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Abstract:

This paper explores the possibility of creating a Building Information Modeling (BIM) solution capable of generating a whole-building Life Cycle Inventory (LCI) for Life Cycle Assessment (LCA) using the Industry Foundation Classes (IFC) data model as a platform. This is accomplished by outlining the theoretical, methodological, and technical bases for creating such a tool. A process has been proposed to formally link LCA and BIM databases in order to allow for automated file transfers, improve the consistency of LCIs, and provide an initial bridge between the two fields. Using a methodology developed by the buildingSMART alliance, an Information Delivery Manual (IDM) for LCA has been created. This document, which includes Process Maps, Exchange Requirements and Functional Parts, can be used to supply solution providers with a technical understanding of the information and properties that must be exchanged to conduct an LCA study. This work acts as a proof-of-concept for BIM-based LCA, and speaks to the feasibility of a solution that would allow for the use of a BIM as the sole data source for an LCI file that is able to be directly transferred into LCA software.

Keywords:

1. Building Information Modeling (BIM)
2. Life Cycle Assessment (LCA)
3. Life Cycle Costing (LCC)
4. Industry Foundation Classes (IFC)

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(signature)

MASTER THESIS

(TBA4905 Building and Material Engineering, Master Thesis)

Spring 2011
for
Tobin Rist

A path to BIM-based LCA for whole-buildings

BIM-baserte LCA modeller: En løsning for bygninger

BACKGROUND

Buildings are widely estimated to use 40% of the energy produced in the developed world, and an even greater percentage of the electricity. In addition, the amount of natural resources and embodied energy contained within building materials is a massive investment. In Norway, it is estimated that the built environment represents 70% of fixed assets, and has a replacement value of approximately 5000 billion NOK. In Europe (the EU15 countries), the building and construction industry has about 14 million employees and turnover of about EUR 1000 billion. Globally, more than 111 million people are working within the sector, and construction activities amount to about 10% of the gross domestic product.

Because of this huge influence on society, it is critical for the building construction industry to be aware of its impact, and develop effective modeling tools that are capable of measuring where they come from and how they can be reduced. Building Information Modeling (BIM) is a very relevant platform for such solutions because it has the potential to measure both the material and energy use of a building.

Traditionally, performance indicators have been focused on the construction phase of a building, but life cycle thinking allows for a more holistic understanding of how buildings will behave over time, and provides a better basis for decisions during the design phase. Life cycle assessment (LCA) is a common methodology used to model the environmental impacts of a product or service, but is not widely used in the building industry.

It is unclear if LCA is an appropriate methodology for whole-buildings due to its complexity, or if such a data intensive process could be effectively incorporated into the BIM toolkit. If possible, BIM-based LCA would provide the building industry with a reliable tool for measuring their environmental impact and a means to identify areas for improvement – a clear benefit to society.

TASK DESCRIPTION

Overview

In this master thesis, the student should first analyze the LCA methodology to determine how it could be applied to the whole-building scale. The student should then investigate the basic BIM data structure to see how such technology could be applied to LCA. The student should ultimately propose a theoretical solution for producing a BIM-based LCA tool, and present conclusions regarding the feasibility and utility of such a tool within industry.

Aims and purpose

- Is LCA possible and/or appropriate at the whole-building scale?
- How can a whole-building LCA be performed?
- Can BIM be used to perform whole-building LCA?
- What elements are needed for BIM-based LCA?
- How can a BIM-based LCA tool be created?

GENERAL ABOUT CONTENT, WORK AND PRESENTATION

The task description for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the supervisor and professor in charge at the Department. (Also including external cooperative partners where this is applicable).

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include: (templates are found on http://www.ntnu.no/bat/skjemabank)

- Standard report front page.
- Title page with abstract and keywords (signed by the student).
- Summary and acknowledgement. Table of content including list of figures, tables and enclosures. If useful and applicable a list of important terms and abbreviations should be included.
- The main text.
- Clear and complete references to material used, both in text and figures/tables. This also applies for personal and/or oral communication and information.
- Text of the Thesis (these pages) signed by the professor in charge.
- The report must have a complete page numbering.
- The thesis may possibly be written as a scientific article. The report must come with report front and title pages and, if necessary, with appendices that document the work performed in the process of writing of the article.

Submission procedure

- The complete, original report (un-bounded).
- Two copies (bounded).
- If applicable: X additional copies if agreed upon for instance with external partner (to be paid for by the Department or the external partner)

- CD with the complete report (pdf-format) and all assisting or underlying material.
- A brief (one to two A4 pages including possible illustrations) popular science summary of the work, aiming at publication on the Department's web-site. Include a copy of this html document on the CD. Template is found on: http://www.ntnu.no/bat/skjemabank

The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.

Advice and guidelines for writing of the report is given in: "Writing Reports" by Øivind Arntsen. Additional information on report writing is found in "Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave ved Institutt for bygg, anlegg og transport" (In Norwegian). Both are posted on http://www.ntnu.no/bat/skjemabank

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc
Separate description to be developed, if and when applicable.

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The health, safety and environmental (HSE) work at NTNU shall constitute continuous and systematic efforts that are integrated into the primary activities. NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. Information in English on HSE is given on: http://www.ntnu.no/hse. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with the ***Fieldwork HSE Guidelines*** http://www.ntnu.no/hms/retningslinjer/HMSR07E.doc. General HSE provisions that apply in all laboratories and workshops are given on: http://www.ntnu.no/hse/labhandbook.

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Start and submission deadlines
The work on the Master Thesis starts on **January 17, 2011**

The thesis report original (not bounded) and 2 bounded copies and the CD as described above shall be submitted at the latest on **June 14, 2011 at 1500 hrs**.

Professor in charge: Rolf André Bohne

Department of Civil and Transport Engineering, NTNU

Date:

Signature
Professor in charge

Foreword

This report has been written as a master thesis meant to satisfy all study points required in the final semester of the MSc Industrial Ecology program – Environmental Systems Analysis track – at NTNU for Spring 2011.

The research evaluates how LCA methodology can be applied at the whole-building scale, and how to link the tools and databases from each field. The work focuses on Building Information Modeling (BIM) and life cycle costing (LCC) as potential means to streamline the LCA process and make the method more accessible to the building industry. The ultimate aim of this research is to determine if BIM-based LCA is possible, and if so, how such a solution could be achieved.

Thank you

I would like to thank all the professors and staff at IndEcol for their input and support, as well as my fellow classmates; many of whom have become close friends over these past two years. I want to specifically thank my adviser Rolf André Bohne, who I've been collaborating with almost since I arrived, for giving me the chance to freely pursue my interests and providing support when I need it. I also want to thank Håkon Gissinger and Håvard Bell for finding the time to meet with me to pass along their industry insight when asked.

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1. Introduction

In the building industry context, life cycle thinking represents the convergence of Life Cycle Costing (LCC), Life Cycle Assessment (LCA), and Building Information Modeling (BIM). LCC provides a long-term perspective in terms of cost, LCA reveals where environmental impacts arise throughout the building lifecycle, and BIM provides a platform capable of holding and organizing this information in a comprehendible way. The ability to model a building over its entire lifespan provides decision makers with the holistic perspective that is required to deliver optimal outcomes – for both private and public interests.

Whole-building LCA methodology is not actively used on many building projects today, but life cycle thinking is becoming more common. This can be seen in the use of Environmental Product Declarations (EPDs) at the product level, LCC at the project level, and support of green certification systems at the industry level.

The Norwegian Public Construction and Property Management organization, Statsbygg, has declared a goal that EPDs or similar LCA information will be delivered for all of the main products in their building projects (Peuportier et al. 2009). This is a signal to building product manufacturers (BPMs) that they will have to take the EPD process seriously if they want to be specified on government projects in the future.

Statsbygg also requires that an LCC is conducted for all building projects, which forces cost estimators to begin thinking in life cycle phases. Measuring cost is obviously not the same as measuring environmental impacts – financial interests have always been a primary concern in the building industry – but beginning to model the life cycle of a building is a step toward LCA. The process of producing a quantity take-off (QTO) for cost estimation is very similar to building a life cycle inventory (LCI) for LCA.

Also, the market has embraced green building certification systems as valuable differentiators that can raise rents and produce positive publicity for corporate tenants. The two most widely used systems, LEED and BREEAM, have both chosen to adopt LCA methodology as a foundation for measuring sustainability (Trusty 2006). So effectively, everyone involved in these programs will at least have to become familiar with the basic concept, if not proficient at its application on the whole-building scale. All these factors combined suggest that LCA will become more commonly used and therefore more influential in the design of buildings.

Because the LCA industry is tiny in comparison to the building industry – estimated to be $5.6 trillion globally – if it wants to be included, it has to play by AECOO rules (Young et al. 2009). This means using their semantic and syntactic systems, adapting tools to fit with their design software and workflows, making the best of time and data limitations, and delivering results that are understandable and valuable to building professionals. This does not mean sacrificing the legitimacy of an LCA for expediency, but rather recognizing the potential benefit of getting the AECOO industry on board, and making a concerted effort to ease the transition.

This paper represents a first step in that direction – it attempts to show how LCA and BIM databases can be formally linked to automate file transfer, improve the consistency of LCIs, and provide an initial bridge between the two fields. An Information Delivery Manual (IDM), which includes Process Maps, Exchange Requirements and Functional Parts, has been created to allow for the use of a BIM as a data source capable of transferring model information directly into LCA software. An IDM, created by a domain expert, is necessary to provide software developers with a clear understanding of what information and properties are needed to conduct an LCA study. Future work will aim to add BIM tools with the capacity to automatically produce LCAs, which will require a new IFC model view definition (MVD), or some other proprietary software link to join the two tools.

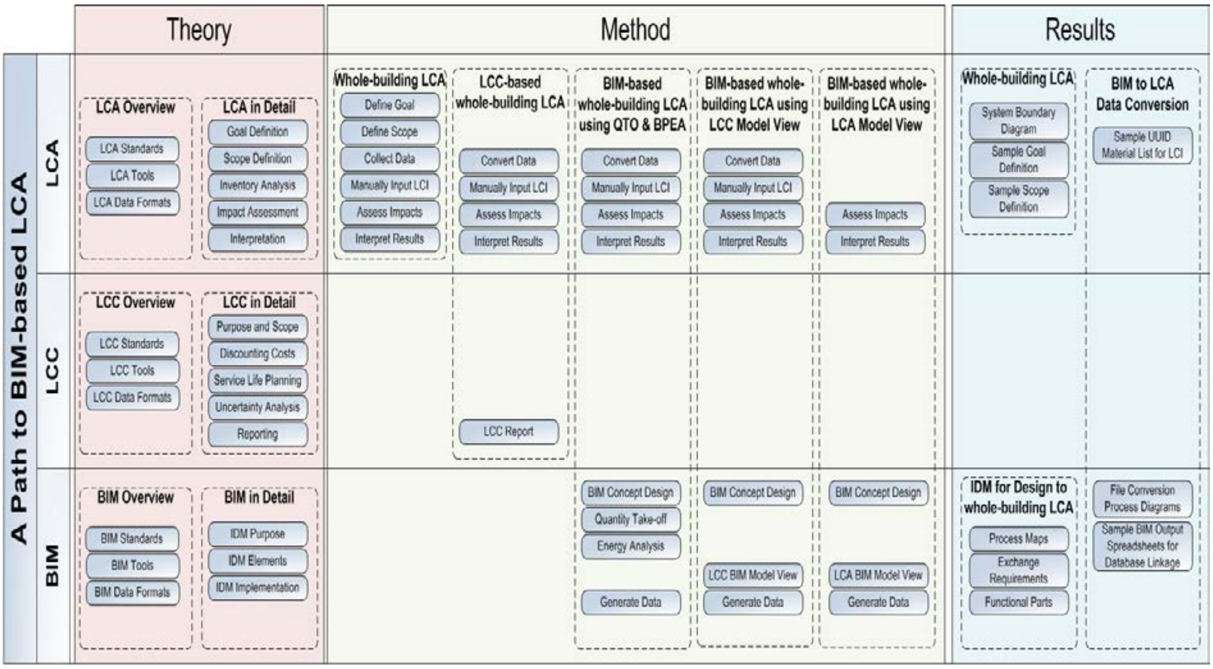
It is estimated that costs of owning and occupying an office building over a 30 year period have a ratio of 1:5:200 – where total construction cost is a fifth of maintenance costs, and one two hundredth of building operation costs with staffing included (Davis Langdon 2007b). Similarly, LCA results indicate that roughly 80% of environmental impacts can occur after the construction phase of an average office building (Glaumann et al. 2010). These findings provide clear motivation for finding ways to reduce use-phase costs and impacts, and consequently the importance of effective life cycle modeling.

There are very few absolute answers when evaluating the relative sustainability of design decisions; small contextual details matter, and can completely alter conclusions. A model will always be limited in scope – it can only optimize according to the chosen indicators and system boundaries – but a larger scope provides a more complete basis for decisions. The life cycle perspective is critical to achieving the highest performing buildings possible, because anything less is incomplete; it leaves out significant areas of interest. LCC is an important step for the industry to take, but it is not the end of the road, because it only considers one dimension of performance. Adding energy analysis for operational performance is another important step, because traditionally this has been where the majority of impacts occur, but it is still not the whole picture. LCAs of individual building materials are important building blocks of a whole-building LCA, but can be misleading when used alone.

Project teams will not be able to see the entire performance picture until a whole-building LCA with acceptable detail, accuracy and scope can be delivered within a reasonable timeframe during the planning and design phases. Integrated teams are only as good as the information they have to share with each other, and LCA can be a source of that knowledge. BIM has acted as a catalyst to facilitate collaborative methodology, but understanding the linkages between embodied energy and operational energy, service life planning and life cycle costs – these are the ways that buildings move past high-performance to zero emission.

1.0.1 Content Overview

This paper is meant to explore the possibility of creating a software solution to produce whole-building LCAs using BIM as a platform. This is accomplished by outlining the theoretical, methodological, and technical basis for creating such a tool. Below is a Content Map that shows the overall structure of the paper; each major section is a different color, with 3 main topic areas – LCA, LCC, and BIM – running through the entire length of the paper. More detailed portions of this map will be used at various times throughout the paper to provide context for the reader – usually at the beginning of topic sections and/or major sub-sections.



Figur 1. Content Map: A Path to BIM-based LCA

1.0.2 Existing Efforts & Industry Context

Industry interest in developing a BIM compatible LCA tool that could produce timely and accurate comparative analysis during the design process is high. For this reason, there have been a number of efforts to develop such a tool, and these have produced varying results. Some of the more notable efforts include LCADesign, which was developed in Australia from 2001-2006. Another ongoing effort is the CILECCTA project, which is funded by the European Commission and aims to produce a Life Cycle Cost Analysis (LCCA) tool that combines Life Cycle Inventory (LCI) data and codified Price Banks (PB) across Europe (CILECCTA 2011).

In the case of LCADesign, the underlying data conversion and calculation methodology remain opaque – the process maps and exchange requirements are considered proprietary and therefore cannot be examined. This paper is an effort to create completely transparent processes that are based on open-source platforms that can be accessed equally by industry, and used by the public sector for benchmarks and performance standards.

When using LCA to support decisions, it is especially important that the underlying assumptions are clear to the user. LCA is a very data intensive process, and if inaccurate or inappropriate data is applied to a model, the results can easily be distorted. In the special case of buildings, geographic data becomes even more important for conclusions, and every site will have unique characteristics. With this being the case, it is critical that users understand what data they are using, how valid their model is, and what types of applications are appropriate for results.

2. Theory

The Theory section is divided into the three main topic areas – LCA, LCC, and BIM – but also into Overview and Detail sections within each of those topics. Each Overview section covers standards, tools and data formats to provide context and an overarching framework to build on. Each Detail section provides a theoretical and procedural overview for implementing those standards, tools, and data formats.

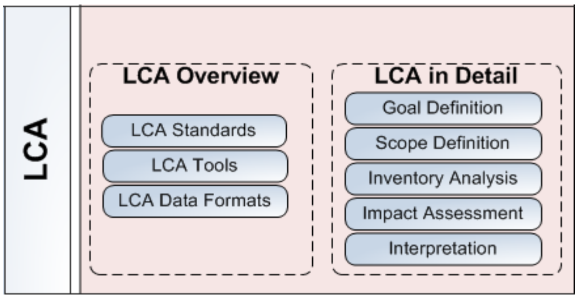
Such details are necessary to systematically translate these procedures into an IFC-based software compatible language and adequately define information exchange requirements. The procedural background is included in the Theory section because this paper seeks to address the creation of a BIM solution that builds on these basic analysis tools using the IDM methodology. Therefore, the method in this case is the creation of the IDM and the linkage of BIM and LCA database structures.

2.0.1 Clarification of Terms

In an effort to avoid ambiguity, a summary of similar terms used in the LCC and LCA fields shall be discussed and compared to those being used in this paper. For the purposes of this paper, an LCC is considered to include all that which is demanded by ISO standard 15686-5: Buildings and constructed assets – Service-life planning – Part 5: Life-cycle costing (ISO 2008). An LCA is considered a quantification of all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any good or service – as defined by the ILCD Handbook: General guide for Life Cycle Assessment (Joint Research Centre 2010). It is critical to understand the difference between LCC, which is purely an economic indicator, and LCA, which uses environmental impact indicators and does not address financial costs directly.

When discussing cost estimation terminology, it is important to understand the scope that each analysis type represents. LCC aims to consider all direct tangible costs from every life-cycle phase of a building, but it often excludes externalities and non-construction costs. Full Cost Accounting (FCA) is a term that represents the broadest scope of costing, and aims to identify direct, indirect, and intangible costs (Gluch & Baumann 2004). There are a number of other terms that have a similar meaning, and these include: Total cost accounting (TCA)(I), Full cost pricing (FCP), and Full cost environmental accounting (FCEA). Additionally, there are some terms that are closer to the definition of LCC, and these are: Total cost assessment (TCA) (II) and Whole life costing (WLC) (Gluch & Baumann 2004).

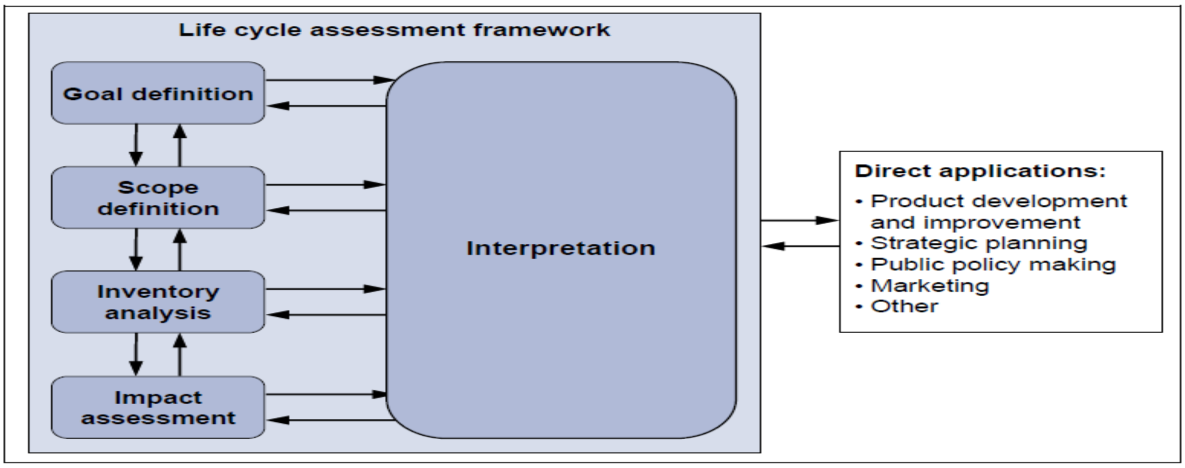
Lastly, there is a version of Life cycle cost assessment or analysis (LCCA), which attempts to add cost information to an LCA – this means that an LCA must be conducted, and through the environmental impact assessment, the additional cost is determined (Gluch & Baumann 2004). This paper seeks to accomplish the reverse transformation – from LCC to LCA – because it is assumed that LCC is a more common practice in the building industry and therefore a better gateway to adoption of LCA. There is also a large amount of uncertainty in estimating the full cost of environmental impacts, and once those impacts have been monetized it is possible to discount their impact over time – a practice that is contrary to the rules of LCA.



Figur 2. Content Map: LCA Theory

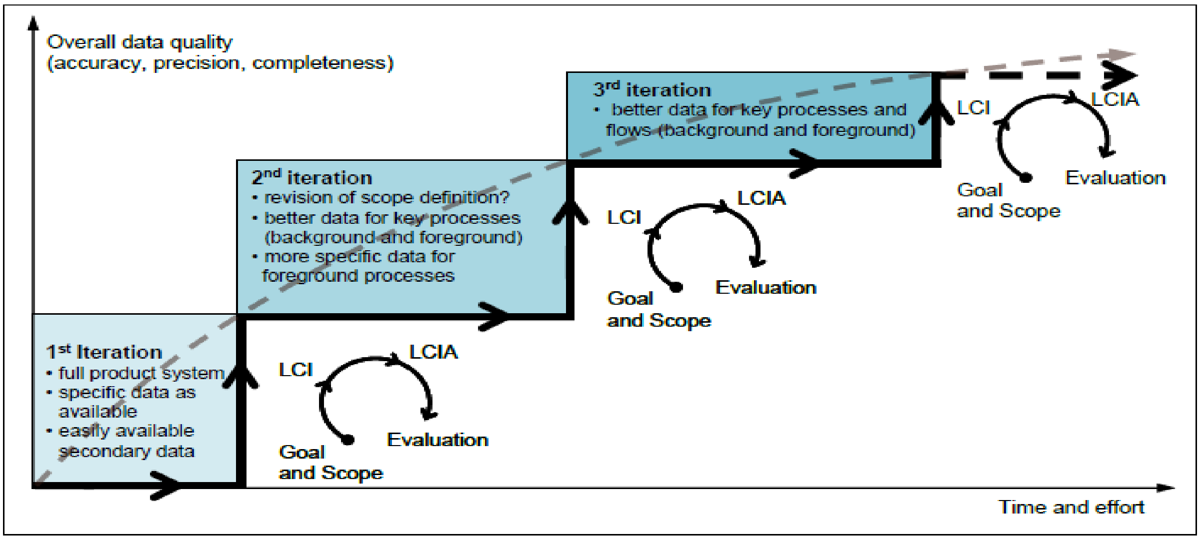
2.1 LCA Overview

Life Cycle Assessment (LCA) is an emerging methodology that attempts to quantify the overall impacts of a product or service from a holistic perspective that considers all material and energy inputs as well as human health and ecological impacts over the entire lifecycle. A modern LCA utilizes existing databases that have experimentally established the impacts of basic production processes. These databases are most assuredly not comprehensive, and often it is important to gather project specific data for the most central processes in an LCA for accuracy purposes. The diagram below provides an overview of the major elements in any LCA – the Scope Definition, Inventory Analysis, Impact Assessment, and ongoing Interpretation. These processes will be discussed in greater detail in a later section.



Figur 3. LCA Concptual Diagram (Joint Research Centre 2010)

The basic concept diagram above does not fully address the iterative nature of LCA methodology. In reality, each step in that process would likely be repeated, as well as the entire process after further or more detailed data has become available. The diagram below shows the iterative arc of revision necessary to achieve a more complete and precise inventory leading to a more accurate impact assessment. This is especially relevant in the case of assessing buildings because the LCA iterations could be scheduled to match the corresponding iterations in the design process – from concept to schematic to detailed design.



Figur 4. Iterative LCA process (Joint Research Centre 2010)

2.1.1 LCA Standards

2.1.1.1 ISO for LCA in the building sector

There are three ISO Standards that form the basis for conducting LCAs within the building sector. In summary, ISO 14040 defines the procedures of LCA generally, ISO 14025 defines the procedures for developing an environmental declaration program, and ISO 21930 provides the procedures for creating environmental declarations for building products. See more detailed descriptions below:

ISO 14040

ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements (ISO 2010b). It covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA (ISO 2010b). The intended application of LCA or LCI results is considered during definition of the goal and scope, but the application itself is outside the scope of this International Standard (ISO 2010b).

ISO 14025

ISO 14025:2006 establishes the principles and specifies the procedures for developing Type III environmental declaration programs and Type III environmental declarations. It specifically establishes the use of the ISO 14040 series of standards in the development of Type III environmental declaration programs and Type III environmental declarations (ISO 2010a). It establishes principles for the use of environmental information, in addition to those given in ISO 14020:2000 (ISO 2010a). Type III environmental declarations as described in ISO 14025:2006 are primarily intended for use in business-to-business communication, but their use in business-to-consumer communication under certain conditions is not precluded (ISO 2010a).

ISO 21930

ISO 21930:2007 provides the principles and requirements for type III environmental declarations (EPD) of building products. It contains specifications and requirements for the EPD of building products. Where this International Standard contains more specific requirements, it complements ISO 14025 for the EPD of building products (ISO 2010c).

This standard provides a framework for and the basic requirements for product category rules as defined in ISO 14025 for type III environmental declarations of building products. It does not define requirements for developing type III environmental declaration programs. Requirements for type III environmental declaration programs are found in ISO 14025. The working environment is not included in ISO 21930:2007 because it is normally a subject for national legislation (ISO 2010c).

2.1.1.2 Product Category Rules (PCR) and Environmental Product Declarations (EPD)

In the building industry, one of the most common applications of LCA methodology is to support the creation of an EPD for a material or product. Government agencies with large real estate holdings such as Statsbygg and GSA are beginning to demand that their building projects specify materials that have an EPD when possible. This has an impact on the market as Building Product Manufacturers (BPM) begin to perform EPDs for government contracts, and then want to advertise their "green" achievements to the private market. Once they are using the EPD system, it is to their advantage to have the entire industry keeping score by the same rules. Because the EPD system is based on LCA methodology, it is more difficult to "green wash," or falsely claim superior environmental performance through marketing rather than substance. ISO 21930 requires that if an EPD is going to be used for comparison of building products, and then for material specification, the use stage must be accounted for (Folvik & Wærp 2009).

In Norway, Næringslivets Stiftelse for Miljødeklararsjoner (EPD-Norge) oversees the creation of Product Category Rules (PCR) for all industries. There are currently four categories of product rules, which include: Construction, Energy, Packaging and Paper, and Furniture. The EPD register for building materials currently has fifty-one different items, with some repetition of similar products, but more are in the declaration phase (Folvik & Wærp 2009).

The information included within an EPD includes a Product Specification that lists materials, the percentage of the total weight that each material represents, as well as the kilograms per functional unit (FU). Environmental Indicators are listed; these include GWP (kg CO2-eq), Energy Use (kWh), Recycled Materials (as a percent), and Indoor Air Classification according to EN 15251:2007.

The EPD also includes a table to show Use of Material and Energy Resources categorized by Renewable and Non-Renewable. Energy Use is also broken down by purpose – a graph shows type of energy used for Transport, Raw Materials, Manufacturing and Packaging, etc. A series of emissions and environmental impacts tables show the results for mid-point indicators such as GWP, Ozone depletion, Acidification, and Eutrophication, as well as detailed emissions to air and water.

In the final section, an EPD includes a detailed Waste Treatment table that shows how much of each functional unit is recycled, used to produce energy, sent to landfill, and is considered hazardous or radioactive. There is also a system diagram that shows what phases were considered, where the boundaries are – they usually begin with raw materials, and finish with waste collection and sorting rather than include landfill or energy production.

2.1.1.3 CEN TC 350 – Sustainability of construction works

Independent of ISO, the European Committee for Standardization (CEN) has put together a Technical Committee (TC) to develop methods that will assess the sustainability aspects of new and existing construction works. These standards will differ from the ISO standards in that they will assess entire buildings rather than EPDs for materials.

> *The standards will describe a harmonized methodology for assessment of environmental performance of buildings and life cycle cost performance of buildings as well as the quantifiable performance aspects of health and comfort of buildings.* (CEN 2010)

CEN TC 350 has incorporated LCA in their methodology through collaboration with the ENSLIC (Energy Saving through Promotion of Life Cycle Assessment in Buildings) project that was co-financed by the European Commission and Intelligent Energy for Europe program. Thus far, only the NS EN

15643-1:2010 General Framework has been completed, but there will be three additional standards at the framework level that cover environmental, social, and economic performance, as well as two additional levels – building and product – that will also have standards to assess those performance dimensions (CEN 2010).

Building Stages: Product, Construction, Use and End-of-Life

The table below shows the basic CEN framework for the life cycle stages of a building, as well as the inputs that should be included within each stage. This particular version was taken from an article written by an author of the ENSLIC project, and therefore has added a simplified methodology column that is not included in the standard.

Tabell 1. Life cycle stages of a building

Stage	Module	Simplified LCA methodology: stages included
Product stage	Raw materials supply	Yes
	Transport	Yes
	Manufacturing	Yes
Construction process stage	Transport	No
	Construction-installation on-site processes	No
Use stage	Maintenance	No
	Repair and replacement	No
	Refurbishment	No
	Operational energy use: heating, cooling, hot water (and lighting – only for large tertiary buildings)	Yes
	Operational water use	No
End-of-life stage	Deconstruction	No
	Transport	No
	Recycling/re-use	No
	Disposal	No

(Zabalza Bribián et al. 2009) *adapted from CEN TC-350

2.1.1.4 ILCD – Methodological Framework

The International Reference Life Cycle Data System (ILCD) was developed to give guidance for consistent and quality assured Life Cycle Assessment data and studies. It provides detailed technical guidance to the ISO 14040 and 14044:2006 standards on Life Cycle Assessment (LCA) (Joint Research Centre 2010). The ILCD Handbook was developed for practitioners, and is meant to create more standardized results in the field of LCA, as well as correct some common errors in the implementation of the LCA methodology and the resulting interpretations of impact assessments. It is this standard that will be used as a guide for standardizing LCA methodology in BIM terms for whole-building LCA studies.

2.1.2 LCA Tools

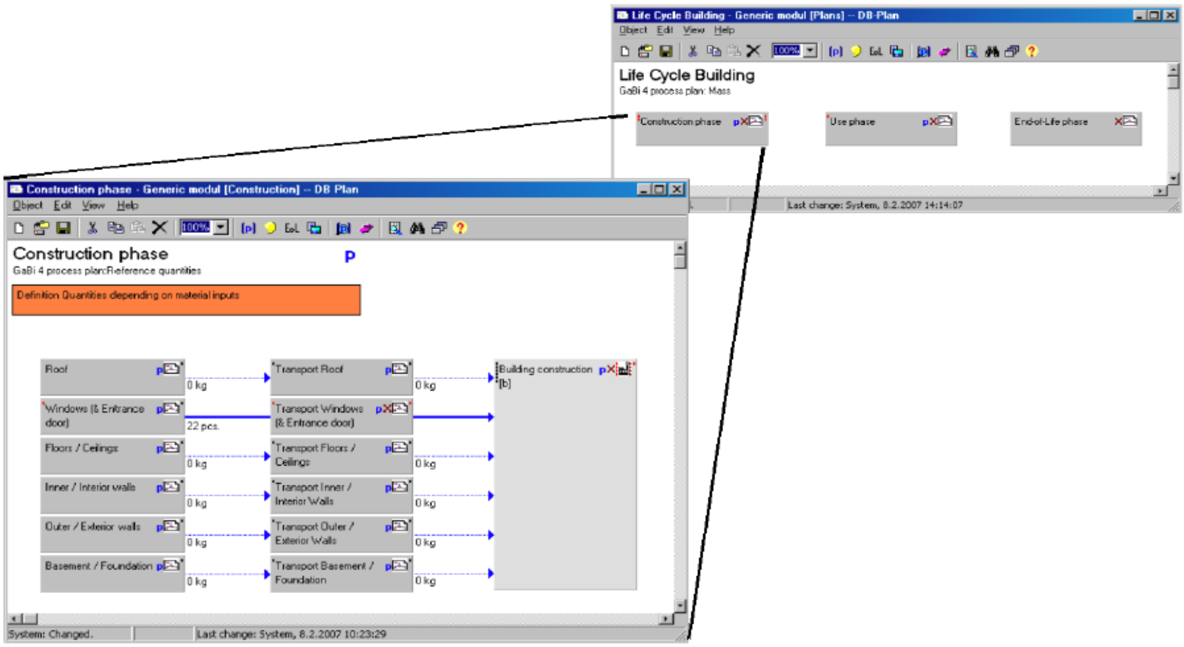
The table below shows a list of the most commonly used LCA software tools available. As this is an emerging methodology, there are many regionally produced tools that were developed by smaller organizations. This means that their user interface is not as polished as BIM tools, and the amount of capital available for improvement is much less. GaBi and SimaPro are the two most commonly used generic LCA software programs. To apply these generic software tools to buildings takes some expertise because the model must be created from scratch – there are no prompts for required material and energy data.

Tabell 2. Generic LCA tools

Boustead	www.boustead-consulting.co.uk
Eco-it	www.pre.nl
Ecopro	www.sinum.com
Ecoscan	www.ind.tno.nl
Euklid	www.ivv.fhg.de
KCL Eco	www.kcl.fi/eco
Gabi	www.gabi-software.com
LCAit	www.ekologik.cit.chalmers.se
Miet	www.leidenuniv.nl/cml/ssp/software
Pems	www.piranet.com/pack/lca_software.htm
SimaPro	www.pre.nl
Team	www.ecobilan.com
Wisard	www.pwcglobal.com
Umberto	www.umberto.de

(Zabalza Bribián et al. 2009)

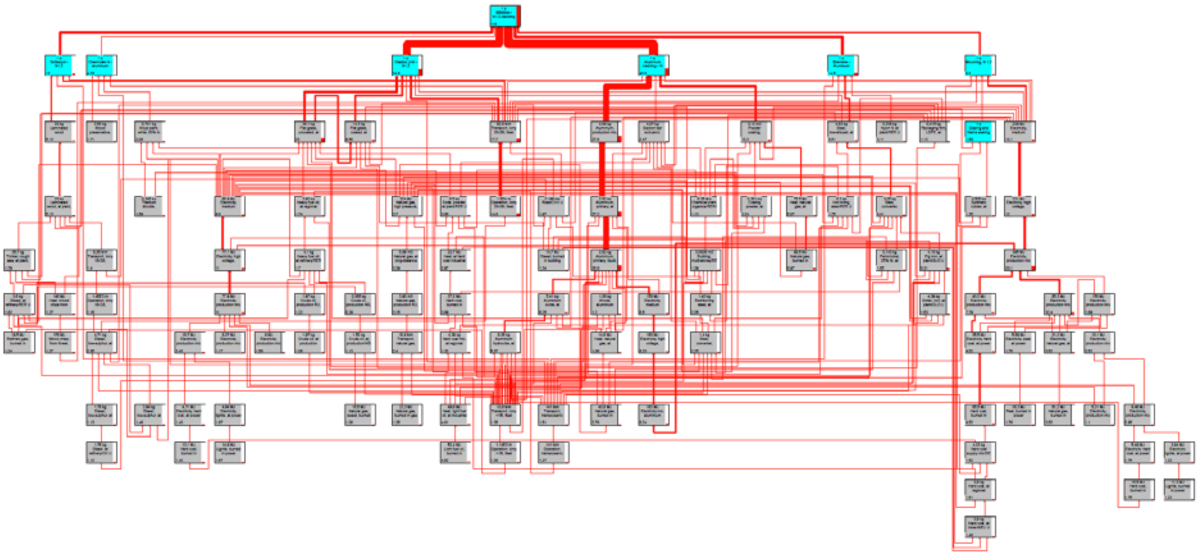
The image below shows a simple overview of the way generic LCA software – in this case GaBi 4 – can model an entire building life cycle. The lower screen shot shows all the major building elements modeled during the construction phase (roof, floors, windows, foundation, etc.), while the upper screen shot shows the three major life cycle phases considered (Construction, Use, End-of-Life).



Example of how a building could be modelled in GaBi 4

Figur 5. Whole-building LCA model in GaBi (Peuportier et al. 2009)

An example of the complexity of an LCA system can be exhibited by the flow diagram of all processes associated with a window. In this example, the window has six major component parts: softwood, chemicals, glazing unit, aluminum cladding, brackets, and mounting. The figure below shows the full network diagram that includes all background processes that are used to produce those six components – at the top in blue – and eventually the completed window. Each row of processes represents a tier in the production cycle – the lower a process the further in the background it is. The thickness of the red line indicates how much each process contributes to the overall system. In this case, global warming potential (GWP) has been selected, which means that the unit being measured is kilograms of carbon dioxide equivalents.



Figur 6. LCA network diagram of a window (Dahlstrøm 2010)

2.1.2.1 Building Specific LCA Software

The following table shows the LCA software tools that have been developed exclusively for the building industry. This means that the practitioner has some assistance in creating their model by being prompted for specific data, but they all still require manual input. These tools are very regional, many of them only available in languages other than English – EQUER and LEGEP as examples. ATHENA and BEES (Building for Environmental and Economic Sustainability) are the only tools available in North America, and they are both based on the US Life Cycle Inventory (US LCI) database. The BEES project – created by NIST (the National Institute of Standards and Technology) – is producing a public building material LCA product list. In Europe, the Ecoinvent database is the primary source for LCA data, but this has been augmented for the building industry by LCA consulting companies like PE International – the makers of GaBi.

Tabell 3. Building specific LCA tools

ECO-QUANTUM	www.ecoquantum.nl
LEGEP	www.legep.de
EQUER	www.izuba.fr
ATHENA	www.athenaSMI.ca
OGIP	www.ogip.ch/
ECO-SOFT	www.ibo.at/de/ecosoft.htm
ENVEST 2.0	envestv2.bre.co.uk
BECOST	www.vtt.fi/rte/esitteet/ymparisto/lcahouse.html
BEES	www.bfrl.nist.gov/oae/software/bees.html
GREENCALC	www.greencalc.com
ECOEFFECT	www.ecoeffect.se

(Zabalza Bribián et al. 2009)

2.1.2.2 ENSLIC

The ENSLIC project was a three year study of LCA methodology as it applies to buildings. It was split into six work packages (WP) that had various deliverables from conducting a state-of-the-art report on the use of LCA in the building sector, to the development and implementation of guidelines and a tool to conduct a whole-building LCA.

Where the ILCD Handbook cannot address specific methodological issues for each industry, ENSLIC is an effort to address those related to the building industry – and especially the challenges of modeling the operation phase of a building. Very durable products are the hardest to model because their lifespan presents so much variance.

Part of the solution to this problem is to keep models as simple as possible. The ENSLIC method attempts to simplify the LCA methodology for buildings while maintaining the most crucial elements in terms of overall impacts. The project has also produced a tool that is meant to reduce the number of errors made by practitioners by eliminating subjectivity in selected parameters.

The image below shows the front page of the ENSLIC tool that represents an adaptation of some of the building specific LCA tools listed above. Unlike GaBi or SimaPro, this tool provides an assessment procedure, but currently must be used as an Excel spreadsheet. This is a common state of development for these types of tools – energy analysis can be either estimated using assumptions from building details, or must be performed in separate software.

Tabell 4. ENSLIC Guidelines

Assessment procedure and corresponding templats

These templates should be filled in to simplify comparison. Blue squares are mandatory and yellow voloùntary. Improvement suggestions to this first template draft are welcome.

	Step	Template
1	**State the purpose of the study** (project development, impact comparison, classification, etc)	Assessment
2	**Choose assessment tool**	Assessment
3	**State the system boundaries for the assessment**	Assessment
4	**State scenarios for the reference time** (steady state, regular retrofit, cost development etc)	Assessment
5	**Define targets, references, benchmarks etc** (impact, depletion, energy use, ... Country or EU average, target,..)	Targets
6	**Describe the building** (Name, type, size, location etc)	Building
7	**Collect data** a) Environmental data that is not in the tool (emissions per Joule,	Not here
	b) Building data depending on assessed stages	Data input
8	**Perform assessment** (trial and error if targets should be reached)	Assessm. res
9	**Present results** (graphs, tables, analysis, eventually desired improvements etc)	Assessm. pres
10	**Validate** (check results relative to purpose, check calculations fulfillment of requirements etc.)	Validation

(Glaumann et al. 2010)

2.1.3 LCA Data Formats

2.1.3.1 EcoSpold

The first version of EcoSpold was launched in 2000 to facilitate LCI data transfer, and now all important LCA tools have an interface to upload files in this format (Weidema & Müller-Beilschmidt 2009). In 2008, the Ecoinvent Centre started a revision of EcoSpold, and an expert working group was formed to provide input. The final release of the new data format occurred in early 2010, and implementation in the Ecoinvent database is scheduled to release in 2011.

The table below shows a summary of the types of data that are included in an Ecospold file. Basically, the Process Info describes what the underlying process is, the Flow Info shows what goes in and out of the process, and the last two categories allow users to identify the source of the data and the person who performed the calculations.

Tabell 5. Ecoinvent data categories

Worksheet Name	Information contained in worksheet
Process Info	Properties of the process data, for example: • the region and time period • representativeness • sub-processes included • general comments • links to sources and people (detailed on the source and person info sheets described below)
Flow Info	The basic life cycle inventory (LCI) data: • flows into the process from nature and from other processes • flows out of the process to nature and to other processes This sheet also allows for: • flow-specific comments • specification of uncertainty data for each flow
Source Info	Bibliographic information for sources used to generate the unit process ("flow info") data.
Person Info	Basic contact information for the person(s) involved in preparing the data spreadsheet.

(NREL 2004)

Process Info Example

The table below was taken from the public US LCI Database, and it represents the layout of the original Ecospold data format. While the new version has some added features, it is not fundamentally different. This particular file describes oriented strand board (OSB) processing in the US Southeast, and this spreadsheet outlines how OSB processing is defined. Note that it mentions the process has multi-outputs; therefore allocation must be used and will be covered in greater detail within the flow information.

Tabell 6. Ecospold process info for OSB

	U.S. LCI Database - www.nrel.gov/lci
Name	Oriented strand board processsing, at plant, US SE
Infrastructure process ?	no
Unit	kg
Amount	1
Process Type	Multioutput process.
Scope & Boundaries	includes production of wood from seedlings, harvesting and reforestration through manufacturing of OSB includes phenol formaldehyde resin, MDIA resin and slack wax manufacture and use in the Board product
Category	Wood Product Manufacturing
Subcategory	Engineered Wood Member (ex. Truss) Mnf.
Number of Co-Products	3
Energy value type	Gross values (meaning "higher heating values", HHV)
Included Processes	Gate-to-gate system analysis
Allocation	This module contains some type of allocation. Please read complete module
Aggregation	None
Infrastructure Included	no
Formula (optional)	
Data Years	1999
Geographical Representation	US Southeast
Technological Representation	typical
Representativeness: Supply %	
Representativeness: Production %	represents 18% of all OSB production in region
Sampling Procedure	
Extrapolations	
Uncertainty Adjustments	
Data Published In	Data has been published entirely in 'referenceToPublishedSource'.
Preparer	Jamie Meil
Reference to Main Source	2
General Comment	Base process data presented with allocations to within process co-products noted. Refer to allocation worksheet for specifics. All allocations performed using mass or volume., number of co-products produced, some hogfuel remains in system Important note: although most of the data in the US LCI database has undergone some sort of review, the database as a whole has not yet undergone a formal validation process. Please email comments to lci@nrel.gov.
Review Status	This data file has had a partial critcal review
Module Info File Name	
EcoSpold XML File Name	
Streamlined Spreadsheet File Name	
EcoSpold Spreadsheet File Name	
US LCI Data Module Report File Na	MR_Oriented_Strand_Board_(OSB)__US_SE_at_mill_gate_(allocated_Profile).pdf
US LCI Detailed Spreadsheet File N	DS_Oriented_Strand_Board_(OSB)__US_SE_at_mill_gate_(allocated_Profile).xls
Database Version	1.6.0

(NREL 2004)

Flow Info Example

This is the flow information for OSB processing, and one can see the major flow categories are: Inputs from the Technosphere, Inputs from Nature, Outputs to Nature, and Product/Co-Product Outputs. Notice that there are four different products that result from this process, and therefore the impacts must be divided between those outputs in order to avoid being double counted.

Tabell 7. Ecospold flow info for OSB

(blue shading indicates no input required)	Flow	Location	Category	SubCategory	Infrastructure Process	Units	Quantity
Inputs from Technosphere	Electricity, at grid, Eastern US	US			no	kWh	3,298E-01
	Natural gas, combusted in industrial boiler	US			no	m3	3,672E-02
	Diesel, combusted in industrial boiler	US			no	L	1,252E-03
	Liquefied petroleum gas, combusted in industrial boiler	US			no	L	4,646E-03
	Gasoline, combusted in equipment	US			no	L	1,971E-04
	Dummy_Hogfuel-Biomass (50% MC), combusted in industrial boiler	US			no	kg	6,583E-01
	Phenol formaldehyde, at plant	US			no	kg	3,339E-02
	Methylene diphenyl diisocyanate resin, at plant, US SE	US			no	kg	6,425E-03
	Slack wax, at plant, US SE	US			no	kg	1,520E-02
	Softwood logs with bark, harvested at average intensity site, at mill, US SE	US			no	m3	2,465E-03
	Transport, combination truck, average fuel mix	US			no	tkm	1,058E-01
	Dummy_Water, at user	US			no	kg	8,280E-02
Inputs from Nature							
Outputs to Nature	Particulates, unspecified		air	unspecified		kg	4,843E-04
	VOC, volatile organic compounds		air	unspecified		kg	1,717E-03
	Carbon dioxide		air	unspecified		kg	1,890E-02
	Acetaldehyde		air	unspecified		kg	1,032E-04
	Acrolein		air	unspecified		kg	3,709E-05
	Methanol		air	unspecified		kg	3,126E-04
	Phenol		air	unspecified		kg	1,906E-05
	Formaldehyde		air	unspecified		kg	8,819E-05
Product / co-product outputs	Oriented strand board product, US SE	US				kg	1,000E+00
	Bark mulch, at oriented strand board production, US SE	US				kg	3,520E-02
	Fines, at oriented strand board production, US SE	US				kg	1,433E-02
	Dust and scrap, at oriented strand board production, US SE	US				kg	7,181E-03

(NREL 2004)

The table below shows how they have allocated impacts according to physical methods using either mass or volume as stated in the process info. This means that the OSB receives the vast majority of impacts because it represents the largest portion of the physical output.

Tabell 8. Allocation factors for OSB

		Allocation Factors Oriented strand board product, US SE	Bark mulch, at oriented strand board production, US SE	Fines, at oriented strand board production, US SE	Dust and scrap, at oriented strand board production, US SE	Allocation Method
Inputs from Technosphere	Electricity, at grid, Eastern US	0,9466	0,0330	0,0136	0,0068	Physical
	Natural gas, combusted in industrial boiler	0,9466	0,0330	0,0136	0,0068	Physical
	Diesel, combusted in industrial boiler	0,9466	0,0330	0,0136	0,0068	Physical
	Liquefied petroleum gas, combusted in industrial boiler	0,9466	0,0330	0,0136	0,0068	Physical
	Gasoline, combusted in equipment	0,9466	0,0330	0,0136	0,0068	Physical
	Dummy_Hogfuel-Biomass (50% MC), combusted in industrial boiler	0,9466	0,0330	0,0136	0,0068	Physical
	Phenol formaldehyde, at plant	0,9466	0,0330	0,0136	0,0068	Physical
	Methylene diphenyl diisocyanate resin, at plant, US SE	0,9466	0,0330	0,0136	0,0068	Physical
	Slack wax, at plant, US SE	0,9466	0,0330	0,0136	0,0068	Physical
	Softwood logs with bark, harvested at average intensity site, at mill, US SE	0,9466	0,0330	0,0136	0,0068	Physical
	Transport, combination truck, average fuel mix	0,9466	0,0330	0,0136	0,0068	Physical
	Dummy_Water, at user	0,9466	0,0330	0,0136	0,0068	Physical
Inputs from Nature						
Outputs to Nature	Particulates, unspecified	0,9466	0,0330	0,0136	0,0068	Physical
	VOC, volatile organic compounds	0,9466	0,0330	0,0136	0,0068	Physical
	Carbon dioxide	0,9466	0,0330	0,0136	0,0068	Physical
	Acetaldehyde	0,9466	0,0330	0,0136	0,0068	Physical
	Acrolein	0,9466	0,0330	0,0136	0,0068	Physical
	Methanol	0,9466	0,0330	0,0136	0,0068	Physical
	Phenol	0,9466	0,0330	0,0136	0,0068	Physical
	Formaldehyde	0,9466	0,0330	0,0136	0,0068	Physical
Product / co-product outputs	Oriented strand board product, US SE	1,0000				Physical
	Bark mulch, at oriented strand board production, US SE		1,0000			Physical
	Fines, at oriented strand board production, US SE			1,0000		Physical
	Dust and scrap, at oriented strand board production, US SE				1,0000	Physical

(NREL 2004)

Universally Unique Identifiers (UUID)

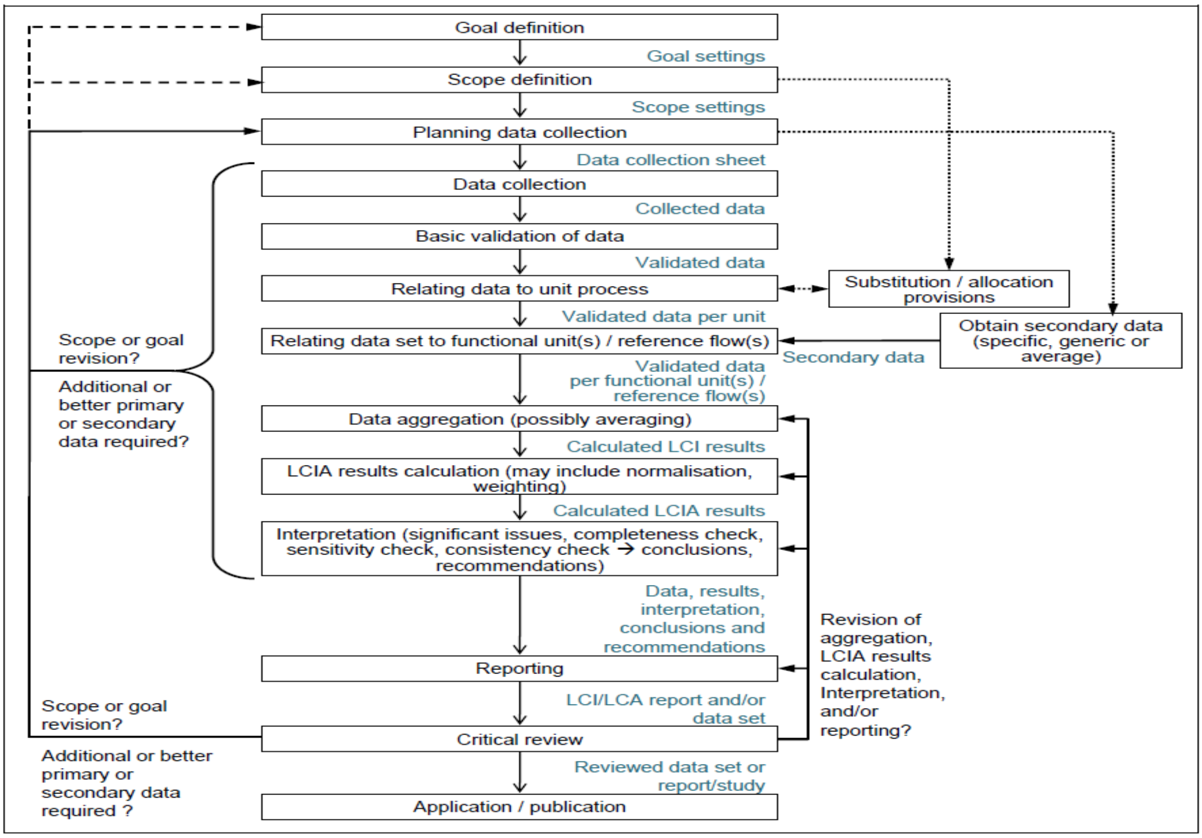
EcoSpold v2 has several additions to the original format, but some notable ones are the use of tags for grouping activities, UUIDs for internal references in datasets, and inclusion of GIS compatibility (Weidema & Müller-Beilschmidt 2009). UUIDs – 32 digit combinations of letters and numbers that have an infinite number of possibilities – are the same as the system used in BIM software, and present a possible way to link the two types of data.

International Reference Life Cycle Data System (ILCD)

In addition to methodology, the ILCD system establishes a data format that will be used as a standard for the European Lifecycle Database (ELCD), and is harmonized with the most common LCA data format – EcoSpold – for which a new version will be released in 2011 (Weidema & Müller-Beilschmidt 2009). The ELCD is a public data creation effort aimed at generating a common and dependable data source for LCAs. It is focused on the European region, and on key materials, energy carriers, transport, and waste management.

2.2 LCA in Detail

The following section is a detailed account of LCA principles and practices according to the standard established by the ILCD Handbook. This level of detail is included for the purpose of establishing a formalized process to produce an ILCD compatible output from a BIM using the IFC schema. The figure below, taken from the ILCD Handbook, is a more detailed flow diagram showing more of the steps in an LCA, focusing on the inventory data collection (Joint Research Centre 2010). This section will primarily focus on the Goal Definition, Scope Definition, and Inventory Analysis steps because at this point the intention is to generate a sufficiently complete, precise, and accurate LCI in accordance with the ILCD provisions and in a format that is compatible with LCA software.



Figur 7. ILCD Handbook: Detail of inventory data collection (Joint Research Centre 2010)

2.2.1 Goal Definition – Purpose & Target Audience

The goal definition defines the decision-context of the study, identifies the intended applications of the results, and names the targeted audiences (Joint Research Centre 2010).

2.2.1.1 Goal Overview

Six aspects shall be addressed and documented during the goal definition:

- Intended application(s) of the deliverables / results
- Limitations due to the method, assumptions, and impact coverage
- Reasons for carrying out the study and decision-context
- Target audience of the deliverables / results
- Comparative studies to be disclosed to the public
- Commissioner of the study and other influential actors

(Joint Research Centre 2010)

2.2.1.2 Major Concepts

For the purposes of BIM-based LCA, this section would be used to define the use case: purpose of the study, which project team members are involved, how they are involved, what phases it will be used in, and the extent of external use of results. In addition to these guiding decisions, it must be determined in which context the study will be taking place. This is because different situations will require fundamentally different methodology.

LCA Decision Situations

There are three archetypal goal situations for LCA – micro-level decision support, macro-level decision support, and accounting – and each of these require different modeling practices in order to assure accuracy and applicability of results. The table below outlines each situation, and provides a label of Situation A, B and C that will be used throughout this paper. The methodological implications of each situation will be discussed in the Scope definition section, but generally speaking, situation B requires additional consideration of the potential production consequences from various decisions – the others are based on existing technology.

Tabell 9. Fundamental LCA situation definitions

	Situation A: "Micro-level decision support"	**Situation B: "Meso- or macro-level decision support"**	**Situation C: "Accounting"**
Characteristics:	- Product related questions - 1 – 10 years in the future - Specification of existing or developing products - Limited share of total production in sector - Production/Use/End-of-Life have no large scale impact on capacity in background system	- Raw material strategies, technology scenarios, policy options - 5 – 10+ years in the future - Impact on background system	-Entirely descriptive, referring to past or present -Micro, mesa, or macro-level -Based on decisions that have already been made

(Joint Research Centre 2010)

Depending on the application and audience of a study, all three of these situations could be relevant for LCAs of buildings. If the results of an LCA will remain internal and applied to only a single project, then situation A is probably adequate. But if a large governmental organization wants to evaluate its building practices and compare alternative choices, then situation B methodology must be applied because it could have impacts on background production of building product manufacturers (BPMs). It may also be of use to get a basic account of the impacts an existing building is generating – this is situation C because the results will not be compared with any alternatives.

2.2.2 Scope Definition – What to Analyze & How

The scope of an LCA study is a detailed definition of the product or system that will examined. In addition, the purpose of the Scope Definition is to establish the methodological, quality, reporting, and review requirements in accordance with the goal of the study (Joint Research Centre 2010).

2.2.2.1 Scope Definition – Overview

The information required for a scope definition includes:

- The type(s) of the deliverable(s) (see Appendix 1 for a list from the ILCD)
- Function(s), functional unit, and reference flow(s)
- LCI modeling framework and handling of multifunctional processes and products
- System boundaries, completeness requirements, and related cut-off rules
- LCIA impact categories to be covered and methods to be applied
- Other LCI data quality requirements regarding technological, geographical and time-related representativeness and appropriateness

- Types, quality and sources of required data and information, and required precision and maximum permitted uncertainties
- Special requirements for comparisons between systems
- Identifying critical review needs
- Planning reporting of the results

(Joint Research Centre 2010)

2.2.2.2 Scope Definition - Major Concepts

Determining the scope of a study is a process of building on the goal definition; it takes what was implicit and makes it explicit. This requires an interpretation of the goal, and thus there are many possibilities – as long as they fall within the requirements of the overall purpose. Several types of deliverables can be selected, each with different characteristics and data requirements. There is very little limitation on how a functional unit can be defined, and the system boundary is equally fluid. But the completeness and representativeness of an LCA will be judged according to these parameters, and for this reason, it is important to clearly define the functional unit and system boundary in this stage. Moving forward, it would most likely be advantageous for the building industry to standardize such decisions for simplified comparison.

Functional Unit

The functional unit is the central purpose of an LCA – it is the product or process being modeled, and must be quantitatively defined by parameters that can produce specific masses or volumes of inputs and outputs. In the case of building materials, it may be a certain amount of that material that can then be applied to projects at their specified quantity. But in the case of a whole-building LCA, the functional unit is actually the building itself, and all the functions it must perform, as well as the time period it will be expected to perform those functions. It should not go into design details, because many different designs can serve the same function, and that is part of the reason for performing the LCA in the first place. It should define things like: occupancy, conditioned space, internal environmental quality, and so on. These functional parameters ensure that a comparative LCA will evaluate equivalent functional units.

LCI Modeling Framework

The modeling framework refers to the methodological decisions that are taken regarding the given situation – A, B or C – and the types of processes that fall within the system boundary. As an example, when the LCA study falls under situation B, a consequential LCA must be conducted in order to properly consider the outcome of a long-term or large scale decision. Also, if a process has multiple products or byproducts, it makes it more difficult to determine how much of the impacts from that process should actually be attributed to the functional unit being modeled. During the scope definition phase, the situation and resulting methodology must be selected. A more detailed description of modeling multi-functionality will be covered later in the Inventory Analysis section.

Attributional vs. Consequential

Attributional life cycle modeling depicts an actual or forecasted supply-chain – along with the use and end-of-life value chain – embedded into a static technosphere (Joint Research Centre 2010). In contrast, Consequential life cycle modeling depicts a supply-chain as it is theoretically expected to be as a result of the analyzed decision. The model interacts with markets, and represents a dynamic technosphere that is reacting to additional demand. A key step in consequential modeling is the identification of the marginal processes, starting from the decision and building the process chain life cycle model around them (Joint Research Centre 2010).

In general, Consequential modeling is only necessary if it is determined that the decision being analyzed in a comparative LCA will have significant effects on the background production system.

System Boundary and Cut-Off Criteria

The system boundary defines which stages of the life cycle, and which processes within those stages will be included in the analysis. The first represents a qualitative assessment of what is important to consider for meaningful results. In some cases only extraction and manufacturing are important – cradle to gate – while in other circumstances it would be necessary to include transport from plant or the use phase of competing products.

The quantitative definition of the system boundary can be created once the critical phases have been identified. In practice it is impossible to include all processes and background impacts; therefore a practitioner must exclude those that have too little impact to be relevant. This is done by defining cut-off criteria, which determine the percentage of the total theoretical impact that must be accounted for in an LCA in order to be considered complete. As an example, if 95% coverage is determined acceptable, then all of the foreground and the most important background processes are modeled until only 5% of theoretical environmental impact remains and can be cut-off.

Inventory Data Quality

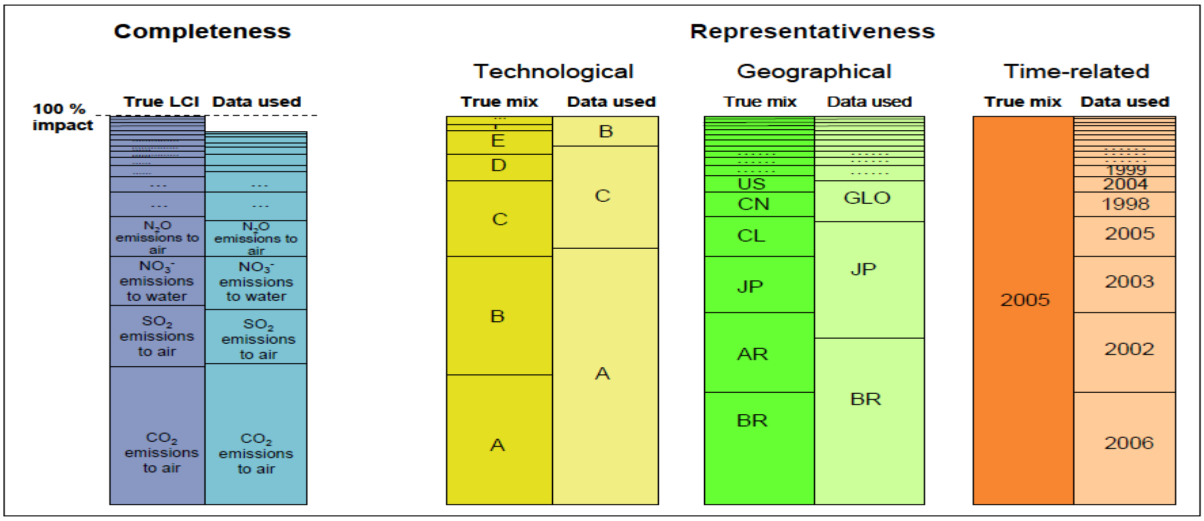
Depending on the determined goal and scope, there will be varying requirements for data quality, which is defined by three aspects: accuracy, precision/uncertainty, and completeness (Joint Research Centre 2010).

Accuracy is measured in terms of the overall representativeness of the inventory and method used in depicting the functional unit. **Representativeness** is a cumulative result of the appropriateness of the selected data for each inventory process, as well as the method used to analyze that data (Joint Research Centre 2010). The **appropriateness** of a process is determined by three factors: technology, location, and time period. The closer these elements match the actual case, the more appropriate the data is, and therefore the more representative the inventory will be. The appropriateness of a method is determined by the goal definition, as well as consistency and reproducibility of the results.

Precision/uncertainty can be expressed in terms of **variance** or **variability**. Variance is stochastic uncertainty, which is introduced into a model by measurement error or other random sources. Variability is introduced into a model when a practitioner must use data that is not completely appropriate, or chooses a methodology that is not appropriate for a given goal definition or functional unit (Joint Research Centre 2010).

Completeness represents the estimated percentage of total impacts that have been captured by the inventory. Due to time and data limitations it is often not possible to achieve 100% coverage of theoretical impacts, but understanding how the inventory relates to that ideal helps to put it in proper perspective.

The diagram below illustrates these concepts by showing a hypothetical case where the theoretical true mix of parameters is compared to the data actually used. Even though the technology, location, and time period are not an exact match, and the model does not capture all impacts, this may still be acceptable depending on the goal of the study.



Figur 8. ILCD Handbook: Inventory completeness and representativeness (Joint Research Centre 2010)

LCI Model Validity

The term **validity** refers to the overall quality of the inventory data and the resulting impact measurements of an LCA study (Joint Research Centre 2010). According to the criteria defined previously – accuracy, precision/uncertainty, and completeness – a level of quality can be determined for a given LCA. The ILCD Handbook has created a table of **Quality Levels** and numerical **Quality Ratings** that are based on quantitative measures of Completeness and Precision, and semi-quantitative and qualitative expert evaluation of the Accuracy factors – Technological, Geographical, Time-related, and Methodological appropriateness. Quality Levels range from *Very Good* to *Very Poor*, and Quality Ratings are on a scale of one to five – with one being the best.

As an example, over 95% Completeness and a Precision/Uncertainty of less than 7% is considered *Very Good* and receives a Quality Rating of one (Joint Research Centre 2010). For the three data Accuracy categories, ILCD uses the following language to describe a quality rating of one: "Meets the criterion to a very high degree, having no relevant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality" (Joint Research Centre 2010).

Once a quality rating has been determined for all categories, the overall Data Quality Rating (DQR) can be calculated using the following formula:

$$DQR = \frac{TeR + GR + TiR + C + P + M + X_w * 4}{i + 4}$$

Formel 1. ILCD Handbook: Data Quality Rating (Joint Research Centre 2010)

TeR = Technical Representativeness
GR = Geographical Representativeness
TiR = Time-related Representativeness
C = Completeness
P = Precision/Uncertainty
M = Methodological Appropriateness & Consistency
Xw = Weakest quality level obtained (highest numeric value) among data quality indicators
i = number of applicable data quality indicators (some may be excluded if not relevant)

The following table provides a basic description of various DQR ranges in terms of what practitioners should aim for, and could potentially be used to establish what goals and uses are appropriate for a given study.

Tabell 10. Relative data quality ratings

Overall data quality rating (DQR)	Overall data quality level
≤ 1.6[218]	"High quality"
>1.6 to ≤3	"Basic quality"
>3 to ≤4	"Data estimate"

(Joint Research Centre 2010)

Planning Reporting

Forms of Reporting

- Classic: detailed project report, directed at LCA experts, executive summary for non-technical readers, documentation of method and assumptions.
- Condensed: electronically exchangeable report in the form of a data set, document individual unit processes, not appropriate for comparison.
- Very Condensed: executive summary of full report with non-technical language

Levels of Reporting

- Internal – only practitioners
- External – well defined list of recipients
- Comparative Assertion – available to the public

(Joint Research Centre 2010)

2.2.3 Inventory Analysis – Collecting, Modeling, Calculating

This is the phase where data collection takes place, and modeling of the system is to be completed (Joint Research Centre 2010). This is to be done using the goal and scope definitions as guidance, building on those requirements in terms of identifying specific data sources and planning the process.

2.2.3.1 Inventory Analysis – Overview

The inventory phase involves the collection of data for:

- Flows to and from processes (elementary resources and emissions, land use, product flows, waste flows)
- Other information identified as relevant in the scope definition (statistical data, process and product characteristics such as function and functional units)

The steps to create a life cycle inventory include:

- Identifying processes that are required for the system
- Planning of collection of raw data and data sets from secondary sources
- Collecting unit process inventory data for foreground system
- Developing generic LCI data for missing inventory data
- Obtaining complementary background data as unit process or LCI result data
- Aggregation and averaging LCI data across process or products
- Modeling the system by connecting and scaling the data sets for functional unit
- Solve multi-functionality of processes according to attributional or consequential rules

- Calculate LCI results (sum all inputs and outputs of all processes within system boundaries – if completely modeled only the reference flow (final product) and elementary flows)

(Joint Research Centre 2010)

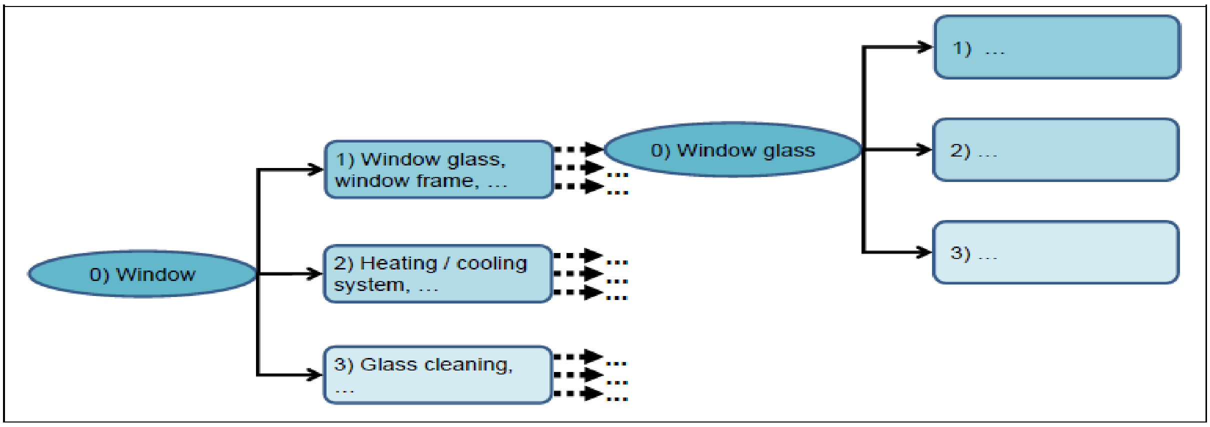
2.2.3.2 Inventory Analysis – Major Concepts

Once a scope has been defined, the processes that are included in the system boundary have to be identified and their flow data collected. In the case of buildings, the foreground processes are those associated directly with the construction and use of the building itself, and the background processes are those activities involved in the manufacture of materials and generation of electricity.

The inventory analysis step represents the majority of the time and effort required to produce an LCA, and it is with this step that a BIM tool could greatly reduce the required effort by automating much of the data collection process. Currently, a practitioner must manually inspect construction documents to determine material inputs, estimate operational energy use, and then transfer these totals to some version of LCA software. BIM can already supply much of the material and energy use data automatically if a model has the necessary information embedded in the building objects and spaces. But a critical question for LCA practitioners is whether an adequate quality of data can be obtained through these methods. As discussed earlier, the representativeness, precision and completeness must meet a specific threshold when applying BIM data to whole-building LCAs in order to be ILCD compliant.

Indentifying Processes in Attributional Modeling

From the LCA perspective, there are multiple tiers of processes – the foreground system that provides for the functional unit, and then the background tiers that are increasingly detached from the final outcome. Below is a diagram that shows this concept using a window as an example – the window itself is Level 0, the production of window elements represent Level 1, the related functions within a building are examples of Level 2, and a tertiary process such as maintenance is Level 3. These levels are relative to the chosen functional unit, but each process could itself be a functional unit – as is shown by the window glass being set at Level 0 with its own background processes.



Figur 9. Impact tiers for a window (Joint Research Centre 2010)

In the case of an entire building, the functional unit would fall to the left of the window in this diagram. This means that Level 1 processes would include the function of individual materials and equipment – windows, HVAC, etc. – used by the building, all on-site activities during construction and operation, as well as impacts from refurbishment and disassembly. This identification process does not result in an endless list of processes to be included because of the cut-off rules mentioned before.

Identifying Processes in Consequential Modeling

In the special case of modeling multi-functionality and/or predicted large scale market changes, consequential modeling can be used, but it is only required for situation B studies. The basic steps for determining which processes will be impacted by the decision, and therefore should be included, are the following:

- Decide which primary and secondary consequences and constraints are to be integrated into the model
- Identify processes that are operated or displaced due to these consequences
- Analyze the considered consequences taking into account constraints, and model the consequential life cycle starting from the decision in the foreground

(Joint Research Centre 2010)

This type of modeling is more complex than attributional modeling because it requires multiple areas of expertise outside of the basic skill set required for LCA. Some of these include: technology development forecasting, scenario development, market forecasting, general and partial-equilibrium modeling (Joint Research Centre 2010).

Planning Data Collection

Specific, average, or generic data can be used in an LCA, and it is critical to understand where each is appropriate (Joint Research Centre 2010). Specific data is collected from producers or operators; as primary data it is the highest quality option and should be used for foreground processes whenever possible (Joint Research Centre 2010). In the building industry, this could be provided by EPDs generated by private BPMs.

But in practice, this specificity is often not possible, and so sometimes an average market mix must be assumed – this is usually the case in LCAs attempting to model a regional electricity generation mix. Generic unit process data can also be used for common technologies – such as run-of-the-river hydroelectricity generation.

During early design phases, when exact materials have not been specified, generic or average secondary data could be used to identify "hotspots" where more detailed specific data would make the most impact. Secondary data is also acceptable for processes that represent small quantitative impacts, as well as standardized services or products that merely require scale adjustment (Joint Research Centre 2010).

Collecting Unit Process and LCI Data

Unit process data are the basis of all LCI work, and the procedure for assembling them are the same for both attributional and consequential modeling (Joint Research Centre 2010). In an ideal case, they relate to a single process; such as the transport of a specific good by a specific model of truck. But as mentioned above, this is not always possible, so in cases where generic or average data is considered superior these aggregated data can be used. The main guidance from ILCD in this task is to avoid "black box" processes that combine a number of sub-processes, but when this cannot be avoided, attempt to be as transparent as possible and document what it contains (Joint Research Centre 2010).

Types of Flows

Input flows include:

- Elementary flows
    - material and energy resources
    - land use
- Product flows
    - energy carriers
    - chemicals and materials

- consumables
- parts and components
- semi-finished products
- complex products
- services of all kinds

Output flows include:

- generated waste
- emissions to air, water, and soil
- other environmental aspects such as noise

(Joint Research Centre 2010)

Tracking input and output flows of a building can be applied to more than just energy and materials. As an example, water scarcity and land use have become critical issues facing future development in the built environment. The ILCD Handbook recommends using the latest IPCC carbon dioxide emission factors for land transformation, and categorizing both input and output flows of water (Joint Research Centre 2010). This could highlight the use of grey and recycled water in buildings, and add to their business case by better accounting for their environmental impact in the design process.

Modeling Multi-Functionality

If a process provides more than one function – meaning it delivers several "co-products" – it is "multifunctional" and impacts must be split between these functions (Joint Research Centre 2010).

If possible, the best solution to this challenge is Subdivision. This entails splitting the larger process, and collecting data for the mono-functional process being analyzed by the system. This is the only completely correct and exact solution under attributional modeling assumptions (Joint Research Centre 2010).

An alternative solution is to use System Expansion by adding or removing the impacts from an equivalent mono-functional product to simulate the co-product that is not the basis of the study. Depending on the functional unit of the comparative study, more or less functionality must be modeled in order for two products to be functionally comparable.

The final – and least desirable – option is to use Allocation (Joint Research Centre 2010). This method solves the multi-functionality problem by splitting impacts according to a chosen criterion. This variable could be energy content, mass, market price, etc, but using simplistic proportional attribution assumptions will introduce an unknown amount of uncertainty into the model.

The table below shows a summary of preferred procedures for each of the LCA study contexts:

Tabell 11. Methodological guidance for different LCA situations

	Situation A: "Micro-level decision support"	Situation B: "Meso- or macro-level decision support"	Situation C: "Accounting"

Guidance:	- LCI of existing supply chain applying attributional modeling - Apply multifunctionality hierarchy: subdivision > system expansion > allocation - If additional co-product cannot be absorbed by market, then use Situation B	- For processes identified as being affected by the analyzed decision, use consequential modeling as a mix of long-term marginal processes	-C1: existing co-product benefits outside the system are considered using system expansion -C2: multifunctionality is split using allocation -Cannot directly be used for decision support or comparisons of alternative measures

(Joint Research Centre 2010)

2.2.4 Impact Assessment – Health, Environment, and Resources

Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the inventory is translated into impact indicator results related to human health, the natural environment, and resource depletion (Joint Research Centre 2010).

2.2.4.1 Impact Assessment – Overview

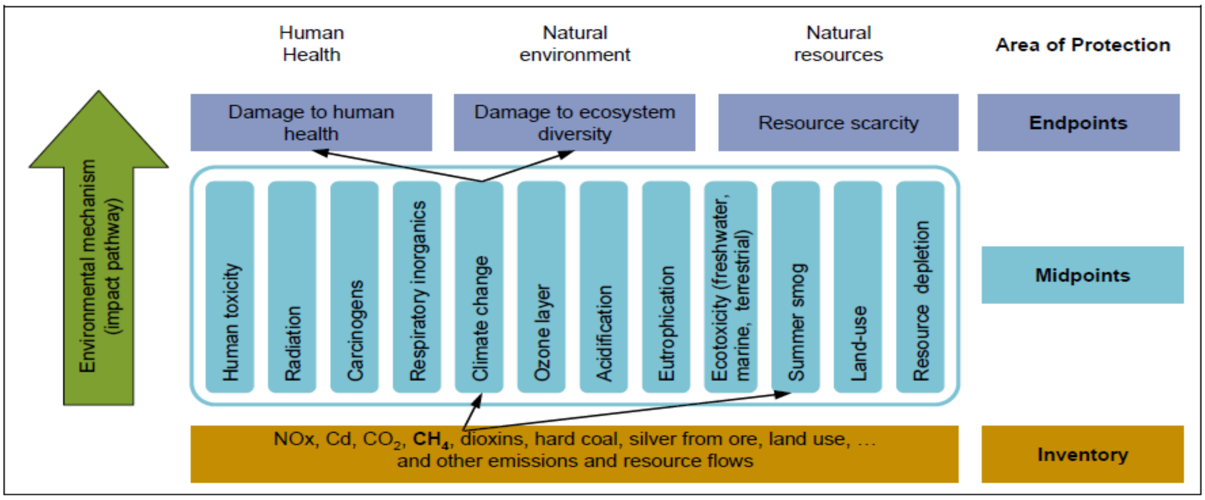
The Impact Assessment phase includes the following steps:
- Individual inventory data from the LCI are multiplied with characterization factors
- (Optional step) Results can be multiplied with normalization factors (country, average person)
- (Optional step) Normalized results can be multiplied by weighting factors – this is done to add importance to specific impact categories (global warming), or areas-of-protection

(Joint Research Centre 2010)

2.2.4.2 Impact Assessment – Major Concepts

When the LCI is complete, the emissions from every process are known, but it is difficult to understand what it all means. For this reason, the Impact Assessment step consolidates this information into more meaningful impact categories. The initial step is to group emissions that are known to contribute to similar impacts into a single indicator – kilograms of carbon dioxide equivalents (CO2-eq) is an example for global warming potential (GWP). Every greenhouse gas that contributes to global warming is converted to the equivalent amount of carbon dioxide that would produce the same level of warming. The calculation of these factors is done by a small number of industry experts, and then built into LCA software to ensure their consistent application. At this level of consolidation, they are known as mid-point indicators, and still represent physical units of emissions.

Mid-point indicators can be useful if a decision maker merely wishes to minimize one impact category – such as global warming – but they say little about the actual impact on humans and the environment. For this reason, end-point indicators have also been developed by experts that attempt to quantify the collective impact of all categories into measures of qualitative value, such as disability adjusted life years (DALY) – a measure of the expected reduction in a population's healthy lifespan. The figure below shows a simplified example of how this is done.



Figur 10. ILCD Handbook: Impact indicator levels (Joint Research Centre 2010)

In order to predict the impact of emissions on human health and ecosystems, it is required to conduct scenario analysis that makes assumptions regarding future conditions. This introduces uncertainty into the modeling, and it is for this reason only experts are tasked with developing end-point indicators.

Normalization and weighting are also central to adapting mid-point indicators into more meaningful results. Normalized results show the relative importance of the emissions for all the impact categories in the context of a given region. It may be the case that a very large amount of greenhouse gases are emitted by a process, but because it is relatively small compared to regional emissions, it is more important to focus on Acidification Potential (AP), which initially appeared much less important due to lower emission values.

Weighting is slightly different because it introduces opinion into the analysis by allowing users to determine the relative importance of different impact categories. Some industries have a clear focus on reducing their carbon footprint, in which case they would most likely add weight to GWP. This is not a problem, but any weighting must be documented so users understand how a conclusion was reached.

2.2.5 Interpretation – Conclusions, Recommendations, and Limitations

Life cycle interpretation evaluates the results of an LCA in order to answer the original questions posed by the goal definition. This interpretation relates to the intended applications of the LCA study and can be used to develop recommendations (Joint Research Centre 2010).

2.2.5.1 Interpretation – Overview

The iterative steps of interpretation include:

- Identification of significant issues
- Evaluate issues according to impact on results
- Evaluate solutions regarding completeness and consistency

The final interpretation steps include:

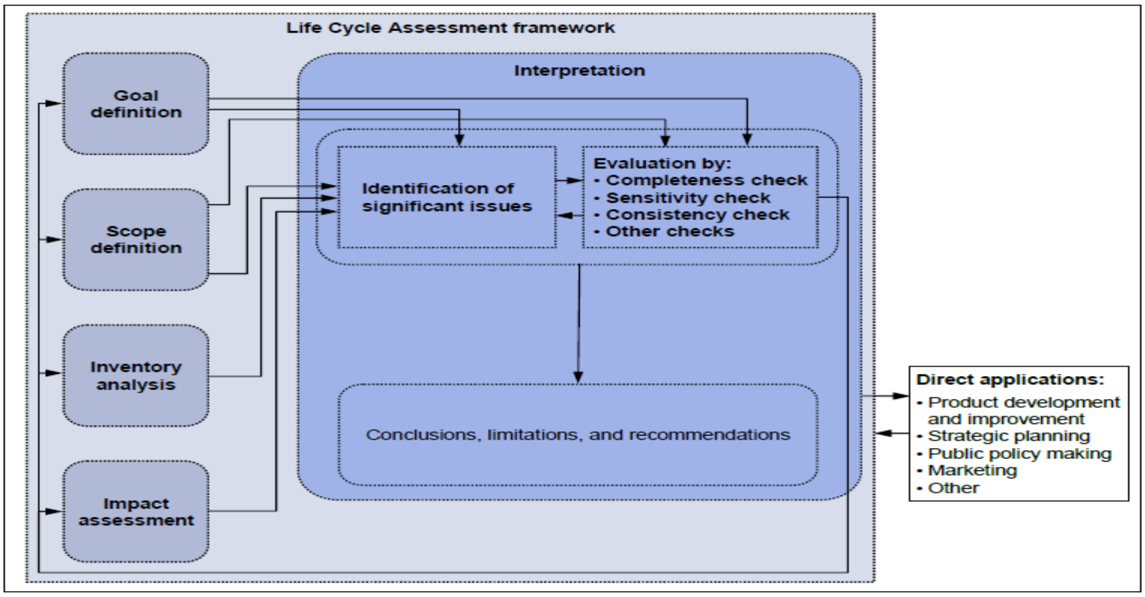
- Evaluate study limitations
- Formulate conclusions
- Establish recommendations

(Joint Research Centre 2010)

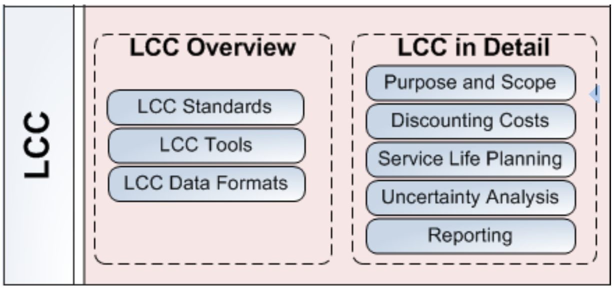
2.2.5.2 Interpretation – Major Concepts

The interpretation phase is ongoing throughout the iterative LCA process, but the final conclusions and recommendations should be limited in scope to only answer the questions originally posed by the goal definition. Using the initial intentions of the study as a guide ensures that the system boundaries and functional unit remain appropriate for any conclusions that are reached (Joint Research Centre 2010).

Below is an expanded version of the basic LCA concept diagram that details the role of interpretation throughout the LCA process. Identification of significant modeling issues regarding completeness, sensitivity, and consistency are included at every stage, while conclusions, recommendations, and limitations are summarized at the end of a study.



Figur 11. ILCD Handbook: Interpretation step in detail (Joint Research Centre 2010)

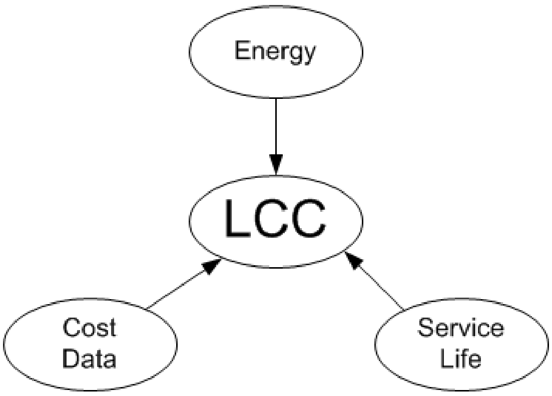


Figur 12. Content Map: LCC Theory

2.3 LCC Overview

Life Cycle Costing (LCC) is a tool for assessing the total cost performance of an asset, including the acquisition, operating, maintenance, and disposal costs (Davis Langdon 2007b). In the case of buildings, it is used to evaluate and compare different designs that vary both in initial construction, but more importantly predicted operational costs during the use of the building. It is estimated that costs of owning and occupying an office building over a 30 year period have a ratio of 1:5:200 – where total construction cost, is a fifth of maintenance costs, and one two hundredth of building operation costs with staffing included (Davis Langdon 2007b). This provides clear motivation for reducing maintenance requirements and improving internal environmental quality for staff, as well as the importance of LCC to model projected use phase costs.

The figure below shows the three major input categories for LCC – cost data, service life, and energy consumption. Cost data is used as a multiplier to estimate expenditures according to specified construction materials and energy consumption, but service life predicts the recurrence of those expenditures. It is this time element that can reveal the benefit of specifying more durable materials that require greater upfront investment.



Figur 13. Basic LCC model inputs (Edvardsen et al. 2009)

The basic life cycle cost equation can be written as the following:

Life-cycle costs =		Initial Investment Costs
	+	(PV) Replacement Costs
	–	(PV) Residual Value
	+	(PV) Energy Costs
(PV = Present Value)	+	(PV) Operation, Maintenance & Repair (OM&R)

Formel 2. Basic life cycle cost equation (Addison 2002)

These costs can be grouped into those that are Investment-related – initial investment, capital replacement, and residual value – as well as those that are Operations-related – energy and OM&R.

2.3.1 LCC Standards

2.3.1.1 NS3454: Life cycle costs for building and civil engineering work

The original NS 3454 was first created in 1988, and was meant to be used for the calculation of the annual costs of buildings. Then in 1996 there was a study called: *Samspillet I byggeprosessen – Tabellprosjektet* that was used to update the older standard to the scope it currently covers – the current version was released in 2000 (Standard Norge 2000). This was the first standard of its kind in Europe, and has been used in the development of later ISO and data standardization efforts.

2.3.1.2 10 CFR 436 – Subpart A: US DOE Methodology and Procedures for LCC Analyses

The US Department of Energy (DOE) codified the rules for performing LCC analysis of investments for energy and water conservation and renewable energy resource projects (US DOE 1990). These rules apply to new and existing buildings that are owned or leased by the federal government. Since this time, the practice of conducting LCC analysis is mandated for all federal projects (Addison 2002).

NIST Handbook 135: Life-cycle costing manual

This manual expands on the methodology and criteria established in the above US DOE Federal Energy Management Program (FEMP) rules, it aids in the implementation by explaining LCC methods, defining measures of economic performance used, describing assumptions and procedures to follow, giving examples and referencing software for reporting (Fuller & Peterson 1996). Annually updated energy prices and discount factors are also provided and required for use.

2.3.1.3 Davis Langdon Study

In 2006-07, the European Commission funded a study to establish a common LCC methodology "in order to improve the competitiveness and overall performance of construction" (Davis Langdon 2007a). At this time the only other LCC standard in Europe was the Norwegian Standard 3454 – the ISO standard 15686-5 was still in planning phases (Davis Langdon 2007b). The Davis Langdon study was considered in the development of the ISO standard, as well as for the LCC-DATA project that will be discussed later in the Data Format section.

2.3.1.4 ISO 15686 – 5: Buildings and constructed assets -- Service-life planning -- Part 5: LCC

ISO 15686 – 5 was completed in 2008, and represents the most recent LCC standard available in Europe (ISO 2008). For this reason, it will be used as a guide for the detailed theory section in this paper. As with other ISO standards, it aims to establish a clear terminology, framework, and set of guiding practices and principles. It does not provide a step-by-step process outline, which is provided by the Davis Langdon study and will be referenced in this paper.

2.3.2 LCC Tools

2.3.2.1 Building Life-Cycle Cost Program (BLCC) – US DOE

The BLCC is a software tool developed by the Federal Energy Management Program (FEMP) and the National Institute of Standards (NIST) – it draws on standards from the American Society for Testing and Materials (ASTM) (Addison 2002). The figure below shows an Excel version that was created for users that wish to have spreadsheets of all data and calculations to ensure complete transparency, but a more simplified user interface also exists. The software is free for the public to use and is the standard software for US government building projects (Fuller & Peterson 1996).

Tabell 12. BLCC sample spreadsheet

Life-Cycle Costs Summary
Glazing Selection Example Analysis

Case	Description	One-Time Costs 1st year $	One-Time Costs LCC PV $	1st year $	Total Utility Undisc LCC PV $	LCC PV $	Maintenance 1st year $	Maintenance LCC PV $	Total Undisc LCC PV $	Total LCC PV $	Net Savings NS	Simple Payback yrs	Discnt'd Payback yrs	Investment Related PV $	Operations Related PV $	Saving-to-Invest Ratio SIR	Adjusted Internal Rate-of-Return AIRR
	Life-Cycle COSTS																
Base	Single Clear	$54 300	$54 300	$681 630	$15 479 029	$10 820 840	$0	$0	$15 533 329	$10 875 140	n/a	n/a	n/a	$54 300	$10 820 840	n/a	n/a
Alt 1	Single Pane Azurlite **	$74 880	$74 880	$655 380	$14 884 058	$10 404 697	$0	$0	$14 958 938	$10 479 577	n/a	n/a	n/a	$74 880	$10 404 697	n/a	n/a
Alt 2	Calif Series - Water White Crystal	$482 040	$482 040	$645 720	$14 665 348	$10 251 677	$0	$0	$15 147 388	$10 733 717	n/a	n/a	n/a	$482 040	$10 251 677	n/a	n/a
Alt 3	Calif Series - Sea Foam Low-E Clear	$383 760	$383 760	$639 220	$14 516 052	$10 147 637	$0	$0	$14 899 812	$10 531 397	n/a	n/a	n/a	$383 760	$10 147 637	n/a	n/a
Alt 4	Calif Series - Tahoe Blue	$332 280	$332 280	$639 140	$14 516 807	$10 147 665	$0	$0	$14 849 087	$10 479 945	n/a	n/a	n/a	$332 280	$10 147 665	n/a	n/a
Alt 5	Viracon - VE1-55 - Low-E Clear	$169 650	$169 650	$642 060	$14 576 444	$10 190 651	$0	$0	$14 746 094	$10 360 301	n/a	n/a	n/a	$169 650	$10 190 651	n/a	n/a
Alt 6	Viracon - VE1-85 - Low-E Clear	$174 330	$174 330	$662 150	$15 032 076	$10 509 282	$0	$0	$15 206 406	$10 683 612	n/a	n/a	n/a	$174 330	$10 509 282	n/a	n/a
Alt 7	Viracon - VE7-55 - Low-E Azurlite	$256 470	$256 470	$626 930	$14 234 256	$9 951 168	$0	$0	$14 490 726	$10 207 638	n/a	n/a	n/a	$256 470	$9 951 168	n/a	n/a
Alt 8	Viracon - VE7-85 - Low-E Azurlite	$245 540	$245 540	$636 780	$14 456 988	$10 107 057	$0	$0	$14 702 528	$10 352 597	n/a	n/a	n/a	$245 540	$10 107 057	n/a	n/a
Alt 9	**PPG - SolarBan 2000 ***	$224 660	$224 660	$628 370	$14 267 425	$9 974 265	$0	$0	$14 492 085	$10 198 925	n/a	n/a	n/a	$224 660	$9 974 265	n/a	n/a
	** alternative with least life-cycle cost*																
	*** alternative with most rapid simple payback*																
	Life-Cycle SAVINGS (negative entries indicate increased costs)																
Alt 1	Single Pane Azurlite **	($20 580)	($20 580)	$26 250	$594 971	$416 144	$0	$0	$574 391	$395 564	$395 564	0,8	0,8	$20 580	$416 144	20,2	16,2% **
Alt 2	Calif Series - Water White Crystal	($427 740)	($427 740)	$35 910	$813 681	$569 164	$0	$0	$385 941	$141 424	$141 424	11,9	16,8	$427 740	$569 164	1,3	4,2%
Alt 3	Calif Series - Sea Foam Low-E Clear	($329 460)	($329 460)	$42 410	$962 977	$673 204	$0	$0	$633 517	$343 744	$343 744	7,8	9,8	$329 460	$673 204	2,0	6,0%
Alt 4	Calif Series - Tahoe Blue	($277 980)	($277 980)	$42 490	$962 222	$673 175	$0	$0	$684 242	$395 195	$395 195	6,5	8,0	$277 980	$673 175	2,4	6,7%
Alt 5	Viracon - VE1-55 - Low-E Clear	($115 350)	($115 350)	$39 570	$902 585	$630 189	$0	$0	$787 235	$514 839	$514 839	2,9	3,2	$115 350	$630 189	5,5	10,2%
Alt 6	Viracon - VE1-85 - Low-E Clear	($120 030)	($120 030)	$19 480	$446 953	$311 559	$0	$0	$326 923	$191 529	$191 529	6,2	7,4	$120 030	$311 559	2,6	7,0%
Alt 7	Viracon - VE7-55 - Low-E Azurlite	($202 170)	($202 170)	$54 700	$1 244 773	$869 672	$0	$0	$1 042 603	$667 502	$667 502	3,7	4,1	$202 170	$869 672	4,3	9,2%
Alt 8	Viracon - VE7-85 - Low-E Azurlite	($191 240)	($191 240)	$44 850	$1 022 042	$713 784	$0	$0	$830 802	$522 544	$522 544	4,3	4,8	$191 240	$713 784	3,7	8,6%
Alt 9	**PPG - SolarBan 2000 ***	($170 360)	($170 360)	$53 260	$1 211 604	$846 576	$0	$0	$1 041 244	$676 216	$676 216	3,2	3,5	$170 360	$846 576	5,0	9,8% *
	** LCC Choice*																
	*** Simple Payback choice*																
LCCa choice vs Simple Payback choice		($149 780)	($149 780)	$27 010	$616 633	$430 432	$0	$0	$466 853	$280 652	$280 652						

Analysis Assumptions:

DOE/FEMP Fiscal Year	2008	
Real Discount Rate for this Analysis	3,0%	
Study Period (years covered by the LCC analysis)	25	
# of Years before Project Occupancy or Opration	0	
DOE Fuel Price Escalation Region	4	*(West)*
Analysis Sector	2	*(Commercial)*

(Addison 2002)

2.3.2.2 LCProfit – Statsbygg

Starting in 1998, Statsbygg decided that all projects would have LCC calculations performed by the design team. LCProfit is the software that they developed to fulfill this requirement, and it is based on the legal foundation for demands regarding federal acquisitions that was enacted in 2001 (Statsbygg 2011).

The figure below shows the cost categories used according to the NS3454 framework; the numbering system provides a way to itemize costs within the larger header categories. This structure is very similar the BLCC system used by the US DOE.

Tabell 13. Cost categories for LCC from NS3454

STANDARD CATEGORIES						ADDITIONAL CATEGORIES		
REAL ESTATE AND PROPERTY MANAGEMENT								
	FM – Facilities Management							
	MOMD							
1 Capital-cost	**2 Management cost**	**3 Operating cost**	**4 Maintenance cost**	**5 Development cost**	**6 Unused**	**7 Servicing and/or support costs for the core activities**	**8 Potential of the property**	**9 Unused**
10 (Unused)	20 (Unused)	30 (Unused)	40 (Unused)	50 (Unused)	60 (Unused)	70 (Unused)	80 (Unused)	90 (Unused)
11 Project cost	21 Taxes	31 Daily operation	41 Scheduled maintenance	51 Current rebuilding	61	71 Administrative office management	81 Rebuilding	91
12 Residual cost	22 Insurance	32 Cleaning services	42 Replacements	52 Official rules and requirements	62	72 Switchboard and receptionist services	82 Additions / extensions	92
13	23 Administration	33 Energy	43	53 Upgrading	63	73 Canteen and/or catering services	83	93
14	24	34 Water and sewage	44	54	64	74 Furniture, fixtures and fittings	84	94
15	25	35 Waste disposal	45	55	65	75 Moving workplaces and/or job rotation	85	95
16	26	36 Watchguards and security	46	56	66	76 Telecommunications and IT-services	86	96
17	27	37 Outdoor	47 Outdoor	57 Outdoor	67	77 Postal and messenger services	87 Outdoor	97
18	28	38	48	58	68	78 Supplies and copying services	88	98
19 Miscellaneous	29 Miscellaneous	39 Miscellaneous	49 Miscellaneous	59 Miscellaneous	69	79 Miscellaneous	89 Miscellaneous	99

(Statsbygg 2011)

2.3.2.3 Versus – Holte Byggsafe

Versus is a private software solution that was developed by Holte Byggsafe and claims to be capable of producing LCCA studies. A temporary trial version is available for testing the software, but it does not offer full functionality and projects cannot be saved. Versus was not tested for the background of this paper.

2.3.2.4 Multimap – MultiConsult

Multimap is a tool that was developed by MultiConsult to assist the Norwegian government in assessing the state of their building portfolio. The tool utilizes NS3424 principles to evaluate the state of existing buildings by grading their current state on scale of 0 to 3 – where zero means there are no problems. In addition, there are approximately sixteen parameters that are used to determine the appropriateness and adaptability of the design, which are considered service life indicators for required renovation costs in the future (MultiConsult 2011). This tool is then meant to be used to compare the lifecycle costs of various options including: refurbishment, repurposing, or demolition and new construction. This tool is privately owned software, and is not available to public.

2.3.2.5 LCC-DATA – European Commission

The LCC-DATA project (2006-2009) was meant to simplify LCC data access and storage in order to extend the use of LCC in construction and improve the decision process in terms of sustainable development (Grini & Krigsvoll 2007). The project consisted of six work packages that covered: management, cost classification framework, data collection, calculations, communication, and dissemination. The end result was an interactive database for project LCC data, many case studies from a variety of countries and building types, as well as feedback from all participating countries (CRES & Kikira 2009).

It is interesting to note that many of the participants named the time requirement for data entry as a major barrier to data contribution (CRES & Kikira 2009). As part of the project, an Information Delivery Manual (IDM) was also created for the purpose of generating an LCC from a BIM, but an automated software solution was not developed.

Because many of the cost categories in LCC are parallel to LCA processes, the LCC-DATA IDM will be used as an example for this paper to extend the IFC methodology to the LCA field. Though LCC and LCA are similar in their use of life cycle modeling, LCA is a much more data intensive process and requires a more complex transformation of basic quantity data, so the scope will be limited to producing an LCI rather than a full impact assessment.

2.3.3 LCC Data Formats

2.3.3.1 Basic material cost data

Building material costs are documented annually for industry by various organizations internationally in order to produce specification manuals – such as MasterFormat in the US and BCIS in th UK – that allow architects and costing professionals to model and budget for the overall costs of a building. Until recently, this was always a time intensive process that required a large amount of manual calculation and specialized staff. Within the past few years, BIM technology has improved to the point where more companies feel comfortable using automated quantity take-offs from their models and are producing cost estimates from this data (Young et al. 2009).

Construction Classification Systems (CCS)

Part of the reason that the QTO function can be effective is that products have been organized in a universal taxonomy and an online searchable database. The ISO TC59/SC13/WG6 developed an electronic framework for tagging and managing of objects and their attributes according to ISO 12006-2: Organization of Information about Construction Works (OCCS 2010). This was used to create the OmniClass Construction Classification System or OCCS, which consists of a number of different tables that organize construction entities in various ways. Some examples include: construction function and form, as well as products, properties, and materials. OmniClass is the broadest of all classification systems, but it utilizes existing structures from other systems such as

Uniclass and MasterFormat. All of these systems are based on the ISO standard and therefore are not completely foreign to each other.

The table below provides the name of each OmniClass Table and examples of what is contained within them.

Tabell 14. Example content of various OmniClass tables

Table 22	**Work Results**: cast-in-place concrete, structural framing, finish carpentry, ceramic tiling, hydraulic freight elevators, interior lighting (a combination of **Products)**
Table 23	**Products:** concrete, common brick, door, metal window, curtain walls, paint (a combination of **Materials** or **Materials** used in their original form**)**
Table 41	**Materials:** metallic compounds, rocks, soils, timber, glass, plastics, rubbers (basic chemical compounds defined by a set of **Properties**)
Table 49	**Properties:** color, width, length, thickness, depth, diameter, area, fire resistance, weight, strength, moisture resistance (property definitions must reference a construction entity)

2.3.3.2 Life cycle cost and service life data

Service life data for LCC has not been widely used or available until recently in the building industry, and therefore there is no consensus on a classification system. The LCC-DATA project was created to address this issue, and support the implementation of such a standard, but did not achieve a final agreement (CRES & Kikira 2009).

The table below shows how LCC-DATA categorized cost variables associated with different building functions and phases. While there are still many different versions of this cost framework, the differences are not fundamental, and therefore it will be assumed that this system is acceptable and it will be used for the purposes of this paper. As a result of LCC's recent spread, there are efforts to incorporate this function into BIM tools – such as the CILECCTA project – but it is still in development.

Tabell 15. LCC-DATA cost categories

Category	Description
Capital costs	All investments towards completion including decommissioning by the end use of the facilities.
Administration costs	Activities for administration, required payments and insurance costs.
Operating costs	Include daily, weekly and monthly activities that are repetitive within a one-year period for building and technical installation systems that shall satisfy given functional demands and requirements.
Maintenance costs	Include all activities and efforts put forward in a period of more than one year. For example, planned maintenance, replacement and emergency repairs, so that the building and technical systems satisfies the original level of quality and functional re
Development costs	Includes activities as a result from change in demand from core activities, the authorities, total refurbishment, or all activities to raise the construction standards in relation to the original level.
Consumption costs	Consumption includes resources in terms of energy, water, and waste handling.
Energy	All costs related to energy supplies including oil, electric and heating.
Heating	
Cooling	
Electricity	
Water and drainage	All costs related to water consumption including intake water, waste water including cleaning
Waste Handling	Includes all costs from internal transport, compression, source separation, collecting (hired container), transporting related to waste and taxes for landfill.
Cleaning costs	All activities inside and outside for satisfactorily meeting cleaning demands.
Service costs	All non-building related activities in support of the core activities.

(Grini & Krigsvoll 2007)

2.4 LCC in Detail

The following section is a detailed account of LCC principles and practices primarily according to the standards established by ISO, but also others that were discussed earlier. This level of detail is included for the purpose of comparing the results of an LCC and LCA in order to combine the processes and make data collection more efficient. It is also aimed at establishing a formalized process to produce an ISO compatible output – of both an LCC and LCA – from a BIM using the IFC schema.

The table below created by the Davis Langdon study summarizes the LCC methodology in a fifteen step process – three of these steps (written in grey) deal with risk and sensitivity analysis and are considered voluntary. This methodology was developed largely with public sector clients in mind, because they have a unique role as large scale property developers and owners, as well as long-term tenants able to benefit from operational life cycle efficiency gains. There were also a number of case studies conducted at the time to test implementation and evaluate the results (Davis Langdon 2007b).

For the purposes of this paper, these steps have been grouped into five main categories that have been identified as the central tasks for LCC practitioners: defining the purpose and scope, collecting data and determining service life, creating a discounted cost model, assessing uncertainty, and interpreting/reporting results. In the table below, these task categories can be grouped in the following way:

- Define purpose and scope: **Steps 1 – 7**
- Collect cost data and define service life: **Step 8**
- Create discounted cost model (LCC): **Steps 9 and 11**
- Assess uncertainty: **Steps 10, 12 and 13**
- Interpret and report results: **Steps 14 and 15**

An important point to take away from this outline is the clear parallels between the steps of an LCC and an LCA. Because this paper is focused on the use of LCC data collection for the purpose of creating an LCA, the first eight steps in this process are the most critical, as well as the uncertainty and sensitivity analysis to evaluate data quality. If these steps are performed for an LCC, it would be simple to incorporate them into an LCA study.

In the interest of differentiating between the two analyses methods, and understanding the non-linear transformations of the cost data, the discounting process will be covered in detail. It is a critical difference between LCC and LCA that financial costs have a time value, whereas environmental impacts in the distant future are equally detrimental as those created today.

Tabell 16. Davis Langdon LCC methodology

	STEP	OUTCOME / ACHIEVEMENT
1	Identify the main purpose of the LCC analysis	• Statement of purpose of analysis • Understanding of appropriate application of LCC and related outcomes
2	Identify the initial scope of the analysis	Understanding of: • Scale of application of the LCC exercise • Stages over which it will be applied • Issues and information likely to be relevant • Specific client reporting requirements
3	Identify the extent to which sustainability analysis relates to LCC	Understanding of: • Relationship between sustainability assessment and LCC • Extent to which the outputs from a sustainability assessment will form inputs into the LCC process • Extent to which the outputs of the LCC exercise will feed into a sustainability assessment
4	Identify the period of analysis and the methods of economic evaluation	• Identification of the period of analysis and what governs its choice • Identification of appropriate techniques for assessing investment options
5	Identify the need for additional analyses (risk/uncertainty and sensitivity analyses)	• Completion of preliminary assessment of risks/ uncertainties • Assessment of whether a formal risk management plan and/or register is required • Decision on which risk assessment procedures should be applied
6	Identify project and asset requirements	• Definition of the scope of the project and the key features of the asset • Statement of project constraints • Definitions of relevant performance and quality requirements • Confirmation of project budget and timescales • Incorporation of LCC timing into overall project plan
7	Identify options to be included in the LCC exercise and cost items to be considered	• Identification of those elements of an asset that are to be subject to LCC analysis • Selection of one or more options for each element to be analysed • Identified which cost items are to be included
8	Assemble cost and time (asset performance and other) data to be used in the LCC analysis	Identification of: • All costs relevant to the LCC exercise • Values of each cost • Any on-costs to be applied • Time related data (e.g. service life/maintenance data)
9	Verify values of financial parameters and period of analysis	• Period of analysis confirmed • Appropriate values for the financial parameters confirmed • Taxation issues considered • Application of financial parameters within the cost breakdown structure decided
10	Review risk strategy and carry out preliminary uncertainty/ risk analysis	• Schedule of identified risks verified • Qualitative risk analysis undertaken – risk register updated • Scope and extent of quantitative risk assessment confirmed
11	Perform required economic evaluation	• LCC analysis performed • Results recorded for use at Step 14
12	Carry out detailed risk/uncertainty analysis (if required)	• Quantitative risk assessments undertaken • Results interpreted
13	Carry out sensitivity analyses (if required)	• Sensitivity analyses undertaken • Results interpreted
14	Interpret and present initial results in required format	• Initial results reviewed and interpreted • Results presented using appropriate formats • Need for further iterations of LCC exercise identified
15	Present final results in required format and prepare a final report	• Final report issued, to agreed scope and format • Complete set of records prepared to ISO 15686 Part 3

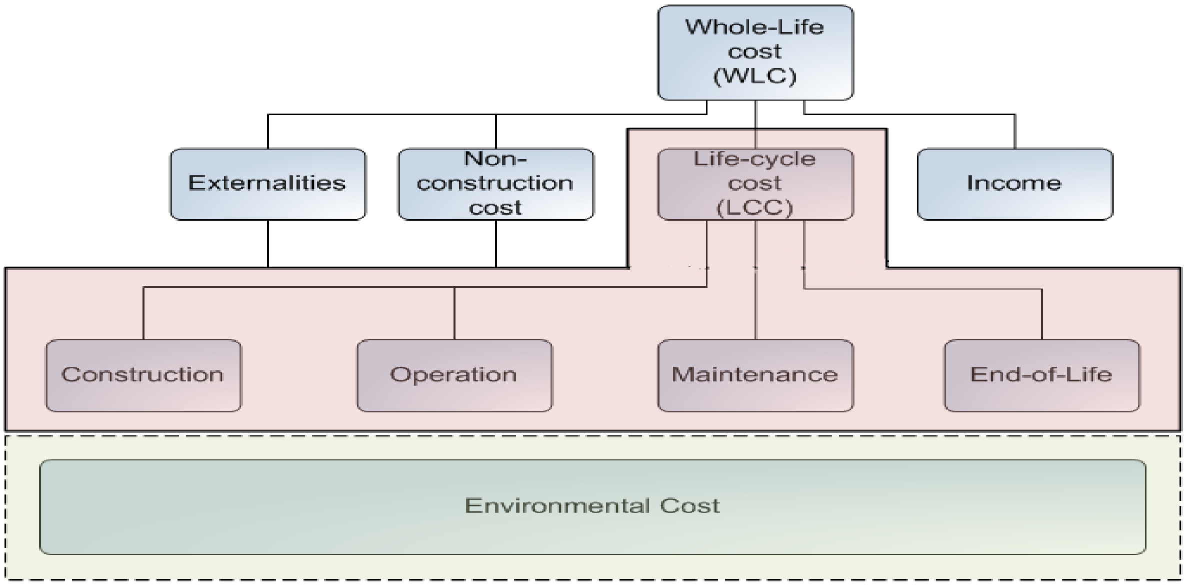
(Davis Langdon 2007a)

2.4.1 Defining the purpose and scope

According to ISO standard 15686-5, the purpose of life cycle costing should be to quantify overall life cycle costs for input into a decision making process, and should consider inputs from environmental, design, safety, functionality, and regulatory compliance assessments (ISO 2008). The standard also stipulates that “quantification should be on the level of detail that is required for key project stages,” and that the scope should be agreed upon with a client at the outset. Using LCC to compare different options requires that they meet all functional, operational, maintenance, aesthetic and any other performance specifications (ISO 2008).

2.4.1.1 Cost categories to include in LCC analysis

Beyond including a defined list of costs associated directly with a constructed asset, the ISO standard stipulates that non-construction and occupancy costs should be considered in an LCC, as well as local, national, and international policy impacts in the foreseeable future (ISO 2008). The diagram below shows the scope boundaries of an LCC as defined by ISO. It does not necessarily include all costs; an all inclusive scope is referred to as the whole-life cost (WLC) by the standard. The broken line around environmental costs shows that they should be considered within the scope of an LCC, but recognizes that they are often intangible costs, if not considered an externality.



Figur 14. ISO 15686-5 conceptual model of LCC (ISO 2008)

2.4.1.2 Levels of LCC analysis

As mentioned previously, there will be different levels of detail according to the purpose and phase of the study. LCC analysis generally falls into three categories, and the following is a summary of a figure provided by the ISO standard.

Strategic – high level planning	Examples: Safety and durability, location, maintainability
System – major building elements	Examples: Foundation, cladding, ventilation, finishes
Detailed – product specifications	Examples: Concrete type, MEP plant and equipment, paints

(ISO 2008)

2.4.1.3 Typical analysis at different stages of the life cycle

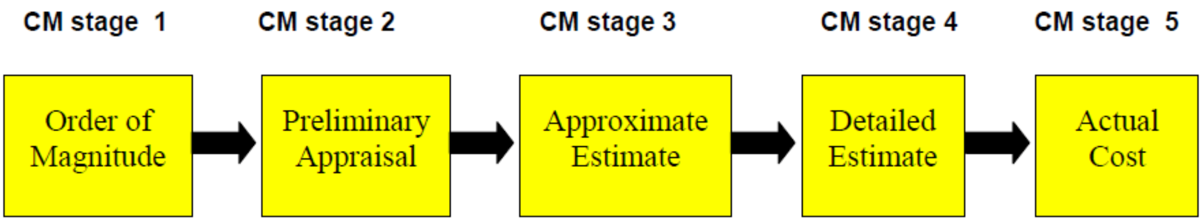
Project investment and planning	WLC/LCC strategic options analyses, pre-construction
Design and construction	LCC during construction (scheme, functional, system, and detailed component levels)
During occupation	Cost-in-use LCC, post-construction
Disposal	End-of-life/end-of-interest LCC

(ISO 2008)

2.4.2 Collection of cost data and defining service life

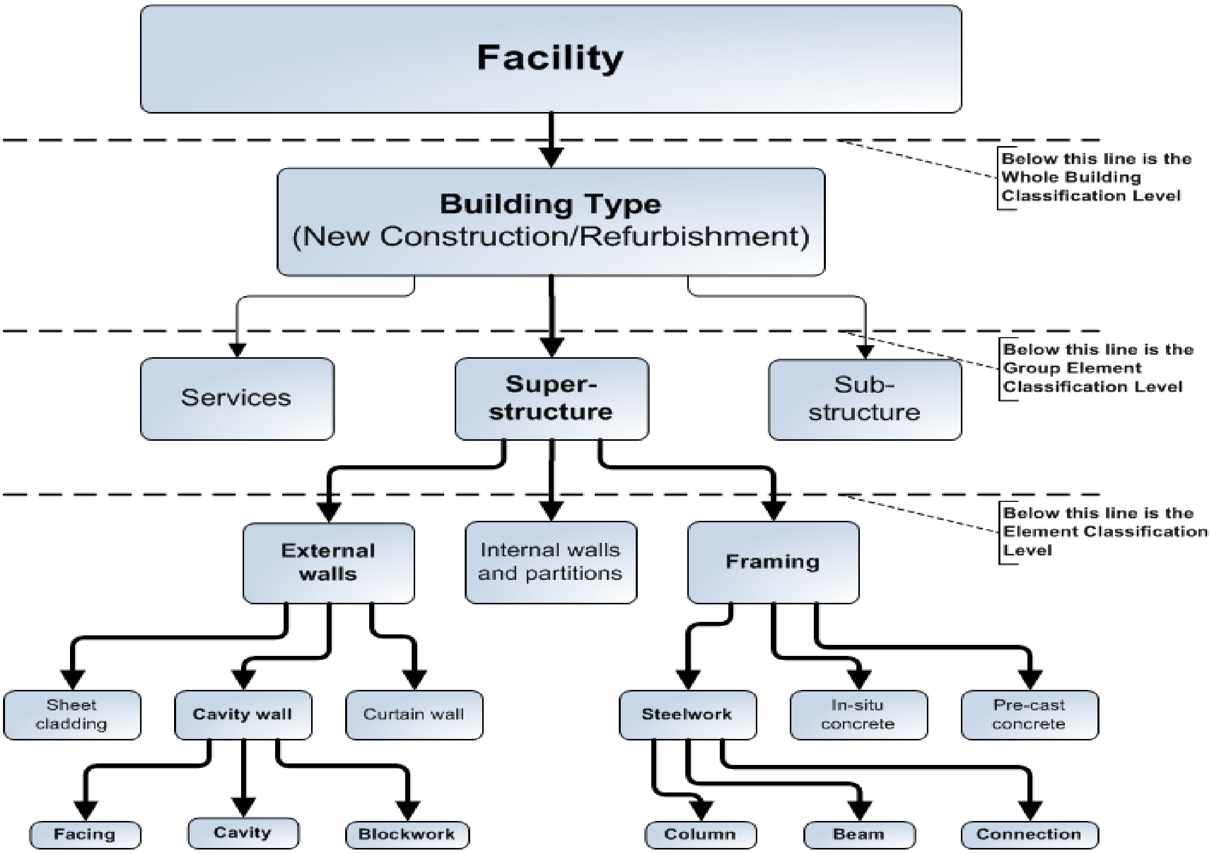
2.4.2.1 Data Collection

Depending on the purpose and modeling stage, this process will vary widely in terms of detail and time requirement. The following flow diagram shows the progression of cost modeling (CM) detail over the course of a construction project.



Figur 15. LCC-DATA: Progression of cost modeling (Edvardsen et al. 2009)

In more specific terms, the iterative development of the cost model can be described as a progression from generic building type, to group element, to element, to product specification. This idea is summarized in the diagram below that was recreated from the IDM created for the LCC-DATA project. Please note that the bold arrows represent an example path for the purpose of explaining the concept; the diagram is not an exhaustive representation of all objects and cost elements taken into account by an LCC.



Figur 16. LCC-DATA: Building element classification (Edvardsen et al. 2009)

Each of the cost modeling stages – Order of Magnitude, Preliminary Appraisal, Approximate Estimate, Detailed Estimate, and Actual Cost – can be related to this progression through the following definitions from the LCC-DATA IDM:

- **Order of Magnitude**: 'Objects' may be limited to just a 'building' or 'civil engineering works' of a 'type' in a 'location' and the cost required is an overall budget value broken down into these major parts (e.g. external works, preliminaries and contingencies). The cost in use stage and for demolitions/end of life can then be the key number of the same magnitude.
- **Preliminary Appraisal**: 'Objects' may be 'elements' of a particular 'material' and 'configuration' of building shape with broad specification and the cost required is still an overall value, but broken down into the elements of the construction project. A 'configuration' of building 'shape' means element unit quantities (EUQs) or measures of shape, such as wall to floor ratios etc. from which EUQs can be derived. When more exact information is available, also the use stage costs can be modified. Energy costs can be determined by use of energy demand calculations.
- **Approximate Estimate**: 'Objects' may be 'elements' that comprise a further collection of other 'component objects' of a particular 'standard' (or sub-elements). The cost required is still an overall value broken down into elements, but with more detailed evidence of how that value has been deduced through detailed costs of the elemental parts of the project. On this level, alternatives in technical solutions may be used to determine the differences in Life Cycle Costs.
- **Detailed Estimate**: 'Objects' are fundamentally equivalent to those in the Approximate Estimate, but possibly measured in more detail or with added 'attributes' such as 'construction process' which provides the basis of more accurate costing of the elemental parts of the project. When materials and solutions are chosen, the differences in maintenance scenarios can make basis for more exact life cycle costs.
- **Actual Cost**: 'Objects' are fundamentally equivalent to those in the Detailed Estimate, but are measured from their incorporation into the project. Both actual costs and detail estimates for objects may be maintained so as to provide an immediate comparison of expected and realized construction. When the as built situation is known, Life Cycle Costs can be recalculated giving basis for cost bearing rent or also for support in future Facility Management.

(Edvardsen et al. 2009)

This cost modeling (CM) progression can be further linked to the standard project stages established by buildingSMART and the IDM methodology according to the table below. The project stages listed apply to all IFC based BIM software, and are used to clarify at which point during the building lifecycle the information exchange will be taking place.

There are eleven stages in total, starting with steps 0 – Portfolio Requirements and 1 – Conception of Need, which have not been included in the table below due to their lack of relevance. Also steps 9 and 10 have been excluded – Operation/Maintenance and Disposal – because they occur after the costing scope of the LCC-DATA IDM.

Tabell 17. Cost modeling compared to IFC project stages

CM Stage	Name		Project Stage	Name
1	Order of Magnitude	→	2	Outline Feasibility
			3	Substantive Feasibility
2	Preliminary Appraisal	→	4	Outline conceptual design
3	Approximate Estimate	→	5	Full conceptual design
4	Detailed Estimate	→	6	Coordinated design and procurement
			7	Production information
5	Actual Cost	→	8	Construction Information

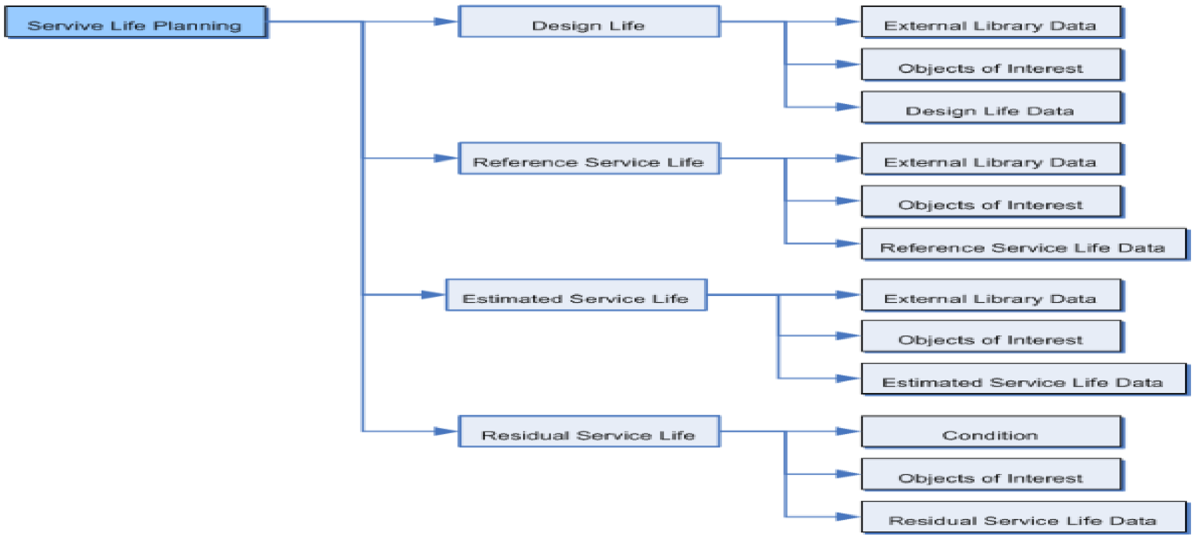
(Edvardsen et al. 2009)

This framework can be used to establish the required detail of information according to project stage and study purpose, as well as a planning tool to determine appropriate data sources and data collection process.

2.4.2.2 Service Life Planning

The previous steps have provided material cost data and possibly some maintenance costs according to specification guides if a Detailed Estimate has been performed. But service life planning is different because it aims to predict the functional lifespan of major building elements – the refurbishment and replacement costs over the expected lifespan of the building.

This process can be conducted in four distinct stages of a building's lifecycle – Design Life, Reference Life, Estimated Service Life, and Residual Service Life (Edvardsen et al. 2009). Each step represents a progressively later stage in the building's lifespan, and therefore an increase in available information and accuracy of results. The figure below shows this in a schematic diagram created for the LCC-DATA IDM:



Figur 17. Service life planning phases (Edvardsen et al. 2008)

Design Life: Product information is aggregated at the whole building level and specifications of whole systems, only the design life of a product can be determined.

Reference Life: Individual products and manufacturers/suppliers are identified.

Estimated Service Life: Later design stages and during construction, when the configuration and location of products has been fully established. It becomes possible to analyse the service life of products according to 'in use' conditions. These conditions can vary the reference service life depending on factors such as exposure to weather, aggressiveness of the local environment and other degrading (or upgrading) factors.

Residual Service Life: The condition of a product may be checked from time to time during the operational stage, and a residual service life can be assessed. If degradation is more than has been expected, the residual service life may be reduced to less than the value that might have been expected from the estimated service life.

(Edvardsen et al. 2009)

2.4.3 Discounting costs to present values

A central element of LCC is the calculation of the present value (PV) of future cashflows. This is done by assuming a rate that estimates the time value of money – a measurement of the investment potential of currently held capital. For the private sector, the discount rate should represent the opportunity cost of investing capital in a building project. This can represent the following: interest cost of a loan, loss of interest from deposit, loss of return on investment elsewhere, actual return achieved on capital, or required rate of return for an investor (ISO 2008). The public sector usually determines its own discount rate according to long-term opportunity cost. Generally speaking, a higher assumed discount rate discourages long-term investments because cashflows in the distant future are modeled to become rapidly worthless and costs meaningless.

This can be seen in the calculation of Net Present Value (NPV) – the term used to describe the current value of an investment with a stream of future costs or cashflows.

$$NPV = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n}$$

Formel 3. Net present value of a construction project

Cn = cost or cashflow in year *n*
d = “real” discount rate (exclusive of inflation)
n = number of years after the base date
p = period of the analysis

2.4.3.1 “Real” Cost vs. “Nominal” Cost

Beyond the ability to invest elsewhere, a second factor that creates a time value of money is the gradual inflation of prices, which reduces the purchasing power of money over time. In order to accurately value future costs, a rate of general inflation is assumed, and the result is the “nominal” cost. The “real” cost is simply current prices projected for future goods and services – both “nominal” and “real” costs are assumed to include foreseeable future technology and efficiency gains. For LCC analysis, it is required to use “real” discount rates in order to maintain a constant currency for calculations. This is achieved in the following way:

$$Cn = P_0 * (1+i)^n$$

Formel 4. Nominal cost or cashflow

Cn = cost or cashflow in year *n*
P_0 = present cost of goods or services in year 0
i = assumed rate of general inflation
n = number of years after the base date

$$PV = \frac{Cn}{(1+D)^n}$$

Formel 5. Present value using nominal cost

PV = present value of the future cost (without isolating inflation cost)
Cn = cost or cashflow in year *n*
D = minimum rate of return on an alternative investment, the cost of borrowed capital
n = number of years after the base date

$$d = \frac{(1+D)}{(1+i)} - 1$$

Formel 6. "Real" discount rate

d = “real” discount rate (exclusive of inflation)
D = minimum rate of return on an alternative
i = assumed rate of general inflation

investment, the cost of borrowed capital

$$PV = \frac{Cn}{(1+d)^n}$$

Formel 7. Present value using real cost

PV = present value of the future cost (with inflation factored out)

Cn = P_0 (assuming *d* is "real")

d = "real" discount rate (exclusive of inflation)

The critical point of this procedure is to factor out an assumed inflation from costs in order to allow for the use of current costs throughout the model. For the purposes of LCC analysis, the inflation of energy prices – known as escalation – should be calculated separately from the rest of goods and services (Fuller & Peterson 1996).

2.4.4 Assessment of Sensitivity and Uncertainty

Due to the large scale and long-term nature of construction investments, there is inherent risk in the unknown economic factors that may ultimately determine the profitability of a project. The purpose of LCC is to reduce this risk by modeling likely outcomes, but it is important to understand the uncertainty attached to the results of an LCC. It is also helpful for decision makers to understand how much the results of an LCC are impacted by various inputs, and therefore which data they should focus on finding greater detail.

There are two major categories of methodologies to produce this sensitivity and uncertainty analysis: deterministic and probabilistic (Fuller & Peterson 1996). Deterministic approaches use single-value inputs to measure the impact on project outcomes, and an analyst subjectively determines the degree of risk. In a probabilistic study, a large number of alternative outcomes are selected and each assigned a probability. Generally speaking, deterministic methods are simpler, but if adequate data and time is available, probabilistic methods can more effectively deal with a broad range of possibilities and provide a statistical risk assessment according to a weighted average. The table below outlines the various methods used in both categories:

Tabell 18. Deterministic and Probabilistic uncertainty assessments

APPROACHES TO UNCERTAINTY ASSESSMENT			
Deterministic		**Probabilistic**	
1.	Conservative Benefit and Cost Estimating	1.	Input Estimates Using Probability Distributions
2.	Breakeven Analysis	2.	Mean-Variance Criterion and Coefficient of Variation
3.	Sensitivity Analysis	3.	Decision Analysis
4.	Risk-Adjusted Discount Rate	4.	Simulation
5.	Certainty Equivalent Technique	5.	Mathematical/Analytical Technique
6.	Input Estimates Using Expected Values		

(Fuller & Peterson 1996)

2.4.4.1 Sensitivity Analysis using Monte Carlo simulation

Once an LCC model has been completed, sensitivity analysis can help reveal which variables are most important in terms of impacting results. Because every data measurement has a limit to its accuracy, it must be represented by a range that the actual value will most likely fall within – this is called a confidence interval (Doubilet et al. 1985). Data values can also be assigned an assumed probability distribution according to their characteristics – normal distribution is most common. The Monte Carlo simulation method calculates sensitivity probabilistically by randomly varying all data values within their confidence interval and according to their probability distribution simultaneously.

The entire process can be carried out by a basic software tool that can complete the large number of calculations necessary in a short period of time. The result of this sensitivity analysis – if a sufficient number of outcomes are considered – should show the complete range of LCC values that are possible given all the uncertainty within every data entry. As an advantage over deterministic methods, it can expose unexpected sensitivity within a model that an analyst may not have expected.

2.4.4.2 Benchmarking risk with Breakeven Analysis

Breakeven analysis allows an analyst to understand the minimum required benefit for an investment to be economically advantageous. It is therefore a simple way to create benchmarks for comparison against the predicted performance of uncertain variables, and provide decision makers with a basis for assessing financial risk (Fuller & Peterson 1996). The equation below shows how this can be calculated by solving for the breakeven value:

$$S = \Delta C$$

$$[\Delta E + \Delta OM\&R + \Delta W] = [\Delta I_0 + \Delta Repl - \Delta Res]$$

where

S	=	Operational savings for the alternative relative to the base case,	
ΔC	=	Investment-related additional costs for the alternative relative to the base case,	
ΔE	=	$(E_{BC} - E_A)$	Savings in energy costs attributable to the alternative,
$\Delta OM\&R$	=	$(OM\&R_{BC} - OM\&R_A)$	Difference in OM&R costs,
ΔW	=	$(W_{BC} - W_A)$	Difference in water costs,
ΔI_0	=	$(I_{0A} - I_{0BC})$	Additional initial investment cost required for the alternative relative to the base case,
$\Delta Repl$	=	$(Repl_A - Repl_{BC})$	Difference in capital replacement costs,
ΔRes	=	$(Res_A - Res_{BC})$	Difference in residual values, and

where **all amounts are in present values.**

Formel 8. Breakeven analysis of risk (Fuller & Peterson 1996)

2.4.5 Reporting of LCC analysis

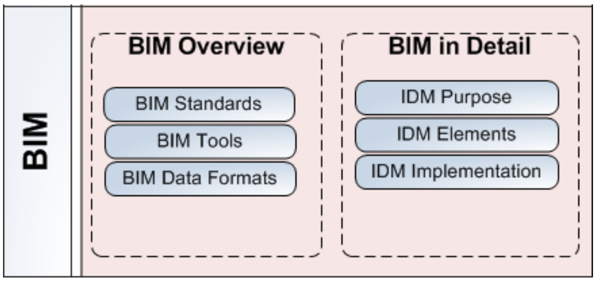
According to ISO, the results of an LCC analysis should be documented in a report that clearly defines "the purpose, scope, key assumptions, limitations, constraints, uncertainties, risks and effects of any sensitivity analysis" (ISO 2008). The standard also provides the following list of deliverables:

Tabell 19. LCC reporting according to ISO 15686-5

A) Executive summary	G) Alternatives considered in analysis
B) Purpose and scope – costs included or excluded and period of analysis	H) Discussion and interpretation of results – including risk assumptions and exclusions
C) Statement of objectives	I) Graphical representation of results
D) Materials under consideration	J) Replacement and maintenance plan – if supported by level of analysis
E) Assumptions made	K) Presentation of conclusions and recommendations for further work
F) Constraints and risks identified	

(ISO 2008)

As seen in previous sections, the reporting requirements for LCC are also quite similar to those defined for LCA. If such reports could be produced in a coordinated procedure it would reduce the time requirements.



Figur 18. Content Map: BIM Theory

2.5 BIM Overview

The term Building Information Modeling (BIM) represents a broad concept that does not have a universally accepted meaning across industry. For the purposes of this paper, a BIM will be defined according to the National Building Information Modeling Standard (NBIMS) as "a digital representation of physical and functional characteristics of a facility…[that] serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward" (NIBS & bSa 2007).

2.5.1 BIM Standards

2.5.1.1 NBIMS

The National BIM Standard (NBIMS) is being developed by a Project Committee from the US Chapter of the buildingSMART alliance (bSa) – which is housed in the non-profit National Institute of Building Sciences (NIBS). The first version was released in late 2007, and was meant to provide an approach for developing an open BIM standard (NIBS & bSa 2007). It was not a consensus standard at the time, but a final document is projected to be produced by the end of 2011 (NIBS & bSa 2010).

The importance of this standard for interoperability is that it clearly defines – as CAD Standards do – proper practices across all of the AECOO industry. When inserting, extracting, updating, or modifying information in a model, NBIMS will provide guidance – it is a collaboration and information sharing standard (NIBS & bSa 2007). Having such a resource removes uncertainty and reduces risk for all operators, and is meant to encourage the market to move to an interoperable strategy.

2.5.1.2 Software Development Schemas

At the software development level, there has been an ongoing effort for more than a decade to create a universal standard or schema that can be interchanged between all the various software platforms that are used in building construction. The International Alliance for Interoperability (IAI) was originally formed to address this problem, and now continues to work on these issues as the buildingSMART alliance (bSa) with member organizations all over the world. They created the Industry Foundation Class (IFC) schema as a non-proprietary platform for industry developers to use for data exchange. In parallel, the Green Building XML (gbXML) schema has been developed for use with data transfer to energy simulation software. These two data models are the most commonly used in industry, but IFC is only whole-building schema that has the potential to be fully interoperable (Khemlani 2004).

The main issue, whether communicating between people or computers, is to maintain the meaning of objects when exchanging information. These schemas are designed to do just that – a window in a BIM maintains its specified properties in an energy model. Though this process has been going on for a while, the ability to seamlessly transfer this information is still not perfect due to varying data requirements for different applications. But despite these limitations, programs like Revit, ArchiCAD and other BIM software can generate an IFC or gbXML file that can be directly input into energy modeling software. Some of the geometry may have to be adjusted to ensure accuracy, but it still represents a huge efficiency opportunity.

This paper will focus on the IFC schema as LCA depends on object properties other than those available in gbXML. Also, bSa provides a methodology for domain experts to create a "roadmap" for software solutions that will be implemented for LCA.

2.5.1.3 IFC – Industry Foundation Classes

The IFC schema is a comprehensive BIM data model that is based on a set of object properties outlined in the OmniClass construction classification system. This makes it applicable to all industry domains, but also means that the vast amount of information within an IFC model cannot be transferred effectively all at once – to use the IFC schema, Model View Definitions (MVD) must be created. Software applications designed to access specific information must go through an IFC compatibility certification process to prove they fulfill their purpose and meet IFC interoperability standards. MVDs ensure that only the appropriate data is extracted from a BIM and transferred to the various other trade-based software applications.

2.5.1.4 ISO 29481-1 BIM – Information delivery manual Part 1: Methodology and format

This ISO standard has been developed to provide a basis for reliable information exchange/sharing, and to create a methodology and format for the creation of an IDM (ISO 2010). This standard, along with bSa guidance documents and example IDMs, will be used for the detailed outline of the IDM methodology in this paper.

2.5.1.6 ISO Standard based on IFC2x4

The buildingSMART alliance has also submitted the IFC specification as an ISO Publicly Available Specification, and a New Work Item has been initiated with the ISO group to make the IFC2x4 specification a an International Standard – ISO 16739 (Liebich 2010).

2.5.2 BIM Tools

2.5.2.1 Energy Analysis

Energy simulation engines can be divided into tiers according to the detail and accuracy of their models, as well as their validity in terms of use for certification programs. It is important to differentiate between those that are meant for detailed modeling, and those that produce rough estimates for iterative design purposes. Below is a table created from a US National Renewable Energy Lab (NREL) position paper that organizes the authors' evaluation of common energy simulation engines into three tiers of modeling accuracy – any BIM design software that produces energy analysis is built on one of these engines.

Tabell 20. Tiers of Energy Simulation Engines

Tier 1	EnergyPlus, ESP-r, TRNSYS, Carrier HAP, Trane TRACE, *VIP-energy
Tier 2	DOE-2, APACHE-SIM, *VIPCore
Tier 3	Spreadsheets, regressions, ad-hoc design/analysis

*VIP-energy and VIPCore were added by the author according to defined criteria for tiers

(Torcellini et al. 2010)

The table below shows which design software has energy modeling capabilities that are approved for certification from standards such as ASHRAE, ISO, ANSI/ASME, and LEED EA credit 1 – the simulation engine for each is included in parenthesis.

Tabell 21. Certification of Energy Analysis Results

Approved for Certification	Bentley Tas/Hevacomp (EnergyPlus) IES VE-Pro (APACHE) DesignBuilder (EnergyPlus)
Not Approved for Certification	IES VE-Gaia EcoDesigner (VIPCore) Ecotect (DOE-2)

Bentley Hevacomp, IES VE-Pro, DesignBuilder

Each top tier simulation engine can be run manually using a non-BIM user interface, and a semi-automated IFC compatible file transfer has been created for EnergyPlus, but there is a class of energy modeling software that is essentially a graphical user interface (GUI) for simulation engines. These tools can show what the IDF file from EnergyPlus actually looks like in 3-D, and provide visual assurance that the model has been translated correctly. This category of energy analysis software also has the advantage of being able to generate certifiable results as they are based on full versions of the simulation engines.

EcoDesigner, Ecotect, IES VE-Gaia

The modeling time of top tier energy simulation software in the AECOO industry has been reduced from weeks to hours by making it IFC compatible, but this can still be too long for designers wishing to quickly check the impacts of their adjustments in real-time. The software industry has addressed this need by simplifying the process, shortening the time requirement, but also making some compromises in the accuracy of the energy models. The goal is to get a general idea of how an action will impact the overall performance of the building without forcing a modeler to stop working.

Graphisoft is the developer of ArchiCAD and also worked as an implementer in the buildingSMART AECOO-1 Joint Testbed for implementing IFC compatible energy analysis tools. They have developed a simplified energy analysis tool called EcoDesigner as a plug-in for ArchiCAD. It generates a basic energy model using standardized data and some user inputs for location and function, material performance in structures, openings, and mechanical systems. The energy simulation is based on VIPCore calculation from Strusoft, but cannot be used for certification. The Swedish company's standalone analysis engine – VIP-energy – is certified in accordance with ANSI/ASHRAE BESTEST Standard 140-2001 (Thoo 2010).

Ecotect from Autodesk and VE-Gaia from IES are similar in that they are simplified energy modeling tools that are based on more complex simulation engines, and therefore cannot be used for meeting codes or regulations. They are slightly different from EcoDesigner in that they are separate from the drafting software like ArchiCAD or Revit that is used to produce the geometry of the building.

2.5.2.2 Basic Cost Estimation

Autodesk QTO and Tokmo

The buildingSMART AECOO-1 Testbed used Tokmo software for cost estimation, but architectural tools like Revit can export to Autodesk QTO to perform quantity take-offs (QTO). Model checking software like Solibri also has the capability of producing simple object lists, so if all that is needed is a spreadsheet with material quantities, then this basic function is sufficient. The main advantage of using a specialized costing tool is if it has built in assumptions regarding construction quantities, service life planning, and maintenance that go beyond basic material inputs. This functionality is also valuable for LCA applications when determining the inventory.

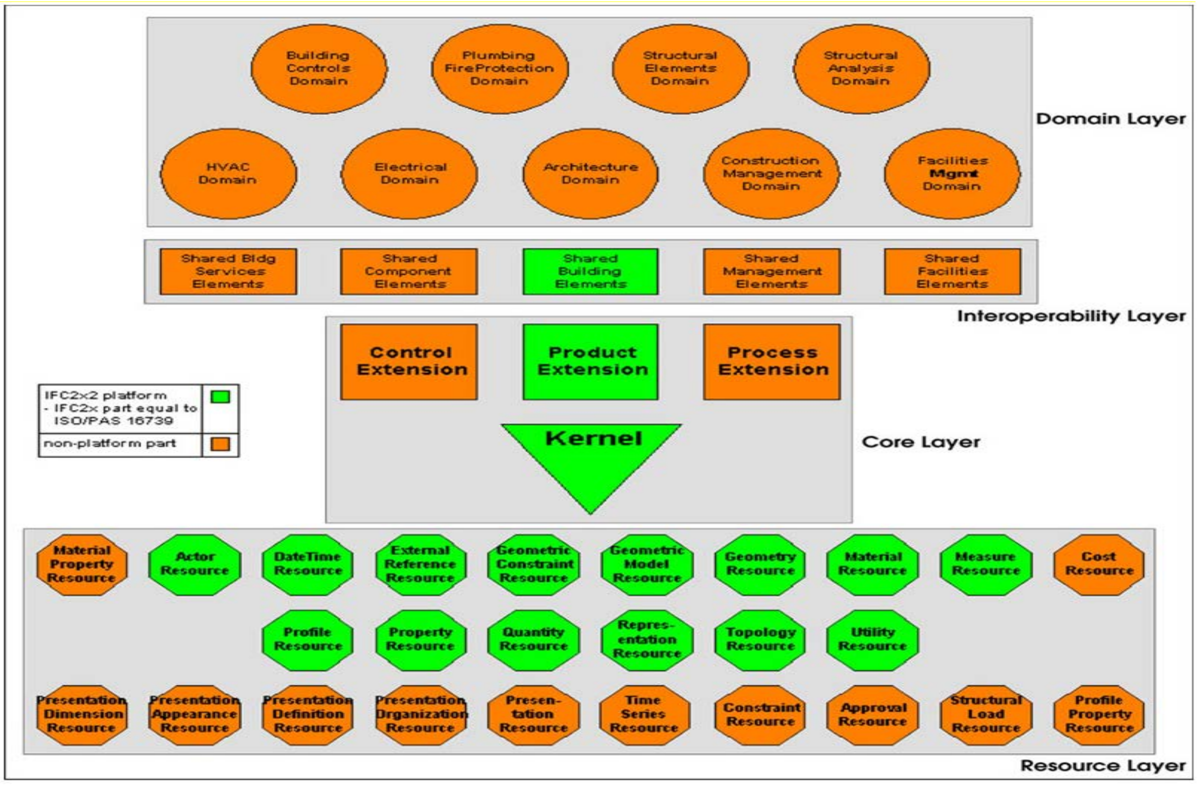
ISY Calcus

The ISY Calcus software created by Norconsult utilizes cost information from existing databases – such as the Building Cost Information Service (BCIS) – to link BIM objects to material costs. The effectiveness of this solution is limited by the material classification system, and its ability to identify BIM objects as they are labeled in a model. In practice, if the objects are not adequately labeled it makes the creation of a dependable cost model more challenging and labor intensive.

2.5.3 BIM Data Formats

2.5.3.1 IFC Information Layers

The diagram below shows the overall structure of the IFC schema, and outlines the progression from basic concepts to domain specific building elements. Each layer is made up of elements from the previous ones, and it is the Interoperability and Domain layers that eventually become elements within the exchange requirements that populate an MVD.



Figur 19. Layers of the IFC schema (Khemlani 2004)

The *resource layer* contains basic properties such as geometry, material, quantity, measurement, date, cost, and more. These properties are not specific to buildings, and many of the resource definitions come from the STEP standard. The IFC effort closely parallels another collaborative representation effort known as STEP (STandard for the Exchange of Product model data) (Bazjanac 1997). The International Standards Organization (ISO) created STEP to define standards for the representation and exchange of product information.

The *core layer* defines abstract concepts that link the resource layer and upper layers. This includes the Kernel schema that defines concepts such as actor, group, process, product, and relationship. The Product Extension schema is used to define abstract building elements such as space, site, building, building element, and annotation. The other two schemas describe similarly abstract elements regarding process and control in construction.

The *interoperability layer* contains categories of common entities used across building construction and operation. As an example, the Shared Building Elements schema includes definitions for beams, walls, doors, and windows. The Shared Facilities Elements includes definitions of occupant, asset, and furniture type.

The top layer, or the *domain layer,* contains trade specific definitions for architecture, structural engineering, and HVAC along with others. Examples of this include footing, pile and plate for structural engineering, and boilers, chillers, and coils for HVAC (Khemlani 2004).

Built on top of this schema are the MVDs that allow for specific information exchanges during the building process, such as Design to BPEA and Design to QTO. Before the software requirement specification (MVD Bindings) can be created, non-technical exchange requirements must first be determined by the domain experts (Architects, Engineers, Contractors, etc.) within the Information Delivery Manual (IDM) (See 2009b).

2.5.3.2 OmniClass CCS

Omniclass Table 49: *Properties* is the basis of the IFC schema and where the two data models intersect (Grant & Ceton 2006). Such a system allows for the QTO function of a BIM to deliver unambiguous results that can be related directly to a specification references such as the Construction Specifications Institute's (CSI) MasterFormat.

In addition, there have been commercial search tools developed by McGraw-Hill Construction and Autodesk using OmniClass Tables 23 and 49 to integrate their product database with BIM software products like Revit (Jones & Lien 2009). Autodesk Seek allows the user to search for a product using the OmniClass classification system and delivers manufacturer specific and generic BIM renderings of the building element.

Globally Unique Identifiers (GUID)

The technical basis for creating a directory of all objects associated with building models is GUIDs – a 32 character combination made up of numbers and letters that allows for an infinite number of objects identified uniquely. This level of specificity is required because of the vast number of products and properties that can exist in the building industry. This assures that there will never be a limit on the classification system as more and more objects must be included in a model, and it allows for precise retrieval of information from a BIM acting as a central project database.

2.6 BIM in Detail

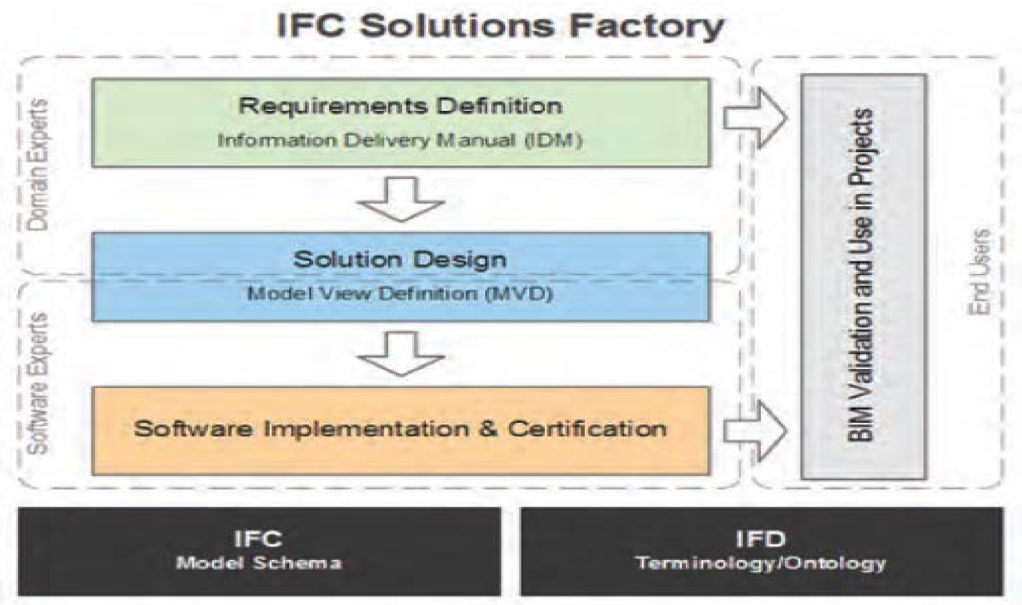
There are a wide variety of BIM applications and areas of interest, but this section is not meant to be comprehensive – it will only focus on the development and application of an Information Delivery Manual (IDM), as this is the central BIM related task being addressed by this paper. The data conversion methodology – BIM to LCA – will be addressed in the methodology section as there is no established standard or theoretical basis for this process.

2.6.1 Purpose of an Information Delivery Manual (IDM)

The central purpose of an IDM is to understand the "business requirements for information exchange and/or sharing and developing an object model and software implementations that can be used by practitioners within the industry to satisfy those requirements" (Wix 2007). All IDMs created by buildingSMART and their partners must conform to ISO/FDIS 29481-1:2010 principles as mentioned before.

Below is a conceptual diagram of the IFC Solutions Factory, which was conceived by bSa to address the issue of making the IFC schema more usable and standardized for the building industry.

The division between Domain Experts and Software Experts can be seen in the middle of the Solution Design task, and it is the IDM that creates the bridge between these areas of expertise.



Figur 20. Conceptual diagram of the IFC solutions factory (See 2009a)

2.6.1.1 General Content

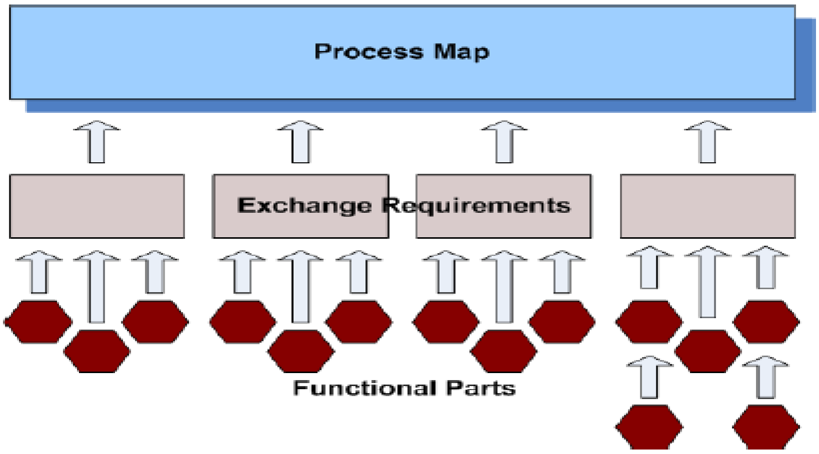
As outlined by the ISO 29481 standard, an IDM will:

- Describe the need for information exchange between processes
- Specify how to capture the information needing to be exchanged between these processes
- Identify the actors sending and receiving information
- Define, specify and describe the information being exchanged to satisfy the requirements at each point of the business process
- Ensure that definitions, specifications, and descriptions are provided in a form that is useful and easily understood
- Create detailed specifications of the information captured within exchange requirements to facilitate the development of software building information systems
- Ensure that the information specifications can be made relevant to local working practices

(ISO 2010)

2.6.2 IDM Structure

The most basic element in this structure is the *functional part* – everything else is built from an exhaustive pool of these detailed technical specifications that are stand alone schemas – like the cells of an organism. In the same way that there are single-celled organisms, as well as much more complex multi-cellular organisms, these *functional parts* can be combined to form an *exchange requirement*.



Figur 21. Basic IDM technical architecture (Wix 2007)

"An exchange requirement represents the connection between process and data. It applies the relevant information defined within an information model to fulfill the requirements of an information exchange between two business processes at a particular stage of the project" (Wix 2007).

Exchange requirements are the core value that the IDM delivers, because they make BIM data understandable and accessible to a broad range of users. Once the *functional parts* have been categorized in this way, what used to be only information is now actionable knowledge. Built around an *exchange requirement* is the *exchange requirement model*, which is the technical solution for that exchange, and is schema dependent.

Process maps and *business rules* are also built on top of this structure using Business Process Modeling Notation (BPMN). These added filters allow *exchange requirement models* to be modified for specific regional or business needs of users. They can be applied to an *exchange requirement* that has different demands for different phases and elements in the project.

2.6.2.1 Components of an IDM

There are three components of an IDM – Process Maps, Exchange Requirements, and Functional Parts – and they are presented below in the same order that an IDM would be organized. Within each component section, there is a more detailed description of the summary and technical information that must be included, as well as an example figure to show formatting and provide a more practical understanding of what is meant.

In addition to the three major components, there are also two introductory sections in an IDM. An *IDM Component Header Information* section at the start of an IDM includes a change log for administrative purposes. It allows a reader to know what has been done, who did it, and when it was updated. Also a *Description of the Use Case* is provided as an overview that should be understandable by final users and other non-technical readers. It provides context for the IDM as well as the motivation for its creation.

Process Maps

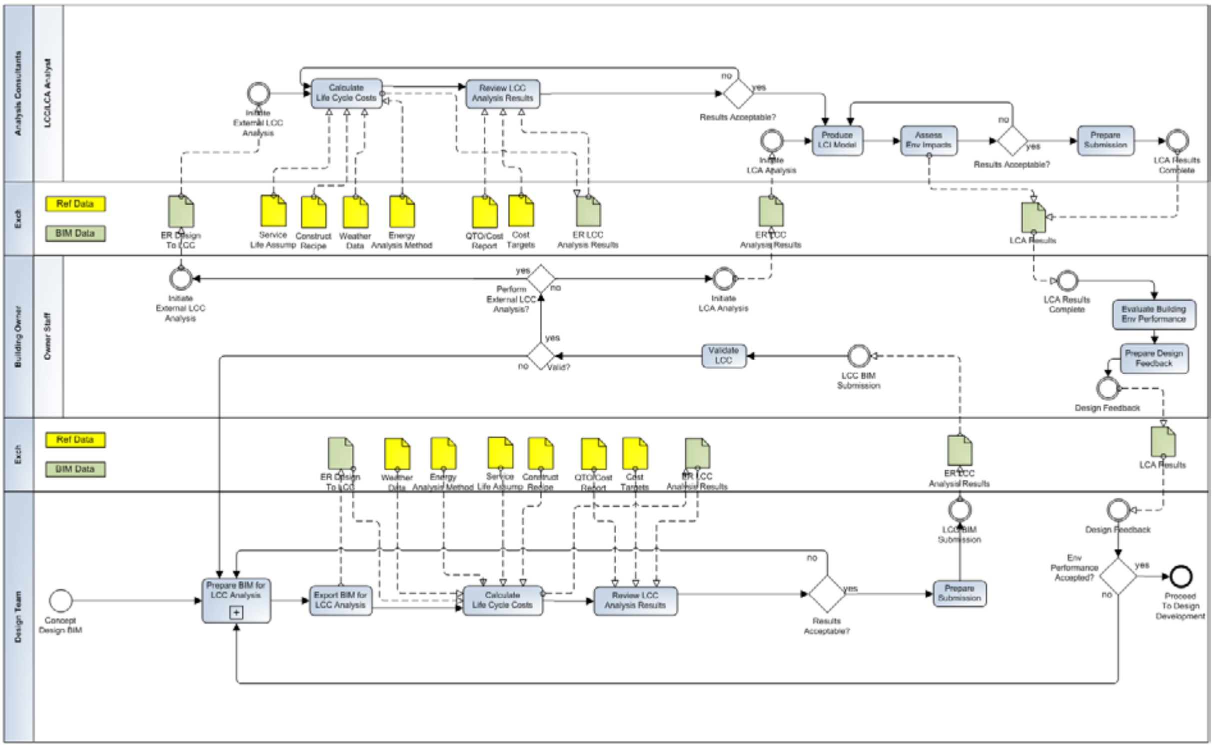
The purpose of a process map is to describe the flow of activities within the boundary of a particular business process, the roles played by the actors involved, together with the information required, consumed and produced (ISO 2010). There are two levels of process maps: the first provides an overview of the overall BIM process, the sequence of sub-processes and tasks, and high-level information exchanges that will occur. A second level process map is created for every BIM sub-process, and clearly defines the sequence of tasks to be performed by a given role. At this level, a more detailed flow diagram for each BIM sub-process is created by the responsible parties. Both types of map are created using Business Process Modeling Notation (BPMN), which provides a uniform visual representation of the relationship between processes and exchanges (Anumba & Messner 2010).

As outlined by the ISO 29481 standard, a Process Map will:

- Set the boundary for the extent of the information contained within the process
- Establish the activities within the process
- Show the logical sequence of the activities
- Include the exchange requirements within the boundary of the process
- Include a comprehensive description of the overall process

(ISO 2010)

The figure below is meant to provide a general idea of what a process map looks like – it shows an example top level map for LCC analysis. It has been formatted according to Business Process Modeling Notation (BPMN) – the horizontal “swimming lanes” represent roles within the project team, the blue rectangles are tasks, and the yellow and green icons are data objects that are used and created throughout the process. Yellow icons are external reference data, while green icons are BIM generated data from model exchanges. The diamonds are decision gateways, and circles are entry and exit points from swimming lanes between project roles.



Figur 22. Example process map for BIM-based LCC

In addition to the flow diagram shown above, a brief plain language description of each task, data object, decision gateway, and referenced exchange requirement should be provided to complement the graphical representation. These are meant to be understandable by end users, and provide relevant details for completion of the overall exchange – some examples of these descriptions are provided below:

Tabell 22. Example task descriptions for an IDM

Prepare/Adjust BIM for LCA

Type	Sub-Process
Documentation	At this point, the Concept Design BIM is passed to the appropriate designer to prepare the BIM for LCA. The designer may still be the architect, any other design consultant or any combination. Details of this sub-process are described in a later section (Wiggins & See 2009).

Export BIM for Analysis

Type	Task
Documentation	Once the BIM has been prepared for LCA and validated in the Prepare/Adjust BIM for LCA task, it is exported to IFC for LCA. At this point, all the required exchange requirements in ER Arch Concept to LCA Inputs have been met (Wiggins & See 2009).

Analyze Life Cycle Impacts

Type	Task
Documentation	The designer is now ready to generate a Life Cycle Inventory (LCI) in preparation for preparing the Impact Assessment (LCIA). The actual LCA task is outside the scope of this Manual. The estimating application may use previous BIM-based LCC analysis results, or combine the results from basic QTO and BPEA.

Exchange Requirements

An exchange requirement (ER) is a description of a set of information that needs to be exchanged to support a particular business requirement at a particular stage of a project (ISO 2010). This contains both a non-technical and technical description that is meant for end users such as architects and engineers, but can also be used by a software developer for guidance. The sections within an exchange requirement are:

- **Header** that identifies the exchange requirement name, creator and the project stages for which the requirement is used.
- **Overview** that states the aims and content of the requirement in non-technical text form – the overview is intended to be understood by an executive/end user.
- **Technical description** that identifies a table of information units needed to satisfy the requirement

(Wix & Espedokken 2008)

As outlined by the ISO 29481 standard, an Exchange Requirement will:

- Include the life cycle stage(s) for which the exchange requirement is used
- Provide an overview that states the aims and content of the exchange requirement using terminology that is familiar to the end user
- Include a set of information units (ex. walls, windows, etc.) that is broken down to provide the following information for each: an identifying name, a description about the information exchanged, the identity of the functional part within which the detailed technical content of the informational unit is described, and the information that needs to be exchanged for the provisions of the exchange requirement to be satisfied.

(ISO 2010)

The table below shows the project stages (0 – 10) that have been defined by the builidngSMART alliance – as part of the header it shows in which phases the ER will be used.

Tabell 23. IFC: project stages for IDMs

0	Portfolio requirements	
1	Conception of need	
2	Outline feasibility	
3	Substantive feasibility	
4	Outline conceptual design	X

5	Full conceptual design	X
6	Coordinated design and procurement	
7	Production information	
8	Construction	
9	Operation and maintenance	
10	Disposal	

(Wiggins & See 2009)

The table below shows only a portion of the technical description of the Design to QTO (Concept) exchange requirement created for the AECOO-1 Testbed. The complete table continues to define all the building elements that must be quantified for costing purposes. The "Type of Info" column identifies the *primary functional parts*, the "Information Needed" column covers the *attributes* of the primary functional part that are relevant, the "Req/Opt" columns determine what is mandatory, and the "Data Type" and "Units" detail exactly what type of information will satisfy the requirement.

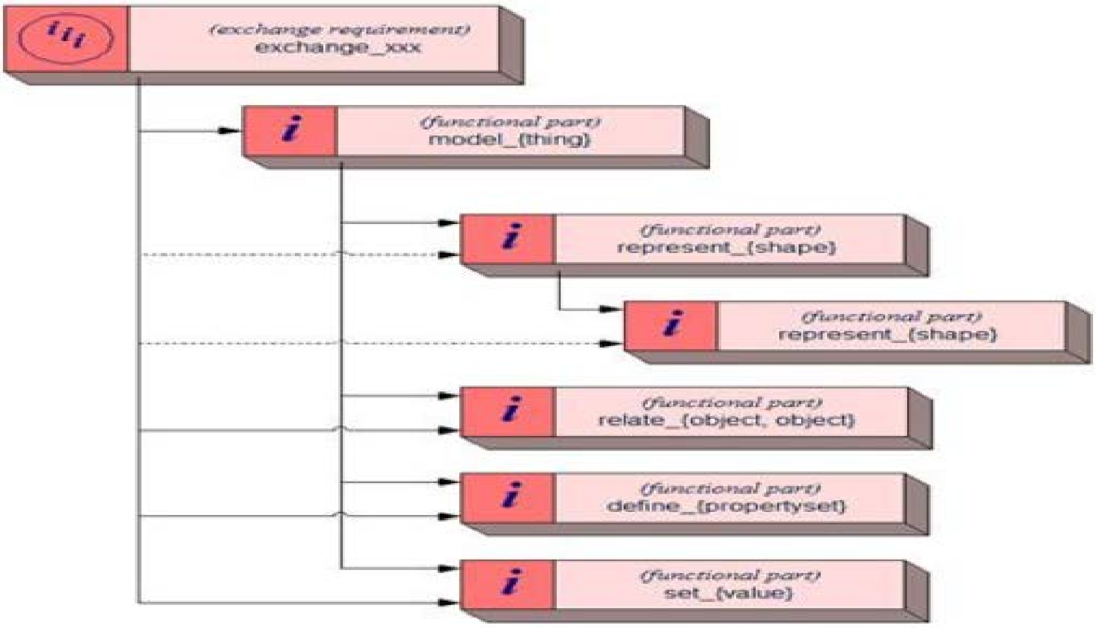
Tabell 24. IFC: example exchange requirements

Type of Info	Information Needed	Req	Opt	Data Type	Units
Project	The following properties should be included:				
	- Identification	X		String	
	- Client information (name, address, phone, email)		X	String	
	- Model author (name, address, phone email)		X	String	
Site					
	- Address (number, street, city, ZIP, country)		X	String	
	- Global coordinates	X		triples	
	- Site elevation (datum)(relative to sea level)	X		Real	
Building					
	- Identification	X		String	
	- Description		X	String	
	- Functional classification (OmniClass Table 11)		X	String	
	- Location (relative to site origin)	X		triples	
	- Orientation (deviation from true north, clockwise)	X		Real	
	- Elevation (relative to site datum)	X		Real	
	- Building height	X		Real	

Functional Parts

A functional part is a description of a unit of information used by a solution provider to support an exchange requirement (ISO 2010). Within the context of IFC, the most basic functional part can be either an attribute of an entity/object or a property within a property set. A property set is an attribute that does not universally exist for an object and therefore must be separately defined. As an example, U-value is an attribute, while regional building codes require a property set (Khemlani 2004). Functional parts are also built on other functional parts, so object attributes and property set properties can be combined to make the concept of modeling a door – specifying door name, width and height dimensions, shape representation, etc.

The figure below shows how this process works; an exchange requirement (ER) is built up from a number of primary and secondary functional parts (FP). Primary FPs deal with key elements to be exchanged, and they represent models in their own right – model_door, model_window, or model_slab – but they must be one specific idea (ISO 2010). Secondary FPs handle actions that are used by models and exchange requirements, such as define_quantity, set_thermal_properties, and represent_line.



Figur 23. IFC: nested data structure (Wix & Espedokken 2008)

As outlined by the ISO 29481 standard, a Functional Part will provide the following:

Non-Technical Info

- An overview that states the aims and content in non-technical text form (this can be a source for the description of an information unit in the "Information Needed" column of an ER)

Technical Info

- A detailed breakdown of the entities and properties required and how they are configured
- Establishes a reasonable sequence in which the entities and properties are defined

When creating an IDM, it is usually not necessary to generate the technical information that defines a functional part because they are re-usable and can just be referenced in the table created for the exchange requirement (shown above). BuildingSMART has a reference system that shows all existing functional parts in full schematic detail.

The figures below are an example of the main sections in a functional part, and have been taken specifically from the functional part: model_door. They show the overview, a small portion of the detailed technical information table, the lists of required entities/data types/property sets/functional, and some reference EXPRESS code that identifies the principle material used in the door (as part of the style attribute of a door type definition). This is included primarily to show the level of detail required to produce such comprehensive definitions of all attributes and properties associated with something as simple as a door.

Overview

Provides the information concerning doors required for a basic building model.
This information includes:

- Specification of door name and description if required
- Width and height dimensions of the door
- Shape representation of the door
- Specification of door type (style)and identification of the type (style) to which a door occurrence conforms
- The material forming the basic construction of the door occurrence
- The number and general layout of the door panels
- Indicator for whether geometry of the door is determined by the style information or by lining and panel properties
- Lining thickness, depth and offset
- Threshold thickness, depth and offset
- Transom thickness and offset
- Casing thickness and offset
- Panel depth and width
- Panel operation
- Panel position

Note that a door can have multiple sets of data concerning lining, threshold, transom, casing, and panel depending on the number of each that are within a particular door construction.

Figur 24. IFC: door functional part overview (Wix & Espedokken 2008)

Results

Model of door occurrence(s) including shape representation and other basic information

Description	Entity/Pset/Functional Part	MAN	REC	OPT
Model the door type (style)				
Set the global unique identifier	IfcDoorStyle.GlobalId::IfcGloballyUniqueId	✓		
Apply the owner history	IfcDoorStyle.OwnerHistory::fp_apply_owner_history	✓		
Specify the name of the door style	IfcDoorStyle.Name		✓	
Specify a description for the door style	IfcDoorStyle.Description			✓
Set the principal material from which the door is constructed from the predefined selection	IfcDoorStyle.ConstructionType::IfcDoorStyleConstructionEnum		✓	

Figur 25. IFC: door functional part technical definition (Wix & Espedokken 2008)

IFC Entities Required

- IfcBuildingElement
- IfcDoor
- IfcDoorLiningProperties
- IfcDoorPanelProperties
- IfcDoorStyle
- IfcElement
- IfcObject
- IfcProduct
- IfcPropertyDefinition
- IfcPropertySetDefinition
- IfcPropertySet
- IfcRoot
- IfcTypeObject
- IfcTypeProduct

IFC Datatypes Required

- IfcDoorPanelOperationEnum
- IfcDoorPanelPositionEnum
- IfcDoorStyleConstructionEnum
- IfcDoorStyleOperationEnum
- IfcGloballyUniqueId
- IfcIdentifier
- IfcLabel IfcLabel
- IfcLengthMeasure
- IfcNormalisedRatioMeasure
- IfcPositiveLengthMeasure
- IfcRatioMeasure
- IfcText

IFC Property Sets

- Pset_DoorCommon

IDM Functional Parts

- fp_apply_owner_history
- fp_define_property_set
- fp_map_representation
- fp_place_object
- fp_property
- fp_represent_product
- fp_style_shape_aspect

Figur 26. IFC: door functional part referenced entities (Wix & Espedokken 2008)

```
TYPE IfcDoorStyleConstructionEnum = ENUMERATION OF
   (ALUMINIUM,
    HIGH_GRADE_STEEL,
    STEEL,
    WOOD,
    ALUMINIUM_WOOD,
    ALUMINIUM_PLASTIC,
    PLASTIC,
    USERDEFINED,
    NOTDEFINED);
END_TYPE;
```

Figur 27. IFC: door functional part sample EXPRESS code (Wix & Espedokken 2008)

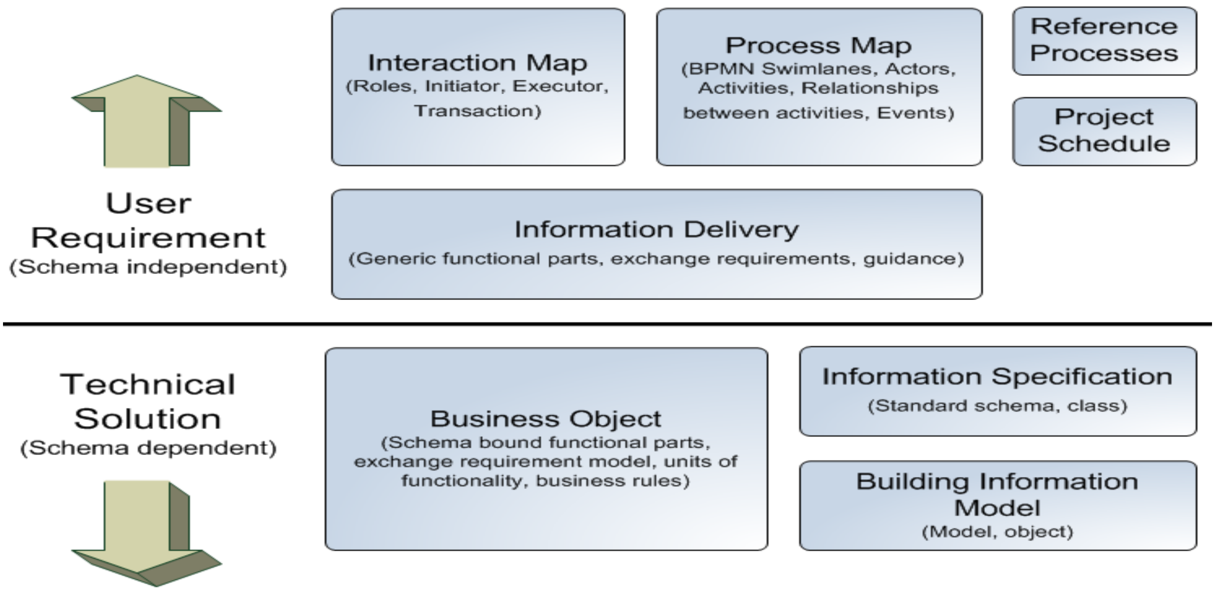
As stated before, functional parts are the most basic elements within the IFC schema, and therefore their generic definition is as specific as an IDM can be. A schema bound functional part is defined by EXPRESS coding language, and therefore must be re-defined in every new release of IFC or any other BIM schema.

2.6.3 IDM Implementation

Once an IDM has been created it can be used by solution providers to create IFC compatible BIM software that performs the business process and information exchange that is being modeled. The division between domain experts – architects, engineers, etc. – and software developers can be understood along the lines of User Requirements versus Technical Solutions.

User Requirement vs. Technical Solution

The major difference between these two concepts is that a *user requirement* is schema independent, and a *technical solution* is schema dependent. This means that the first is an "unvarying specification of what a user wants to achieve," and the second is "bound to a particular information model and to a particular version (or release) of that information model" (ISO 2010). The figure below shows this divide graphically – it should be noted that the two sides are linked through the Information Delivery user requirement and the Business Object technical solution components through the functional parts discussed previously.



Figur 28. IFC: User requirement vs. technical solution – adapted from the ISO 29481 standard (ISO 2010)

The table below is a summary of all elements contained within each IFC component:

Tabell 25. IFC: User requirement vs. technical solution perspectives

User Requirement Perspective	-**process maps** describing the overall process in which information exchange occurs -**interaction maps** describing the actor roles and transactions between them -**information delivery** describing the information exchange needs -**reference processes** that are stored exchange descriptions captured at information delivery -**project schedule** of occurrences of processes in the context of a project
Technical Solution Perspective	-**business objects** comprising the exchange requirement models -**functional parts** bound to an information model (schema) -**business rules** together with the **information specification** from which IDM schemas are derived and building information models whose content is specified by IDM schemas

(ISO 2010)

2.6.3.1 MVD – Model View Definition

A *model view definition* is the set of information from the BIM that can be supported by a specific software application meant to perform one or several business processes – such as daylight simulation for energy analysis. By using software that is certified IFC compliant, a user can export data from the appropriate BIM *model view* directly, and know that the defined objects and parameters will be maintained in the new application.

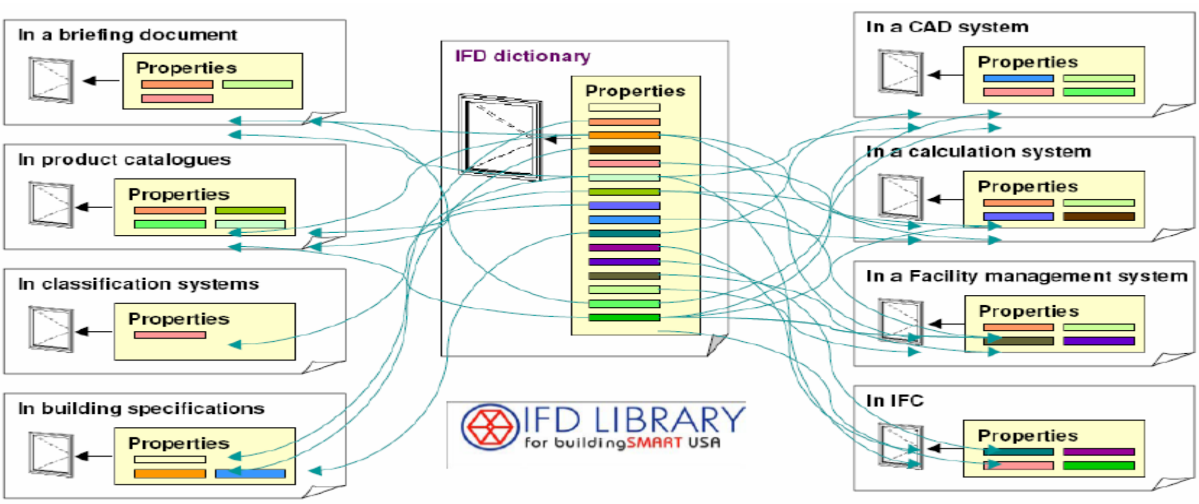
While the *exchange requirements* and *process map* in an IDM are descriptions of the required information and process for a given solution, an MVD Binding diagram – which describes how the information links to the IFC schema – represents the actual coding requirements for software developers.

2.6.3.2 IFD – International Framework for Dictionaries

The IFD Library serves as an ontological framework for industry to ensure that they understand and reference the same concepts when exchanging models and information – it functions according to ISO 12006-3 principles (Grant et al. 2009). The focus areas identified for standardization to improve industry performance are: codes and regulations, specifications and standards, cost types, product data, and operations and maintenance data (Grant et al. 2009). It is “an open library, where concepts and terms are defined, semantically described and given a unique identification number… this allows all the information in the IFC format to be tagged with a Globally Unique ID (GUID)” (Grant et al. 2009).

The IFD Library is integrated into BIM software as the GUID that is viewable for each element in the model. This GUID represents a collection of properties – as defined by OmniClass 49 – that exhaustively define that element. In this way, the concept becomes an independent entity and is separated from any particular language. Thus it can be universally referenced by users all over the world, and be unambiguously re-translated into their language of choice.

The diagram below shows how a single concept in the IFD library can have many properties that will be referenced in different situations by various project team members, but must always refer back to the same underlying entity.

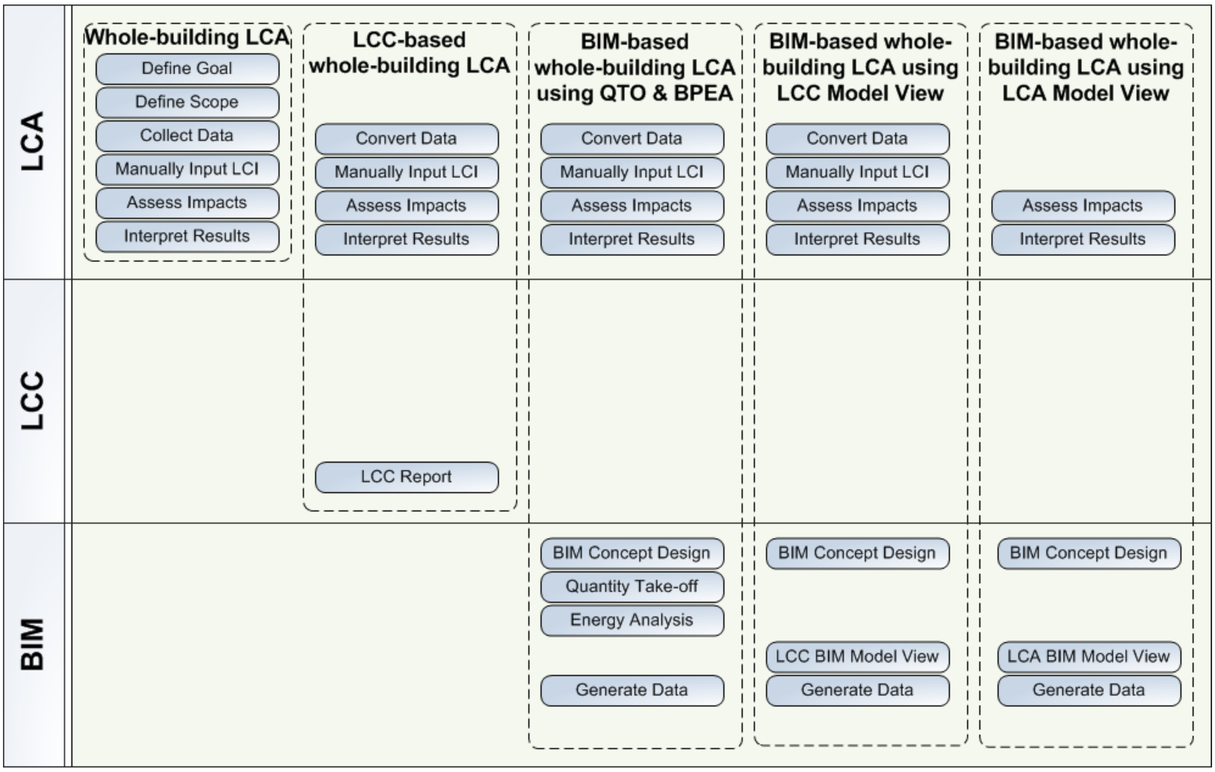


Figur 29. IFC: IFD Library conceptual diagram (Grant & Ceton 2006)

The Construction Specification Institute (CSI) along with buildingSMART Norway, Construction Specifications Canada (CSC) and the STABU Foundation are contributing to the contents of the IFD Library. There is also a more recent effort to refine the library to an even greater level of detail that would identify all the sub-parts within complex building elements – such as windows and wall systems. This would allow for a better understanding of raw material requirements, and also make the data transformation to LCA elementary processes much more straightforward.

3. Method

The Methodology section looks at how existing LCC and BIM processes can potentially be used to streamline the generation of a whole-building LCA. It also looks at how BIM data can be converted to an LCA compatible format that would automate the transfer of an IFC file. The figure below shows how the methodology section progresses toward this conclusion – note that the number of manual steps decreases as additional model views are created for specific business processes.



Figur 30. Content Map: Methodology section

In the first section, example guidelines for creating goals, scopes, and LCIs for whole-buildings are discussed according traditional LCA methodology and the ILCD standard. This portion is used to provide a benchmark of what a future tool will have to produce – the guidelines are written in the context of identifying key elements that will be required for a future BIM exchange requirement.

In the next phase, LCC methodology and BIM functionality are introduced as a potential means of exploiting existing industry data collection requirements for the costing task during the design phase of a building project. Quantity take-offs are already being done to estimate cost – whether LCC is used or not – and therefore could be used as a basic material data source for a life cycle inventory (LCI). Basic BIM functionality – as it relates to quantity take-off for costing and energy analysis – is assessed in greater detail to evaluate how it could be applied to LCA.

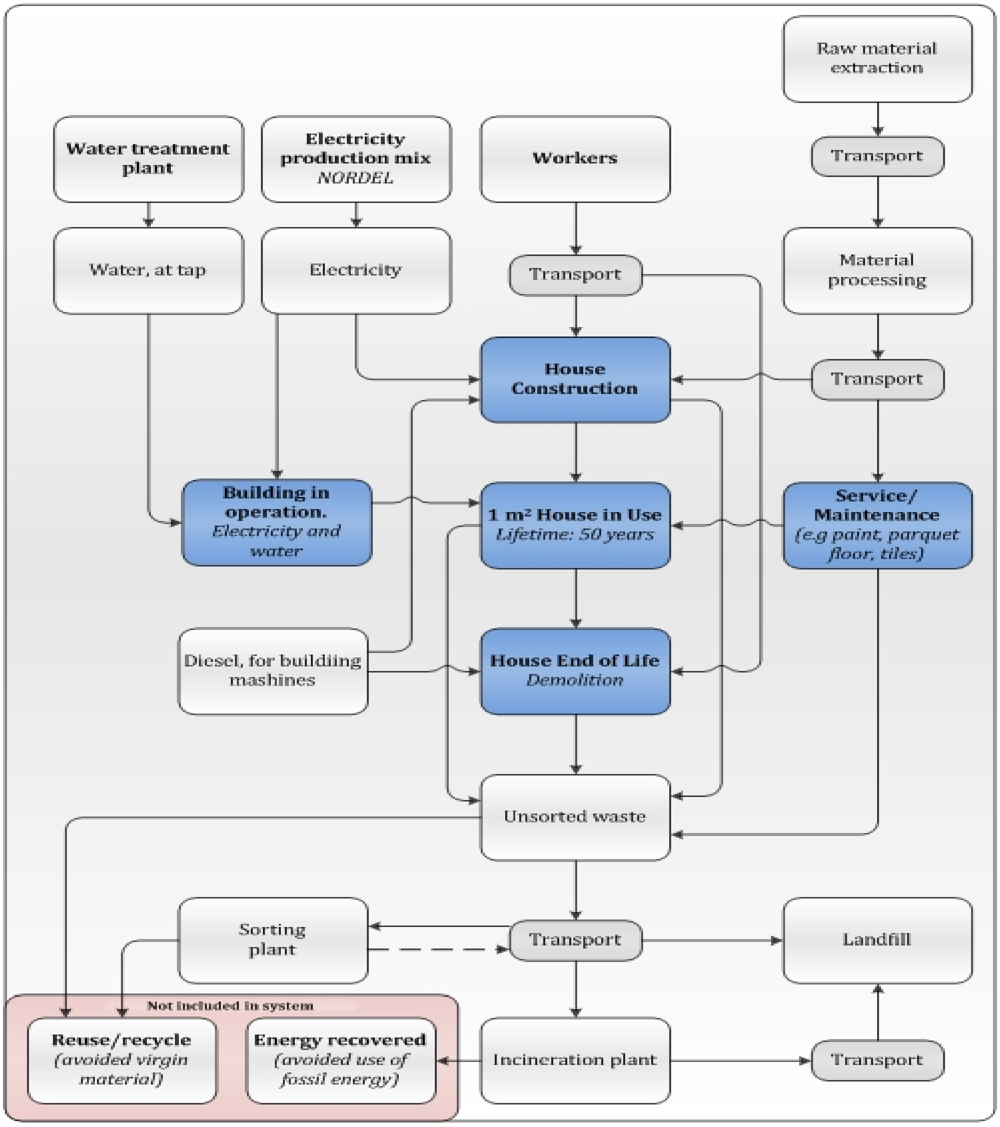
In the final methodology section related to IDM development, the specific elements required for defining the exchange requirements for Design to LCA are examined. This includes a detailed summary of the theoretical functional parts and property sets that would need to be created in order to identify the necessary data within a BIM.

The last methodology piece is the data conversion from IFC BIM to EcoSpold LCA formatting. This is a separate task from the IDM because it is outside the scope of the exchange requirements defined by this paper. The business process is defined as the creation of an EcoSpold compatible file that would be able to generate a complete impact model within LCA software – this scenario does not assume the production of a new hybrid software solution. While completely incorporating building-design and LCA software may be ideal, that option has been purposely discarded to focus on a simpler and less costly path to BIM-based LCA.

3.1 Whole-building LCA

Life Cycle Assessment most easily models consistent manufacturing processes that occur under controlled circumstances and produce a single product with an easily predicted lifespan and end-of-life outcome. None of this is true for buildings, and therefore conducting whole-building LCAs presents some special challenges: a comparatively long life, frequent changes, multiple functions, many different components, seldom many of the same kind, cause local impacts, integrated into the infrastructure making system boundaries tough to define (Glaumann et al. 2010). For that reason, there is a strong case for efforts to simplify whole-building LCAs, if it can be done without sacrificing too much of the representativeness and completeness of the results.

The boundary diagram below shows how a whole-building can be modeled in terms of an LCA scope. The diagram is a summary of all the processes that should be included in the LCA, those processes that fall outside the boundary – recycling and energy recovery – are not assumed to be included in the system.



Figur 31. Whole-building LCA boundary diagram (Dahlstrøm 2011)

3.1.1 Goal and Scope of a whole-building LCA

As mentioned in the Theory section, there are some basic parameters that must be satisfied by the Goal and Scope Definitions. The following is how that generic methodology can be applied to a whole-building functional unit, as well as a discussion of how such a process could be standardized into Goal and Scope Type libraries.

3.1.1.1 A basis for creating standard goal and scope libraries

There is no established standard for determining the goal and scope of a whole-building LCA, but it is clear that they are largely determined by the phase of the building project, and the corresponding applications and data availability. The following tables represent a theoretical structure for organizing generic goal and scope definitions within the building industry.

The Goal Matrix shows that for each building phase and LCA Situation – A, B, or C – multiple generic Goal Types could be created and stored in a Goal Type Library. Each Goal Type could be relevant in multiple building phases, but would have to be applied differently across Situations because of fundamental methodological differences. An example Goal Type would be to produce a comparative carbon footprint assessment of multiple design alternatives in the early design phase using building level data for the owner to review and make a final decision.

Goal Matrix

Building Phases	Pre-Design	Schematic Design	Detail Design	Construction Docs	Early Operation	Mid-Life Review	End-of-Life Review
Situation A: "Micro-level decision support"	Goal A1 Goal A2	Goal A2 Goal A3	Goal A3 Goal A4	Goal A4	Goal A5 Goal A6	Goal A6	Goal A7
Situation B: "Meso/macro-level decision support"	Goal B1						
Situation C: "Accounting"	Goal C1						

Figur 32. Goal matrix conceptual diagram

The Situation – in LCA terms – depends on the scale and timeframe of a study. If the LCA is to be comparative but only applied to a single building project – Situation A – it is not likely to impact the industry as a whole, or the background production capacity of building material producers. But if the LCA is to be used by a government organization for policy implementation – Situation B – then the consequences of the decision must be considered in terms of its impact on long-term production and consumption trends. LCA deals with this type of scenario by using Consequential methodology, and determining the marginal technologies that will be impacted by the decision.

The final application of LCA – Situation C – is for accounting purposes only. In this case, the results model an existing situation and will not be used for decision support. This type of LCA may be used to document the performance of a building after it has been designed or constructed, and more detail can be included to achieve more accurate results.

In the Results section of this paper, some example Goal Types will be created for the early design phase using Situation A, but there are many different options and deliverables, see Appendix 1 for a list of proposed LCA applications from the ILCD Handbook.

Scope Matrix

Building Phases	Pre-Design		Detail Design		Early Operation		End-of-Life Review
		Schematic Design		Construction Docs		Mid-Life Review	
Goal Definitions	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Situation A: "Micro-level decision support"	Scope A1.1 Scope A1.2 Scope A1.3	Scope A2.1 Scope A2.2	Scope A3.1 Scope A3.2	Scope A4.1 Scope A4.2	Scope A5.1	Scope A6.1 Scope A6.2	Scope A7.1
Situation B: "Meso/macro-level decision support"	Scope B1.1						
Situation C: "Accounting"	Scope C1.1						

Figur 33. Scope matrix conceptual diagram

The Scope Matrix is essentially a sub-set of the Goal Matrix – for each Goal Type (A1, A2, B1, etc), there are multiple scopes that could be used depending on the data that is available and the underlying purpose of the study. An example of this could be an *ENSLIC Scope*, which utilizes the inventory identified by the ENSLIC simplified methodology to capture the majority of impacts from the most impactful materials in the early design phase (Malmqvist et al. 2010).

If time permits and the data are available, a more complete scope is preferable at any phase, but it is critical to use a standardized system for transparency, consistency, and comparability purposes. In this way, it would be straight forward for another practitioner to input the same model in different regions and weather conditions to assess results and compare performance using a consistent framework. In the Results section, example Scope Types will be established as a model for this methodology: LCC-based and ENSLIC-based scopes.

3.1.1.2 Goal guidelines for whole-buildings

For a potential Goal Type library, there are five basic properties that must be satisfied: Applications, Use-case (Comparative), Audience (Public), Active Roles, and Limitations. As shown in parenthesis, the Use-case must declare if the study will be comparative, and the Audience property must show if it will be made public. These properties are described in more detail below:

Intended application(s) of the deliverables/results

Choosing the application of deliverables will largely determine the Situation and methodology in which the LCA study will be conducted. Below is a categorized list from the application options provided by the ILCD Handbook – these are considered by the author to be the most common and relevant for whole-building analysis in each given Situation.

For **Situation A**, the following applications could be relevant:

- Comparison of specific goods or services
- Development of a life cycle based Type III environmental declaration (e.g. Environmental Product Declaration) for a specific good or service
- Development of the "Carbon footprint", "Primary energy consumption" or similar indicator for a specific product

For **Situation B**, the following applications could be relevant:

- Policy development: Forecasting & analysis of the environmental impact of pervasive technologies, raw material strategies, etc. and related policy development
- Policy information: Identifying product groups with the largest environmental improvement potential

For **Situation C**, the following applications could be relevant:

- Policy information: Identifying product groups with the largest environmental impact
- Monitoring environmental impacts of a nation, industry sector, product group, or product
- Corporate or site environmental reporting including calculation of indirect effects in Environmental Management Systems (EMS)

Reasons for carrying out the study and decision-context

This property of the goal definition should expand on the Use-case of the LCA study and provide details necessary to determine the data quality requirements, as well as the methodology to be used – attributional or consequential (Joint Research Centre 2010). Standardized Use-cases can be established for specific business processes within the building life cycle – concept design LCA comparison for overall performance purposes, or detail design LCA for material specification comparison are two examples.

Target audience of the deliverables/results

For LCA of a building project, this section should identify all internal roles that will be viewing results, technical versus non-technical audiences, as well as any outside parties that will be able to access the study. Such analysis may only be considered relevant to architects, engineers and owners, but for integrated project delivery, it may be advantageous to include the contractors who will be implementing the strategies. Revealing the "big picture" to trades that must focus on minute details allows them to prioritize their decisions according to the overall goal.

Comparative studies to be disclosed to the public

It must be stated in the goal definition if a comparative study will be made public because of additional execution, documentation, review and reporting requirements that have been put in place due to potential consequences for external companies, institutions and customers. Because most building projects are unique – not a directly comparable product – this would likely only be relevant if comparative results for product specifications were made public, but any intention of making results public should be included regardless.

Commissioner of the study and other influential actors

This section should identify which project team members financed the study, or any other organizations that have relevant influence over the study – this includes the practitioners that perform the study (Joint Research Centre 2010).

Limitations due to the method, assumptions, and impact coverage

There are many limitations for whole-building LCAs, but they can be consistently categorized across all building projects, and their relative importance evaluated for each case. Some projects will have less or lower quality data available, but for the purpose of creating a Goal Type library, it should be possible to quantitatively determine benchmarks in each category for Use-cases and Deliverables according to the Cost Modeling phases discussed earlier.

The limitations of a whole-building LCA study can be summarized by the following categories:

- **Data availability** is limited in the early design phases when building material specifications and detailed energy-use models have not been created. There is also limited LCA data available for building materials generally.
- **Data quality** is varied across many different sources and trades, and therefore can be hard to determine for the overall model. As an aggregation of a number of smaller products and processes, the level of data quality is recommended to be measured at the product level – where EPDs can be used as they are developed.

- A **functional lifespan** is difficult to determine for a building because it must model both **service life** of building elements, as well as the **adaptability** of the structure to market demand. There could be a situation where a building meets physical requirements, but the local market demands re-purposing – a risk that is challenging to predict.
- **Operational energy use** represents the majority of impacts from a building over its lifespan – it must be modeled using standard occupancy assumptions – but will be largely determined by occupant behavior that is unpredictable.

3.1.1.3 Scope guidelines for whole-buildings

For a potential Scope Type library, there are six basic properties that must be satisfied: Type of deliverables, Functional unit, Allocation methods, Data validity requirements (including completeness, precision, and accuracy or Data Quality Rating), Impact categories, and Review and Report requirements. As shown in parenthesis, the data validity is determined by a number of factors that are combined to produce a Data Quality Rating (DQR). All these properties are described in more detail below:

The type(s) of the deliverable(s)

The types of deliverables required are derived from the applications selected in the goal definition – the most common of those from the ILCD Handbook include:

- Life cycle inventory (LCI)
    - Unit process study (single operation or black box)
    - Partly terminated system data set
    - LCI results
- Life cycle impact assessment (LCIA) and Interpretation
    - Non-comparative LCA
    - Comparative LCA
        - Non-assertive
        - Assertive (superiority, inferiority, equality are explicitly concluded)
- Detailed LCI model of the analyzed system (for scenario analysis)

(Joint Research Centre 2010)

These deliverable types can then be applied to the applications that were determined in the Goal Definition section:

For **Situation A** applications, the following deliverables are relevant:

- Comparative LCA study, EPD, or Life cycle based Type I Ecolabel of the system

For **Situation B**, the following applications could be relevant:

- Comparative LCA study

For **Situation C**, the following applications could be relevant:

- LCI Results, Non-comparative LCA study

Function(s), functional unit, and reference flow(s)

In the case of a whole-building LCA, the functional unit is actually all the functions a building must perform for an assumed number of occupants over an assumed time period. The functional unit should not go into design details, because many different designs can serve the same function, and the comparison of those alternatives is part of the reason for performing the LCA in the first place.

For the purpose of creating a Scope Type library, there could be some standard dimensions that should be defined by all functional units, but there will also need to be an opportunity to supplement these with project specific parameters. Some of the basic properties could include: occupancy, useable floor area, conditioned space, and internal environmental quality. These basic functional parameters ensure that a comparative LCA will evaluate equivalent functional units.

LCI modeling framework and handling of multifunctional processes and products

For a whole-building LCA, there will only be a few cases where multi-functional processes will have to be dealt with, and they involve the use of by-products usually produced during the manufacture of other building products. Some examples of this include the wood chips used in OSB taken from lumber production and the use of recycled glass for fiberglass insulation.

Multi-functionality is more critical for Situation B LCA studies because there will be an impact on material availability for other industrial products. In consequential LCAs, this must be taken into account as these other products may begin to source virgin material that increases the overall impacts of an economy.

System boundaries, completeness requirements, and related cut-off rules

The system boundary makes explicit the processes that are included in the foreground system, and must be determined according to the goal definition established previously. In the case of a building, the foreground system should contain all major building elements and operational functions that create the majority of impacts linked to the functional unit – the service of the building. But during the planning process, it is useful to gauge the level of completeness that will be achieved by a set of primary processes.

As mentioned before, the majority of impacts of a building can be modeled by a few key elements, and therefore it may be possible to reduce the scope of the LCA without sacrificing completeness. Generally speaking, cut-off rules could most likely be set around 95% for a building, and this could be satisfied measuring only the impacts from operational energy-use and major building material components.

LCIA impact categories to be covered and methods to be applied

The building industry tends to focus on the carbon footprint of buildings, but as water scarcity becomes an issue, along with stricter land use and indoor environmental quality regulations, there is an increasing need for added impact categories. Because LCA software can easily produce a wide-range of indicators, the most important consideration is the relevance and clarity of results for decision makers. More information does not add value if it clouds the most important issues, therefore producing a set of expanded and meaningful standardized indicators for buildings to be compared is critical for LCA. The EPD system is likely the proper forum for this, but currently the product category rules (PCR) have not produced a consistent system – some EPDs have only carbon footprints, while others have a broad range of impact categories.

Other LCI data quality requirements regarding technological, geographical and time-related representativeness and appropriateness

As discussed in the Theory section, the validity of an LCI can be judged according to the Quality Level (a qualitative assessment) and Quality Rating (a quantitative assessment) of the Accuracy of data that has been used to model each element in the system, as well as the Completeness and Precision of the system as a whole. There are three criteria for representativeness (or accuracy) of data, and they are Technology, Geography, and Time-related factors.

A whole-building as a functional unit represents a very complex system that has to be sub-divided into many different product-level processes. For some of those products, EPDs exist that can be used as a basis for analysis, but the remaining materials – and operational energy-use – must be modeled manually through further sub-division into sub-parts and eventually broken down into unit processes that can be modeled from existing LCA data. For this reason, it is not realistic to acquire primary data for all materials, and therefore data accuracy will vary widely according to what is available, and when the calculations were produced. What can be done is to focus on acquiring accurate data for the most impactful material categories, and ensure that the energy-mix that is selected accurately portrays the local situation.

In the case of materials, determining precise quantities should not be an issue because construction documents are available, but accurately modeling production can be. To solve this, it may be possible to establish a generic Quality Level and Quality Rating for material categories – windows, walls, slabs – and apply those to all instances in a model. When combined across all categories, this would reveal an overall data quality picture. It could also determine where new EPDs would make the greatest impact – for example where new technology has recently been established or geography plays an important role in determining impacts.

Types, quality and sources of required data and information, and required precision and maximum permitted uncertainties

Currently, the most common sources for data collection are construction documents, BPMs, and EPDs, and as mentioned previously, the quality of data varies widely. There is probably not enough data available to institute a very strict requirement on precision, but possibly a minimum Quality Level and Quality Rating would prevent any LCA from producing deceiving results – this could be especially effective for sensitive variables that have a large impact on results.

As an example, a Quality Level of “Fair” or Quality Rating of 3 out of 5 demands that process data qualitatively “meets the criterion to a sufficient degree, while having need for improvement” – it quantifies this as 75-85% Complete with 10-15% Uncertainty (Joint Research Centre 2010).

Special requirements for comparisons between systems

The complete function of a building is difficult to define, for example, there are aesthetic factors that cannot be quantified and indoor environmental qualities that are a challenge to measure. These sorts of considerations may need to be taken into account if LCA results are going to be used in practice. It may be possible to weight the LCA results according to an aesthetic score, or predicted worker efficiency resulting from competing daylighting designs. These are things that cannot be standardized, and therefore will not be addressed methodologically in this paper.

Identifying critical review needs

There are three types of review stipulated by ISO and the ILCD Handbook – independent internal review, independent external review, and external panel review – depending on the intended application of a study (Joint Research Centre 2010). These may be useful for any project, but they are not required if the study will only be used internally for design comparison. If a government agency is using LCA in a Situation B study, then they will definitely have to use external reviewers that meet the qualification standards to be deemed an expert (Joint Research Centre 2010).

Planning reporting of the results

Depending on the selected deliverables and target audience, the ILCD Handbook recommends that reporting is planned out according to required format – classical, condensed, or executive summary. If an LCA study is to remain internal and used only as a design guide, this step is less important and can probably adhere to whatever format the project team desires.

3.1.2 Life Cycle Inventory of a whole-building LCA

As mentioned in the Theory section, there is a basic procedure that must be satisfied in order to create an LCI. The following is how that generic methodology can be applied to a whole-building functional unit, as well as a discussion of how such a process could be standardized for assuring data quality – completeness, precision, and accuracy.

3.1.2.1 A basis for determining data quality and whole-building LCA validity

The LCA theory section discussed generally the need to establish data quality and measure of a study's validity according to the ILCD standardized method, but whole-building LCAs present a special case. Normally a product-based LCA has a clear functional unit whose production is dominated by a particular technology, and the precision and completeness of measurements can be estimated with a reasonable level of certainty. Buildings are different; they represent a combination of many products and technologies whose functionalities must come together to perform the overarching building function.

This means that trying to estimate how appropriate the data is regarding technology, geography, and time period becomes much more difficult – it is essentially a compilation of summarized assumptions. It is also not clear at which level – unit process, product, or building – these aspects of representativeness should be evaluated. For the purpose of this paper, data quality will be determined at the product level; where the Environmental Product Declaration (EPD) system has established some basis for comparison.

The diagram below shows an example of a window using this method; even though it has six different component parts, the validity of the data is determined only for the entire window unit. If this were required for each component part, the task would likely become unmanageable for the purposes of such an LCA study. Even in this case, all of these product data quality ratings (DQR) still have to be aggregated to the building scale in order to represent the validity of the whole-building model.

Sorted by BIM Object

Source Object	IFD GUID	Component Name (BIM)	IFD SignUp GUID	Process Name (LCA)	LCA UUID	Representativeness Quality Rating (1 - 5)					
						Technology (TeR)	Geography (GR)	Time-related (TiR)	Completeness (C)	Precision (P)	Methodology (M)
Window	?	**softwood:** **laminated pine, glue**	?	laminated wood (Mikado) Glue, for wood products, at plant, Norway (Mikado) Polyurethane, rigid foam, at plant/RER U	proprietary proprietary [illegible]	1	2	2	1	1	1
		glazing unit: **glass (coated & uncoated), spacer, desiccant, primary sealant, secondary sealant,**	?	Flat glass, coated - at plant Flat glass, uncoated - at plant Disposal, building, glass sheet, to sorting plant/ NORDEL Argon, liquid, at plant/RER U - NORDEL Polybutadiene, at plant/RER U Polysulphide, sealing compound, at plant/kg/RER Styrene-acrylonitrile copolymer, SAN, at plant/kg/RER Glass fiber, at plant/kg/RER Steel. Low alloyed at plant Sheet rolling, steel/kg/RER Zeolite, powder, at plant/RER U	[illegible]						
		aluminum cladding: **aluminum, section bar extrusion, power coating**	?	Aluminium, production mix, at plant/RER U - NORDEL Section bar extrusion, aluminum/RER U - NORDEL Powder coating, aluminum sheet/RER U - NORDEL							
		brackets: **hinge, head slides, pivot sleeve & pins, handle, espagnolettes, guides, end keeps, lockbox, U-profile,**	?	Steel. Low alloyed at plant Section bar rolling, Aluminum, production mix, cast alloy, at plant/kg/RER Zinc coating, pieces/RER U PA - nylon 6, at plant/kg/RER Polypropylene, granulate, at plant/kg/RER Injection molding/kg/RER							
		mounting: **frame seal, glazing seal**	?	Polyethylene, LDPE, granulate, at plant/RER U Injection moulding/kg/RER Polyurethane, flexible foam, at plant/RER U EPDM - Synthetic rubber, at plant/RER U							
		chemicals: **wood preservative, alkyd primer, acrylic top coat**	?	Wood preservative, organic salt, Cr-free, at plant/kg/RER Robot spray system with Akzo Nobel US Robot spray coating with Akzo Nobel USa 55 Alkyd paint, white, 60% in H2O, at plant/kg/RER							

Data Quality Rating (DQR)	1,6

Figur 34. Sample BIM-based data quality rating (DQR) output

3.1.2.2 LCI guidelines for whole-buildings

To establish a potential standardized whole-building LCI procedure, there are five basic steps that must be satisfied: Identify processes, Collect data, Scale data, Allocate impacts, and Calculate results. These steps are described in more detail below:

Identifying processes that are required for the system

This exploratory process entails taking a detailed account of the materials and energy-use that will be required over the life of a building. Once a high-level inventory has been established according to the system boundary, this must then be further broken down into sub-parts and eventually unit processes. This procedure should start to reveal if appropriate LCA data already exists as a part of databases such as Ecoinvent, or if it will have to be collected from primary sources to meet a required data quality baseline.

Planning of collection of raw data and data sets from secondary sources

For those building elements that unit processes or EPDs do not already exist, elementary flows will have to be determined from primary or secondary sources of raw data. Elementary flows represent the most basic inputs into industrial processes, and can be used to model a unit process that outputs the sub-part or material needed for the building LCA. This could be acquired from BPM product specifications, interviews with industry manufacturers, or identifying an alternative unit process that falls within the data quality requirements of the study. This type of data collection is obviously more time consuming and therefore would likely have to be removed for a broader adoption of LCA to be possible.

Collecting unit process inventory data for foreground system

Once it is determined that all elements in the functional unit – the building – can be modeled by a set of unit processes, then the inventory data can be collected. Essentially, identifying all the unit processes established a structure for storing the quantity data, but did not document the quantities themselves. After this step, the foreground quantities will be known, and will be ready to populate the model.

Developing generic LCI data for missing inventory data

If there are any holes in the foreground inventory that cannot be removed by the previous steps, and it is determined that it is important for the completeness of the study, then generic data assumed closest to the actual case must be used. This is most likely not an issue with whole-building LCAs because of the limited number of large impact areas, and the availability of reasonable estimates in most cases.

Obtaining complementary background data as unit process or LCI result data

This step should not be an issue for a whole-building LCA because of the aggregated nature the functional unit – it is the combination of many product LCAs. It would be unlikely that after collecting data for all the building materials and operational energy-use, that it would be necessary to collect supplementary data from the background production processes for each of those materials. This would definitely make such analysis too time consuming to be used in the context that is being suggested by this paper.

Aggregation and averaging LCI data across process or products

If process data has been collected for an entire material category – such as insulation or concrete – then it would be necessary to aggregate and average those results to get one process that can be used in the LCA study. This step may not be necessary for many of the more impactful materials because industry efforts – such as the BEES database created by NIST – have attempted to produce a wide variety of studies for the most commonly used high-impact materials. Using cement as an example, the BEES project has produced approximately seventeen different LCA variations that model a range of Portland cement substitutions.

Modeling the system by connecting and scaling the data sets for functional unit

This is a critical step for ensuring that the LCA model is scaled to the impacts of the determined functional unit or reference flow. Until now, the quantity data collected for the foreground system has not been connected to the unit processes to accurately model scale – it represented a generic building recipe with equal use of all materials represented in the inventory data. By scaling the data for the functional unit, the material masses and energy-use totals are made to match the actual building project being studied.

Solve multi-functionality of processes according to attributional or consequential rules

As mentioned before, multi-functionality will likely not be a big issue for a whole-building LCA because of the aggregated nature of such a complex system, and the relatively small impact each material has on the whole. In an LCA study that has one product – such as cement production – there are fewer background processes, and therefore each has the potential to have a large impact on the system. For a whole-building, the foreground system is a collection of those single-product LCAs, which do not generally have meaningful co-products, and therefore any multi-functionality occurs in the background where its impact is small.

This can be understood in terms of window production – any by-products of making windows will have nowhere near the value and therefore have no consequence on production practices. This means that the impacts from energy and materials should all be allocated to the window itself.

In the case of oriented strand board, previous EPDs have allocated all impacts to the high-grade boards and beams that are produced in lumber yards, and therefore no impacts are associated with the wood chips that make-up OSB. This means that the glue that is used to make OSB represents almost all of the impacts. The importance of this practice is reduced further because the two products are often used on the same building, and therefore the OSB fraction of impacts are counted anyway, also it is unlikely that demand for OSB will drive industry to start chipping high-grade lumber.

Calculate LCI results – sum all inputs and outputs of all processes within system boundaries

The last step in the LCI procedure is to calculate the mid-point indicators associated with all the unit processes that make up the functional unit. In practice this is not performed by a practitioner, but is an automated function of LCA software once the unit processes have been assembled into a scaled hierarchical model – according to building elements and phases.

3.2 BIM-based whole-building LCA

Life Cycle Assessment faces a fundamental dilemma: the largest impact an LCA can have is in the early-design phase, but this is when the necessary data is most scarce (Glaumann et al. 2010). Reducing the time requirement for an LCA could potentially allow designers to check the impacts of their designs earlier, but with current tools, this is not possible. LCA and Environmental Impact Assessments (EIA) are carried out in later phases after most major design decisions have been made, and serve primarily as a documentation of impacts rather than a strategic information source that can actually make an impact on design. The models more accurately identify "hotspots" in later stages, but they do much less to change the actual outcome (Glaumann et al. 2010).

The overarching issue for BIM-based LCA is that the two fields remain very separate worlds with virtually no overlap of tools, terminology and data structure. LCA is a generic methodology, and for that reason, its tools have traditionally been developed to be generic and applicable to any sector. The result is that buildings must be modeled in both BIM and LCA software separately, and there is no direct information flow from one to the other.

Because of this software and modeling disconnect, whole-building LCAs remain too time consuming and esoteric for most in the building industry, and therefore remain a specialized field for academics and consultants. It is doubtful that the building industry will adapt its tools or processes to fit with the much smaller LCA industry, so if LCA practitioners wish to establish themselves within the AECOO workflow, they will be the ones responsible for closing the communication gap.

The primary applications for BIM – beyond producing the building model itself – are scheduling and cost estimation (Young et al. 2009). This paper will focus mainly on the cost calculation functionality of BIM – specifically quantity take-off (QTO) and building performance and energy analysis (BPEA) – because it is these elements that relate more directly to the potential of BIM-based LCA. Using BPEA and QTO, a BIM is currently capable of generating the data that is required to produce a whole-building LCA, but this is not commonly done.

Life Cycle Costing (LCC) requires the calculation of service life, in addition to basic QTO for costing and BPEA functions. Because of this, it represents an even stronger link to the possibility of whole-building LCA. There has been some BIM development of LCC tools – such as the LCC-DATA IDM – but it is still quite new for the building industry, and it has been mostly governmental bodies that have pushed for its adoption.

Essentially an LCC analysis has already produced the LCI for an LCA, but instead of using environmental impact multipliers to find mid-point indicators, it uses cost multipliers to find costs over the lifespan of the building. This means that once BIM-based LCC tools exist, it could be relatively simple to transform the pre-cost life cycle inventory results into an LCA.

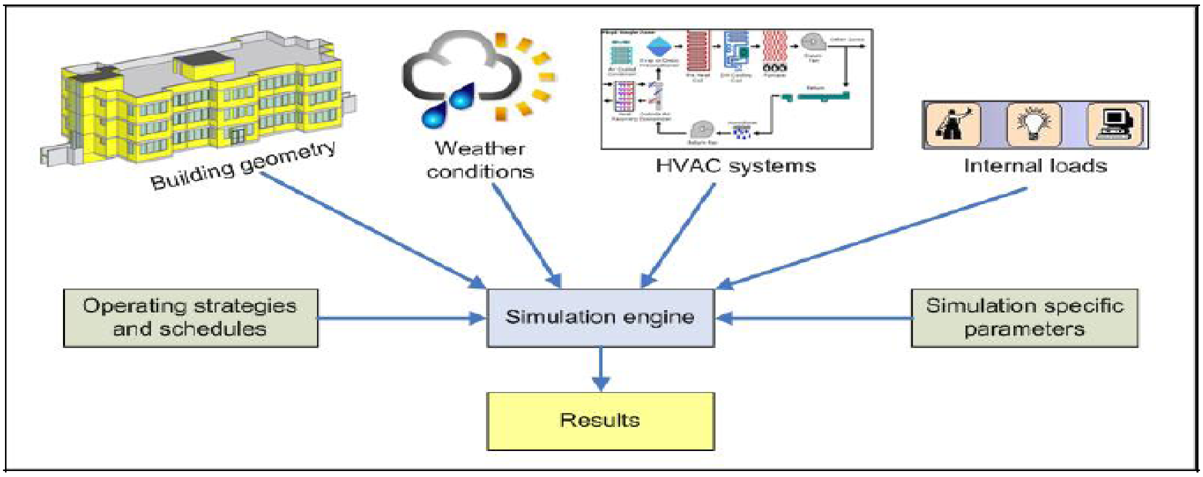
3.2.1 BIM-based QTO/BPEA with Manual LCA Data Input

3.2.1.1 BIM-based Energy Analysis

For regulatory and cost reasons, industry has developed robust BIM-tools for modeling operational energy-use in buildings. The architectural BIM acts as a warehouse of information that can be exported to energy simulation software packages designed for these specific calculations. This function is not currently comprehensive or without challenge for energy modeling, even for IFC compatible simulation engines like EnergyPlus, but having the data in a centralized dynamic model simplifies many of the steps and removes elements of human error.

The information requirements of energy simulation are more difficult to satisfy with current BIMs than those of QTO. This is because they require high-level operational information like internal loads and HVAC schedules to be accurate, and this type of information is not yet included in models. For this reason, it has been primarily the transfer of geometry and the corresponding thermal properties that was the focus of BIM information transfer to energy analysis software.

Below is a diagram that shows the input data that is required to generate an energy simulation of a building.



Figur 35. Basic inputs for energy analysis (Maile et al. 2007)

Importing the building geometry may be the most basic function a BIM can serve, but it can still greatly reduce the time required for analysis; "Based on our own projects and performance analysis, we have found that 50% of the time it takes to build and analyze an energy model is spent simply re-creating the building geometry in a new application" (Krygiel & Nies 2009). Most energy analysis software does not go beyond this point, requiring manual input of internal loads and HVAC operating schedules.

A case study used to implement IFC QTO and BPEA MVDs, called the AECOO-1 Joint Testbed, was conducted by a number of organizations including: US General Services (GSA), Statsbygg, Lawrence Berkeley National Laboratory (LBNL), and the Open Geospatial Consortium (OGC). As part of this project, LBNL created a Geometry Simplification Tool (GST) that allows for shorter simulation run-time, and the same project aims to automate the input of HVAC systems from IFC files (OGC et al. 2009). As the automation of this process increases, many barriers to use are overcome: time, specialized staff, and subjectivity of models (Maile et al. 2007).

Beyond increased use of energy modeling for performance optimization of buildings, as team hours per energy model decrease, more alternative models can be generated, delivering superior results as a comparative tool for planning. Though some may argue that the actual performance of a building has too many variables to accurately predict, and will be determined largely by occupant behavior, these relative comparisons can quantify proportional gains regardless of the end use.

AECOO-1 Joint Testbed: IDM for BIM-based Energy Analysis

The basic purpose of this view is to allow designers to create a usage profile and cost of energy consumption within buildings in both the conceptual and schematic design phases. The aim is to have an impact on overall building design, determine feasibility in an energy context, and establish targets (See 2009b). Below is an outline of the exchange requirements defined in the IDM:

Scope of this view:

The scope includes spaces with associated energy information and proposed energy analysis zones.

Exchange Requirement Overview

The building model will provide specific information about:

- the building, its location, composition, overall shape and orientation
- the shape and location of adjacent buildings
- building stories within the building
- spatial configuration

Additional requirements specific to this model view:

- space type and function for internal load assumptions and conditioning requirements
- building element construction type for thermal characteristics
- space boundaries that define relation with building elements
- energy targets
- HVAC zoning, daylighting, use of photovoltaics

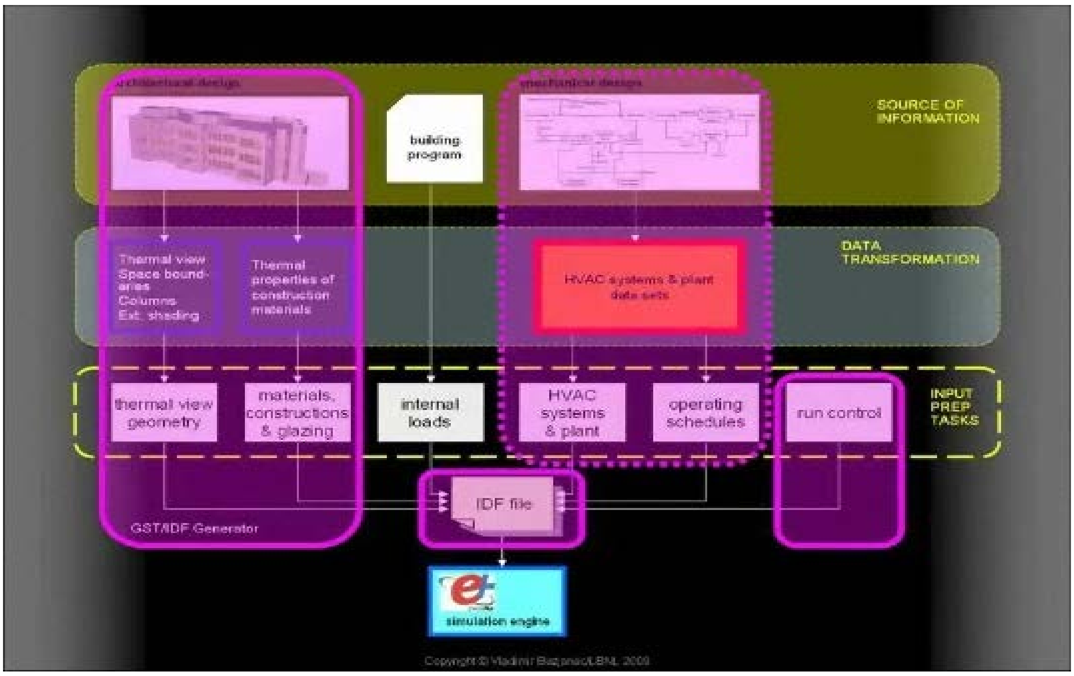
(See 2009b)

Energy Analysis for AECOO-1 Joint Testbed Model

The diagram below represents the information flow that was used by theAECOO-1 Joint Testbed – the software used was a result of responses from a general call for collaboration. The architectural model is created in ArchiCAD, that model is checked for compliance with energy simulation requirements by Solibri Model Checker, and then the geometry is simplified by the LBNL GST tool, and finally the energy simulation is performed by the EnergyPlus engine.

Figur 36. AECOO-1 BPEA workflow diagram (OGC et al. 2009)

The actual simulation for the AECOO-1 Testbed was conducted by LBNL, and the diagram below provides all sources of information, how they were transformed, and what is input into the final EnergyPlus IDF file. The highlighted areas with a solid border indicate where information was automatically generated using either the IFC file, or semi-automated prompts included in EnergyPlus. These include: thermal view geometry, materials/constructions/glazing, the run control for simulation, and the IDF file for EnergyPlus. The highlighted area with the dotted border – HVAC systems and schedules – was not yet automated, but was in development during the presentation in early 2010.



Figur 37. Inputs for LBNL EnergyPlus simulation (OGC et al. 2009)

The implementers at LBNL emphasized the importance of semi- and fully-automated data input for consistency of simulations. If the methodology is standardized within programming code, then it can be systematically evaluated and reproduced (OGC et al. 2009).

Using this process, a complete baseline energy analysis can be completed in less than an hour – a task that used to take weeks when geometry had to be recreated and software run-time was longer (OGC et al. 2009). For the testbed there were multiple models created with various modifications involving glazing, shading, and roof design, and each time the simulation took under ninety minutes.

3.2.1.2 BIM-based Quantity Take-Off

The same project – coordinated by the buildingSMART alliance (bSa) – focused on creating IDMs and MVDs for design teams to use in the early design process. The four exchange requirements created for this project include: Design to Spatial Program Validation, Design to Energy Analysis, Design to Circulation/Security Analysis, and Design to Quantity Takeoff for Cost Estimating (See 2009b).

The process of creating a QTO from a BIM has been improved with the creation of such an MVD – it makes it possible for an IFC file to be uploaded by cost estimating software directly. The MVD and supporting Exchange Requirements ensure that there is a sufficient amount of detail included in the model for cost estimating software to be effective.

AECOO-1 Joint Testbed: IDM for Quantity Takeoff for Cost Estimating

The basic idea behind this view is that designers provide design object quantities, which can be used as underlying quantities that drive the calculation of construction quantities (See 2009b). Below is an outline of the exchange requirements defined in the IDM:

Scope of this view:

The scope includes the building, space, elemental quantities and descriptions intended for use in the preparation of a cost estimate.

Exchange Requirement Overview:

The building model will provide specific information about:

- the building, its location, composition, overall shape and orientation
- the shape and location of adjacent buildings
- building stories within the building
- spatial configuration

The building model will provide conceptual information about:

- the building services
- the building structure
- the site design
-

Additional requirements specific to this model view:

- space type and function
- building elements construction type

(See 2009b)

QTO for AEECO-1 Joint Testbed Model

The flow diagram below – taken from a presentation given by the team of implementers in the testbed – shows their process for conducting a QTO using only a BIM.

Figur 38. AECOO-1 QTO workflow diagram (OGC et al. 2009)

The simplicity of the process is a result of the compatibility of tools, and this is a result of much effort being put into creating a transparent and unambiguous definition of the information to be exchanged. Once the IDM and MVD have been created, then it is quite simple for use-specific software to use the input from that model view. In this case, Tokmo was used and could generate a complete cost model in around two minutes (OGC et al. 2009).

Such models must still be scrutinized by knowledgeable professionals, but this sort of time reduction completely changes the use of cost estimation. Rather than being a reactionary process that is performed as a check to ensure budgetary targets are met, the cost modeling results can drive design.

3.2.1.3 Applying QTO and BPEA results to LCA

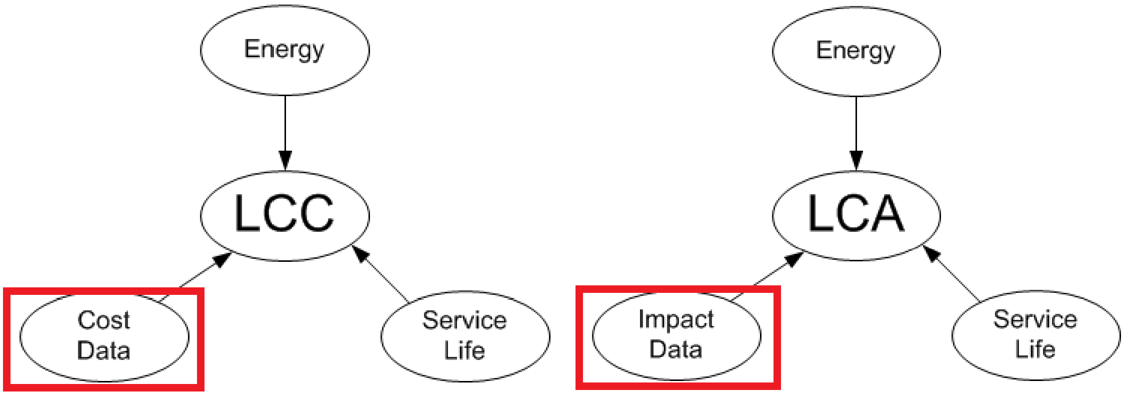
Under this scenario, the results will produce a basic inventory list of materials being used in the initial construction of the building, and a simulation of annual energy use. This requires that an LCA practitioner produce a service life model for the building and its elements, and a corresponding maintenance and refurbishment schedule – adding materials and processes to the inventory. It also would require the estimation of any increases in energy demand due to aging or faulty mechanical equipment and envelope function over the lifespan of the building.

Once the complete life cycle inventory was complete, an LCA practitioner would then have to create the LCI model in an LCA software tool – requiring manual data categorization and input. The primary benefit of using BIM is that the basic material list can be produced automatically, and the energy simulation time is reduced as stated before.

3.2.2 BIM-based LCC with Manual LCA Data Input

Assuming LCC and LCA models have the same scope; the only difference between the two is that one measures cost and the other measures environmental impact. The figure below – adapted from the LCC-DATA IDM – illustrates this point by comparing the three inputs that are required for both analysis methodologies. They both estimate operational energy use and service life of building elements, but they use different multipliers to interpret what that inventory means for a project.

While in theory the transformation between these two models may be straightforward, in practice it is a much more complex task to produce the impact data than obtain cost data – which is readily available for products. If EPDs were as prevalent in spec books as prices, then it would be equivalent, but because this data does not exist for most products, it must be produced using LCA databases made up of elementary flows and unit process data.



Figur 39. Comparison of LCC and LCA inputs – adapted from LCC-DATA IDM (Edvardsen et al. 2009)

What this means, in terms of using BIM-based LCC analysis, is that the inventory would have to be converted back to physical units by removing the price multiplier. If an interim inventory already exists – where future expenses have not been discounted – then this could be used as the LCI for an LCA. But if only the final LCC results are available, and future cashflows have been discounted, then it is not a linear transformation to remove price. Once an acceptable LCI is available for an LCA study, then it would have to be manually input into LCA software and unit processes identified and combined to generate a model.

Implications of discounting future impacts

One of the major methodological differences between cost-based life cycle analysis and that of environmental impact assessment is the discounting of future flows. Future cash flows can be reduced in value according to an assumed discount rate because of the time value of money, but environmental impacts incurred in the future are equally detrimental as those that occur today. If future flows of carbon dioxide were discounted, then it would encourage poor long-term planning by hiding the impacts that occur far off in the future.

One of the dangers of monetizing environmental impacts – such as in LCCA – is that once those costs have been mixed with standard costs, they can be discounted along with all the others. Once the cost of those impacts has been reduced, then their importance has been diminished also.

There are scenarios in which one could speculate that energy production will be cleaner in the future, reducing the impacts of energy use over time, but the level of change is very uncertain, and other externalities might have an equally negative impact. Estimating the cost of externalities is very difficult to do accurately, and building those assumption into an LCA makes it all the more difficult to get a clear understanding of what the true environmental impacts will be. For that reason, future emission flows are not discounted, and if emission costs are monetized, it should be made clear what that cost represents in actual physical values.

3.2.2.1 Relevance of Basic Cost Estimation and Energy Analysis

The BIM function of quantity take-off allows cost estimators to get an accurate account of the materials that will be initially required to construct the building. This step is useful for LCA because it similarly must create an inventory, but once financial cost is introduced into the calculation, the two methods diverge. If an LCC report does not leave this initial step as a separate inventory, then an LCA practitioner would have to reverse all cost calculations according to assumed prices and discount rates.

LCA also requires an estimation of operational energy-use to account for the impacts that result from the production of electricity and on-site fuel consumption. This is likely a much simpler conversion process because it is likely the calculated energy demand will be reported in a standard format that can be extrapolated over the assumed lifespan according the functional unit of an LCA.

Though the production mix – which technology was used to produce the electricity – does not matter for costing purposes, this is vital for LCA. The relatively long operational lifespan of most buildings makes the energy consumption during the use phase the dominant impact category, but this can be manually input by the LCA practitioner when entering the LCI data.

3.2.2.2 Relevance of Service Life Planning

As part of the LCC-DATA IDM, a list of exchange requirements for a Service Life Planning MVD has been created for an IFC BIM model. It has defined these requirements for multiple phases of the building design process, with the level of detail and expected accuracy increasing over time as more is known about specifications for materials and equipment. Given that Service Life Planning must currently be conducted separately from a BIM, this presents a step forward in simplifying the process for life cycle modeling and possibly maintenance planning in the future.

The service life portion of the IDM supports the production of an LCA because it allows a modeler to better predict the quantities of various materials that will be required for an assumed lifespan of the building. In this way, the LCA becomes more dynamic by including product lifespan in the initial calculations.

Such an MVD would also be valuable for life cycle planning by providing a better comparison of material versus operational energy impact shares as they change over time. For example, if a building is expected to last fifty years, it might not make sense to build to a passive standard due to the immediate material impacts. But if the lifespan is extended to eighty years, the impact proportions end up crossing and the saved energy makes the passive standard a better option.

For existing buildings, this may be even more useful because the material needs can be more accurately modeled and compared with new constructions. If a building is reaching the point where it will need major rehabilitation, then the material impacts and energy efficiency gains from renovation must be weighed against the potential for new construction with greater design freedom. The lifespan again is a critical variable, because a renovated building will have a shorter lifespan than a new construction, and also most likely achieve less operating efficiency. So over time, even though the renovation used less material and created less impact initially, it may be the case that after fifty years the new construction becomes a more sustainable solution.

These are just examples of the considerations that this type of analysis allows, and does not represent any specific case study. The central point is that developers will ultimately determine what their decision parameters are, but this type of modeling allows them to objectively compare the options and make educated decisions – and using an MVD streamlines the process making it more realistic to include earlier in the design process.

3.2.3 Complete BIM-based LCA

The previous examples have shown how existing BIM functionalities can be adapted to produce whole-building LCAs, but all of them require some manual conversion and input of data. They are an attempt to expedite the LCA process by providing semi-automated BIM solutions, but they do not represent a fundamental change. The main opportunity for improvement would be to enable LCA tools to communicate directly with existing design tools such as Revit and ArchiCAD. The LCI process could become completely automated because LCA tools could utilize the data stored in BIM objects such as material type, space relationships, material quantities, etc., and translate them into the unit processes that LCA software understands.

This type of linkage does not yet exist largely because the LCA data classification system is not compatible with BIM data – the materials and processes cannot be easily matched. This challenge will be discussed in greater detail later in the Data Conversion section, but potentially any type of existing LCA tool – that reads Ecospold files – could be linked to BIM models. BIM tools can produce QTOs in spreadsheet format, with material type and volume organized in any number of ways – so even simple tools such as ENSLIC could be made to directly use the BIM output for generating an

LCA. More robust software tools – like SimaPro or GaBi – could create a similar upload solution with the added benefit of their added functionalities of flow diagrams and sensitivity analysis.

Once the input of building data is fully automated, there becomes much less room for error, and the reduction in time allows for greater inclusion and experimentation in the design process. Ideally the communication between LCA and BIM software would be two-way, but most likely this is less realistic unless a fully integrated IFC based solution was developed as part of architectural design software.

3.2.3.1 IDM for Design to LCA

As shown before, the basic elements of a whole-building LCA are energy analysis, quantity take-off, and service life planning. Completed IDMs and MVDs already exist for QTO and BPEA, and an IDM has been written that includes a service life element for LCC analysis. Though these exchanges were not necessarily designed to conduct LCAs, they meet the needs of such a model when combined. The next step is to determine how they should be combined most effectively, and to write an IDM for Design to LCA.

Using the LCC IDM as a model, the service life exchange requirements and the basic inventory of materials and energy-use are useful for a BIM-based LCA tool, but the final results of an LCC analysis cannot be linearly transformed into environmental impacts. So when developing an IDM for LCA, the final results from the LCC-DATA IDM – ER _Results_of_LCC_Analysis – cannot be imported and used directly as source data.

One option to solve this would be to use results from more basic exchange requirements – such as ER_QTO_to_Design, ER_Energy_Analysis_Results, and ER_Exchange_Service_Life_(Design) – as input, while the functional parts defining life cycle activities that are called for in the broader LCC IDM – such as maintenance, cleaning, service costs – are incorporated into the LCA exchange requirements separated from cost factors.

A second option would be to define all LCA exchange requirements from functional parts – essentially recreating the QTO, BPEA and service life functions – specifically for the LCA purpose. This would allow one model view to satisfy all LCA requirements, and possibly make it more efficient to transfer files to a comprehensive software solution by eliminating unnecessary objects and attributes. But such a solution is not the goal of this paper, and would likely be only slightly more economical in terms of IFC file size, so the previously produced QTO, BPEA, and service life exchange requirements will be utilized as precursors.

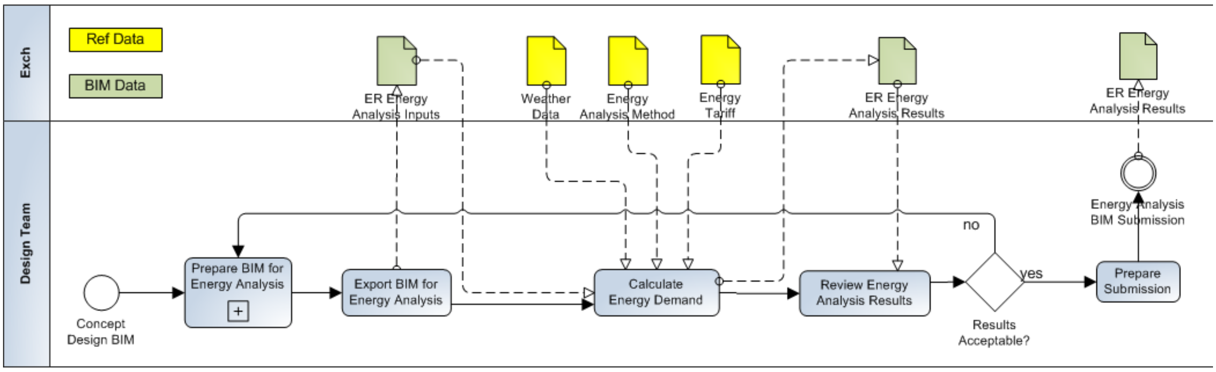
3.2.3.2 Process Mapping for LCA

Because the IDM for LCA will be based largely on results from existing exchange requirements, the top level process is quite simple – it involves preparing the BIM, exporting the prepared model, calculating the LCA results externally, and then reviewing those results. Preparing the BIM is a sub-process that must be defined in further detail, because it involves establishing the goal, scope, and object classification for production of an LCI – both process maps for LCA are included in the final IDM in the Results section.

The BIM Preparation sub-process for LCA requires input from external goal and scope type libraries – these are currently hypothetical and are only discussed as a potential method. The classification of BIM objects in LCA terms – equivalent to Ecospold data formatting – is done through a property set that identifies the set of LCA UUIDs that correlate to the GUID attached to all building elements. This conversion – a hypothetical property within the IFC schema – would have to be created manually for each BIM object. In the Data Conversion section, this is done for a sample window that was modeled in LCA software.

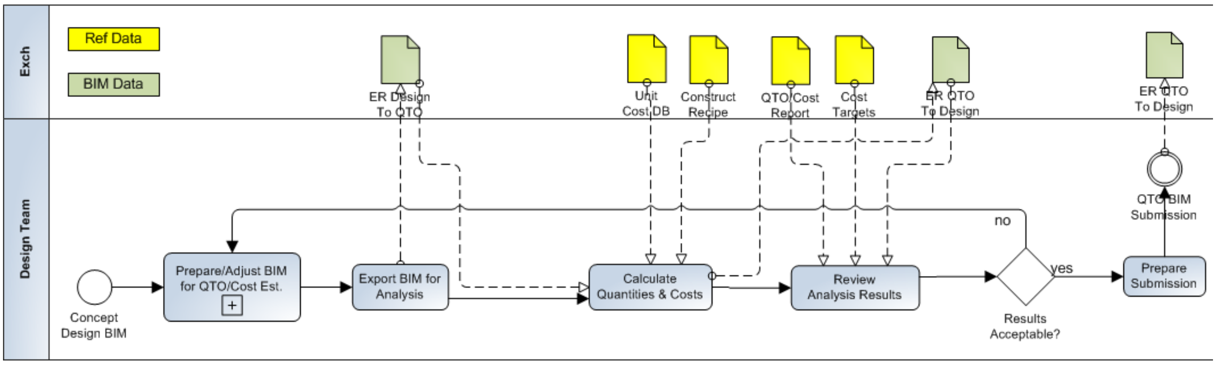
Related Process Maps

The process maps below were adapted from the AECOO-1 IDMs for QTO and BPEA – they represent the core process of the design team during each exchange. These are the level one process maps, level two maps exist for each of the Preparation steps that are required before the BIM can be exported and calculations made. In the first map, the BPEA exchange requirements are satisfied, which produces a BIM that can be used to transfer the required geometry and thermal information. In addition, the calculations require outside data for weather conditions, energy simulation algorithms, and energy tariffs are added for cost consideration.



Figur 40. Sample process map for energy analysis (Welle & See 2009)

The QTO process map below follows a similar procedure, but external data is taken from industry space and construction type libraries to label BIM objects, and it uses industry cost databases for costing applications.



Figur 41. Sample process map for quantity take-off (Wiggins & See 2009)

In the level two process maps, there is more detail regarding the creation of space and construction type libraries for a project, and assigning those classifications to objects in the BIM. These steps are pre-requisites for LCA, and the IDM created for this paper assumes that those steps have already been completed and validated.

3.2.3.3 Exchange Requirements for LCA

The two exchange requirements created for LCA will be called: ER_Design_to_LCA_(Concept) and ER_LCA_Results. The first describes the exchange of data from a BIM to an LCA software tool, and the second describes the reporting of results to the project team. In this case, the results will not be in the form of an IFC file, but rather an LCA report that outlines the impacts according to the application described in the goal and scope definitions.

The major transformations that take place in preparing the BIM for conducting an LCA are the assigning of **Goal** and **Scope** types, as well as the addition of LCC-based service life assumptions to the basic QTO data that was calculated previously. This will result in a life cycle inventory (LCI) that considers all **activity categories** – rather than costs – throughout the lifespan of the building, with those activities grouped in the same categories created by the LCC-DATA project. In addition to the raw LCI quantities that have been calculated, an **LCA ID** will be added to each BIM object to allow for the transfer of data to LCA software. The following sections expand on the details of these property sets, and attempt to lay the groundwork for creating the technical definition of LCA specific functional parts.

Goal Type Properties

The table below outlines the properties within the theoretical LCA Goal property set that will be required by a BIM for a Design to LCA exchange – the functional parts that provide the basis for each property have been included as a reference.

Tabell 26. IDM: LCA Goal properties

LCA Goal – Properties	Description
Commissioner of the study	FP_Model_Actor – this is the actor who initiated the LCA and will primarily determine its goal and scope.
Influential actors	FP_Model_Actor (can be more than one) – these are the actors who will provide modeling input for the LCA.
Target audience	FP_Model_Actor (can be more than one) – these are the actors that will have access to the LCA results, and it should explicitly indicate if the study will be made public.
Project phase	FP_Set_Project_Context – this is used to determine data limitations and requirements, because early design phases require less detail.
Intended applications	*FP_Set_LCA_Goal – at minimum, this requires the user to clarify if the LCA will be used as a comparative study for design decision support, or only for accounting purposes separate from design.

* FP_Set_LCA_Goal is a theoretical functional part that has not yet been defined

Scope Type Properties

The table below outlines the properties within the theoretical LCA Scope property set that will be required by a BIM for a Design to LCA exchange – the functional parts that provide the basis for each property have been included as a reference.

Tabell 27. IDM: LCA Scope properties

LCA Scope – Properties	Description
Deliverables	*FP_Set_LCA_Scope – this requires the user to select all deliverables that will be produced by the LCA from a library
Functional unit	FP_Set_LCA_Scope – functional units have many parameters, but these can be standardized for common requirements
System boundary	FP_Set_LCA_Scope – similar to the functional unit, there are many possibilities, but some pre-defined systems can be used – these will be made up of the standardized elements contained in the boundary diagram shown previously.
Completeness requirement	FP_Define_Quantity – this is a simple quantity that represents the minimum percentage of theoretical impacts that must be reached
Precision requirement	FP_Define_Quantity – this is a simple quantity that represents the maximum uncertainty of data as a percentage
LCIA method	FP_Set_LCA_Scope – this requires the user to identify the impact categories that will be measured for the LCA.

* FP_Set_LCA_Scope is a theoretical functional part that has not yet been defined

LCA Activity Categories

The table below outlines the properties within the theoretical LCA Activity property set that will be required by a BIM for a Design to LCA exchange – the functional parts that provide the basis for each property have been included as a reference.

Tabell 28. IDM: LCA Activity properties

LCA Activity – Properties	Description
Capital processes	*FP_Set_LCA_Activity – includes all activities associated with construction and decommissioning of building.
Admin processes	FP_Set_LCA_Activity – includes all activities for administration and insurance.
Operation processes	FP_Set_LCA_Activity – includes all daily, weekly, and monthly activities that are repetitive within a one-year period for building and technical installation systems for functional compliance.
Maintenance processes	FP_Set_LCA_Activity – includes all repair and replacement activities of technical installation systems that must be planned over a period greater than one year.
Development processes	FP_Set_LCA_Activity – includes all refurbishment activities that result from a change in functional demand for core activities.
Operational energy processes	FP_Set_LCA_Activity – includes all activities associated with heating, cooling and electricity demand.
Water and drainage processes	FP_Set_LCA_Activity – includes all activities associated with intake of water and delivery of wastewater – including cleaning.
Waste handling processes	FP_Set_LCA_Activity – includes all activities connected to internal transport, compression, source separation, collecting, and transport to landfill.
Cleaning processes	FP_Set_LCA_Activity – includes all on-site cleaning activities – inside and outside – necessary to meet functional demand.
Service processes	FP_Set_LCA_Activity – includes all non-building related activities in support of core building functions.

***** FP_Set_LCA_Activity is a theoretical functional part that has not yet been defined

LCA ID Properties

The table below outlines the properties within the theoretical LCA ID property set that will be required by a BIM for a Design to LCA exchange – the functional parts that provide the basis for each property have been included as a reference.

Tabell 29. IDM: LCA ID properties

LCA ID – Properties	Description
GUID	IfcGloballyUniqueId – this unique identifier provides an unambiguous reference to the specific BIM object to be modeled.
LCA UUID	*FP_Set_LCA_ID (can be many) – these unique identifiers classify a single unit process in the Ecospold LCA data format, and in combination will model a single BIM object.
Share of BIM object	FP_Set_LCA_ID – for each UUID, there will be an assumed percentage of the total BIM object quantity associated with it – this allows for scaling of impacts according to modeled values.

***** FP_Set_LCA_ID is a theoretical functional part that has not yet been defined

Related Exchange Requirements

This section discusses precursor exchange requirements that are assumed to already have been satisfied prior to commencing preparation of the BIM for LCI analysis purposes. These are shown here because it is important to understand what this assumption means, and because these details will not be included in the IDM for LCA – they will only be referenced for software developers to understand what is required. This system is convenient for IDM developers because it allows them to avoid re-defining exchange requirements and functional parts that have already been created, but it can be difficult for non-technical readers to fully understand what is going on when they enter the process after much has already been defined.

The table below is taken from the QTO and BPEA IDMs; it provides a summary of what the Concept Design BIM will have to satisfy before it can be validated for use in QTO or Energy Analysis. Because an LCA represents the combination of QTO and BPEA, it is assumed at this point the model meets those minimum criteria, thus these requirements are not included in the Design to LCA IDM.

Tabell 30. IDM: Initial concept BIM requirements

Name	**Concept Design Complete**
Type	Initial Concept BIM
Documentation	It is assumed that the architect has defined a building concept design complete with all the required building elements and space objects. This design provides a proposed building layout including functional and non-functional space configuration and placement of other geometric elements. Non-functional spaces such as technical spaces, circulation spaces, shafts, etc. must be defined by a space object and not left as unidentifiable voids surrounded by geometry. Spaces that represent multi-story spaces such as atria and vertical distribution routes such as shafts, stairways and elevator shafts should be represented as distinct spaces at each level of the building that are related to each other vertically (either via an opening in a slab or an element located at the opening for e.g. safety purposes). For both QTO and BPEA purposes the Concept Design BIM should include: - the site and building location - the building orientation including its relationship to true north - the site and building elevation above a reference datum - the building story information - 3D geometry of adjacent buildings - 3D geometry of the building, including walls (exterior/interior), curtain walls, roofs, floors/slabs, ceilings, windows/skylights, doors, and shading devices - space objects, including those defined by virtual space boundaries **At the end of this task, all exchange requirements from ER Arch Concept to QTO Inputs and ER Energy Analysis should be met.** **ER QTO & BPEA:** Project, Site, Building, Building Stories, Spaces **ER QTO:** Wall, Slab, Opening, Beam, Column, Curtain Wall, Stair Flight, Ramp Flight, Equipment, Plumbing Fixtures, HVAC, Electrical, Hot

	Water Systems, Cold Water Systems and Vertical Transportation Systems **ER BPEA:** Site (Outside Design Criteria), Site Context, Building (Energy Target), Spaces (Thermal Comfort Criteria), Spaces (Ventilation Criteria), Spaces (Ventilation Design), Energy Analysis Zones, Photovoltaics and Building Elements (General), Building Elements (Opaque and Glazing), Material (Opaque), Material Layer (Opaque), Material Layer Set (Opaque)

(Wiggins & See 2009)

The table below provides a description of how the spaces in a model have been identified and can be used in QTO and BPEA through identification of standard properties associated with specific space types according to industry libraries. In addition to this definition, the exchange requirement also outlines the task of assigning each space type to occurrences, as well as defining supplemental spaces that are not defined in the library.

Tabell 31. IDM: Project space type labeling

Name	**Create Project Space Types**
Type	Task
Documentation	This process considers that an industry space type data library exists from which a project specific space type library can be derived. The space type selected drives assumptions for the thermal performance characteristic of the space for energy and cost simulation. The industry space type library may come from a variety of sources. The library may be accessed from a server over the web or from directly within the BIM-authoring application. The project specific space type library contains only definitions of those space types that can be used on the project of concern. A single space object may have one, two, three, or more construction types assigned to it based on the needs of the client. Project space data is expected to provide most of the following: For energy analysis: - space type name - outside air requirements - internal loads of lighting, occupants, equipment - space conditioning requirements - operating schedules for lighting, occupants, equipment For QTO: - relating space (what the boundary defines) - related building element - connection geometry (horizontal and vertical boundaries) - physical or virtual boundary - internal or external space The default assumptions based on the project space type is meant to be a starting point only, and the values may be modified prior to running the simulation.

(Welle & See 2009)

Similar to spaces, construction objects also have to be assigned types from industry libraries that provide assumed properties regarding composition and thermal performance. In Appendices 3 and 4 there are more detailed descriptions – taken from the QTO and BPEA IDMs – of how each part if classified according to either Uniformat or Omniclass construction classification systems.

Tabell 32. IDM: Project construction type labeling

Name	**Create Project Construction Types**
Type	Task
Documentation	This process considers that an industry construction type data library exists from which a project specific construction type library can be derived. The industry construction type data library provides information that drives assumptions for the thermal performance (R-value, reflectance, transmittance, and thermal mass effects) and material characteristics of constructions for LCA modeling. The industry construction type library may come from a variety of sources. The industry construction type library may be accessed from a server over the web or from directly within the BIM-authoring application. The project specific construction type library contains only definitions of those construction types that can be used on the project of concern. A single construction object may have one, two, three, or more construction types assigned to it based on the needs of the client. Project construction data is expected to provide most of the following: - construction type name - material layer sequence for the construction - material layer thermal properties - overall thermal properties of the construction The default assumptions based on the project construction type is meant to be a starting point only, and the values may be modified prior to running the simulation.

(Welle & See 2009)

The final precursor exchange requirement is service life – there are multiple phase specific versions of this, but they primarily vary on where the data comes from, how detailed it should be, and how specific the element categories can be. For this paper, the ER_Service_Life_(Design) from the LCC-DATA IDM will be referenced because the LCA IDM will be used in the Concept Design phase. This exchange requirement covers the request of data, acceptance of data, and the assigning of data to the appropriate BIM objects.

Tabell 33. IDM: Exchnage requirements for service life

Name	**ER_Exchange_Service_Life_(Design)**
Type	Data Object
Documentation	The scope of this exchange requirement is to enable the exchange of information about the design life of a type of product. **General Description** The design life of an element or product is the length of time that it may be expected (is proposed) to perform its required function or work within its specified parameters; in other words, the intended life expectancy of the element or product. For the purpose of this and other exchange requirements concerning

	service life planning, a product is considered here to be an individual item in entirety or a type of individual item about which information might be obtained from a library or catalog whereas an element is considered to be an aggregation or grouping of products. An element may have a design life, and other service life assessments, in the same way as a product. Design Life information is determined by compiling historical or statistical data from a number of sources. It is anticipated that such historical data will either be normalized to 'normal' in-use conditions or will include information about the in-use conditions relevant to the data (in which case the user may need to make an adjustment to the data provided to ensure that it is suitable for the intended use). Design life information may be assigned at any point during the project starting from the earliest point. Initially, the client may set an objective for a design life for the whole construction. As the design progresses and more detail becomes available, design life assessment can progressively become richer. Initially, it may be tied to a whole building or to parts (or levels) within a building. Later, design life may be applied to structures, mechanical and electrical systems and to major building components. Further along the design, product definitions will start to emerge and these can also have a design life assessment. It is expected that design life information will be available from a database or external library reference and information will be needed about the library itself as well as about the design life data. Information required concerning the external library reference includes: - Name of the library - Publisher or authority responsible for making it availalable - Version number or reference - Date on which the version referenced became effective - Address or location of the library e.g. as a web address Design life information delivered for the element or product type includes: - The normally anticipated life expectancy - An optimistic assessment of the design life - A pessimistic value of design life - In-use condition relating to the provided design life (Poor/Normal/Good) - Factor to be applied to the design life provided by the library to ensure that it is suitable for current use

(Edvardsen et al. 2009)

3.2.3.4 Functional Parts for LCA

Many of the functional parts have already been created for the precursor or related exchange requirements, but there are some that are unique to the production of an LCA. These include property sets that define LCA **Goal** and **Scope** Types – these could be used to store standardized types in theoretical Goal and Scope Type libraries. For a given model, there could be multiple goals and scopes selected, and in each case the BIM objects included in the model view would change – which would impact the assignment of QTO and service life data.

In addition, there is a requirement to categorize **activities** – those that must be modeled in an LCA – similar to how costs have been structured for LCC analysis. Once activities have been grouped according to the LCC-DATA cost categories, then they must be further tagged with identifiers that can be understood by LCA software. This is achieved by adding an **LCA ID** for every BIM object that has a GUID – this LCA ID is a list of UUIDs used by the Ecospold data format and most major LCA databases.

Also, there are some properties of existing objects that only matter to LCA – and example would be the **region** of electricity production for a given project. This is important to LCA because every region has a different **energy-mix**, which means that it produces electricity with different technology and in varying proportions. In LCA terms, it is critical to know if the electricity was produced by a coal fired power plant, or by a run-of-the-river hydro electric plant. In the case of coal, the impacts from operational energy use would be much larger than those from the hydro plant, and therefore may change the decision of a designer to use added materials and capital cost to ensure a more energy efficient building over the use phase.

The following sections describe each of these LCA related functional parts in more detail, and begin to lay the technical basis for their inclusion in an IFC solution. All the entities and property sets are theoretical at this point, and would require evaluation by a solution provider to determine the appropriateness of the method.

FP_Model_Site

The model_site FP already exists, but the **region** attribute does not yet exist within its scope because it is not relevant for most BIM functions, but could be added for identifying the proper grid **energy-mix** of a project. This is an attribute because every site would have an energy region in this sense. This function could also be addressed by extrapolating the location of the address according to LCA region definitions, but defining this attribute allows the freedom to purposefully experiment with different energy-mix scenarios for one location.

FP_Set_LCA_Goal

This functional part is mostly focused on identifying actors that fulfill various roles that are specifically relevant for an LCA study – it also creates the LCA application label.

Tabell 34. IDM: Functional part set_LCA_goal

Entity/Pset/FP	**Description**
ifcLca.Commissioner::fp_model_actor	Identify actor that is commissioner of LCA study including name, address, roles, and organizational relationships.
ifcLca.InfluentialActor::fp_model_actor	Identify actors that are influential including name, address, roles, and organizational relationships.
ifcLca.TargetAudience::fp_model_actor	Identify actors that are in the target audience including name, address, roles, and organizational relationships.
ifcProject.Phase::IfcLabel	Set the building stage of the study.
ifcLca.Application::IfcLabel	Set the LCA application of the study.

FP_Set_LCA_Scope

This functional part is a collection of new IFC labels that must be created for a scope definition to be portrayed in a BIM model view.

Tabell 35. IDM: Functional part set_LCA_scope

Entity/Pset/FP	**Description**
ifcLca.Deliverable::IfcLabel	Set the deliverables of the study.
ifcLca.FunctionalUnit::IfcLabel	Set the functional unit of the study.
ifcLca.SystemBoundary::IfcLabel	Set system boundary of the study.
ifcLca.DataCompleteness::IfcLabel	Set required data precision – could be a numeric value (%) or a string based descriptor (high-medium-low).
ifcLca.DataPrecision::IfcLabel	Set required data precision – could be a numeric value (%) or a string based descriptor (high-medium-low).
ifcLca.LciaMethod::IfcLabel	Set the LCIA method of the study.

FP_Set_LCA ID

An essential property that does not currently exist in a BIM is an identifier that allows for LCA UUIDs to be matched to BIM GUIDs. This property set – **LCA ID** – would reference a database of pre-determined combinations of LCA UUIDs that represent a given BIM object. An example would be a window, which has a single GUID in a BIM, but represents a large number of unit processes in LCA software terms. It is this link – one GUID to many UUIDs – that must be created by LCA practitioners to allow for the two types of software solutions to communicate.

Tabell 36. IDM: Functional part set_LCA_ID

Entity/Pset/FP	Description
ifcLca.GlobalId::IfcGloballyUniqueId	Set the global unique identifier.
ifcLca.LcaUuid::IfcLabel	Specify the LCA UUID associated with the BIM GUID.
ifcLca.ShareOfObject::fp_define_quantity	Set the assumed percentage of the reference BIM object quantity associated with the LCA UUID.

FP_Set_LCA_Activity

While the LCC-DATA IDM does not completely fit with what is needed for LCA, the cost categories that have been created for the operational life of a building are useful. These can be used to identify activities – which in LCA terms have environmental impacts – while removing those elements that attach cost. As an example, the LCC-DATA IDM identifies maintenance as an ongoing activity, and then attaches cost assumptions to calculate the contribution to the LCC. But for an LCA, these maintenance activities must be characterized according to their environmental rather than their economic impact.

In the same way that a BIM object will be linked to LCA software through a standardized collection of UUIDs that represent one GUID, the activity of building maintenance must be modeled as a collection of LCA unit processes that can be referenced in LCA software. The complexity of this task will depend on the scope of an LCA. As an example, the ENSLIC scope would only include the cost/activity categories accounted for through QTO and BPEA, which are capital investment and operational energy related activities.

For this functional part, each activity category must be modeled and grouped similar to how it is done with cost modeling. The functional parts FP_Model_Cost_Item and FP_Model_Cost_Schedule have already been created for this purpose. Using these as a guide, it would be possible to create parallel activity models and groups of activities as schedules.

These theoretical functional parts will be referred to as FP_Model_LcaActivity_Item and FP_Model_LcaActivity_Schedule. The first defines activity elements that can be nested to provide a hierarchical structure within the activity model, and used to develop complex groups of activities (Wix & Espedokken 2008). Once this structure has been established, only the high-level activity categories must be referenced to capture all the underlying activities associated with each.

Tabell 37. IDM: Functional part set_LCA_activity

Entity/Pset/FP	Description
ifcLca.CapitalProcess::fp_model_lcaactivity_schedule	Set all activities associated with construction and decommissioning of building.
ifcLca.AdminProcess::fp_model_lcaactivity_schedule	Set all activities for administration and insurance.
ifcLca.OperationProcess::fp_model_lcaactivity_schedule	Set all daily, weekly, and monthly activities that are repetitive within a

	one-year period for building and technical installation systems for functional compliance.
ifcLca.MaintenanceProcess::fp_model_lcaactivity_schedule	Set all repair and replacement activities of technical installation systems that must be planned over a period greater than one year.
ifcLca.DevelopmentProcess::fp_model_lcaactivity_schedule	Set all refurbishment activities that result from a change in functional demand for core activities.
ifcLca.EnergyUseProcess::fp_model_lcaactivity_schedule	Set all activities associated with heating, cooling and electricity demand.
ifcLca.WaterProcess::fp_model_lcaactivity_schedule	Set all activities associated with intake of water and delivery of wastewater – including cleaning.
ifcLca.WasteProcess::fp_model_lcaactivity_schedule	Set all activities connected to internal transport, compression, source separation, collecting, and transport to landfill.
IfcLca.CleaningProcess::fp_model_lcaactivity_schedule	Set all on-site cleaning activities – inside and outside – necessary to meet functional demand.
ifcLca.ServiceProcess::fp_model_lcaactivity_schedule	Set all non-building related activities in support of core building functions.

3.2.3.5 IFC Labels for LCA

The following sections outline the data content that would satisfy the IFC labels created specifically for LCA exchanges.

LCA Goal related labels

Tabell 38. IDM: IFC Label for Goal

Entity/Pset/FP	Description
ifcLca.Application::IfcLabel	Labels: comparative/not comparative

LCA Scope related labels

Tabell 39. IDM: IFC Labels for Scope

Entity/Pset/FP	Description
ifcLca.Deliverable::IfcLabel	Labels: see Appendix 1 for full list
ifcLca.FunctionalUnit::IfcLabel	Labels: Baseline (*see notes below)
ifcLca.SystemBoundary::IfcLabel	Labels: LCC/ENSLIC_LCC (**see notes below)
ifcLca.DataCompleteness::IfcLabel	Labels: high/medium/low (represent estimated percentage)
ifcLca.DataPrecision::IfcLabel	Labels: high/medium/low (represent estimated percentage)
ifcLca.LciaMethod::IfcLabel	Labels: CML 2/TRACI/Eco-Indicator 99/ReCipe

It may not be possible to have simple labels for functional units and system boundaries, because these are complex definitions based on both qualitative and quantitative factors. In the case of a functional unit, it is based on occupancy, indoor environmental quality, conditioned space, useable floor area, expected lifespan, and meeting regulatory code requirements. For a system boundary, the combination of activities that will be included must be determined – this could theoretically be any variation of a vast number of processes in all phases.

Despite this, these labels have been included because it is likely that standardized combinations can be agreed upon for different phases and applications – this is also recommended for comparability and consistency of LCA studies. The factors that are purely quantitative – such as occupancy and floor area – could be input and validated separately. With this in mind, the following labels have been suggested as a starting point:

***Baseline functional unit**: all conditioned space meets code requirements for indoor environmental quality, all structural building elements required for core functions meet code requirements and have a design life greater than 50 years, and building occupancy and useable floor area meet externally defined quantity requirements.

****LCC scope:** includes all mandatory activity categories included in an LCC analysis (Capital, Operating, Maintenance, Development, Energy, Water, Cleaning).

ENSLIC_LCC scope: includes only pre-construction Capital and Energy activities.

LCA ID related labels

Tabell 40. IDM: IFC Labels for LCA ID

Entity/Pset/FP	Description
ifcLca.LcaUuid::IfcLabel	Labels: all UUIDs required for an LCA model.

LCA Activity Item related labels

Tabell 41. IDM: IFC Labels for LCA Activities

Entity/Pset/FP	Description
ifcLcaActivityItem.Name::IfcLabel	Labels: all activities required for an LCA model.

The ontology for this label will be based on the LCA unit processes that the activities will be matched up with for modeling. In some cases this will be similar to cost modeling, where physical objects are produced – such as concrete production. But activities associated with operating and cleaning would be different because it is not worker's salaries that are the major consideration, rather the chemicals and resources used to maintain building functions. By referencing existing LCA studies, required processes from an LCA perspective could provide a basis for naming activities.

LCA Activity Schedule related labels

Tabell 42. IDM: IFC Labels for LCA Activity Schedules

Entity/Pset/FP	Description
ifcLcaActivitySchedule.Name::IfcLabel	Labels: CapitalProcess/AdminProcess/OperatingProcess/ MaintenanceProcess/DevelopmentProcess/ EnergyUseProcess/WaterProcess/WasteProcess/ CleaningProcess/ServiceProcess

3.2.3.6 Including EPDs in BIM-based LCA

The last scenario that must be accounted for is how to incorporate existing EPDs seamlessly into such a system. An EPD represents the equivalent of what an LCA ID would produce after being inserted into LCA software – a summary of impacts for a BIM object, with a list of material shares. The challenge is that any BIM object with a sufficiently accurate EPD could potentially be excluded from the export of ER_Design_to_LCA, but must be somehow included in the final results.

The first solution to this problem would be to simply not use EPDs, model all objects and activities in a uniform manner, and then compare results with existing EPDs to test accuracy. If the upfront time requirement is not too great, creating a comprehensive system of generic materials and activities able to be directly linked to LCA software could be a robust solution.

As EPDs become more common, these results could be used to provide more specific information regarding individual brands that have produced LCAs from their own data. One disadvantage of EPDs in their current state is that they do not all report complete impact assessments across all categories. Another issue is that EPDs often contain proprietary data that a company wishes to remain private, therefore it would not be possible to make public the complete LCA model – and the unit processes used – available for inspection.

A tool like ISY Calcus from Norconsult has gone the complete opposite direction, and uses existing EPDs as the basis for all environmental calculations. This is a simple solution, but will always be limited by the availability of EPDs, and will always depend on opaque data that cannot be inspected by users. The EPD system has regulations that companies must comply with to ensure that the results are trustworthy, but as this paper has shown, goal and scope definitions, along with data quality and underlying assumptions, can make significant differences in results. For an LCA to be completely trustworthy, it would also have to be completely transparent.

A hybrid approach is possible if each EPD could have its own LCA ID in this system, or the results returned from the LCA software could be combined with the existing totals contributed by the objects with EPDs. But this sort of implementation issue can be left to solution providers to decide; this paper delivers an IDM that has the potential to model all objects at the unit process level. This way, it is possible to understand impacts down to the unit processes, and compare that performance to an EPD of the exact product that has been specified.

3.3 BIM to LCA Data Conversion

This process is currently done manually by LCA practitioners who analyze either BIMs or architectural drawings to determine which LCA data correlates to the materials specified for a new construction or renovation. For modularity purposes, LCA databases remain very elementary in their data categorization, therefore to model construction material classification databases – such as OmniClass and MasterFormat – these unit processes must be aggregated.

3.3.1 LCA Data Sources

3.3.1.1 Ecoinvent, ELCD, and US LCI Databases

Two of the largest and most used LCA databases for building materials are Ecoinvent – created by the Swiss Centre for Lifecycle Inventories – and US Life Cycle Inventory Database, which is maintained by the National Renewable Energy Lab (NREL). Ecoinvent data sets can be accessed in basic form for a fee, but are also used by major LCA software tools such as SimaPro and GaBi. The US LCI database is free to access, and is used by the BEES software from the National Institute of Standardization and Technology (NIST), as well as the ATHENA Institute's Impact Estimator.

In terms of practical implementation, Ecoinvent and US LCI data is modularly designed, and therefore processes must be assembled using basic inputs – such as gravel, lime, cork, rubber, and cement. In SimaPro and BEES, many of these basic elements have been combined into processes that represent generic products, which can simplify the creation of an LCI for a whole-building.

3.3.1.2 EPDs as a Data Source

As the use of EPDs expands, these become a growing resource for LCA data in the building sector. This resource differs from the generic LCA databases in that they are product based, which means that a project could specify materials according to the EPD itself, and the LCA practitioner would know exactly what the impacts would be for that product. This provides a much less ambiguous result in a whole-building LCA, but the obvious challenge is to create enough support for EPDs to be effective. Currently, there are only a small number of EPDs available for the majority of building materials, but as large government organizations get behind the effort, more companies will be inclined to create them and grow the resource.

3.3.2 Linking OmniClass and the IFD Library to LCA Databases

A big question for LCA is how best to fit in with the existing tools and structure of the building industry. Part of the solution is to organize LCA data in the same way that architects and specification books do – OmniClass, MasterFormat and IFD GUID are examples. This is not a simple task because the classification systems do not have a direct correlation to each other. The LCA databases are designed with a bottom up approach that favors characterizing basic processes and combining them to make complete products, while the building industry works with functional solutions based on work results. This type of LCA data will likely become more common with the expansion of the EPD system, but for now, it may be more effective to link existing data in ways that the building industry tools understand. Construction Classification Systems (CCS) such as OmniClass have multiple tables designed to define building elements in different ways – by Product, Material, Work Result, etc – so it is possible to match LCA Materials to those in OmniClass.

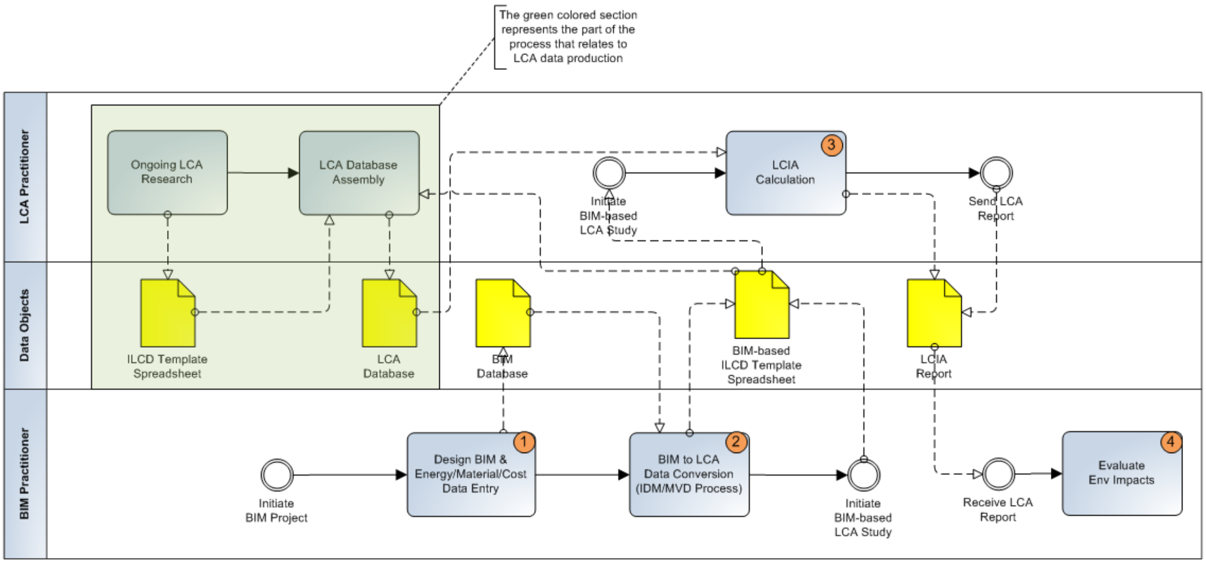
If this intermediate effort to link LCA databases to OmniClass were to be undertaken, it would first have to be determined which OCCS table is the best fit. It also may not be possible for LCA data to be classified by any one of these tables, but would require an allocation scheme for the *Material* makeup of *Products*. And because the LCA process databases are much less comprehensive, this would mean grouping all those elements in OmniClass that fit within each generic process category defined by software such as SimaPro or BEES.

3.3.2.2 Using GUIDs and UUIDs

Another approach would be to bypass OmniClass and use the GUIDs (Globally Unique Identifiers) and UUIDs (Universally Unique Identifiers) to link BIM and LCA tools. Both systems have embedded unique identifiers in their models to ensure that elements can be unambiguously stored and referenced. Both BIM and LCA also have new versions of their schema being released in 2011 – IFC2x4 and EcoSpold v2 respectively. Within these systems are the capability to store information that could potentially reference the other – environmental impact psets (property sets) for IFC, and tags for process grouping in EcoSpold. It is this method that will be described in this paper, and an example of a window is provided as a proof of concept in the Results section.

3.3.3 Data Conversion Roadmap

The figure below provides a “big picture” perspective of how BIMs could fit into the LCA industry as a source of high-quality process data from building projects. The critical link occurs in step two, where a BIM produces a file type that conforms to ILCD standards and can be read by LCA software. Once this is possible, then it is a simple task to transfer the knowledge of a BIM to the unit process level of an LCA database. This means that EPDs created using LCA software could be imported into BIM design software, and energy-use results from a BIM could be translated into environmental impacts in LCA modeling software.

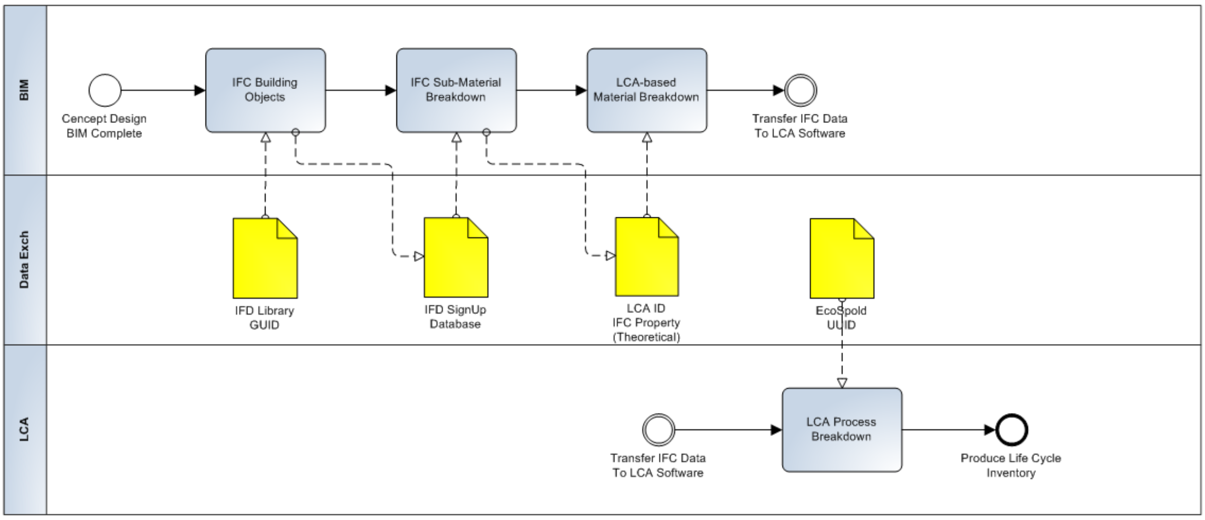


Figur 42. BIM to LCA data conversion roadmap

3.3.4 Data Conversion Process

As a high-level process summary, the flow diagram below shows how a data conversion process could take place. With the existing IFD Library – or a future IFD SignUp material level database in development – there is a way to link global identifiers from the two industries. Such a system requires a conversion database that translates the GUIDs from both sides – the LCA ID property in this case.

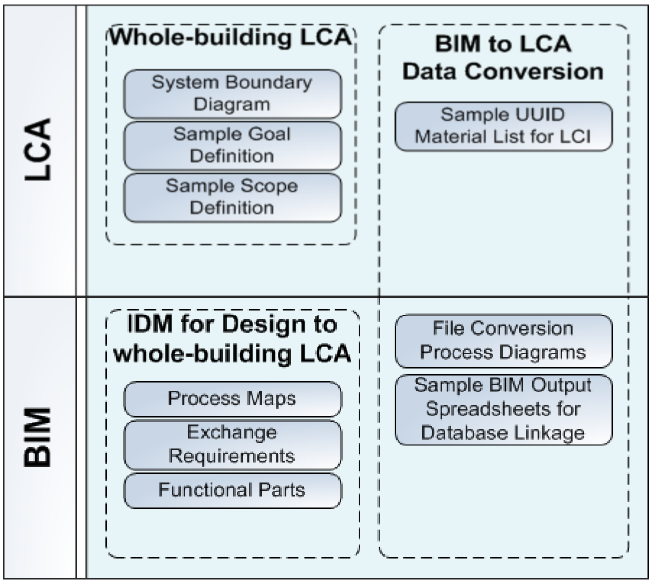
Because the conversion would mean one BIM GUID to many LCA UUIDs, such a system would have to be created by LCA practitioners that understood how to create generic models for each BIM object. As an example, a particular window has one GUID in a BIM, but in LCA terms, it is made up of wood, glass, metals, gases, chemicals, etc. and each one of those sub-parts is made up of even smaller unit processes necessary for production.



Figur 43. Data conversion flow diagram

The amount of time that it would take to create a functional set of LCA IDs that is able to model a whole-building will vary with the openness of public databases – such as US LCI – with the details of UUIDs associated with the processes they have used in their models. As mentioned before, many generic LCAs of building products have been created in an effort to simplify modeling of whole-buildings, but they normally do not provide specific unit process data, only a boundary diagram with generic process descriptions.

Another dimension of producing an LCA ID would be to determine the proportional representation of each unit process. This could be done by using the average mass or volume proportions of a given building material – in the case of a window, there would be an assumed mass of glass for a given area. This would introduce some systematic error, but it is assumed that the proportional differences between comparable building elements would be acceptable given the scale of the overall functional unit.



Figur 44. Content Map: Solutions

4. Results

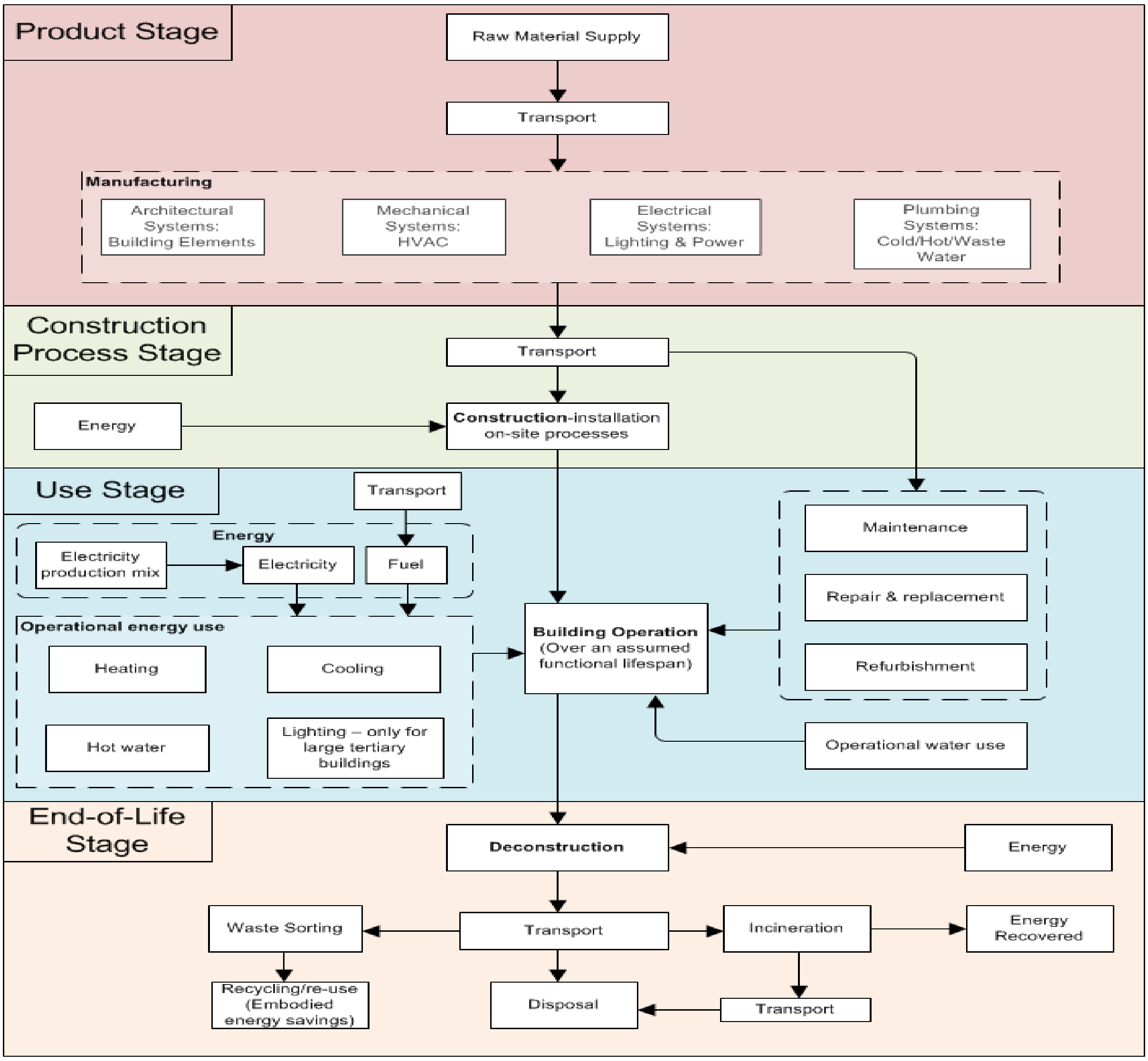
The Results section is divided into three main parts – examples of whole-building goal and scope definitions, an IDM for Design to LCA, and a sample output for BIM to LCA data conversion. In combination, these results are meant to act as a proof of concept that a BIM-based LCA tool is possible utilizing mainly existing solutions, and lay the groundwork for a fully automated tool based on the IFC open-source BIM schema.

4.1 Whole-building LCA

Before a process can be automated, it must be standardized so that the steps and results can be validated. This section attempts to create some goals and scopes that can serve this purpose by formalizing the details of existing recommendations from the LCA and LCC fields – based on the ENSLIC and LCC-DATA projects. These initial examples are only meant to show how such a system could work, they would have to be agreed upon by industry, evaluated for accuracy and relevance, and any number of additional goals and scopes could be added as needed.

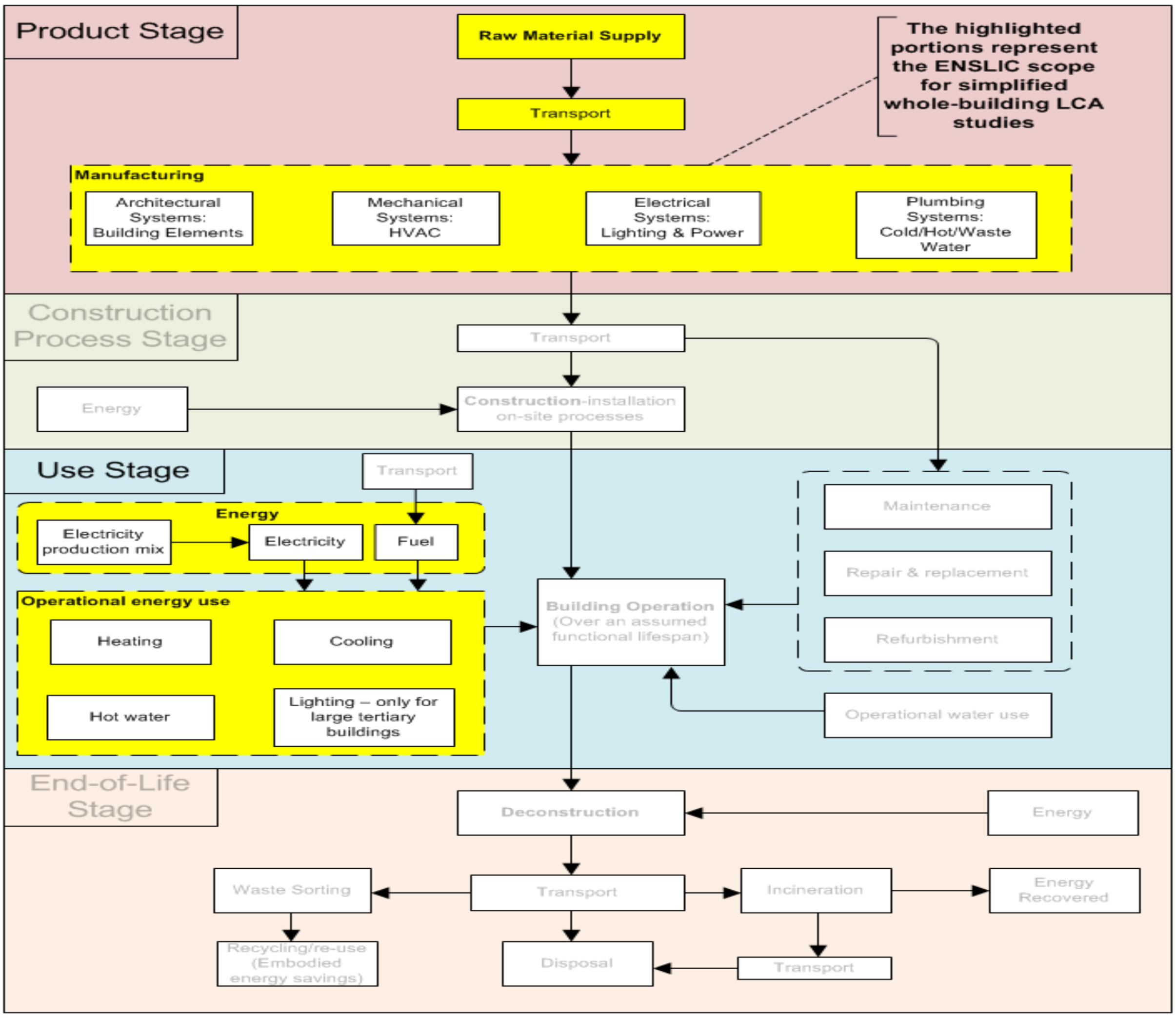
4.1.1 System Boundary Diagram

Using the CEN framework as a guide, processes can be categorized according to building life cycle phases, and manufacturing and operational energy use can be disaggregated to allow for a more refined scope. The boundary diagram below represents these adaptations – the manufacturing categories have been selected according to those used in the AECOO-1 Testbed QTO Model View Definition (See 2009b). This was done because they represent specialized trades, and therefore data will come from different project roles, and it allows for scope definitions to take into account which information is available at different phases in a project.



Figur 45. Boundary diagram using CEN building stages

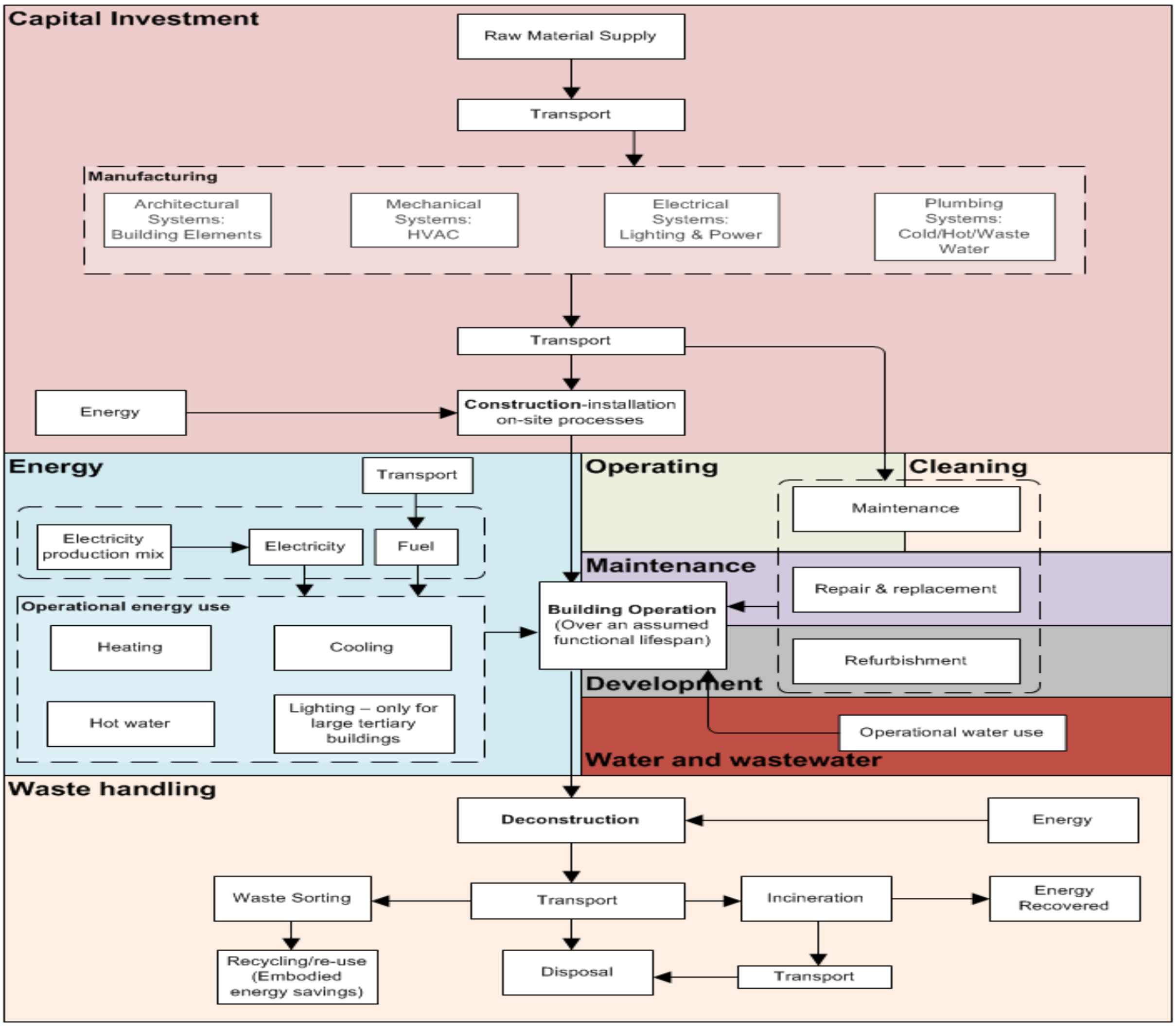
The boundary diagram below highlights the processes that the ENSLIC project determined were critical for capturing the vast majority of impacts (Malmqvist et al. 2010). From viewing the figure, it can be seen that all the processes in the Construction and End-of-Life phases have been eliminated, and all that remains is Building material manufacturing and Operational energy use. It is estimated that, "depending on the energy performance of a building, up to 90% of the building impacts" can be accounted for using this scope (Peuportier et al. 2009).



Figur 46. Boundary diagram using ENSLIC scope

A second boundary diagram can be used to organize the processes according to the LCC cost categories established by the LCC-DATA project. Note that the Administration and Service categories are not included – this has been done because these activities are difficult to isolate in such a system, and they are deemed less important in terms of overall environmental impacts.

If the ENSLIC scope is applied to the LCC activity categories, it reveals that only the Capital and Energy activity categories would have to be labeled in a BIM for it to provide adequate data for a relatively complete whole-building LCA. This makes the BIM preparation step for Design to LCA much more straightforward as less data must be collected.



Figur 47. Boundary diagram using LCC-DATA cost categories

4.1.2 Example Goals

4.1.2.1 Comparative Internal LCA Goal

The table below represents the IFC labels that would be used to define the goal in this case – bold terms are discussed further below:

Tabell 43. Example Goal: Comparative internal study

LCA Goal	**Properties**
Commissioner of the study	Owner
Influential actors	Architect, LCA Consultant
Target audience	**Owner, Design Team**
Project phase	Concept design
Intended applications	**Comparative**

If an LCA study is going to be used during the early design phase, it is probably not appropriate to allow the public to see the iterative process. For this reason, the target audience of such a comparative LCA would be limited to selected members of the project team. Also, in order to make a comparative LCA public, there are added requirements to ensure that manufacturers or other outside parties are not impacted by inaccurate results that lead to poor recommendations.

4.1.2.2 Non-Comparative Public LCA Goal

The table below represents the IFC labels that would be used to define the goal in this case – bold terms are discussed further below:

Tabell 44. Example Goal: Non-comparative public study

LCA Goal	Properties
Commissioner of the study	Owner
Influential actors	Architect, LCA Consultant
Target audience	Owner, Design Team, **Public**
Project phase	Construction
Intended applications	**Non-comparative**

Another scenario would be to release an impact assessment of a building once the design process has been completed. In this case, it could be useful to show high performance achievements, and therefore releasing the results to the public makes sense. For this scenario, an independent review would likely be required in order to confirm results.

4.1.3 Example Scopes

Both the scopes discussed below assume a comparative LCA goal because they are discussed in terms of use during the design process, which requires a comparison of solutions to aid decision makers.

4.1.3.1 LCC-based Scope

The table below represents the IFC labels that would be used to define the scope in this case – bold terms are discussed further below:

Tabell 45. Example Scope: LCC-based

LCA Scope	Properties
Deliverables	Comparative LCA
Functional unit	Baseline
System boundary	**LCC**
Completeness requirement	**high**
Precision requirement	**high**
LCIA method	**ReCipe**

If there is adequate data available from LCC analysis, then it may be possible to model all the mandatory activity categories for an LCA. The scope below assumes a high level of completeness for this reason – likely over 95% – as well as high data precision. The LCIA method chosen – ReCipe – produces a variety of endpoint indicators that extrapolate impacts from estimated emission flows.

4.1.3.2 ENSLIC_LCC Scope

The table below represents the IFC labels that would be used to define the scope in this case – bold terms are discussed further below:

Tabell 46. Example Scope: ENSLIC-based

LCA Scope	Properties
Deliverables	Comparative LCA
Functional unit	Baseline
System boundary	**ENSLIC_LCC**
Completeness requirement	**medium**
Precision requirement	**medium**

LCIA method	**CML 2**

In the case of less data availability or time restrictions, the ENSLIC scope can be applied to capture only the most impactful areas. The completeness label is set to medium because it may not be possible to accumulate enough of the theoretical impacts, and the data quality would likely be lower as well.

The LCIA method chosen – CML 2 – delivers midpoint indicators such as CO2 equivalents, but also utilizes fate analysis. These types of methodology choices can be determined by the Commissioner of the study, and should represent the importance placed on specific performance criteria and target audience. As long as the method is listed, readers of the study can understand the underlying assumptions. Because the calculations are made outside of the BIM software context, there will be no impact on the fundamental LCI produced by a BIM.

4.2 IDM – Concept Design to LCA

The following document is a complete Information Delivery Manual (IDM) that is designed to be used as a stand-alone reference to produce the IFC binding for a model view definition (MVD) and ultimately a software solution. The business process defined by the IDM is Concept Design to LCA – the exchange of information required to produce a whole-building LCA from a BIM in the early design phase. Due to the similarity of requirements, the structure has been based on elements from the Concept Design BIM 2010 and LCC-DATA project IDMs – these sources are referenced in the Change Log at the beginning of the document. Due to formatting issues, the process maps from this IDM have also been included in Appendix 5 as full page images.

Information Delivery Manual: Concept Design to LCA

(IDM) Table of Contents

(IDM) 1. Process Model – Life Cycle Assessment at Concept Design Phase

Change Log		
29/03/11	Initial creation – adapted from the Concept Design BIM 2010 Energy Analysis IDM (Welle & See 2009), Quantity Take-off IDM (Wiggins & See 2009), and LCC-DATA IDM (Edvardsen et al. 2009).	Tobin Rist
20/05/11	Edits creating exchange requirements.	Tobin Rist

(IDM) 1.1 Overview

Life Cycle Assessment (LCA) is a method of accounting for all environmental impacts associated with a building from design to deconstruction. The lifecycle of a building is defined by four distinct phases: Product, Construction, Use, and End-of-Life (CEN 2010). The main analytical elements of an LCA include: Goal Definition, Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation (Joint Research Centre 2010). This Manual addresses only the first three elements – goal, scope, and inventory – because the calculation of impacts is considered to be performed by an external solution.

Goal and scope definitions shape the application, methodology, and content of the study, while the inventory provides specific quantities for calculations. Due to the similarity with LCC analysis, the activity categories created for an LCA can match the cost categories for costing, and for this reason, the same QTO function can be used to determine inputs for the Product phase.

During the concept design phase, BIM elements are modeled in accordance with existing costing methodology:

- Walls and slabs by area
- Windows by count by size
- Structural system by facility area
- Heating system by facility area
- Cooling system by facility area

(Wiggins & See 2009)

Also in line with LCC, the LCA Use phase can be modeled using BPEA and service life planning. A building's predicted operational energy use – as specified by the CEN TC-350: Sustainability of construction works – is considered heating, cooling, hot water, and lighting requirements of major tertiary buildings (CEN 2010). Production of the energy model itself is considered outside the scope of this Manual, the only input required is a value for total annual energy demand. Service life planning can be used to adjust the basic QTO for maintenance and development activities, and the remaining operational activities can be modeled in line with their description for LCC calculations.

The output of this process is a valid IFC file for use by BIM compatible LCA software, as well as a spreadsheet that conforms to EcoSpold and ILCD data format conventions. This data set should be able to be read by all standard LCA software.

(IDM) 1.1.1 Design Phases

1.1.1.1 Iterative Process

LCAs are performed in iterative loops of goal and scope definition, inventory data collection and modeling (LCI), impact assessment (LCIA), and with completeness, sensitivity and consistency checks (Evaluation) as a steering instrument (Joint Research Centre 2010). This is parallel to the building design process, and therefore could operate in sync with existing industry workflows.

1.1.1.2 Conceptual

The first iteration could be performed during the concept design phase when only basic detail is known, but design goals and performance targets are being determined. Comparative LCA methodology is based on systems thinking, which is inherently strategic and could aid in guiding long-term planning. Some assumptions will have to be made, but if they are applied consistently across all options being considered, then the comparative advantages can be evaluated (Wiggins & See 2009).

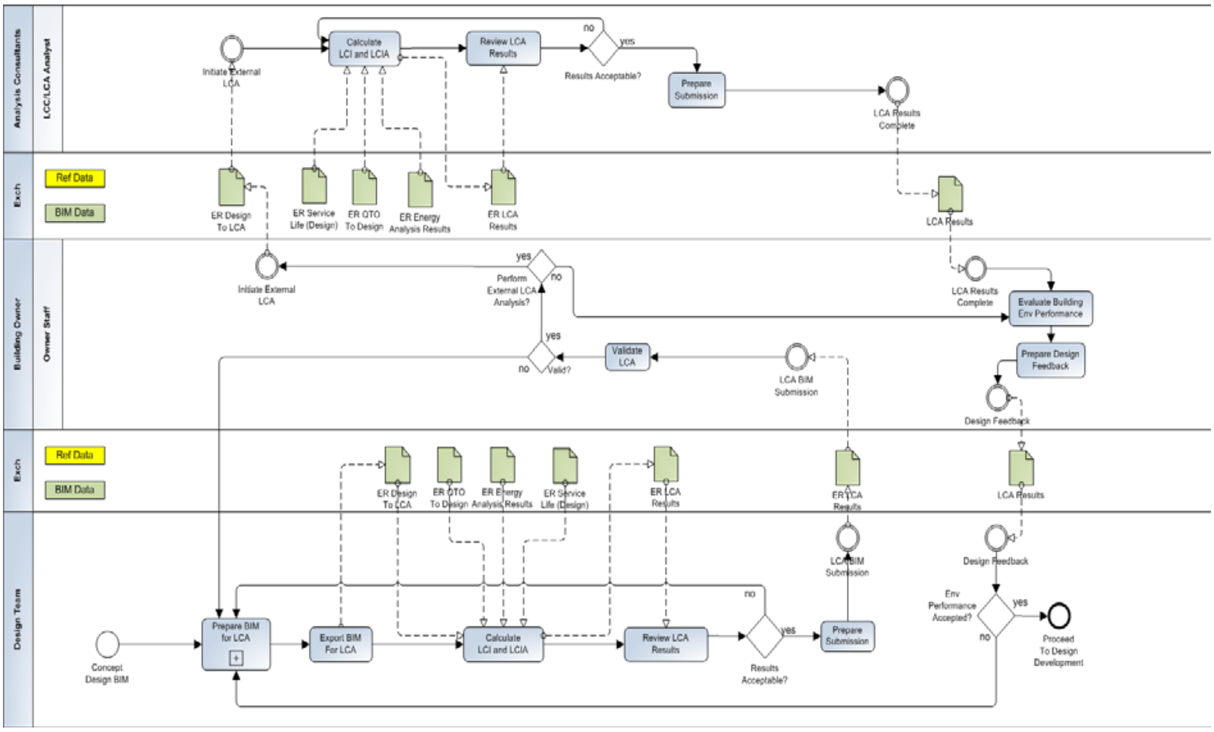
1.113 Detailed

The second iteration could be performed during the schematic design and construction document phase when more secondary data is available for the lifecycle inventory. At this point, there should be geometric and building system information to inform energy models and more precise quantity take-offs (Wiggins & See 2009). The process remains the same, but the evaluation differs in terms of completeness, sensitivity and consistency checks.

(IDM) 1.2 Specification of Process

(IDM) 1.2.1 Concept Design Phase LCA

Within the process map, the conceptual design phase of the project is shown, and the progression of tasks is depicted for each role involved in an LCA study.



1.2.1.1 Concept Design Complete

Type	Initial Concept BIM
Documentation	It is assumed that the architect has defined a building concept design complete with all the required building elements and space objects for ER_Design_to_QTO and ER_Energy_Analysis_Inputs, and that all required objects are defined according to ER_Service_Life_(Design).

1.2.1.2 Prepare/Adjust BIM for LCA

Type	Sub-Process
Documentation	At this point, the Concept Design BIM is passed to the appropriate designer to prepare the BIM for LCA. The designer may still be the architect, any other design consultant or any combination. Details of this sub-process are described in Section 1.22.

1.2.1.3 Export BIM for Analysis

Type	Task
Documentation	Once the BIM has been prepared for LCA and validated in the Prepare/Adjust BIM for LCA task, it is exported to IFC for LCA. At this point, all the required exchange requirements in ER Design to LCA (Concept) have been met.

1.2.1.4 Calculate Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA)

Type	Task
Documentation	The designer is now ready to generate a Life Cycle Inventory (LCI) in preparation for producing the Impact Assessment (LCIA). The actual LCA task is outside the scope of this Manual. The estimating application uses previous BIM-based QTO, BPEA, service life planning and activity category results to develop an LCA model and calculate environmental impacts.

1.2.1.5 Review LCA Results

Type	Task
Documentation	As the actual LCA task is outside the scope of this Manual, so is the review of an LCA. At this point, all the exchange requirements of the ER Design to LCA should be met. The results may be evaluated directly from the Life Cycle Impact Assessment (LCIA) prepared by an LCA application, or the results may be checked using a BIM model checker using the IFC file with the results written back to it – if such a tool exists. However, if an LCA is performed, the results of the LCA are obtained and evaluated against any environmental impact targets that may exist. If the targets are not achieved, then the designer must go back to Prepare/Adjust BIM for LCA and make further modifications to the building geometry, constructions, or some other building design variable. If the targets are achieved, the designer can move forward to Submission. It is frequently the situation where the designer is evaluating a given design not just against its environmental impacts, but also against other performance targets such as cost, energy performance, etc. If a design meets the LCA targets, but falls short of energy performance targets, for example, and vice versa, then the design can be "failed" and designer will have to further iterate on the building design.

1.2.1.6 Prepare Submission for Review/Approval

Type	Task
Documentation	Once the designer is satisfied with a design, they will prepare a submission package for client review/approval.

1.2.1.7 Validate BIM for LCA

Type	Task
Documentation	After receipt of the IFC BIM complete with ER Design to LCA (Concept) and an Impact Assessment (not in the scope of this Manual), the client will use a data validation tool to verify that the BIM meets the requirement of the MVD.

1.2.1.8 Analyze Life Cycle Impacts

Type	Task
Documentation	As the actual LCA task is outside the scope of this Manual, so is the Analyze Life Cycle Impacts task. The client may use internal staff or hire an outside consultant to verify the designer's LCIA results. The estimating application may use previous BIM-based QTO, BPEA and service life planning results.

1.2.1.9 Review LCA Results

Type	Task
Documentation	The results of the client LCIA are obtained and evaluated. The results are reviewed to ensure accuracy and integrity.

1.2.1.10 Prepare Analysis Report

Type	Task
Documentation	Once the client LCIA results are verified and approved, an analysis report is prepared comparing the results of the client analysis with those of the designer.

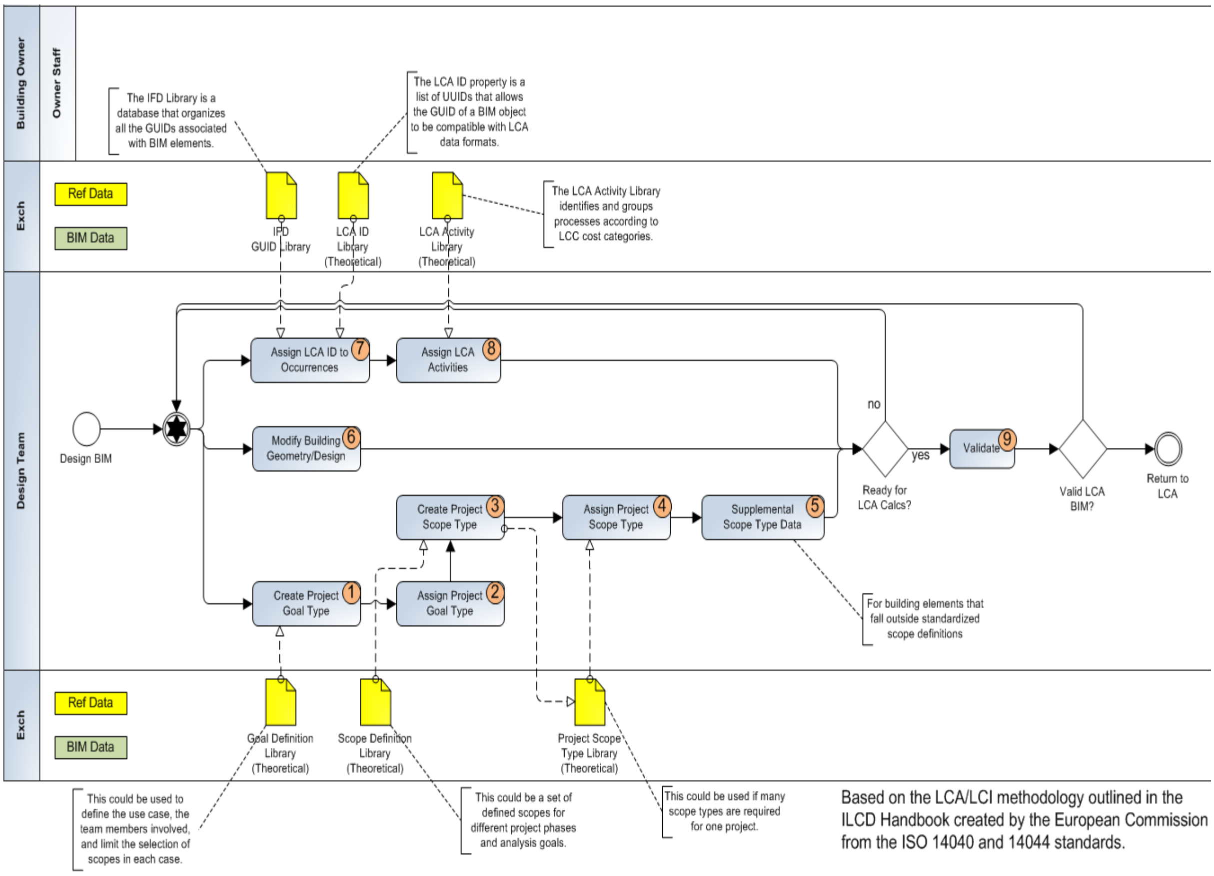
1.2.1.11 Evaluate Environmental Impacts

Type	Task
Documentation	The client will evaluate the analysis report submitted by their internal staff or consultant. Environmental impacts will be evaluated against the targets, resulting in a "yes or no" decision for the design.

1.2.1.12 Prepare Design Feedback

Type	Task
Documentation	The client will document the resulting quantities and LCIA (which may or may not include an independent LCIA for comparison/validation), and recommendations for the design team. The design feedback package will be delivered back to the designer, and will include either an approval or rejection of the design originally submitted to the client by the designer.

(IDM) 1.2.2 Prepare/Adjust BIM for LCA



1.2.2.1 Create Project Goal Type

Type	Task [1]
Documentation	This process considers that an industry Goal Type data library exists from which a project specific goal definition can be derived. The industry goal type library may be accessed from a server over the web or from directly within the BIM-authoring application. A goal type explicitly defines the use case for an LCA, which requires the following information: - Commissioner of the study and influential actors - Target audience of the deliverables (Team Members and/or Public) - Project Phase (Conceptual or Schematic) - Reason for carrying out the study (Comparative or Accounting) When a Project Phase is selected, there are a set of corresponding assumptions that relate to Limitations from data availability, as well as appropriate Intended Applications for deliverables. These are based on ILCD guidelines for LCA Goal Definition (Joint Research Centre 2010).

1.2.2.2 Assign Project Goal Type

Type	Task [2]
Documentation	Once the project goal type definition has been created, the designer may assign the goal type to the model.

1.2.2.3 Create Project Scope Type

Type	Task [3]

Documentation	This process considers that an industry Scope Type data library exists from which project specific scope definitions can be derived. The industry scope type library may be accessed from a server over the web or from directly within the BIM-authoring application. Given the iterative nature of LCA modeling, multiple scopes may be used on the same project at different phases of the design process. A scope type explicitly defines the building elements to be included in an LCA, which requires the following information: - List of deliverables in line with Intended Applications - Functional equivalent (functional building description: type of use, number of users, requirements for indoor air quality, thermal climate, safety, any other performance requirements) (Malmqvist et al. 2010) - System boundaries (geographic, building phase, background processes) - Completeness and precision requirements (percentage of total impacts, approved data sources, maximum uncertainty) - LCIA methodology (impact categories, normalization and weighting) - Special requirements for comparisons between systems (Joint Research Centre 2010) Given the need to simplify LCA methodology for implementation, standardized scenarios could be created to automate this process while remaining transparent in the underlying assumptions.

1.2.2.4 Assign Project Scope Type

Type	Task [4]
Documentation	Once the project scope type definition has been created, the designer may assign the scope type to the model.

1.2.2.5 Supplemental Scope Type Data

Type	Task [5]
Documentation	This task deals with individual elements that may not be defined fully within the project scope type library, or not defined to the designer's satisfaction, but are determined to fit within the selected scope. Initial data may be taken from a library template, but is then updated (or added) for the particular element being dealt with. Upon completion, information about this element may be saved back to the project scope type library for future application. At the end of this task, the following exchange requirements from ER Design to LCA (Concept) should be met: Goal and Scope. (Wiggins & See 2009)

1.2.2.6 Modify Building Geometry/Design

Type	Task [6]

Documentation	In this step, the designer makes any necessary modifications to the building geometry or any other building design parameters related to project construction types, space types, and service life. This ensures that the model satisfies all classification requirements for LCA IDs to be applied. (Wiggins & See 2009)

1.2.2.7 Assign LCA ID to Occurrences

Type	Task [7]
Documentation	This process considers that a BIM element library exists from which a project list of GUIDs can be derived. In the future, construction objects could be further broken down into component materials with their mass or volume values maintained. This material inventory would then be tagged and exported according to LCA process database conventions. The industry object or material type data library could come from a variety of sources, including the IFD Library and IFD SignUp Database project. The LCA ID labels correspond to the EcoSpold and ILCD data formats. The LCA ID label groups a number of unit/production process UUIDs, or a single system process UUID, which in itself is a series of unit processes linked together to form a material or product. For the purpose of LCA modeling, total annual operational energy mix would be classified as an equivalent variable to material inputs. On-site renewable energy production would have to be separated from grid based sources due to LCA database conventions. Assumptions regarding the make-up of grid based energy supply would have to vary by region, but that can be addressed by adding an LCA Region (energy-mix) attribute to the *Site* functional part. At the end of this task, the following exchange requirements from ER Design to LCA Inputs should be met: *Goal, Scope,* and *LCA ID*.

1.2.2.8 Assign LCA Activities to Occurrences

Type	Task [8]
Documentation	This process considers that an LCA Activity library exists from which a project list of processes can be identified and grouped according to LCC cost modeling procedures. A comprehensive list of Activity Items are created, which are then grouped into Activity Schedules that parallel the cost categories created by the LCC-DATA project. At the end of this task, the following exchange requirements from ER Design to LCA Inputs should be met: *Goal, Scope, LCA ID and LCA Activities*.

1.2.2.9 Validate BIM for LCA

Type	Task [9]

Documentation	After goal, scope, LCA ID and LCA Activities are satisfied, and any other modifications to the building are made; the BIM is ready to be validated for LCA analysis. Validation will take place by exporting an IFC file and using a model checker to ensure the MVD requirements have been met.

(IDM) 1.3 Specification of Data Objects

1.3.1.1 Industry Goal Type Library (Theoretical)

Type	Data Object
Documentation	The industry goal type data library explicitly defines the use case for an LCA, and requires the following information: - Commissioner of the study and influential actors - Target audience of the deliverables (Team Members and/or Public) - Project Phase (Conceptual or Schematic) - Reason for carrying out the study (Comparative or Accounting) When a Project Phase is selected, there are a set of corresponding assumptions that relate to Limitations from data availability, as well as appropriate Intended Applications for deliverables. These are based on ILCD guidelines for LCA Goal Definition (Joint Research Centre 2010).

1.3.1.2 Industry Scope Type Library (Theoretical)

Type	Data Object
Documentation	The industry scope type library explicitly defines the building elements to be included in an LCA, and requires the following information: - List of deliverables in line with Intended Applications (from Goal definition) - Functional equivalent (a general building description: type of use, number of users, requirements for indoor air quality, thermal climate, safety, any other performance requirements) (Malmqvist et al. 2010) - System boundaries (Activities and phases to be included) - Completeness and precision requirements (percentage of total impacts, approved data sources, maximum uncertainty) - LCIA methodology (impact categories, normalization and weighting) (Joint Research Centre 2010) Given the need to simplify LCA methodology, standardized scenarios could be created to automate this process while remaining transparent in the underlying assumptions.

1.3.1.3 Project Scope Type Library (Theoretical)

Type	Data Object

Documentation	The project scope type data library is derived for the project from the industry scope type library, and reflects any modifications or additions the designer has made to the industry source data. If different scopes will be used at different times in the project, this library can contain multiple scope types.

1.3.1.4 IFD GUID Library

Type	Data Object
Documentation	The IFD GUID Library categorizes BIM objects according to their properties, and labels them with a unique identifier. In the future, this system could further break down construction objects into their component materials, maintaining mass and volume values for the purpose of generating a material inventory that is more compatible with LCA data. The industry material type data library could come from a variety of sources, including the IFD Library and IFD SignUp Database project.

1.3.1.5 LCA ID Library (Theoretical)

Type	Data Object
Documentation	The LCA ID Library contains sets of universally unique identifiers (UUID) used to link BIM object data to LCA data. The LCA ID UUIDs correspond to EcoSpold and ILCD unit or system processes. A unit or production process is a building block component that often must be combined with other unit processes to make a consumable material or product. A system process is a series of unit processes that have already been linked together to form a material or product.

1.3.1.6 LCA Activity Library (Theoretical)

Type	Data Object
Documentation	The LCA Activity Library contains activity items and activity schedules or groups that correspond to the unit or system processes in LCA software. This is necessary because cost items and schedules do not capture all the information that is required for LCA models.

(IDM) 1.3.2 Exchange Requirement Data Objects

(IDM) Precursor Exchange Requirements

1.3.2.1 ER_QTO_to_Design

Type	Data Object
Name	ER_QTO_to_Design
Documentation	Exchange of complete set of information regarding basic quantity and/or cost reports. The exchange requirement assumes that the information provisions outlined in the exchange requirement ER Design to QTO Inputs (Concept) have been satisfied. (Wiggins & See 2009)

1.3.2.2 ER_Energy_Analysis_Results

Type	Data Object
Name	ER_Energy_Analysis_Results
Documentation	Exchange of complete set of energy simulation output information including comfort metrics, peak load information, annual energy consumption, and utility rate information. (Welle & See 2009)

1.3.2.3 ER_Service_Life_Planning_(Design)

Type	Data Object
Name	ER_Service_Life_Planning
Documentation	The scope of this exchange requirement is to enable the exchange of information about the design life of a type of product. The design life of an element or product is the length of time that it may be expected (is proposed) to perform its required function or work within its specified parameters. (Edvardsen et al. 2009)

(IDM) LCA Exchange Requirements

1.3.2.4 ER_Design_to_LCA

Type	Data Object
Name	ER_Design_to_LCA_(Concept)
Documentation	Exchange of complete set of data required to perform an LCA according to the ILCD methodological framework. This includes: Goal, Scope, Material Inventory, and Energy Mix.

1.3.2.5 ER_LCA_Results

Type	Data Object
Name	ER_LCA_Results
Documentation	Exchange of complete life cycle impact assessment (LCIA) as determined by the goal, scope, functional unit and intended applications.

(IDM) 1.4 Specification of Decision Point Gateways

1.4.1.1 Ready for LCA Calculations?

Type	Decision Point
Documentation	At this point the designer must decide if all the desired design changes have been made and the model is ready for production of an LCI. If so, the model is ready for calculations, if not, the designer must further modify the building design.

1.4.1.2 Valid LCA BIM?

Type	Decision Point

Documentation	After deciding that the model is ready for analysis, the designer uses a model checker to ensure that all the input exchange requirements have been met. This step also takes place when a client evaluates the BIM model submitted to them by the designer. If the BIM meets the requirements determined by the rule checking sets in the model checker, then the BIM is valid – if not, it is not valid.

1.4.1.3 Results Acceptable?

Type	Decision Point
Documentation	The designer evaluates the results of the LCA study and compares them to any targets or alternative designs – depending on the applications determined in the goal and scope definitions. If the design is found to be optimal according to the decision criteria, then it is acceptable. If a target is not met or another solution is found to be superior, then the designer must further modify the building design.

1.4.1.4 Perform External LCA?

Type	Decision Point
Documentation	The client may want to perform an independent LCA study to validate the results of the designer's analysis. This independent study can be conducted by the building owner's staff, or by a consultant.

1.4.1.5 Results Complete?

Type	Decision Point
Documentation	The internal staff or consultant that is conducting the independent study determine if the results of their analysis are accurate, complete and conform to the client's work order.

1.4.1.6 Environmental Performance Accepted?

Type	Decision Point
Documentation	The designer reviews the design feedback from the client for design approval or rejection.

(IDM) 2. Exchange Requirements for Design to LCA

Name	Exchange of Design to Life Cycle Assessment
Identifier	ER_Design_to_LCA

Change Log		
29/03/11	Initial creation – adapted from the Energy Analysis IDM (Welle & See 2009), Quantity Take-off IDM (Wiggins & See 2009), and LCC-DATA IDM (Edvardsen et al. 2009).	Tobin Rist
20/05/11	Edits creating exchange requirements.	Tobin Rist

0	Portfolio requirements	
1	Conception of need	
2	Outline feasibility	
3	Substantive feasibility	
4	Outline conceptual design	X
5	Full conceptual design	X
6	Coordinated design and procurement	
7	Production information	
8	Construction	
9	Operation and maintenance	
10	Disposal	

(IDM) 2.1 Overview

The scope of this exchange requirement is the exchange of information about building, space, and activity descriptions intended for use in preparation of a Life Cycle Inventory (LCI). The purpose of the exchange requirement is to support the coordination of model quantities with the needs of the LCA practitioner using standard industry software.

The building model will provide specific information about:

- the building, its location, composition, overall shape and orientation
- the shape and location of adjacent buildings
- building stories within the building
- spatial configuration
- space type and function ID from project space type library
- building elements construction type ID from construction type library
- service life of building elements

The building model will provide conceptual information about:

- the building services
- the building structure
- the site design

Additional requirements specific to this model view:

- LCA Goal and Scope types
- LCA ID for all processes within the Scope
- LCA Activities for all processes within the Scope

Task	Scenario
Identify Object	Building is of a type defined by the functional unit determined by the Goal and Scope Type selected for analysis.
Quantify Elements	The method of measurement is one functional unit – this includes all required building and site element impacts over an assumed lifespan.
Calculate LCI	The method of impact calculation is determined by the Goal and Scope Type selected – it should outline the impact categories being measured for the functional unit. The scale of impact depends on the Life Cycle Inventory (LCI) established by QTO, BPEA, service life of building elements, and total activity required over the lifespan of the building – according to the cost categories outlined in LCC-DATA.
Summarize LCIA	The environmental impacts across all selected indicators is summarized and totaled for the functional unit.

(IDM) 2.2 Exchange Requirements – Concept Design to LCA

Precursor	It is assumed that a building concept design has been completed with all the required building elements and space objects for QTO, BPEA and service life planning.	ER_Design_to_QTO ER_Energy_Analysis_Inputs ER_Service_Life_(Design)

Please note that additional comments have been added to help explain the structure of this table – the instances are highlighted in **bold text** and can be read in the footnotes.

Type of Info	Information Needed	Req	Opt	Data Type	Units
Project	The following properties should be included:				
	- Identification	X		String	n/a
	- GUID			GUID	n/a
	- Client information (name, address, phone, email)		X	String	n/a
	- Model author (name, address, phone email)		X	String	n/a
Site					
	- Address (number, street, city, ZIP, country)		X	String	n/a
	- **Region (for LCA energy-mix)**[1]	X		String	n/a
Building					
	- Identification	X		String	n/a
	- GUID			GUID	n/a
	- Description		X	String	n/a
	- Functional classification (OmniClass 11)	X		String	n/a
	- Gross area	X			
LCA Goal					
	- Commissioner of the study	X		String	n/a
	- Influential actors	X		String	n/a
	- Target audience of the deliverables (Team Members and/or Public)	X		String	n/a
	- Project Phase	X		String	n/a
	- Reason for carrying out the study (Comparative or Accounting)	X		Bool	n/a
LCA Scope					
	- Deliverable	X		String	n/a
	- **Functional unit**[2]	X		String	n/a
	- System boundary	X		String	n/a
	- Completeness requirement		X	Real	%
	- Precision requirement		X	Real	%
	- LCIA methodology	X		String	n/a
Building					

[1] This is a new attribute for site created to allow for LCA specific regional definitions to be identified.

[2] A functional unit is made up of many criteria, but in this case it is assumed that a standardized description of these exists in an industry library and can be referenced.

Information					
	- Cleaning areas (by category)			Real	m^2
	- Basic QTO totals			Real	kg
	- Operational energy demand			Real	kWh
	- Operational water use			Real	m^3
	- Operational waste			Real	kg
Use Information [3]					
	- Number of users			Int	n/a
	- Type of user			String	n/a
LCA ID [4]					
	- GUID			GUID	n/a
	- List of LCA UUIDs			UUID	n/a
	- **Shares of BIM object** [5]			Real	%
LCA Activity Information [6]					
	- **Capital processes** [7]	X		Real	kg
	- Administration processes		X	Real	kg
	- Operation processes	X		Real	kg
	- Maintenance processes	X		Real	kg
	- Development processes	X		Real	kg
	- Operational energy processes	X		Real	kg
	- Water and drainage processes	X		Real	kg
	- Waste handling processes	X		Real	kg
	- Cleaning processes	X		Real	kg
	- Service processes		X	Real	kg

[3] This basic occupancy number can be applied to waste and water use assumptions – these are not established by either the QTO or BPEA.

[4] The LCA ID property links the GUID of a BIM object to the list of UUIDs that correspond to the LCA unit processes that make up that object.

[5] Each LCA ID will assume a generic division of mass for a given BIM object, and then allocate that percentage of the total mass to the constituent parts.

[6] Activity is substituted for Cost in the LCA context, thus each activity category contains the flows from the unit processes associated with the completion of that activity.

[7] This category includes all upfront investment and construction activities prior to occupancy; the mass calculation is produced using the quantity data from the QTO, which is proportionally assigned to specific LCA unit processes through the LCA ID property. The procedure of proportional attribution is repeated for all activity categories.

(IDM) 3. Exchange Requirements for LCA Results to Design

Name	Exchange of Life Cycle Assessment Results to Design
Identifier	ER_LCA_Results_to_Design

Change Log		
29/03/11	Initial creation – adapted from the Energy Analysis IDM (Welle & See 2009), Quantity Take-off IDM (Wiggins & See 2009), and LCC-DATA IDM (Edvardsen et al. 2009).	Tobin Rist
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0	Portfolio requirements	
1	Conception of need	
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4	Outline conceptual design	X
5	Full conceptual design	X
6	Coordinated design and procurement	
7	Production information	
8	Construction	
9	Operation and maintenance	
10	Disposal	

(IDM) 3.1 Overview

The scope of this exchange requirement is the transfer of information about LCI and LCIA results as defined by the applications selected in the goal definition. The purpose of the exchange requirement is to enable coordination of this information with other design roles and make these results available to the target audience determined by the goal definition. The exchange requirement assumes that the information provisions outlined in ER_Design_to_LCA_(Concept) have been satisfied.

Information that is provided by this exchange requirement includes:

- Links to reports generated by the LCA modeling application

(IDM) 3.2 Exchange Requirements – LCA Results to Design

Type of Info	Information Needed	Req	Opt	Data Type	Units
Project	The following properties should be included:				
	- Identification	X		String	n/a
	- Client information (name, address, phone, email)		X	String	n/a
	- Model author (name, address, phone email)		X	String	n/a
	- URL for Life Cycle Inventory (LCI)			URL	n/a
	- URL for Life Cycle Impact Assessment (LCIA)			URL	n/a

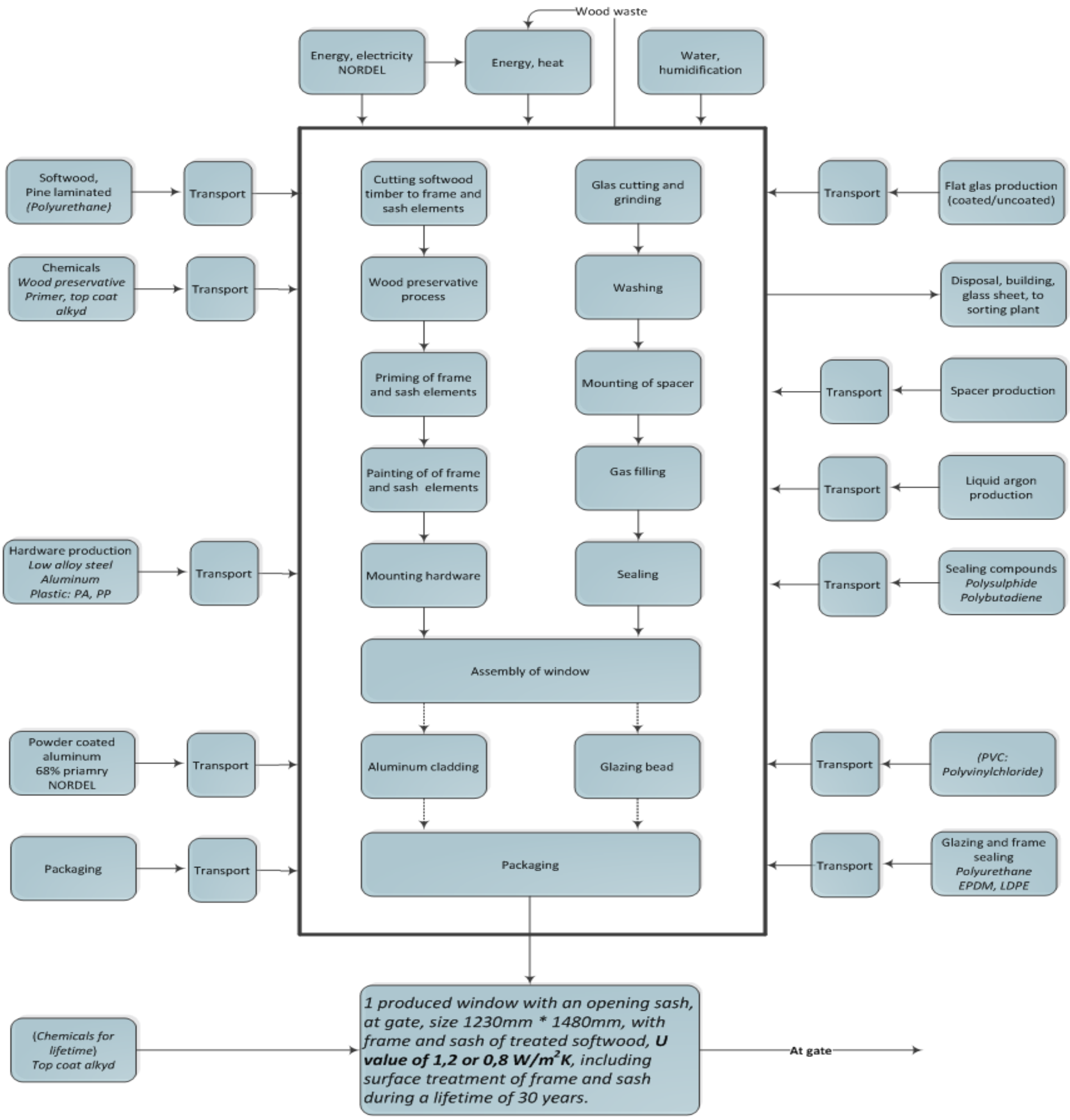
-------------------------------- End of IDM --------------------------------

4.3 BIM to LCA Data Conversion

Previously in this paper, the discussion surrounding the linkage of BIM and LCA databases has been largely theoretical, but this section aims to show that such a system is possible in practice. This is achieved by taking an LCA of a window, identifying the UUIDs that represent the unit processes that make up the components of that window, and then linking them to the GUID that represents a similar window in the IFD Library.

4.3.1 Data Output

The following boundary diagram was produced for an LCA study of a window; it can be used as a guide to identify the required unit processes and acts as a visual aid to understanding the flow of the system. For BIM-based LCA to work it is not enough to identify a window only as a building element, a window must also represent all the underlying processes that are used to construct it and model its function once it is included in a building.



Figur 48. Window LCA boundary diagram (Dahlstrøm 2010)

The figure below is extrapolated from the LCA study above, it shows a sample spreadsheet that is meant to model a hypothetical output from a BIM that has completed the Design to LCA exchange requirements. It is able to produce a list of component processes from a generic window GUID, along with a list of UUIDs and the scale of demand for each. Given this list as input, LCA software could create a model of the window, attach all background flows from the database, and calculate the environmental impacts that result from the production of a window. From there, the use phase would be modeled by the window's thermal properties as they are represented in an energy use simulation. Any service life assumptions would be taken from the previously discussed LCC methodology, and used as a multiplier of the manufacturing impacts.

The critical unit of exchange is the LCA ID property set that links all this information together for each BIM object within the defined scope of the LCA study. There is a one-to-many relationship between GUIDs and UUIDs, but there is a one-to-one relationship between GUIDs and LCA IDs.

Tabell 47. Example output for a BIM to LCA exchange of a window

Object Name	IFD GUID	Component Name (BIM)	IFD SignUp GUID	Process Name (LCA)	LCA UUID	Demand	Unit
BIM Window	CD442757-2E3C-4293-B560-06FBB1DDA64C	**softwood:** laminated pine, glue	?	laminated wood (Mikado)	proprietary		kg
				Glue, for wood products, at plant, Norway (Mikado)	proprietary		kg
				Polyurethane, rigid foam, at plant/RER U	47E8F15F-6A0B-4EC5-BE7D-8965CE014081		kg
		glazing unit: glass (coated & uncoated), spacer, desiccant, primary sealant, secondary sealant, inert gas (argon)	?	Flat glass, coated – at plant	A9E29D5C-C101-4560-AFCE-118C572871F3		kg
				Flat glass, uncoated – at plant	E9661FC2-F27F-4B41-87CC-2D55A4BEE0CD		kg
				Disposal, building, glass sheet, to sorting plant/ NORDEL	42B1C202-8308-422E-BFB7-3EFE54DFCEF6		kg
				Argon, liquid, at plant/RER U – NORDEL	A94CE0AD-46F5-407C-B445-671E353875F0		kg
				Polybutadiene, at plant/RER U	D6F5C483-BA24-41A5-850A-0B5DD70C2CC4		kg
				Polysulphide, sealing compound, at plant/kg/RER	9173BFD2-F20E-465B-BE8A-ABA8FD778F7B		kg
				Styrene-acrylonitrile copolymer, SAN, at plant/kg/RER	2256C9B7-4A6B-410F-B6B6-86384DDB9E7F		kg
				Glass fiber, at plant/kg/RER	312155F1-C820-4F4C-9D8F-7C0B2E6A40D5		kg
				Steel. Low alloyed at plant	FA644F9D-222F-466B-AC2F-F63D81CF4EF5		kg
				Sheet rolling, steel/kg/RER	6A0A9487-EFFA-4F8D-A812-90D4BD6E4D66		kg
				Zeolite, powder, at plant/RER U	550C5A0E-5ECF-4480-9A45-934C4567155F		kg
		aluminum cladding: aluminum, section bar extrusion, power coating	?	Aluminium, production mix, at plant/RER U – NORDEL	D913A6A3-9171-4F36-8BDE-FEA419543F72		kg
				Section bar extrusion, aluminum	B7F8DD1C-6F7F-4FDB-B73B-D5C155D02106		kg
				Powder coating, aluminum sheet/RER U – NORDEL	4FE222BE-52BF-4B9F-9CCC-9F1653B10A71		kg
		brackets: hinge, head slides, pivot sleeve & pins, handle, espagnolettes, guides, end keeps, lockbox, U-profile, clips, screws, nails	?	Steel. Low alloyed at plant	FA644F9D-222F-466B-AC2F-F63D81CF4EF5		kg
				Section bar rolling, steel/kg/RER	08A1938C-E7A8-402F-A48C-86FC0C70CA64		kg
				Aluminum, production mix, cast alloy, at plant/kg/RER	C5C052C3-8F05-4C4C-9BA6-7BDA8D4570D1		kg
				Zinc coating, pieces/RER U	A15AA208-FA8D-45EF-A13E-9989DA4C4A48		kg
				PA – nylon 6, at plant/kg/RER	D1E4A30B-882A-4A31-A434-AAEE3ED41600		kg
				Polypropylene, granulate, at plant/kg/RER	0FD6113A-2F80-44BF-B9A9-C549FBA60802		kg
				Injection molding/kg/RER	29AB8111-08A2-42A1-9A28-9FB2F4344670		kg
		mounting: frame seal, glazing seal	?	Polyethylene, LDPE, granulate, at plant/RER U	BB816189-B3A1-47D4-83FA-58382893FF83		kg
				Injection moulding/kg/RER	29AB8111-08A2-42A1-9A28-9FB2F4344670		kg
				Polyurethane, flexible foam, at plant/RER U	63D333B3-5CA7-45C9-9960-4F9D54BAD63D		kg
				EPDM – Synthetic rubber, at plant/RER U	8702B5E4-AB30-4CB9-BD6F-C4668F6F9470		kg
		chemicals: wood preservative, alkyd primer, acrylic top coat	?	Wood preservative, organic salt, Cr-free, at plant/kg/RER	F7DFE81E-C483-4F68-816E-F8C0B45545AB		kg
				Robot spray system with Akzo Nobel US	D843F359-B351-48AE-9395-03BEB43812F4		kg
				Robot spray coating with Akzo Nobel USa 55	D843F359-B351-48AE-9395-03BEB43812F4		kg
				Alkyd paint, white, 60% in H2O, at plant/kg/RER	23FA2CC5-2CFD-4666-A41A-0DD2634EB474		kg

5. Discussion

This section attempts to address the strengths and weaknesses of BIM-based LCA and the IFC development approach from the perspective of both the building industry, as well as the field of LCA. It is assumed that the AECOO industry is primarily concerned with convenience and value-add for project work, while the LCA field is focused on accuracy and transparency of results. This section also reflects on the outcome of the tool development process that includes an IDM and theoretical data conversion method.

5.1 BIM-based LCA in general

This paper focuses mainly on the use of the IFC schema to produce a solution for BIM-based LCA, but there are many different ways to achieve the same outcome. The following section consider the creation of such a tool generically, without the restraints of a specific methodology or schema.

5.1.1 Strengths – Building industry perspective

5.1.1.1 Time, cost, and value

Even for those in the building industry who see LCA's potential value as a design tool, the time requirement and resulting cost of staff-hours often overshadows any positive return. Time, cost and value are all linked, and being inter-connected means that their relationship is not linear. As time decreases, cost and value both change for multiple reasons. Not only does less time improve ROI by reducing labor costs, but it also increases design value by allowing for iterative comparisons. It may also allow LCA to be used in new phases that fundamentally change its impact on a project.

In the past, energy analysis faced similar issues that LCA is facing now – it was too time consuming to be effective. But now, building geometry can be directly transferred, turning weeks of work into hours, and a design can be visualized in easily understandable ways (OGC et al. 2009). This is where LCA has a chance to increase its value by improving the tools and better blending with industry work flows. Currently a whole-building LCA takes weeks to prepare and cannot be adjusted easily after design changes. Much of the process is manual data entry and involves expert interpretation of model data. All this must change if LCA is to ever be widely utilized by more than a niche of specialized designers, and BIM-based LCA is a likely solution.

5.1.1.2 Specialized staff competency

In their current form, even simplified whole-building LCA tools require a relatively high level of expertise to perform environmental analysis and evaluate results (Brick & Frostell 2007). This means that a project team member must have training to develop competency with such tools creating an educational barrier to use. General and comprehensive LCA tools such as SimaPro and Gabi require even more experience to be able to effectively model on a building scale. They demand large amounts of training and a thorough understanding of LCA methodology (Malmqvist et al. 2010). An automated IFC file conversion procedure would allow BIM-based LCA to be performed by a non-specialized staff member with reduced risk of error.

5.1.1.3 Early design contribution

Smart decisions made early in the design process are the cheapest way to impact the performance of a building, and therefore it would be very desirable to have a simple yet dependable model to predict final outcomes in this phase (AIA 2007). The challenge is that the design team has only a general concept of the building, which makes it difficult to predict performance accurately and precisely. Also, there must be a balance between detail and time requirement, so that a model generates constructive results in a timely fashion.

BIM-based LCA cannot solve the data accuracy issues faced in the early design phase, but the time reduction allows for more rapid updating and comparison of models. Broadly speaking, LCA methodology provides a more comprehensive performance model that reduces the risk of overlooking critical indicators.

5.1.1.4 Integrated project delivery

Integrated Project Delivery (IPD) is a project management methodology that aims to increase collaboration and link incentives to project performance. Research has shown that integrated teams are linked to greater efficiency and reduced project costs. The United Kingdom's Office of Government Commerce (UKOGC) estimates that savings of up to 30% can be achieved when "integrated teams promote continuous improvement over a series of construction projects" (AIA 2007).

Achieving higher levels of collaboration requires tools that facilitate information sharing, and in their guide to IPD, the AIA recognizes that Building Information Modeling (BIM) is one of the most powerful tools supporting Integrated Project Delivery (AIA 2007). Thus, if IPD is the methodology of the future, BIM tools are the enablers.

BIM-based LCA complements these existing trends in the AECOO industry toward integrated project teams because it provides a more complete measure of success. The purpose of using innovative collaborative methods is to improve the performance of buildings and the building process from a holistic perspective, but the current tools used to quantify that improvement are not capable of providing designers with the whole impact picture.

5.1.2 Strengths – LCA perspective

5.1.2.1 Access to a major industry and impact on design

The building industry – estimated to represent $5.6 trillion globally – is an enormous economic force that controls massive amounts of resources and produces a product that consumes approximately 40% of the energy produced in developed countries (Young et al. 2009). BIM-based LCA presents the chance to become formally integrated with AECOO tools, and gain a meaningful foothold in the building industry by growing the legitimacy and effectiveness of LCA methodology.

LCA models will assuredly improve as more industry actors contribute to them, but this will not occur until the methodology reaches a threshold of dependability and accessibility that allows it to be effective. This does not currently exist for LCA in the building industry; therefore development of better tools is a precursor to improving design. BIM-based LCA provides access to the design process; it allows for an increased procedural link, an opportunity to standardize whole-building LCA methodology and to quantify environmental performance factors that previously remained mostly unmeasured or qualitative.

5.1.2.2 Best data from industry

Using generic or average data is not ideal for LCA studies; it is something that must be done as a result of limited data availability. In most cases, only the foreground system is measured using primary source data, and sometimes only for a few key processes. This limits the effectiveness of an LCA because material impacts can only be differentiated broadly according to basic volumes rather than compared at a product specification level of detail.

As the EPD system grows, more primary source data from industry will be available at the product scale. As LCA is applied to more whole-building cases, the outcome is the equivalent primary source data at the building scale. BIM-based LCA results from project based industry studies are a valuable resource to the LCA field; it could be a marked improvement on generic and average energy use and material data used for background flows or building stock modeling.

5.1.2.3 Graphically supported material scope

The most basic benefit that 3-D models provide is their ability to convey complicated models in a way that users can intuitively understand. This should not be lost on the LCA field, because even though they do not actually construct buildings, they are very much based in the physical world. Linking LCA software to a 3-D BIM tool allows practitioners to benefit from all the spatial information already stored in such a model.

LCA tools that currently have visualization – like EQUER – are not nearly as robust as the BIM tools created for architects, engineers, and energy analysts, and they require a building to be re-modeled for LCA purposes. BIM-based LCA avoids this added step by utilizing the existing BIM, while delivering the same advantages that visualization brought to clash detection in design – viewers of an LCA can instantly understand the scope and identify missing or conflicting elements. Comparing two LCAs would be as simple as looking at the BIM, and model checking clash detection software could potentially identify all points where two scopes differ.

5.1.3 Weaknesses – Building industry perspective

5.1.3.1 Perceived value of LCA

The building industry will not adopt LCA as a core tool, no matter how much easier it becomes, unless the value-added is clearly defined and perceived to be legitimate. There is a small portion of early-adopters in industry that already see the value of measuring the environmental impacts of materials and energy consumption in building design. But undoubtedly, even if BIM-based LCA were established, some would still question the necessity of this sort of analysis, and perceive it as outside of their core competency. For these industry laggards, it may take legislative change or specific customer demands for them to see a need to use LCA as a planning tool, but this is not something that can be influenced by streamlining the LCA process.

5.1.3.2 Data accuracy and availability limitations

LCI databases will never be complete because industrial processes are always changing and the number of materials, products and services constantly growing. For this reason, data acquisition is considered the biggest challenge facing whole-building LCA (Malmqvist et al. 2010). In response to this reality, programs such as BEES and ENSLIC have focused their attention on high-impact material categories – such as cement in slabs, wood and steel framing, roofing materials, windows and other major components – but BIM-based LCA will not have detailed process data for all building elements.

Given these limitations, the challenge is to determine what the optimal level of precision should be for practical decision making purposes. "In practice, the precision of such tools must only be sufficient to identify hotspots or, in a sensitivity analysis, to establish the minimum level of data precision required to not disturb the results about the hotspots" (Malmqvist 2008).

5.1.3.3 Object labeling requirements

BIM-based LCA can address some of the data availability and consistency issues by automating the collection of inventory data, but it depends on the existence of a precise material and activity classification system. Similar to cost modeling, if objects are not labeled correctly, they cannot be accounted for, and the accuracy of the model suffers. This means that LCA results are largely dependent on either the modeler or a tool such as the IFD Library performing this task precisely, and also requires added time for additional BIM review. Model checkers, such as Solibri, could be used to ensure this step has been completed properly, but as the detail of an LCA increases, so does the number of labels.

5.1.4 Weaknesses – LCA perspective

5.1.4.1 Creating LCA IDs for how many materials?

Similar to the challenge of establishing the EPD system for building products, a representative selection of BIM objects must be modeled in LCA terms before BIM-based LCA is possible. This is done by assigning an LCA ID to each object that transfers the relevant information stored in the model. The creation of an LCA ID requires assembling the LCA processes that make up an object or activity, and determining the proportional demand of each process according to an assumed functional unit. In theory, generic versions of these can be created for a core set of materials and activities that are determined to be most impactful, but it is still not a small task.

The EPD system has been created to provide a sound environmental basis for evaluating and comparing specific products – the responsibility for generating the analysis lies with the building product manufacturer. The scale of this task is massive because it ultimately requires manufacturers to document the performance of all their products, but the LCA ID system is designed to be more generic. LCA IDs can be used in the early design phase prior to specification, and potentially as an industry baseline to determine what a reasonable value would be for each product category. This means that they should not be developed by industry itself, but by independent LCA experts that can evaluate their representativeness. The difficulty of such a task would depend on the number of parties involved, and access to specific unit processes in existing LCA studies of building materials.

5.1.4.2 Can BIM-based inventory results be trusted?

LCA is a new methodology attempting to gain legitimacy in the building industry, and therefore it is of great importance to deliver high quality analysis. When automation is introduced into a process, there is a risk of sacrificing accuracy and transparency for the sake of expediency.

In the case of BIM-based LCA, this could happen if the BIM to LCA data conversion process were implemented as a "black box" that could not be analyzed by third-party reviewers. Being able to see how an LCA ID is formulated – how a BIM object is converted into an LCA model – allows for easy comparison with other LCA studies. This problem can also be avoided by clearly documenting and standardizing goals, scopes and functional units so that whole-building LCAs can be compared and differentiated in a straightforward fashion.

5.2 IFC approach to BIM-based LCA

The IFC approach to creating a BIM-based LCA solution is based on the development of an Information Delivery Manual by domain experts, which can then be used to produce a Model View Definition that is bound to a specific IFC schema release.

5.2.1 Strengths – Building industry perspective

5.2.1.1 Based on open-source schema

Interoperability has been a central challenge for BIM throughout its existence, and IFC has been the open-source answer to ensuring a non-proprietary basis for standardization of file transfer. In 2010 both the AIA & SMACNA issued statements in support of an open standard that could be used by the entire industry for product development. These organizations represent powerful interests within the AECOO industry, their public statements mark an important shift in the BIM landscape toward stronger support for IFC based solutions.

5.2.1.2 IFC is a complete schema

An alternative to IFC is the gbXML schema, which is also an open standard that has been adopted by the AECOO industry for dealing with energy analysis data. gbXML was developed by Green Building Studio before it was a part of Autodesk, and the schema remains non-propreitary – though it is closely linked to software developed by Autodesk and their partners. The fundamental difference between gbXML and IFC is their completeness – regarding building elements and interoperability potential. gbXML is effective for what it does, but will always be limited in scope, while IFC is a complete and open framework for industry to build on. The table below highlights some key differences between the schemas:

Tabell 48. Comparison of IFC and gbXML schemas

	IFC	gbXML	Both
Non-proprietary			X
Energy Analysis			X
Whole-Building*	X		
Fully Interoperable**	X		

* the schema has the potential to model all elements in a building (not just energy)

** external revisions can be re-imported into original BIM model

5.2.2 Strengths – LCA perspective

5.2.2.1 Transparency of method

The IDM methodology is designed to allow domain experts to utilize their expertise to drive solution development; a byproduct of this is that it makes the process inclusive for all LCA practitioners. An IDM contains a plain language overview of the use-case, descriptions of tasks and the type of information required to satisfy a Design to LCA model exchange. While the actual implementation of an MVD will require technical design by solution providers, the level of transparency is high enough that LCA experts will be able to adequately evaluate the representativeness of the results.

5.2.3 Weaknesses – Building industry perspective

5.2.3.1 Inconsistent development process

Non-proprietary solution development is generally less organized than more traditional private efforts, because funding and expertise has to be sourced from a variety of places. The benefit of the outcome is not captured by a single entity, and therefore is less profitable for the developer. These challenges have been facing buildingSMART and the IFC development process since it started. Despite these challenges, it is still beneficial for the industry in general to be able to effectively exchange information between tools without proprietary barriers, and therefore less profit dependent actors such as governmental and educational organizations are critical players in bringing industry together and driving open source development efforts.

5.2.3.2 Open-source is not fully supported by large private solution providers

Large software development companies like Autodesk and Graphisoft benefit from keeping their solutions proprietary because the AECOO industry has to use their file formats as a basis for information exchange. The fact that the IFC schema is open-source allows smaller developers to create specialized tools that are interoperable with these popular design tools, and in so doing create a niche market for themselves. As a result, the software industry is made more democratic, but the large companies sacrifice market share, and therefore are less willing to adapt their solutions to such an open-source platform.

This is a weakness of the IFC system because it means that the private interests of the biggest software developers will always be in contention with the interoperability interests of the AECOO industry. This situation is similar to the struggle between Microsoft/Mac and Linux, where a large majority of the software industry has developed their tools for the Windows or Mac operating systems, while Linux, an open-source alternative, is much less prominent. From the perspective of a BIM-based LCA developer, it would be ideal to maximize interoperability with the most common design software, and for this reason, collaboration with Autodesk or Graphisoft may yield a better product and wider adoption in the AECOO industry.

5.2.4 Weaknesses – LCA perspective

5.2.4.1 Requires learning a new and industry specific system

LCA practitioners already have a set of tools that they use to generate LCA models, and these tools can be applied to any product, service or industry. If a building specific BIM-based LCA tool were to be developed, it would take those modular tools and formally link them to an individual industry standard. This would require an LCA practitioner to specialize, and understand how the information can be transformed into an Ecospold compatible file.

5.2.4.2 Reduces influence of LCA practitioners

LCA consultants currently have a high-level of control and power in the analysis process, but an IDM standard would eliminate the need for some of this expertise. Similar to the automation of manufacturing processes, a BIM that automatically produces an LCI can effectively replace a large portion of the LCA practitioner's job. This reduces their influence and value in the building industry, which is a huge potential market as regulation and market demand drive adoption of LCA in the future. The calculation of impacts and interpretation of results is something that still must be performed by an expert to ensure proper conclusions.

5.3 Evaluation of the tool development process

The development of BIM-based LCA can be done in multiple ways – this section discusses the choices that were made within the IFC framework, as well as with data conversion process. These are two distinct tasks, though the data conversion process must be translated into IFC language as part of the IDM exchange requirements.

5.3.1 IDM development

This initial effort to create an IDM for Design to LCA was meant to be exploratory, and the system of exchange requirements (ER) and functional parts (FP) that was used to organize and transfer data is just one among many options. The creation of an LCA related functional part is most likely necessary because of the different nature of how objects need to be identified, but it is unclear exactly what needs to be included in that functional part. In the version created for this paper the information is divided by Goal and Scope types, and this was done to match the steps required for an LCA, but it may not be necessary in IFC terms. This is because each role and functional unit parameter definitions may be able to be generated by adding additional properties and attributes to existing functional parts.

Similar to the way that "region" was suggested as an additional attribute in the "site" functional part, it may be possible to add LCA actors to the existing "model_actor" FP. Along those same lines, a functional unit is a collection of attributes that define the functionality of a building, and these already exist in various other functional parts. The particular method chosen was developed from a an LCA-centric perspective, and therefore it was simpler to invent new functional parts than attempting to search and extract each data point. A solution provider that is more familiar with the IFC schema may be able to achieve the same result much more efficiently.

Another issue that must be debated is the strategy of using LCC cost categories to group activities for LCA. This was done to provide a common lifecycle basis for the two methods, but it is something that may present data organization problems in some areas. It may be the case that LCA and LCC lifecycle categories should remain separate for optimal simplicity and clarity, but this is difficult to foresee this early in the implementation process. Also, the challenge of modeling maintenance and operational activities might be greater than expected, but may also be avoided due to a relatively small contribution to overall environmental impacts.

5.3.2 Data conversion model

The LCA ID system, based on GUIDs, that is suggested in this paper appears to be theoretically sound, but the practicality of such a method will have to be tested. This can be done manually using a core set of BIM objects to implement the IFD Library and produce a UUID/demand inventory as input in LCA software. The greatest unknown is whether the demand proportion approach for modeling each building element will deliver adequately representative results.

Such generic models would have to be a product of average results for each element, and subjected to sensitivity analysis to determine if it would introduce too much variance for BIM-based LCA results to be useful. Given the relatively small percentage of overall impacts represented by most materials, it may not be of great importance to create a large number of LCA IDs. In terms of precision, generic thermal properties for energy modeling is an example where a "close enough" value provides an effective modeling tool for the purpose required by decision makers. In the window example provided earlier, the proportion of each sub-part – frame, glazing, etc. – would vary by design, but it is assumed that most windows of a given dimension would be within an acceptable range.

Assuming such proportional process demand models are determined to be adequately representative, another challenge will be locating valid LCA studies that can be used as data sources. Public material database efforts, such as BEES, provide their LCA results freely, but do so in an aggregated fashion. They provide process flow charts, but their industry partners will not allow them to release the specific processes used in the calculations. But once again, this is a practical issue associated with implementation, and does not discredit the possibility of such a solution.

6. Conclusions

The following section provides broad conclusions regarding the utility of a BIM-based LCA tool in the building industry generally, as well as a more focused evaluation of the preliminary solution that was produced for that purpose.

6.1 BIM-based LCA in general

6.1.1 Life cycle thinking is necessary for the building industry

It is estimated that costs of owning and occupying an office building over a 30 year period have a ratio of 1:5:200 – where total construction cost is a fifth of maintenance costs, and one two hundredth of building operation costs with staffing included (Davis Langdon 2007b). This provides clear motivation for finding ways to reduce use-phase costs, and consequently the importance of effective life cycle modeling.

The highly technical requirements of the construction phase have driven the development of precise modeling tools for design, and it is clear that the quality of the results of this phase have lasting impacts on the use-phase of a building, but LCC shows that it is the operational costs that should ultimately be optimized. If the critical sources of these costs were better understood and could be reduced or avoided, the return on investment would be much greater than focusing primarily on the construction phase.

This means that optimizing designs for minimal construction costs is a deeply flawed methodology for achieving the highest performance outcomes over the entire lifecycle. The current system is a logical consequence of the segmented interests of architects, engineers, and contractors that are not impacted by post-occupancy costs, but long-term owners, occupants and society benefit from minimizing total costs and environmental impacts over the whole lifecycle of a building.

6.1.2 LCA is coming to the building industry

Whole-building LCA methodology is not actively used on many building projects today, but life cycle thinking is becoming more common. This can be seen in the use of EPDs at the product level, LCC at the project level, and support of green certification systems at the industry level.

The Norwegian Public Construction and Property Management organization, Statsbygg, has as a goal that EPDs or similar LCA information will be delivered for all of the main products in their building projects (Peuportier et al. 2009). This is a signal to the building product manufacturing industry that they will have to take the EPD process seriously if they want to be specified on government projects. Such requirements have an impact on the market as BPMs begin to perform EPDs for government contracts, and then want to advertise their "green" achievements to the private market. Once they are using the EPD system, it is to their advantage to have the entire industry keeping score by the same rules. Because the EPD system is based on LCA methodology, it is more difficult to "green wash," or falsely claim superior environmental performance through marketing rather than substance.

Statsbygg also requires that an LCC is conducted for all building projects, which forces cost estimators to begin thinking in life cycle phases. Measuring cost is obviously not the same as measuring environmental impacts – financial interests have always been a primary concern in the building industry – but beginning to model the life cycle of a building is a step toward LCA. The process of producing a quantity take-off (QTO) for cost estimation is very similar to building a life cycle inventory (LCI) for LCA.

Also, the market has embraced green building certification systems as valuable differentiators that can raise rents and produce positive publicity for tenants. The two most widely used systems, LEED and BREEAM, have both chosen to adopt LCA methodology as a foundation for measuring sustainability. So effectively, everyone involved in these programs will at least have to become familiar with the basic concept, if not proficient at its application on the whole-building scale.

Using LCA methodology makes it more difficult for builders to green wash their projects by choosing points that are easily attained while providing minimal environmental benefit. In the end, the accessibility of LEED may have drawn in some builders that would not otherwise have attempted green building, and the USGBC may end up leveraging this popularity to move many of the companies already engaged further down the sustainability path.

All these factors combined, at every scale in the industry, suggest that LCA will become more commonly used and therefore more influential in the design of buildings. Therefore industry will be looking for better tools to meet such analytical requirements, and BIM-based LCA presents a promising solution.

6.1.3 BIM and LCA need formalized links

The overarching challenge for BIM-based LCA is that the two fields remain separated with only superficial overlap of tools, terminology and data structure. LCA is a generic methodology, and for that reason, its tools have traditionally been developed to be generic and applicable to any sector. The result is that buildings must be modeled in both BIM and LCA software separately, and there is no direct information flow from one to the other.

Because of this software and modeling disconnect, whole-building LCAs remain too time consuming and esoteric for most in the building industry, and therefore remain a specialized field for academics and consultants. It is doubtful that the building industry will adapt its tools or processes to fit with the much smaller LCA industry, so if LCA practitioners wish to establish themselves within the AECOO workflow, they will be the ones responsible for closing the communication gap.

LCA is in many ways where energy analysis was before it got integrated into BIM software – considered interesting by many, but also too time consuming and obscure for the value-added. The ability to utilize IFC files took a process that used to require weeks to complete, and allowed it to be done in an hour (OGC et al. 2009). This not only saves time, it changes the function of an energy model. Energy modeling was once something that could only be done once or twice during a design process; it took too long and therefore could not be used in iterative design.

The other characteristic that makes LCA similar to energy modeling is its requirement of specialized staff training or external consultants. Even the specialized LCA tools designed specifically for whole-buildings remain relatively difficult to use and require some expertise to understand (Brick & Frostell 2007). This used to be the case for energy analysis as well, but tools like EcoDesigner and Ecotect make it much simpler and intuitive to complete. The geometry can be directly transferred, and it already contains the thermal and spatial data that is required to simulate a building's energy consumption.

If a project team wanted to conduct an LCA today without using BIM at all, the task would take weeks. It would require manual calculation of material quantities, followed by manual data entry into a non-visual simulation engine making it difficult to identify errors. Even if they used BIM for quantity takeoffs and energy analysis, they would still have to transfer the material and energy data into either a spreadsheet or software manually. This task could possibly be done by a trained staff member if a simplified tool is available, but if not, an outside specialist would have to generate the model.

The problem with this process is not only that it takes too long and requires specialized staff, but these factors in combination greatly reduce the ability to act on the results. If the findings suggest a certain trouble area, the team can react, but the effect of that reaction will not be known unless another assessment is conducted. This limits experimentation and comparison, and forces guessing at outcomes without actual results.

The implementation of LCA will likely follow a similar path to energy analysis – it will not gain widespread acceptance until it is fully compatible with BIM tools and fits within the building industry's demanding workflow requirements – which means IFC compatible software, and a modeling time measured in hours or not weeks.

6.1.4 The main pieces already exist

As discussed previously, QTO, BPEA, and LCC model views and software tools either exist or are being developed, which makes the creation of an IDM to extend BIM's functionality for LCA much simpler. Using precursor exchange requirements to ensure that the modeling needs for LCA are already met, only a few new functional parts must be created to produce an LCA compatible BIM.

In terms of data formatting, IFC 2x4 and Ecospold v2 are both scheduled to be released in 2011, and both represent good platforms to build a link between BIM and LCA. The GUID and UUID systems for each have already been created and need only to be translated for data interoperability. Such a classification systems allows for unambiguous links between data points and are easily referenced by software developers.

In addition, BIM object model databases are constantly growing and could potentially be linked to EPDs as that system expands and the information becomes available. The growth of BIM has caused manufacturers to recognize the value of providing detailed virtual models of their product that can be inserted directly into a designer's BIM. Resources like Autodesk Seek and SmartBIM provide centralized searchable databases that are accessible online free of charge. This makes a designer's task easier, but also creates more accurate models earlier in the design process, and allows for simplified product comparison.

As an example, a window in the Autodesk Seek database lists its U-value, SHGC, type of glazing, dimensions, color, etc. and can be downloaded in a variety of different file types for various trade-specific BIM software tools. Adding the key environmental performance parameters measured in an EPD to such a system would be a straightforward process.

6.1.5 Government developers have to lead

Life cycle based analysis – both for cost and environmental impact – is most relevant for public sector clients, because they have a unique role as large-scale property developers and owners that are also long-term tenants able to benefit from operational life cycle efficiency gains. Governments have more freedom and motivation to include social economic factors in their evaluation methods than private companies – they have a responsibility to act in the best interest of their citizens, while private profit seeking companies are only responsible to their shareholders. Such freedom allows for the inclusion of the environmental performance indicators that LCA is based on. Given this strategic position, it is critical for public developers to make the most of their influence by pushing the development of holistic tools that reveal the true costs of development. These types of results can be used to show win-win design methods – cheaper and fewer impacts – as well as set performance benchmarks for regulations placed on industry.

This does not mean that such tools should or could not be used by the private sector, but they have less incentive to incur the research, training and software costs associated with such a transition. Obviously construction consulting firms that bid on government projects would be drawn into the process by necessity, and would gain competence that could be applied elsewhere.

6.1.6 Existing BIMs are a resource

As more BIMs are generated for various types of construction projects, more resources are available for future designs – both for new construction and refurbishment. Large public real-estate developers, such as GSA and Statsbygg, have started to require the development of BIMs on all projects. These models may not be able to be directly re-used, but they will be comparable to similar buildings, and provide a meaningful reference for early design phases regarding energy performance, material use, and cost.

These models will also become more valuable for Facility Managers and researchers monitoring building operations, because every BIM has built-in predictions that can be confirmed or disproven. If a model is extremely far off of actual performance, then there may be something wrong with the mechanical systems, or a valuable lesson in creating better BIMs. The point is that BIMs cannot improve without having something to compare results to, whether it be the building itself, or another model of a comparable building. The more historical references there are, the more confidence designers can have trusting BIM results in the early-design phase.

6.1.7 Comprehensive measure of performance

There are very few absolute answers when evaluating the relative sustainability of design decisions; small contextual details matter, and can completely change results. A model will always be limited in scope – it can only optimize according to the chosen indicators and system boundaries – but a larger scope provides a more complete basis for decisions. The life cycle perspective is critical to achieving the highest performing buildings possible, because anything less is incomplete; it leaves out significant categories of impacts. LCC is an important step for the industry to take, but it is not the end of the road, because it only considers one dimension of performance. Adding energy analysis for operational performance is another important step, because traditionally this has been where the majority of impacts occur, but it is still not the whole picture.

LCAs of individual building materials are important building blocks of a whole-building LCA, but can be misleading when used alone. Project teams will not be able to see the entire performance picture until a whole-building LCA with acceptable detail and accuracy can be delivered within a reasonable timeframe during the planning and design phases. The impacts from material inputs in various building types have been calculated to range between 10% and 50% of total lifecycle emissions, which means even at the smallest proportion they are a significant impact on the system.

Moving forward, the LCA scope could be expanded – both in terms of geographic area and number of impact categories – but due to the complex nature of whole-building models, it has been recommended that they first be simplified. As the tools and data improve, it may become possible to effectively model large-scale developments for use in urban planning, and include health effects from indoor exposure.

Integrated teams are only as good as the information they have to share with each other, and LCA can be a source of that knowledge. BIM has acted as a catalyst to facilitate the IPD methodology, but understanding the linkages between embodied energy and operational energy, service life planning and recyclability – these are the ways that buildings move past high-performance to zero emission.

6.2 BIM-based LCA solution evaluation

6.2.1 Design to LCA IDM is more than data conversion

The ILCD Handbook was created to ensure more consistent and accurate LCA models for industry, but also to show there is more to LCA than just calculations. The results of an LCA can have large impacts on production processes, and therefore any assumptions made must be transparent for readers to understand the context. In this way, if BIM is going to be used for LCA, such an exchange must be equally transparent.

This is the reason for the Goal and Scope definitions within the IDM written for this paper, because it is through those steps that readers are able to see the underlying motivation and boundaries of the study. If a BIM-based LCA tool returned results that did not clearly state what elements were included, then designers would not know what parameters they are basing their decisions on, which could lead to erroneous conclusions and poor building performance.

As an example, if only slabs and operational energy use are included in the scope, then any decision that reduces concrete use or reduces energy requirements will be seen as a good result, while it may completely undermine other more important aspects of building design. The use of such a limited scope is not useless, but the designers must understand what it is they are looking at. Thus the Design to LCA IDM has two equally important tasks: collection and transfer of data, but also transparent reporting of scope and context of the study.

6.2.2 Life cycle modeling is the new challenge for BIM

Most of the existing BIM tools are focused on modeling a building as it is to be constructed prior to occupancy, but they are not very proficient at predicting the long-term future performance and material requirements of the same building. LCA and LCC modeling represent a new challenge because they depend on service life predictions, which effectively extend the model into the use and end-of-life phases. There is an IDM for service life planning from the LCC-DATA project, but it has not been applied to develop a model view definition or software solutions. Such a theoretical construct is a useful framework, but there is a clear need for practical implementation to test and improve such a system.

The LCC-DATA IDM was created for measuring cost, but moving forward, it will be necessary to identify the differences between life cycle costs and life cycle environmental impacts. This is a challenge for the proposed LCA ID system, because it will have to interpret what activities are associated with various maintenance and operating requirements. From a cost perspective, such activities are fully represented by the cost of materials and the labor of contractors tasked with repairing and replacing building equipment, but LCA must consider all the input and output flows that are attached to those activities.

LCC has provided insight for building owners because it revealed the relative insignificance of capital costs over the entire lifecycle of a building. In the same way, LCA has already revealed that material impacts are proportionally less important than those from operational energy use; but as mentioned before, very few absolute rules exist in sustainability. If the automation of BIM-based LCC/LCA were to allow for these models to be used in combination, then trade-offs between cost and environmental impacts could be directly assessed, and any win-win solutions could be more easily identified.

6.2.4 Proof of concept has been achieved

The development of BIM-based LCA is primarily a practical pursuit that stems from the realization that better tools are an effective way to make LCA more accessible for the building industry. With this goal as its foundation, BIM-based LCA only has value if it can deliver meaningful LCA results in a significantly more convenient manner than traditional methods. This paper, along with previous work on BIM-based LCC using IFC, has shown that the use-phase of a building can be modeled in a BIM, and thus a satisfactory proof-of-concept for IFC-based LCC and LCA tools has been established. Given this scenario, rather than continuing to research theoretical approaches, it is recommended that intermediate model views and solutions be created using proposed exchange requirements and IDMs.

More speculation on method cannot deliver better answers for design; testing of existing ideas will provide clear guidance for the improvement of methods and tools. The important questions for BIM-based LCA now relate to implementation, and these include: how to efficiently link BIM and LCA databases, how to best categorize activities, what are the most important materials and processes, in what phases is BIM-based LCA most effective, and what scopes are optimal for those phases? These types of questions cannot be answered without applied theory, and through the development process, the realities of what is possible will become clear.

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Appendices

Appendix 1: ILCD List of Intended Applications for LCA

The following LCA applications are the most frequently used ones, but others may be identified and used as well:

- Identification of Key Environmental Performance Indicators (KEPI) of a product group for Ecodesign / simplified LCA
- Weak point analysis of a specific product
- Detailed Ecodesign / Design-for-recycling
- Perform simplified KEPI-type LCA / Ecodesign study
- Comparison of specific goods or services
- Benchmarking of specific products against the product group's average
- Green Public or Private Procurement (GPP)
- Development of life cycle based Type I Ecolabel criteria
- Development of Product Category Rules (PCR) or a similar specific guide for a product group
- Development of a life cycle based Type III environmental declaration (e.g. Environmental Product Declaration (EPD)) for a specific good or service
- Development of the "Carbon footprint", "Primary energy consumption" or similar indicator for a specific product
- Greening the supply chain
- Providing quantitative life cycle data as annex to an Environmental Technology Verification (ETV) for comparative use
- Clean Development Mechanism (CDM) and Joint Implementation (JI)
- Policy development: Forecasting & analysis of the environmental impact of pervasive technologies, raw material strategies, etc. and related policy development
- Policy information: Basket-of-products (or -product groups) type of studies
- Policy information: Identifying product groups with the largest environmental impact
- Policy information: Identifying product groups with the largest environmental improvement potential
- Monitoring environmental impacts of a nation, industry sector, product group, or product
- Corporate or site environmental reporting including calculation of indirect effects in Environmental Management Systems (EMS)
- Certified supply type studies or parts of the analysed system with fixed guarantees along the supply-chain
- Accounting studies that according to their goal definition do not include any interaction with other systems
- Development of specific, average or generic unit process or LCI results data sets for use in specified types of LCA applications

Appendix 2: ISO 15686-5:2008 LCC Cost Classification

Whole-Life cost (WLC)	Non-construction costs	-Land and enabling works -Finance -User support costs (strategic property mgmt, use charges, and admin) -Taxes -Other
	Income	-Income from sales -Third-party income during operation -Taxes on income -Disruption -Other
	Externalities	Undefined
	Life-cycle cost (LCC)	Construction - Professional fees - Temporary works - Construction of asset - Initial adaptation or refurb of asset - Taxes - Other Operation - Rent - Insurance - Cyclical regulatory costs - Utilities - Taxes - Other Maintenance - Maintenance mgmt - Adaptation of asset in use - Repairs and replacement of minor components/areas - Replacement of major systems and components - Cleaning - Grounds maintenance - Redecoration - Taxes - Other End-of-Life - Disposal inspections - Disposal and demolition - Reinstatement to meet contractual requirements - Taxes - Other

Appendix 3: Library Information for BIM Object Types

Type	Data Object
Documentation	At the Concept design stage, designers have not modeled many of the building data objects, yet descriptive data provides useful information for preparing a cost estimate. Site Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Building Object The functional classification source is OmniClass Table 11 (construction entities by function). However, for the Testbed with GSA use the IBC classifications to align with BPEA. Building Story Object No recognized standard functional classification source is identified. Descriptors used by the model are sufficient. Above grade and below grade are common descriptors. Space Object See Section 1.3.1.4 Industry Space Type Library. Wall Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Each object shall have an indicator for load bearing or non-load bearing. Each object shall have an indicator for fire rating (including not applicable). The Testbed for GSA uses the BPEA Industry Construction Types Library to align with the BPEA Thread. Slab Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. The Testbed for GSA uses the BPEA Industry Construction Types Library to align with the BPEA Thread. Beam Object

	The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Column Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Opening Object It does not require an Industry Classification. Door Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Each object shall have an indicator for fire rating (including not applicable). The Testbed for GSA uses the BPEA Industry Construction Types Library to align with the BPEA Thread. Window Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Each object shall have an indicator for fire rating (including not applicable). The Testbed for GSA uses the BPEA Industry Construction Types Library to align with the BPEA Thread. Curtain Wall Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Stair Flight Object The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. Ramp Flight Object The Industry Classification source is UniFormat. See Section See Section 1.3.1.6 Industry Classification Library – UniFormat.. Equipment Object The Industry Classification source is OmniClass table 23, products.

	<u>Plumbing Fixtures Object</u> The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. <u>HVAC System Object</u> The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. <u>Electrical System Object</u> The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. <u>Hot Water System Object</u> The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. <u>Cold Water System Object</u> The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. <u>Vertical Circulation System Object</u> The Industry Classification source is UniFormat. See Section 1.3.1.6 Industry Classification Library – UniFormat. (Wiggins & See 2009)

Appendix 4: Industry Classification Libraries – Uniformat and Omniclass

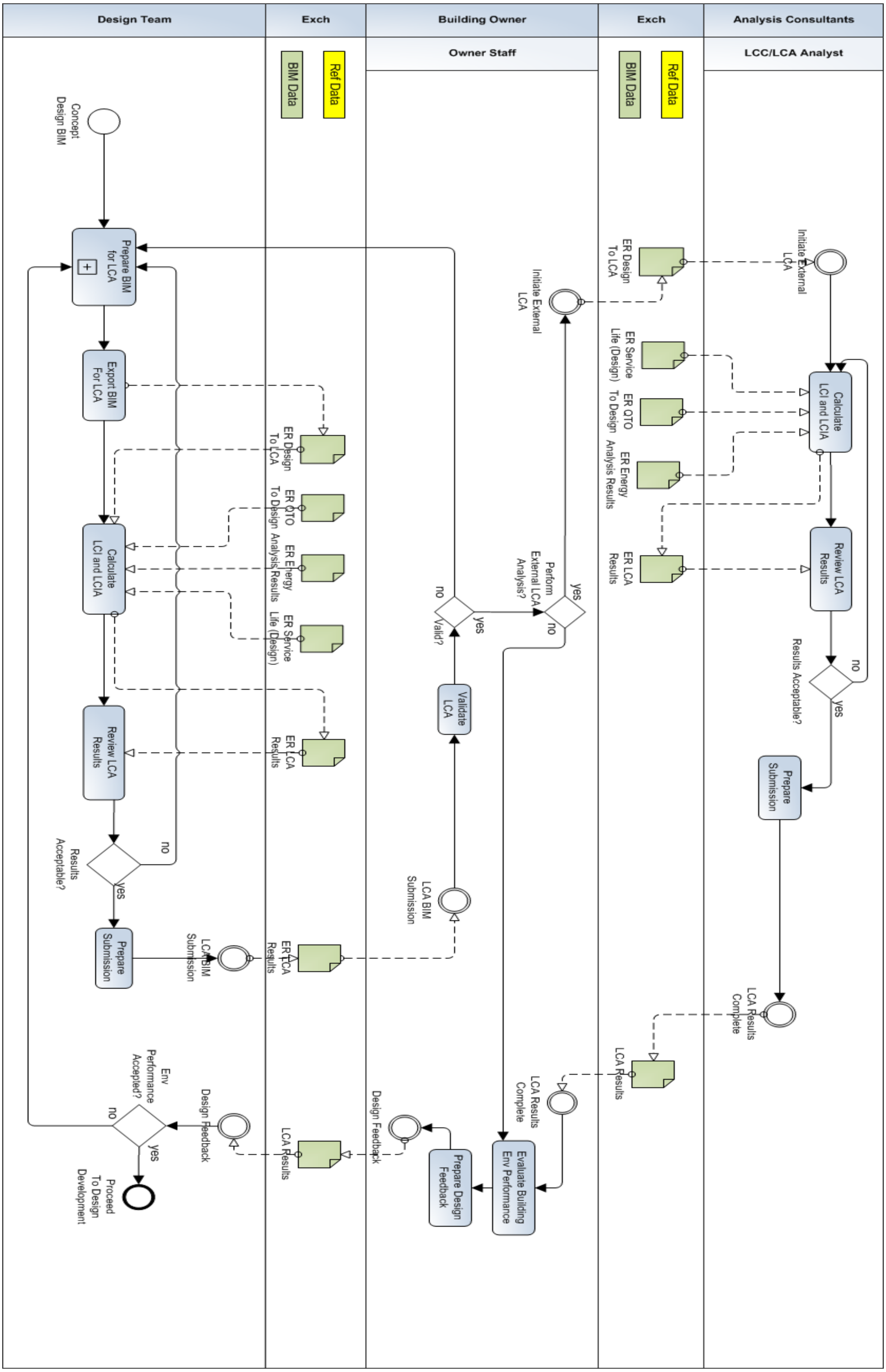
Type	Data Object

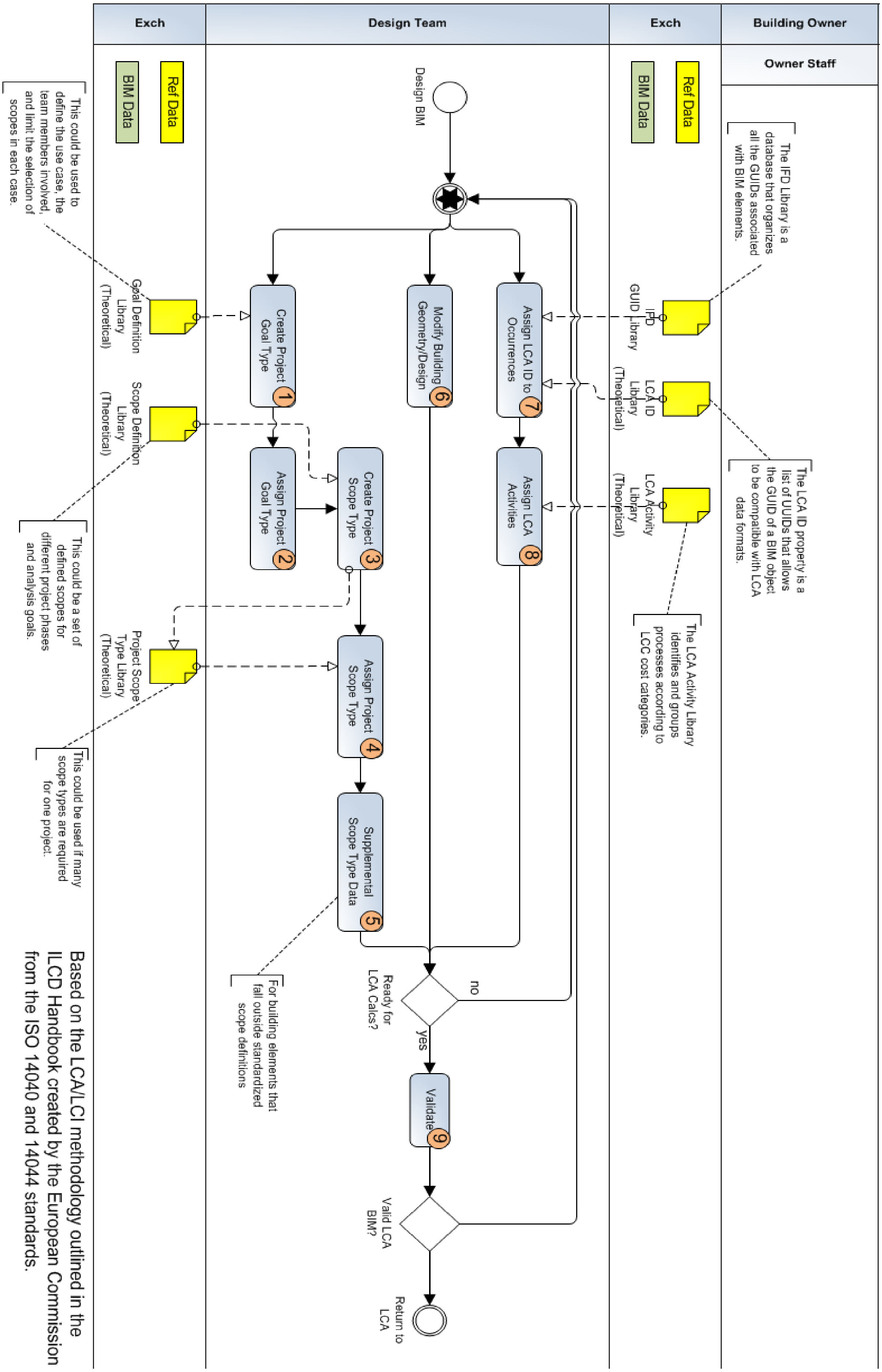
Documentation	The Industry Classification for many Object Types is UniFormat. At the early design stage, designers will not model objects in sufficient detail or will not model the object. This only permits use of the higher level UniFormat element titles, which does not allow UniFormat to convey designer intent to the estimator.
	
	In a one-to-one mapping of modeled object and Industry Classification, some objects not modeled rely on a corresponding Level 2 UniFormat element title: HVAC System Object – D30 Heating, Ventilating and Air Conditioning, Electrical System Object – D50 Electrical, Vertical Circulation Object – D10 Conveying. The Site Object uses the Level 1 element title, G Building Sitework. Other objects, such as Hot Water System and Cold Water System, use Level 3 titles (D2020 Domestic Water Supply).
	
	Modeled objects have similar difficulties. Consider the Beam and Column Objects. Uniformat classifies beams and columns as sub-elements of larger building elements of:
	
	- B1010 Floor Construction (Level 3)
	  - B1010._ Floor Structural Frame (unnumbered Level 4)
	- B1020 Roof Construction
	  - B2010._ Roof Structural Frame
	
	There are unnumbered sub-headings for each unnumbered Level 4 heading that for Structural Frame suggest possible material types.
	
	UniFormat Elements for an Object Type may be in different major element sections of UniFormat. They may not be at the same level in the UniFormat structure. The Wall Object provides an example of both cases:
	
	- A1010._ Wall Foundations has an unnumbered sub-heading of Foundation Walls
	- A2020 Basement Walls
	- B2010 Exterior Walls
	- C1010 Partitions
	
	The ability to use child element titles, a one-to-many relationship, becomes useful as a checklist to convey intent of the designer – especially if accompanied by the ability to include notes as a narrative as well. However, this functionality moves beyond the intent of assigning an Industry Classification to each object.
	(Wiggins & See 2009)

Type	Data Object

Documentation	The Industry Classification for some Object Types is various OmniClass tables. Specific tables referenced include: Table 11 Construction Entities by Function. Table 13 Space by Function. See Section 1.3.1.4 Industry Space Type Library. Table 14 Space by Form. See Section 1.3.1.4 Industry Space Type Library. Table 23 Products. This table include Equipment in section 23-40 00 00 Equipment and Furnishings. As with UniFormat, only higher level titles area useful at early design. Table 33 Disciplines. Specifying and estimating construction and maintenance costs for building elements, identifying workers and estimating associated labor costs needed in the performance of specified procedures, project management and planning. Table 34 Organizational Roles. Specifying and estimating construction and maintenance costs for building elements, identifying workers and estimating associated labor costs needed in the performance of specified procedures, project management and planning. (Wiggins & See 2009)

Appendix 5: Design to LCA Process Maps


Design Team
Exch
Building Owner
Owner Staff
Exch
Analysis Consultants
LCC/LCA Analyst
Ref Data
BIM Data
Ref Data
BIM Data
Concept Design BIM
Prepare BIM for LCA
Export BIM For LCA
Calculate LCI and LCIA
Review LCA Results
Results Acceptable?
Prepare Submission
LCA BIM Submission
ER Design To LCA
ER QTO To Design
ER Energy Analysis Results
ER Service Life (Design)
ER LCA Results
Env Performance Accepted?
Proceed To Design Development
Design Feedback
LCA Results
Validate LCA
Valid?
Perform External LCA Analysis?
Initiate External LCA
Evaluate Building Env Performance
Prepare Design Feedback
LCA Results Complete
Initiate External LCA
yes
no



Based on the LCA/LCI methodology outlined in the ILCD Handbook created by the European Commission from the ISO 14040 and 14044 standards.