inclusion of temporal considerations in LCA. She proposed that "long-lived products" require a "special need to consider temporal aspects," including not only the time-dependency of emission patterns, but that of fate and effects as well.

Fearnside [30] expands on the ideas presented in his 1997 paper, further explaining his permanent gain theory: "if mitigation efforts can delay, say by 10 years, the date at which we reach any given global-warming milestone…then all loss of life and other impacts that would have been sustained during that 10 year period must be considered to be a permanent gain." He considers time horizon choice to be a policy based decision, not a scientific one. According to Fearnside, the emphasis on the 100-year time horizon in the IPCC reports is the "Goldilocks approach," whereby of three presented options for Global Warming Potentials (GWPs), with one high and one low (500 years and 20 years), the middle choice (100 year GWP) will always seem most palatable.

Fearnside [31] discusses the equivalencies between discounting and the choice of a time horizon. He shows that for any proposed finite time horizon (with no discounting), a discount-rate equivalent can be developed for an infinite time-horizon. As the finite time horizon shortens, the discount-rate equivalent increases, approaching infinity as the time horizon approaches zero.

In their discussion of methodological issues regarding assessment of contributions to climate change at the seventeenth session of the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change [32], the effects of nonlinearities and feedbacks were considered. These consist of two important admissions, namely that "Emissions at different points in time will have different effects." and "The effect of emissions of individual sources may depend on emissions of other sources." While the group did not resolve these issues, a set of methods are outlined with which they could be addressed.

Hellweg et al. [33] consider whether discounting is appropriate in environmental decisions involving "tradeoffs between present and future impacts." They introduce the concept of the "storing" of construction materials in buildings, including both the inability to use these materials for another purpose, as well as uncertainty regarding the possibilities of reuse once they are released back into the environment. The paper presents a succinct explanation of the application of discounting in LCA, presenting four "arguments for discounting."

1. Changes in the magnitude of damage (for example, changing background concentrations of pollutants cause a change in impact if emission occurs at a different time)
2. Pure time preference (while individuals show a pure time preference, the authors reject its application across generations on ethical grounds)
3. Productivity of capital (assumes that economic growth will provide increased revenues that can be applied to pay for prevention or damage, but the authors question the ethics of monetization of human lives or natural assets)
4. Uncertainties (about future societies, preferences and damages).

The authors also show that temporal system boundaries are a type of implicit discounting, with a value of 0% "for the time horizon considered" and infinite thereafter.

Building lifetime is generally used as the time-horizon in LCA, but Erlandsson et al [34] question whether this is a defensible approach. Considering that it is not the physical structure but the service function that is desired, they consider whether the service function (a place to live) could be considered continuous and ongoing. They introduce the idea of "sequential life cycles", with the addition of new life cycles onto the end of an existing "linear" building life cycle.

Hellweg & Frischknecht [35] present an overview of the LCA Discussion Forum 22 in Zurich, 2004, where the possible effects of the time-dependency of impacts were discussed. The implicit consideration of temporal choices in LCA (temporal cut-offs and assumed lifetimes) was contemplated relative to explicit consideration. The discussion apparently concluded with agreement that long- and short-term impacts should be treated differently, but that "there was no consensus concerning how future emissions should be included in impact assessment".

Lenzen et al. [36] consider temporal distribution and time scale effects as they relate to corporate sustainability reporting. The authors note that accounting periods are generally shorter than the lifetime of impacts and recovery times, which can vary considerably depending on the type of environmental pressures involved, as well as variations in ecological resilience.

In their study on product lifetime extension, Kagawa et al. [37] investigate the relationship between environmental & economic impacts and the rebound effect. An extension of a product lifetime (automobiles in this case) results in a deferred expenditure for a new product, which can be construed as income. The environmental and economic effects attributable to the lifetime extension depend entirely on the scenario developed to explain the use of this income. The authors chose two scenarios – one in which the income is spent on low-impact services, and one in which it is saved or invested, leading to an increase in higher-impact activities. While the overall expense is constant, the expenditures are shifted to higher- or lower-impact scenarios. Depending on the assumptions made about direct and indirect rebound effects resulting from increased service lifetime, the environmental and economic effects can be positive or negative.

Levine et al. [38] develop a model (the "sequential interindustry model") in order to explicitly address the temporal dimension of environmental impacts in a gradual technological transition, which they consider "may be critical in evaluating the environmental burdens that result." While admitting that the data demands of their model "are not likely to be met at present or at any time in the near future," they recommend the insertion of simulated data in order to overcome the shortcomings of ignoring or simplifying temporal effects.

Reap et al [39] explain how finite limits in LCA present an inherent truncation error, whereby adopting an infinite time horizon effectively discounts short-term impacts, while a finite time limit "effectively discounts long term impacts by truncating the period of consideration."

O'Hare et al. [40] consider temporal accounting issues in their LCA of biofuels and petroleum. They note the "incoherent" application of finite GWPs at different points in time is the "standard approach" in many LCAs. They note that the earlier emissions occur, the longer those emissions will be in the atmosphere relative to some target date, and that "summing emissions over time masks potentially important differences among processes, especially if effects are measured at a fixed target date."

Scheutz et al. [41] provides an excellent description of the scientific basis underlying the IPCC metrics regarding climate change: radiative forcing (RF) and GWP. RF is a quantitative measurement of the effect of a gas on the global energy balance at a specific moment in time. The "initial concentration of a GHG strongly affects the magnitude of RF caused by additional increment in concentration" whereby "as the concentration grows, each new increment in concentration produces less additional forcing than the earlier increments." To incorporate the different lifetimes of gases in the atmosphere, the GWP integrates the RF of a specific gas over a chosen time interval of a pulse emission relative to an equal mass pulse emission of CO_2. The relationship between the two integrated decay curves through a chosen time interval determines the GWP.

As the "Convening Lead Author of the relevant chapter" in the IPCC assessment that established GWP as "the metric of choice," K.P. Shine's [42] opinions on its current use seem especially relevant. He asks whether the adoption of GWP was an "inadvertent consensus" whereby policymakers and the IPCC "each perceived that the other was content with the concept and didn't apply pressure to fully assess alternatives?" The author goes on to express that the choice of any time horizon is implicit discounting, and that there is no scientific basis for the preference of the 100 year time horizon over the other options. He notes that "it is widely believed that the Kyoto Protocol chose a 100 year time horizon because it was the middle one of the three." He notes the uncertainty implicit in any climate metric – estimation of future impacts will depend on future scenarios regarding climate change.

In their discussion of atmosphere and climate metrics for transport, Fuglestvedt et al. [43] include a discussion of the appropriate consideration of time. The authors mention two "important timescales" regarding climate change metrics: "…the lifetime of gases or aerosols in the atmosphere…[and]…the timescale of the response of the climate system to a radiative forcing…" They consider the differences between time-specific and integrated impacts, as well as the similarities between chosen time-horizons and discounting. They consider the lack of transparency in the embedding of discount rates within the GWP in this manner to be "an undesirable property of a metric" and recommend removing implicit "value laden judgments" from metrics in order to make value choices explicit and transparent.

In their discussion of possible directions for the evolution of LCA, Jeswani et al. [44] consider "temporal differentiation." The authors mention that changes through time "could be a key issue" that seems to be addressed in LCA (with its consideration of life-cycle stages), but actually is not.

Verbeeck and Hens [45] question the validity of assumed “time stability” in LCA, whereby usage patterns are assumed to be stable across the lifetime considered. In the presented LCI modelling of low energy dwellings, they assess the impact of upstream production processes, and only “one generation” (30 years) of service life, but include 3 different “usage periods” for sensitivity analysis, (30, 60 or 90 years, but replacement rates or patterns of materials, products & components are based on assumed life spans for the respective material, product or component.). The analysis inventory includes embodied energy & GWP, recurring embodied energy & GWP (from maintenance, replacement, etc.) and operational energy & GWP, but disregards end-of–life altogether. The temporal displacement of impacts and emissions is not considered; all emissions/impacts within the modelled time horizon are weighted equally, and those outside are completely disregarded. The relative impact of GHG emissions are characterized or calculated utilizing GWPs, but no mention is made of the chosen time horizon for the GWP or how the time horizon relates or was adjusted to account for the different building lifetimes.

4. Discussion and Conclusions

Even when temporal issues are not specifically and intentionally considered, temporal choices are inherently made, such as with the choice of time horizon in an assessment. In some cases a specific lifetime may be chosen for consideration in the assessment, but dissimilar lifetimes are chosen for other impacts. A common example is the inclusion of 100 year GWPs in an otherwise shorter term LCA. Another is the use of a single time horizon when consumption, emissions, and impacts occur at different points along the timeline, or may actually occur or extend outside of the boundaries.

The application of GWPs with finite time horizons into an LCA with a different time horizon presents several possible errors. First, if data is being averaged over a given service life, then some emissions are effectively being back-dated to before they occur. Second, the lifetime of some emissions (CO_2) and their impacts will be truncated before they have left the atmosphere – they will persist both physically and effectively past the end of the time horizon. Other emissions (CH_4) will decay completely prior to the end of the period. Averaging over a longer time period is a misinterpretation of the nature of the system.

There is also a need to consider the context of environmental loadings, such as the change in impact of marginal emissions dependant on background concentrations. The same emission at different points in time may cause different environmental pressures and impacts. It follows then that like carbon emissions, material and energy use at different points in time are not equivalent to current emissions and uses, and necessitate a different treatment.

In their consideration of the ‘storing’ of building materials bound in a structure, and unable to be utilized for other purposes, Hellweg et al. [33] bring up the idea of the opportunity cost of materials use, that could also be applied to energy consumption, land use, and emissions.

Structural differences in the energy supply through time also imply that a joule is not just a joule. In the production phase of a construction project (including materials acquisition, transport, construction, etc) many different fuel sources and types of fuels are used, with different environmental impacts and emissions. In the operational phase of a built object other fuel sources may dominate. Depending on the country region or sub-region considered, the electricity source mix continues to evolve through the time horizon considered, with possibly vast differences in impact. The long service life of buildings means that some of the considered phases or activities occur far into the future. There is a need for scenario analysis and consequential LCA to be able to consider the potential changes in the environmental impacts of ongoing activities (such as changes in the environmental impacts associated with energy “production” consumed in the use phase of a building due to changes in the fuel or source mix.

While attributional and consequential LCA can be applied to products and systems with short lifetimes, the uncertainty of the validity of the application increases with lifetime. As a society, we have no way of knowing the value of the considered commodities in 500 years time. There is no historical basis for assuming that high value and high usage commodities today (oil, steel, etc.) will have the same value 500 years into the future; the value of these commodities to future generations may be exponential greater, or close to zero. The assumption that these commodities will be recycled for the same purpose in 500 years seems entirely unjustifiable [33].

5. Final comments

The current approach to LCA generally involves static averages applied to dynamic systems with large uncertainties over large time scales. It is these uncertainties that create the largest difficulty in assessing impacts across large time-scales, and that will dominate the discussion of how to properly account for temporal issues. While sustainability calls for present generations not to compromise future generations in their quest for ever-increasing consumption, it becomes obvious that we have no certainty what future world humans will inhabit, or what they will consider valuable.

Is it the responsibility of present generations to guess the preferred society of 2000 years from now and try to provide for them? Or is it sufficient to provide for the needs of more certain and foreseeable generations, and allow a succession of sustainable paradigms to provide for each successive generation in turn?

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