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VRIJE UNIVERSITEIT BRUSSEL

INTEGRATION OF LCA AND LCC WITH BIM FOR THE ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF BUILDINGS

Rúben Emanuel Cirilo dos Santos

Supervisors: Doctor António Morais Aguiar da Costa

Doctor Lincy Pyl

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Thesis approved in public session to obtain the PhD Degree in

Civil Engineering

Jury final classification: Pass with Distinction and Honour

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Jury

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Abstract

Contemporary society is progressively moving towards a more sustainable development than observed in previous generations. There is a growing concern about the impacts of the developed technology on human health and on the environment. National and international initiatives are taking place in order to promote the well-being of the present generation but, more importantly, make certain that the welfare of future generations is not hindered because of unsustainable practices in present. In this regard, worldwide governments are taking measures to reduce the societal impact on the environment. The Paris Agreement was one of the most recent global convention that aimed to address the climate change threat, gathering the support of 185 countries so far. Deeply concerned about the consequences of the modern society, the European Union has been advocating the development of an efficient and sustainable society considering the environmental, economic, and social impacts of European Member States. Between 1990 and 2016, the European Union successfully reduced the energy consumption and greenhouse gas emissions while increasing the gross domestic product, demonstrating that a development based on the three pillars of sustainability (i.e. economic, environmental, and social) is attainable.

Presently, the built environment is one of the main contributors to greenhouse gas emissions, raw material consumption, and one of the most energy intensive sectors worldwide. Hence, in order to achieve the energy efficiency targets and reduce emissions, it is of vital importance that the most influencing sectors are transformed. Therefore, the architecture, engineering, and construction (AEC) sector must adopt sustainable methodologies and state-of-the-art technologies that contribute to the sustainability of the built environment.

Focusing on the environmental and economic impact of the construction, this research integrates the building information modelling (BIM) technology and methodology with the life cycle assessment (LCA) and life cycle costing (LCC) methodologies. The worldwide digital transformation across the sectors led to a paradigm shift in the construction industry, resulting in the emergence of BIM. Currently, BIM can be perceived as a methodology and as technology, depending on the purpose for which it is used. On one hand, BIM consists in the digital representation of a project (i.e. BIM model), which contains parametric and data-rich objects (technological domain). On the other hand, it focuses on the collaborative environment that is promoted by the use of BIM-based tools and how and when information is to be shared between the stakeholders (methodological domain). The parametric modelling and visualisation power of BIM demonstrates its potential in the different fields of the construction

industry such as schedule management (i.e. 4D BIM), cost estimation (i.e. 5D BIM), sustainability simulations (i.e. 6D BIM), or facilities management (i.e. 7D BIM). Thus, BIM arises as the most suitable mean to perform automatic or semi-automatic simulations in a wide range of domains, particularly in the sustainability domain.

In this regard, LCA and LCC analyses can greatly contribute to the sustainability of the built environment. The life cycle paradigm is increasingly becoming more relevant in all (or most) sectors of the society. The costs and impacts of products or services are no longer perceived as a single cost but, instead, as the sum of all impacts throughout the corresponding life cycle. Therefore, methodologies that consider the life cycle impacts or costs of products/services are progressively being adopted by professionals (e.g. in certification schemes) and by scholars. Both LCA and LCC methodologies are internationally recognised (e.g. in international standards) and used for different purposes.

The integration of LCA and LCC with BIM has been explored in recent literature, being argued that the use of BIM tools can greatly mitigate some of the limitations of LCA and LCC analyses (e.g. time consumed in collecting the input data). Currently, different approaches are observed in the BIM-LCA/LCC integration literature. Scholars either use a wide range of tools for the project modelling and performance of different simulations or use BIM tools to automatically extract the bill of quantities and connect it with LCA/LCC databases. However, a third approach still remains unexplored, which is the incorporation of sustainable information within BIM models to promote automatic simulations and improve information exchange. In this sense, as BIM is fundamentally associated with the exchange and treatment of information throughout a construction project, the interoperability (i.e. capacity to exchange information) between different programs assumes a particularly relevant role in the successfulness of its adoption. Therefore, the identification of useful information to be exchanged between stakeholders for the performance of a sustainability analysis is particularly important.

Therefore, this research intends to answer the following questions: i) Which information can be incorporated in BIM objects to enable a BIM-LCA/LCC analysis?; ii) Which processes and exchange of information are necessary for a framework that implements an LCA and LCC analysis within a BIM-based environment?; and iii) How has an automatic BIM-LCA/LCC analysis to be conducted if the necessary information is incorporated in objects?

To answer the first research question, a review of the existing literature on the BIM role in the sustainable construction is done, with particular emphasis on its integration with LCA and LCC. Furthermore, international standards on LCA and LCC application in the construction industry are overviewed. This process contributes to the identification of the information required to perform Streamlined and Complete LCA and LCC analyses within a BIM-based environment, resulting in the development of the BIM-LCA/LCC framework.

This knowledge is then used to answer the second question, i.e. the processes and information to perform a BIM-based LCA and LCC analysis are mapped. For that purpose, an information delivery manual (IDM) and model view definition (MVD) are proposed, filling a gap in the state-of-the-art in this domain. Moreover, to promote an interoperable information exchange for the implementation of the BIM-LCA/LCC framework, the industry foundation classes (IFC) data schema was used. The IDM/MVD 'BIM-LCA/LCC analysis' contains the What, When, and How all information is to be exchanged and handled in order to facilitate the LCA and LCC analyses within a BIM-based environment.

Building on the first and second answers, a prototype tool is developed to support the answer to the third question. The BIM-based environmental and economic life cycle assessment (BIMEELCA) tool is developed in C# language and uses a Revit application programming interface (API) platform. Moreover, the proposed framework, IDM/MVD and tool are validated with a pilot case study. The case study is an office building under construction in the Netherlands. In this regard, it is observed that an automatic Streamlined LCA/LCC analysis is possible but not a Complete LCA/LCC analysis. The need to provide project-specific information is the main reason why a comprehensive and automatic analysis is not achievable. Nonetheless, the incorporation of information within the BIM model can greatly reduce the workload and consumed time to perform LCA and LCC analyses.

The findings presented in this study indicate that the capacity to add or edit environmental and economic information within the LCA or LCC tools integrated with BIM is fundamental for an accurate analysis of the project. The databases' flexibility and how it reads the information contained within the BIM tools greatly influence the quality and representativeness of the results. If only generic data can be used in the analyses, the obtained results will likely not be as precise as if specific data (e.g. environmental product declarations) were to be used. In this regard, the main contribution of the approach proposed in this research is the use of BIM models as data repositories and the demonstration of how semantically-rich BIM objects can significantly influence the automation of simulations, thus promoting the sustainability of constructions. The work developed in this research is expected to contribute to the development of automatic sustainability simulations, creation of tailor-made BIM objects' libraries, and use of historical data contained within data-rich models for predictive analysis.

Resumo

A sociedade contemporânea está progressivamente a encaminhar-se para um desenvolvimento mais sustentável do que aquele que se tem observado em gerações anteriores. Existe uma maior preocupação relativamente aos impactes da tecnologia na saúde e no ambiente. Iniciativas nacionais e internacionais têm surgido com o intuito de se promover o bem-estar da atual geração, mas, mais importante, certificar-se que o bem-estar de gerações futuras não seja prejudicado devido às práticas insustentáveis do presente. Assim sendo, a nível mundial, os governos estão ao tomar medidas para reduzir o impacte da sociedade no meio ambiente. O Acordo de Paris foi a mais recente convenção global que abordou a ameaça das alterações climáticas, reunindo o apoio de 185 países até o momento. Profundamente preocupada com as consequências da sociedade moderna, a União Europeia tem vindo a promover o desenvolvimento de uma sociedade eficiente e sustentável, tendo em conta os impactes ambientais, económicos e sociais dos Estados Membros. Entre 1990 e 2016, a União Europeia reduziu com sucesso o consumo de energia e as emissões de gases de efeito estufa, aumentando ao mesmo tempo o produto interno bruto, demonstrando que um desenvolvimento com base nos três pilares da sustentabilidade (económico, ambiental e social) é alcançável.

Atualmente, o parque urbano é um dos principais contribuintes de emissões de gases de efeito estufa, consumidor de matérias-primas e de energia elétrica em todo o mundo. Assim, para se alcançar as metas de eficiência energética e reduzir as emissões, é de vital importância que os setores mais influentes sejam transformados. Deste modo, o setor de arquitetura, engenharia e construção (AEC) deve adotar metodologias sustentáveis e tecnologias de ponta que contribuam para a sustentabilidade do parque urbano.

Focando-se no impacte ambiental e económico da construção, esta investigação tem como objetivo a integração da tecnologia e metodologia *building information modelling* (BIM) com as metodologias de avaliação do ciclo de vida (ACV) e custo do ciclo de vida (CCV). A transformação digital a nível mundial, observada em todos os setores, levou a uma mudança de paradigma na indústria da construção, resultando no surgimento do BIM. Atualmente, o BIM pode ser percecionado como uma metodologia e como uma tecnologia, dependendo da finalidade a que se destina. Por um lado, o BIM consiste na representação digital de um projeto (ou seja, modelo BIM), que contém objetos paramétricos e ricos em informação (domínio tecnológico). Por outro lado, foca-se no ambiente colaborativo que é promovido pelo uso de ferramentas BIM e como e quando a informação deve ser partilhada entre as partes interessadas (domínio metodológico). O poder de modelação paramétrica e visualização das ferramentas

BIM demonstra o seu potencial nos diferentes campos da indústria da construção, como na gestão de projetos (i.e. 4D BIM), orçamentação (i.e. 5D BIM), simulações de sustentabilidade (i.e. 6D BIM) ou gestão de instalações (i.e. 7D BIM). Assim sendo, o BIM surge como o meio mais adequado para a realização de simulações automáticas ou semiautomáticas em diversos domínios, particularmente no domínio da sustentabilidade.

Relativamente a este assunto, as análises ACV e CCV podem contribuir bastante para a sustentabilidade do parque edificado. O paradigma do ciclo de vida está a tornar-se cada vez mais relevante em todos (ou na grande maioria) dos setores da sociedade. Os custos e impactes dos produtos ou serviços não são mais percecionados como um custo único, mas sim como a soma de todos os impactes ao longo do respetivo ciclo de vida. Assim sendo, as metodologias que consideram os impactes ou custos do ciclo de vida dos produtos ou serviços estão sendo progressivamente adotadas por profissionais (e.g. em esquemas de certificação) e por académicos. Ambas as metodologias ACV e CCV são reconhecidas internacionalmente (e.g. normas internacionais) e usadas para diferentes propósitos.

A integração da ACV e CCV com o BIM tem sido explorada na literatura recente, sendo argumentado que o uso de ferramentas BIM pode mitigar algumas das limitações das análises ACV e CCV (i.e. tempo consumido durante a recolha dos dados iniciais). Atualmente, foram observadas na literatura diferentes abordagens sobre a integração de BIM-ACV/CCV. Ora os investigadores recorrem ao uso de diversas ferramentas para a modelação de projetos e realização de análises da sustentabilidade ou então usam ferramentas BIM para a extração automática do mapa de quantidades, conectando-o com bases de dados ACV/CCV. No entanto, uma terceira abordagem ainda permanece pouco explorada, consistindo na incorporação de informação relativa à sustentabilidade dentro de modelos BIM, de modo a promover a realização de simulações automáticas e melhorar a troca de informação. Nesse sentido, visto que o BIM está fundamentalmente associado à troca e tratamento de informação ao longo de um projeto de construção, a interoperabilidade (i.e. a capacidade de trocar informação) entre diferentes programas assume um papel particularmente relevante no sucesso da sua adoção. Assim sendo, a identificação de informação útil a ser trocada entre as partes interessadas para a realização de análises da sustentabilidade é particularmente importante.

Deste modo, esta investigação pretende responder às seguintes questões: i) Que informação poderia ser incorporada nos objetos BIM de modo a possibilitar uma análise BIM-ACV/CCV?; ii) Quais os processos e troca de informações necessários para um esquema que implemente uma análise de ACV e CCV dentro de um ambiente BIM?; e iii) Como é que deve ser realizada uma análise automática de BIM-ACV/CCV caso a informação necessária tenha sido incorporada nos objetos?

Para responder à primeira questão de investigação, é feita uma revisão da literatura existente sobre o papel do BIM na construção sustentável, com particular ênfase na sua integração com a ACV e a CCV. Além disso, as normas internacionais sobre a aplicação de ACV e CCV na industria da construção são analisadas. Este processo permite a identificação da informação necessária para a realização das análises simplificadas e completas (i.e. *Streamlined* e *Complete*, respetivamente) de ACV e CCV num ambiente BIM, resultando no desenvolvimento do esquema BIM-ACV/CCV.

O conhecimento adquirido é então utilizado para responder à segunda pergunta, onde os processos e informações necessários para a realização de análises ACV e CCV num ambiente BIM são mapeados. Para tal, um *information delivery manual* (IDM) e um *model view definition* (MVD) são propostos, preenchendo uma lacuna no estado-da-arte neste domínio. Além disso, para promover uma troca de informação interoperacional para a implementação do esquema BIM-ACV/CCV, foi utilizado o esquema de dados *industry foundation classes* (IFC). O IDM/MVD 'Análise BIM-ACV/CCV' contém o Quê, Quando e Como todas as informações devem ser trocadas e tratadas para facilitar as análises de ACV e CCV num ambiente BIM.

Com base nas primeira e segunda respostas, uma ferramenta é desenvolvida para apoiar a resposta à terceira pergunta. A ferramenta de avaliação do ciclo de vida ambiental e económico baseada em BIM (BIMEELCA) é desenvolvida em linguagem C# e usa a plataforma de interface de programação de aplicativos (*application programming interface*) Revit API. Além disso, o esquema IDM/MVD e ferramenta BIMEELCA propostos são validados com um estudo de caso piloto. O estudo de caso representa um edifício de escritórios a ser construído na Holanda. Neste caso, observa-se que é possível uma análise automática de ACV/CCV simplificada, mas não uma análise completa. A necessidade de fornecer informações específicas do projeto é a principal razão pela qual uma análise completa e automática não é viável. No entanto, a incorporação de informação dentro do modelo BIM pode reduzir bastante a carga de trabalho e o tempo consumido para a realização de análises ACV e CCV.

Os resultados apresentados neste estudo indicam que a capacidade de adicionar ou editar informações ambientais e económicas dentro das ferramentas ACV ou CCV integradas com o BIM é fundamental para a realização de uma análise precisa do projeto. A flexibilidade das bases de dados e como as mesmas interpretam a informação contida nas ferramentas BIM influenciam bastante a qualidade e a representatividade dos resultados. Se apenas dados genéricos puderem ser usados nas análises, provavelmente os resultados obtidos não serão tão precisos como no caso de dados específicos (por exemplo, declarações ambientais de produtos) serem utilizados. Neste sentido, a principal contribuição da abordagem proposta nesta investigação consiste no uso de modelos BIM como repositórios de dados e na demonstração de como objetos BIM semanticamente ricos podem influenciar significativamente a automatização de simulações, promovendo assim a sustentabilidade da construção. Espera-se que o trabalho desenvolvido nesta pesquisa contribua para o desenvolvimento de simulações sustentáveis automáticas, criação de bibliotecas personalizadas de objetos BIM, e utilização de dados históricos contidos em modelos ricos em informação para análise preditiva.

Abstract

De hedendaagse samenleving evolueert geleidelijk naar een duurzamere ontwikkeling dan waargenomen in voorgaande generaties. Er is een groeiende bezorgdheid over de gevolgen van de ontwikkelde technologie voor de gezondheid van de mens en voor het milieu. Nationale en internationale initiatieven vinden plaats om het welzijn van de huidige generatie te bevorderen, maar, belangrijker, zorgen ervoor dat het welzijn van toekomstige generaties niet gehinderd wordt door niet-duurzame praktijken in het heden. In dit opzicht nemen regeringen wereldwijd maatregelen om de maatschappelijke impact op het milieu te verminderen. De Overeenkomst van Parijs is een van de meest recente mondiale conventies die de dreiging van de klimaatverandering wil aanpakken en tot dusverre de steun van 185 landen heeft verzameld. De Europese Unie is erg bezorgd over de gevolgen van de moderne samenleving en pleit voor de ontwikkeling van een efficiënte en duurzame maatschappij, rekening houdend met de ecologische, economische en sociale impact van de Europese lidstaten. Tussen 1990 en 2016 heeft de Europese Unie met succes het energieverbruik en de uitstoot van broeikasgassen verlaagd, terwijl het bruto binnenlands product steeg, wat aantoont dat een ontwikkeling op basis van de drie pijlers van duurzaamheid (dat wil zeggen economisch, ecologisch en sociaal) haalbaar is.

Op dit moment levert de gebouwde omgeving de grootste bijdrage aan de uitstoot van broeikasgassen en aan de grondstoffenconsumptie en is het één van de meest energie-intensieve sectoren wereldwijd. Deze sectoren die het meest beïnvloeden moeten worden getransformeerd voor het bereiken van de energie-efficiëntiedoelstellingen en het verminderen van emissies. Daarom moet de sector architectuur, engineering en constructie (AEC) duurzame methoden en state-of-the-art technologieën toepassen die bijdragen aan de duurzaamheid van de gebouwde omgeving.

Dit onderzoek concentreert zich op de ecologische en economische impact van de constructie en integreert de building information modelling (BIM) technologie en methodologie met de levenscyclusanalyse (LCA) en levenscycluskosten (LCC). De wereldwijde digitale transformatie in de sectoren leidde tot een paradigmaverschuiving in de bouwsector, resulterend in de opkomst van BIM. Op dit moment kan BIM worden gezien als een methodologie en als een technologie, afhankelijk van het doel waarvoor het wordt gebruikt. Aan de ene kant bestaat BIM uit de digitale weergave van een project (dit wil zeggen het BIM-model), dat parametrische en gegevensrijke objecten (technologisch domein) bevat. Anderzijds richt het zich op de collaboratieve omgeving die wordt gepromoot door het gebruik van op

BIM-gebaseerde hulpmiddelen en hoe en wanneer informatie moet worden gedeeld tussen de belanghebbenden (methodologisch domein). De parametrische modellering en visualiseringskracht van BIM toont het potentieel ervan in de verschillende gebieden van de bouwsector, zoals schemabeheer (i.e. 4D BIM), kostenraming (i.e. 5D BIM), duurzaamheidssimulaties (i.e. 6D BIM) of faciliteitenbeheer (i.e. 7D BIM). BIM is dus het meest geschikte middel om automatische of semi-automatische simulaties uit te voeren in een breed scala van domeinen, met name in het duurzaamheidsdomein.

In dit opzicht kunnen LCA- en LCC-analyses een grote bijdrage leveren aan de duurzaamheid van de gebouwde omgeving. Het levenscyclusparadigma wordt steeds relevanter in alle (of de meeste) sectoren van de samenleving. De kosten en impact van producten of diensten worden niet langer als één enkele kostenpost beschouwd, maar als de som van alle effecten gedurende de overeenkomstige levenscyclus. Daarom worden methodologieën die rekening houden met de levenscycluseffecten of kosten van producten/diensten geleidelijk door professionals (bijvoorbeeld in certificatieschema's) en door wetenschappers overgenomen. Zowel LCA- als LCC-methodologieën worden internationaal erkend (bijvoorbeeld in internationale normen) en worden voor verschillende doeleinden gebruikt.

De integratie van LCA en LCC met BIM is in de recente literatuur verkend, waarbij wordt betoogd dat het gebruik van BIM-tools een groot deel van de beperkingen van LCA- en LCC-analyses (bijvoorbeeld tijdverslindend bij het verzamelen van de invoergegevens) aanzienlijk kan beperken. Momenteel worden verschillende benaderingen waargenomen in de BIM-LCA/LCC-integratieliteratuur. Experts gebruiken ofwel een breed scala aan hulpmiddelen voor het modelleren van het project en het uitvoeren van verschillende simulaties, of gebruiken BIM-tools om de meetstaat automatisch te extraheren en te koppelen aan LCA/LCC-databases. Een derde benadering blijft echter nog onontgonnen, namelijk de integratie van duurzame informatie binnen BIM-modellen om automatische simulaties te bevorderen en informatie-uitwisseling te verbeteren. Aangezien BIM fundamenteel wordt geassocieerd met de uitwisseling en verwerking van informatie in een bouwproject, neemt de interoperabiliteit (dat wil zeggen het vermogen om informatie uit te wisselen) tussen verschillende programma's een bijzonder relevante rol in bij de succesvolle toepassing ervan. Daarom is de identificatie van nuttige informatie die moet worden uitgewisseld tussen belanghebbenden voor de uitvoering van een duurzaamheidsanalyse bijzonder belangrijk.

Volgende vragen worden daarom is dit onderzoek beantwoord: i) Welke informatie kan worden opgenomen in BIM-objecten om een BIM-LCA/LCC-analyse mogelijk te maken ?; ii)

Welke processen en informatie-uitwisseling zijn nodig voor een kader waarin LCA- en LCC-analyse geïmplementeerd wordt in een op BIM-gebaseerde omgeving?; en iii) Hoe moet een automatische BIM-LCA/LCC-analyse worden uitgevoerd als de benodigde informatie is verwerkt in objecten?

Om de eerste onderzoeksvraag te beantwoorden, wordt een overzicht van de bestaande literatuur over de BIM-rol in duurzame constructies uitgevoerd, met bijzondere nadruk op de integratie ervan met LCA en LCC. Verder wordt een overzicht gegeven van de internationale standaarden voor LCA- en LCC-toepassingen in de bouwsector. Dit proces draagt bij tot de identificatie van de informatie die nodig is voor het uitvoeren van gestroomlijnde en volledige LCA- en LCC-analyses in een op BIM-gebaseerde omgeving. Dit leidt tot de ontwikkeling van het BIM-LCA/LCC kader.

Deze kennis wordt vervolgens gebruikt om de tweede vraag te beantwoorden, dit wil zeggen de processen en informatie voor het uitvoeren van een BIM-gebaseerde LCA- en LCC-analyse worden in kaart gebracht. Daartoe worden een handboek voor informatie-aanlevering ‘information delivery manual’ (IDM) en een ‘model view definition’ (MVD) voorgesteld, waarmee een lacune in de state-of-the-art in dit domein wordt opgevuld. Om een interoperabele informatie-uitwisseling voor de implementatie van het BIM-LCA/LCC-kader te bevorderen, werd bovendien het gegevensschema van de ‘industry foundation classes‘ (IFC) gebruikt. De IDM/MVD 'BIM-LCA/LCC-analyse' bevat Wat, Wanneer en Hoe alle informatie moet worden uitgewisseld en verwerkt om de LCA- en LCC-analyses binnen een BIM-gebaseerde omgeving te vergemakkelijken.

Voortbouwend op de eerste en tweede antwoorden is een prototype ontwikkeld om het antwoord op de derde vraag te ondersteunen. De BIM-gebaseerde ecologische en economische levenscyclusanalyse (BIMEELCA) tool is ontwikkeld in programmeertaal C # en maakt gebruik van een Revit application programming interface (API) platform. Bovendien zijn het voorgestelde kader, IDM/MVD en de tool gevalideerd met een proefcasus. De casus is een kantoorgebouw dat momenteel wordt gebouwd in Nederland. In dit verband wordt opgemerkt dat een automatische gestroomlijnde LCA/LCC-analyse mogelijk is maar geen volledige LCA/LCC-analyse. De noodzaak om projectspecifieke informatie aan te leveren is de belangrijkste reden waarom een uitgebreide en automatische analyse niet haalbaar is. Niettemin kan de integratie van informatie binnen het BIM-model de werkdruk en de verbruikte tijd voor het uitvoeren van LCA- en LCC-analyses aanzienlijk verminderen.

De bevindingen in dit onderzoek tonen aan dat het vermogen om ecologische en economische informatie toe te voegen of te bewerken binnen de LCA- of LCC-tools geïntegreerd met BIM fundamenteel is voor een nauwkeurige analyse van het project. De flexibiliteit van de databases en hoe deze de informatie in de BIM-tools leest, heeft grote invloed op de kwaliteit en representativiteit van de resultaten. Als er alleen generieke gegevens kunnen worden gebruikt in de analyses, zijn de verkregen resultaten waarschijnlijk niet zo precies als wanneer specifieke gegevens (bijvoorbeeld environmental product declarations) zouden worden gebruikt. In dit opzicht is de belangrijkste bijdrage van de in dit onderzoek voorgestelde benadering het gebruik van BIM-modellen als gegevensopslagplaatsen en het aantonen van hoe semantisch rijke BIM-objecten de automatisering van simulaties aanzienlijk kunnen beïnvloeden en zo de duurzaamheid van constructies kunnen bevorderen. Het werk dat in dit onderzoek is ontwikkeld, zal naar verwachting bijdragen aan de ontwikkeling van automatische duurzaamheidssimulaties, het creëren van op maat gemaakte BIM-objectenbibliotheken en het gebruik van historische gegevens in data-rijke modellen voor voorspellende analyses.

Keywords:

building information modelling, life cycle assessment, life cycle costing, environmental impact, information exchange

Palavras-Chave:

building information modelling, avaliação do ciclo de vida, custo de ciclo de vida, impacte ambiental, troca de informação

Trefwoorden:

building information modelling, levenscyclusanalyse, levenscycluskosten, ecologische voetafdruk, informatie-uitwisseling

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List of acronyms

ADPE – Abiotic depletion potential for fossil fuels

ADPM – Abiotic depletion potential of materials

AEC – Architecture, Engineering, and Construction

AP – Acidification potential

API – Application Programming Interface

BIM – Building Information Modelling

BIMEELCA - BIM-based Environmental and Economic Life Cycle Assessment

BPMN – Business process modelling notation

BR – Business rules

BREEAM - Building Research Establishment Environment Assessment Method

EIAM - Environmental Impact Assessment Methods

EP – Eutrophication potential

EPD – Environmental product declaration

ER – Exchange requirements

EUPPD – European Union Public Procurement Directive

FP – Functional parts

GWP – Global warming potential

IDM – Information Delivery Manual

IFC – Industry Foundation Classes

ISO – International Organization for Standardisation

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

LCI – Life Cycle Inventory

LEED – Leadership in Energy and Environmental Design

LOD – Level of Development

MEP – Mechanical, electrical and plumbing

MVD – Model View Definition

ODP – Ozone depletion potential

PE-NRe – Primary energy - non-renewable energy

PE-Re – Primary energy - renewable energy

PM – Process map

POCP – Photochemical ozone creation potential

SC – Sustainable Construction

UI – User Interface

WPF – Windows Presentation Foundation

Chapter 1 – Introduction

A brief overview of the research aims and questions is presented in this chapter. The research design is described, in which a succinct description of the methodology and research steps is given. In the end, the structure of the thesis is presented.

Metropolitan areas are considered primary contributors to climate change, consuming approximately 70% of the global energy [1, 2]. Currently, the building sector is the main contributor of 36–38% greenhouse gas emissions in the EU and US and accounts for 40% of the energy consumption in both regions [3-5]. It is also responsible for 20% of the total energy consumed worldwide, with the residential sector growing between 1.4% and 2.1% per year on average [6]. With the building sector as the main contributor of greenhouse gas emissions and consumer of the half of raw materials in the EU and US [3, 7], it is extremely important to develop adequate regulations to support more sustainable construction, to achieve the Kyoto emission targets and the recent Paris Agreement goals [8]. These statistics show that the European Union must greatly improve the performance of the built environment to achieve the sustainable targets set to 2020, 2030, and 2050, by increasing the energy efficiency of buildings and by reducing the greenhouse gas emissions by 80-95% by 2050, compared to the levels of 1990 [9-15]. Between 1990 and 2016, the EU successfully reduced the energy consumption and greenhouse gas emissions by 22%, while the GDP increase by 54% [13, 14]. This demonstrates that it is possible to have an economic growth while reducing the environmental impacts of the society.

The concept of sustainability has been discussed by several authors in previous decades, having inclusively over 200 definitions [16]. For instance, Schellnhuber [17] argues that sustainability means the capacity to avoid being in catastrophic domains (i.e. situation where the quality of the socio-ecological system fails to provide the necessary resources). Another interpretation of the sustainability concept is presented by Gallopín [18], who argues that, in order for socio-ecological systems to be considered as sustainable, certain attributes must be respected, such as availability of resources, adaptability and flexibility, resilience, robustness, and empowerment. Parkin [16] focused on a scientific perspective and argued that to ensure a sustainable society, a set of four conditions should be respected: materials should not be extracted at a faster rate than they can regenerate; synthetic materials should not be produced at a faster rate than they can be absorbed through natural processes; biodiversity of ecosystems should be preserved; and human needs should be achieved by efficient means. Building on Parkin's premises, Lutzkendorf and Lorenz [19] argued that the sustainable development corresponds to "*a desirable model or overall concept for the process of economies', societies' and individual humans' development or evolution respectively*". However, perhaps the most accepted definition for sustainable development resulted from the Brundtland Report in 1987, as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [20-22]. Presently, the sustainability concept is based on three pillars [19], the environmental, economic, and social, and is supported by the international community, i.e. International Organisation for Standardisation (ISO) through ISO 15392:2008 and by the European Commission through EN 15643-1:2010 [23, 24].

The construction industry can be considered as one of the cornerstones for the sustainable development of society, considering that buildings are of high economic significance and have a substantial impact on the environment and quality of life [25, 26]. Buildings are presumed sustainable if their environmental, economic, and social impacts on the community are properly resolved [27, 28] and contribute to the sustainable development of society [19, 29]. These buildings require thorough multi-disciplinary collaboration among stakeholders from early phases of the project and careful material selection [25, 30, 31]. In the past, it was perceived that buildings that were considered sustainable would initially cost approximately 15% more than traditional ones do [32]. However, several studies now suggest that initial costs of sustainable buildings are not higher than those of traditional buildings [19]. Thus, such buildings are attractive assets for facility owners, including the public and commercial sectors [30].

When designing a sustainable construction, several aspects must be taken into consideration as the life cycle costing, energy consumption and HVAC system design, life cycle environmental impacts, land use, resource usage, natural ventilation, thermal performance, shading systems, sound insulation, daylighting, and preservation of building's cultural heritage [19, 25, 30, 33]. The use of renewable energy in buildings is not a sustainable solution by itself, however, it must be complemented with high energy and thermal efficiency design, so that only the necessary energy is consumed [33].

Considering the aspects mentioned above, several studies have been conducted in the past years. The existing literature on sustainable construction suggests that researchers found the integration of environmental and economic assessment for the promotion of sustainable constructions considerably important [28, 29, 32], where life cycle costing (LCC) and life cycle assessment (LCA) were used. It is argued that construction professionals must be adequately informed of the life cycle of the economic and environmental impacts of buildings for them to influence key stakeholders to employ more sustainable solutions. Integration models of the economic and environmental assessment of the buildings' life cycle are often proposed in the literature, as the economic input-output analysis-based life-cycle assessment (EIO-LCA) model [34, 35], assessment of environmental impacts of buildings and their corresponding eco-costs [36, 37], and the integration of LCC with LCA [19]. In contrast, the social aspect of the sustainability of construction is still being explored due to the complexity of its ramifications between the built environment and the society (e.g. social segregation, urban design quality) [19]. Moreover, the integration of technologies such as building information modelling (BIM) with LCA and LCC has been recently explored in the literature, due to BIM's potential to enhance the sustainable design of construction [38-41].

On one hand, there is the digital representation of a model (BIM model) that contains parametric objects enriched with semantic information of the full life cycle of the project to facilitate the design, construction and operations processes [42, 43]. Recent research shows that the BIM methodology improves the flow of information between the parties involved in a project and encourages new design solutions. It also reduces the amount of time and money expended on a project, through highly accurate cost estimation, clash detection and other mechanisms [44]. Furthermore, the European Union approved the European Union Public Procurement Directive (EUPPD) in 2014 [45], which aims to modernise the existing EU public procurement rules by simplifying the procedures, making them more flexible and encouraging the use of BIM in public works. On the other hand, there are two methods that assess the environmental and economic impacts of the building over its life cycle. For the environmental analysis of buildings, the application of LCA has increased greatly in the past years due to its inclusion in certification schemes as BREEAM and LEED [46-48] and promotion by the European Commission, which is actively encouraging the use of the LCA method to evaluate the potential environmental impacts of products [48-50]. For the economic evaluation of buildings, the use of LCC to understand the benefits over the life cycle cost of green solutions and its requirement in public tenders in some countries encouraged the use of this method recently [51, 52].

The BIM-LCA/LCC integration is currently a new trend in the construction industry, with several scholars arguing that the limitations of LCA and LCC studies could be reduced if BIM tools were used, particularly due to its automatic quantity take-off [47, 48, 52-57]. However, existing approaches either focus on the use of BIM together with several software or solely use it for an automatic quantity take-off. As indicated in the literature, the lack of semantic information within BIM models can lead to ineffective decision-making processes and to models that are not suitable for the operation and maintenance stages [58-62]. Therefore, this research aims to improve the performance of sustainability simulations throughout the project's life cycle by considering BIM, LCA and LCC in an integrated way.

1.1. Research questions and aims

The proposed research focuses on the integration of BIM with LCA and LCC, as the independent variables, to improve the sustainability of the construction, the dependent variable. This research addresses the following questions (Q) and hypotheses (H):

Q1: Which information could be incorporated in BIM objects to enable a BIM-LCA/LCC analysis?

H1: For LCA, products with Environmental Product Declarations (EPDs) can have the LCA results and service life incorporated in the objects, while, for LCC, products can have the corresponding acquisition costs, service life, and density.

Q2: Which processes and exchange of information are necessary for a framework that implements an LCA and LCC analysis within a BIM-based environment?

H2: It is expected that the use of methodologies such as information delivery manual (IDM) and model view definition (MVD) would contribute to the identification of the processes and exchange of information required for a BIM-based LCA and LCC analysis.

Q3: How has an automatic BIM-LCA/LCC analysis to be conducted if the necessary information is incorporated in objects?

H3: Although a streamlined LCA/LCC analysis could be done automatically, considering just the production phase (A1-A3 modules), a complete LCA/LCC analysis cannot.

Moreover, this research expects to achieve the following objectives: i) assess the environmental and economic impact of buildings by using LCA and LCC methods; ii) use BIM-based tools to improve the efficiency and reduce time spent for the LCA and LCC analysis; iii) identify which information can be incorporated in BIM objects to enable LCA and LCC analyses; iv) propose a framework for BIM-LCA/LCC analysis; v) develop a methodology to handle the information exchange required to perform the LCA and LCC analyses within a BIM-based environment; and vi) develop a tool that allows an automatic (early phase of project) and comprehensive (later phase of project) analysis of buildings' sustainability.

1.2. Proposed Research Design

1.2.1. Proposed Methodology

The methodology used in this research will be based on a quantitative approach to test and validate the hypotheses mentioned previously. In that sense, the research design will be based on a systematic review, data mapping, computer simulation, secondary data collection, and pilot case study.

Firstly, a detailed and consistent literature review on key findings about the following concepts is made: Sustainable Construction, LCA, LCC, and BIM. Secondly, the literature that focuses on the integration of BIM with LCA and LCC is analysed.

The information required for a BIM-based LCA and LCC analysis is identified, based on existing models and international standards. Aspects such as the goal of the LCA/LCC study, which type of data is more suitable for each level of development (LOD) of the BIM model, and which environmental impact assessment method is to be used in the LCA study are specified and justified. This resulted in the BIM-LCA/LCC framework, which is used to test and validate the research hypothesis.

Furthermore, the information and processes required for a BIM-based LCA and LCC analysis are mapped and detailed using the information delivery manual (IDM) and model view definition (MVD) methodologies. This contributes to the understanding of What, When and How the information should be shared and used in an LCA and LCC analysis.

The concepts and processes identified in the framework and IDM/MVD are then converted into a prototype tool, which is used in the environmental and economic assessment of construction projects.

At last, the implementation of the proposed framework and research hypotheses validation are tested with a suitable pilot case study. For that purpose, specific environmental and economic data are collected. The results of the proposed approach are then compared with existing traditional approaches.

1.2.2. Expected results

It is expected that the proposed research contributes to the:

- Assessment of the environmental and economic impact of buildings by using LCA and LCC methods;

- Identification of the required information to conduct an LCA and LCC study either at initial or later stages of the projects;
- Development of a framework that can intuitively be used for the environmental and economic assessment of the project;
- Contribution to the background knowledge on BIM-LCA/LCC integration and provide outcomes that can be used by BIM software developers for the development of dedicated applications.

1.3. Chapters of the Thesis

The structure of the thesis is presented next:

In **Chapter 1** a brief contextualisation of the research domain is introduced. Additionally, the research questions and hypotheses are presented. At last, the methodology followed in the research and the expected results are discussed.

Afterwards, an extensive literature review to introduce BIM and its role in the sustainable construction is performed in **Chapter 2**. The gaps in the literature and BIM's potential for the LCA/LCC integration are identified, supporting the research aim.

The research design is then detailed in **Chapter 3**. In this chapter, the research questions and hypotheses are presented, building on the literature review conducted before. Furthermore, the LCA and LCC frameworks are described and the methodology used in this research is explained. Building on the findings presented in this chapter, a BIM-based LCA/LCC framework is proposed.

The proposal of an IDM and MVD that supports the information exchange within a BIM-based environment for the performance of a Streamlined and Complete LCA and LCC analysis is presented in **Chapter 4**. This information contributes to the development of tools that support the execution of the LCA and LCC framework presented in the previous chapter.

A prototype tool that is developed to support the implementation of the framework is described in **Chapter 5**. The required steps to convert the proposed framework into a BIM-based tool are briefly detailed.

In **Chapter 6**, the proposed framework and developed tool are tested and validated through the Pilot Case Study method. In this chapter, the materials and construction elements used in the case study and their respective environmental and economic information are identified. Furthermore, the proposed BIM-LCA/LCC approach is compared with existing traditional approaches.

Lastly, in **Chapter 7**, the general conclusions, main contributions, and further developments are discussed.

Chapter 2 – Review of literature on the role of BIM in sustainable construction

A review on the role of BIM in the sustainable construction literature is performed in this chapter. The content analysis is based on two review articles published in the 'Automation in Construction' journal [63, 64]. The period of analysis of the articles was updated in order to cover the literature published until end of 2018. Moreover, the literature on the integration of BIM with LCA and LCC is explored, in which existing approaches are identified. The findings presented in this chapter will contribute to the improvement of LCA and LCC analyses within a BIM-based environment and, consequently, to the development of a suitable BIM-LCA/LCC framework.

The term "Building Information Model" first appeared in 1992, in the "Modelling multiple views on buildings" article [65]. In this article, the authors proposed a new approach for modelling building information based on multiple aspects (e.g. structural, energy). Since then, the research on BIM (also known as Building Information Modelling) methodology grew significantly (as visualised in Figure 1). Currently, BIM is an emerging paradigm in the construction industry and refers to the use of a shared digital representation of a built object to facilitate the design, construction, and operation processes and to form a reliable basis for decision making [43].

The BIM paradigm is seen as a methodology and as a technology [63]. On the one hand, as a methodology, BIM foster closer cooperation between all the various technical teams involved in the different stages of a construction project's life-cycle [66]. On the other hand, BIM is a 3D technology that digitalises the building and incorporates all the information existing and generated throughout its life cycle, serving as a digital data repository. It is also a parametric model that can be used for several types of analyses (e.g. structural, energy, daylighting). Recent studies show that the BIM methodology improves the flow of information between the parties involved in a project and encourages new design solutions. It also reduces the amount of time and money expended on a project, through highly accurate cost estimation, clash detection and other mechanisms [44]. BIM is, however, only the visible side of a larger digitalisation paradigm, with some inherent challenges, ranging from the structuring of classification systems, mapping processes, supply chain integration, creation of BIM-based objects and their properties, integration of asset management systems, among others.

2.1. Worldwide BIM implementation

Acknowledged as the future of the construction industry, BIM is being standardised through national and international initiatives. In the EU, some countries already have a generalised and compulsory implementation of BIM in their national industry, with the northern countries leading that transformation. One of the key moments in the adoption of BIM was the speech of Francis Maude, Minister for the Cabinet Office of the United Kingdom (UK), in 2012. Francis Maude's speech positioned the UK as the spearhead of BIM compulsory adoption in the EU, stating that from 2016 onwards all Government projects required fully collaborative BIM models, as detailed in the 'Government Construction Strategy' document, published in 2011 [67]. To make that vision a reality, the UK Government created the initiative 'BIM Task

Group' that, alongside with other initiatives as the 'AEC (UK) Initiative' and 'National BIM Library' (NBS), contributed to the development of several documents as the PAS1192-2 [68] (superseded by ISO 19650-1:2018 [69]), the 'AEC (UK) BIM protocol' [70], 'NBS BIM Object Standard' [71], and more recently the 'Digital Built Britain' document, that paves the way for the implementation of BIM level 3 (i.e. BIM projects that focus on life cycle asset management) in a more digitalised British industry [72]. The BIM Execution Plan (BEP), a document that stipulates the procedures, roles, and responsibilities of the stakeholders involved in a project, is another work that was developed based on British standards, such as the PAS1192-2.

Other European countries are also committed to the implementation of BIM such as Norway, that promotes the use of BIM in e-procurement processes since 2000 and has been developing several BIM guides (e.g. 'Statsbygg BIM Manual') [73]. Finland, that has been working on the implementation of BIM since 2001, stated that from 2007 onwards all public projects required open BIM (i.e. using Industry Foundation Class (IFC) format) [74], and developed a set of 13 BIM guides named COBIM [75]. More recently, Germany and France created their own BIM task groups, the 'Planen Baunen 4.0' [76] and the 'Plan Transition Numérique dans le Bâtiment' (PTNB) [77] respectively, with the purpose of developing BIM Roadmaps and implementing a strategy for the gradual adoption of BIM. Recognising the growing concern of its Member States for the standardisation of BIM, the European Commission created the EU BIM Task Group and CEN/TC 442 – BIM, the European Committee for BIM standardisation, responsible for the development of BIM Standards and BIM dissemination [78, 79]. At last, *'Comissão Técnica'* CT197-BIM and the *'Belgian Building Research Institute'* (BBRI) in Portugal and Belgium, respectively, are closely following the work developed in CEN/TC 442, which is currently developing information classification systems, data dictionaries, and guidelines according to the needs of the national markets [80, 81].

Other non-EU countries have also recognised BIM potential and developed their own specifications and standards. In 2003, the US 'General Services Administration' (GSA) [82] created the 'National 3D-4D-BIM Program', which allowed the 'National Institute of Building Science' (NIBS) to develop several BIM standards and guides known as 'National Building Information Modelling Standards' (NBIMS) [83]. Another important document was published in 2007, the 'Construction Operations Building Information Exchange' (COBie) [84], which consists in an Excel file that contains all the information of a BIM model in a structured way.

Singapore is another country that is investing in the adoption of new technologies in industry, since 1998. The Singapore Building and Construction Authority (BCA) enabled an electronic submission of BIM files (BIM e-submission) through the 'COnstruction Real Estate NETwork' (CORENET) in 2008, published in 2010 the 'BIM Roadmap', and the 'Singapore BIM Guide' [85] in 2012. Hong Kong is also promoting the use of BIM since 2006 through the 'Hong Kong Housing Authority', that developed a set of guides and standards for the use of BIM, as the 'BIM Standards Manual' [86]. The 'Hong Kong Institute of Building Information Modelling' (HKIBIM) created in 2009 the initiative that intended to disseminate BIM and train professionals. Furthermore, in 2014, the 'Working Group for BIM Implementation' published the document 'BIM Roadmap' that contains several initiatives for BIM implementation in Hong Kong [87].

2.2. Literature review on Building Information Modelling

A review of the literature on BIM, based on a search in the Web of Science database that focused only on peer-reviewed journal articles, was performed (the methodology is presented in [63]). The review shows that there has been an increase in published peer-reviewed papers on BIM from four, in 2006, to 304, in 2018 (Figure 1). Furthermore, the literature was grouped into several categories according to specific major categories (Figure 2).

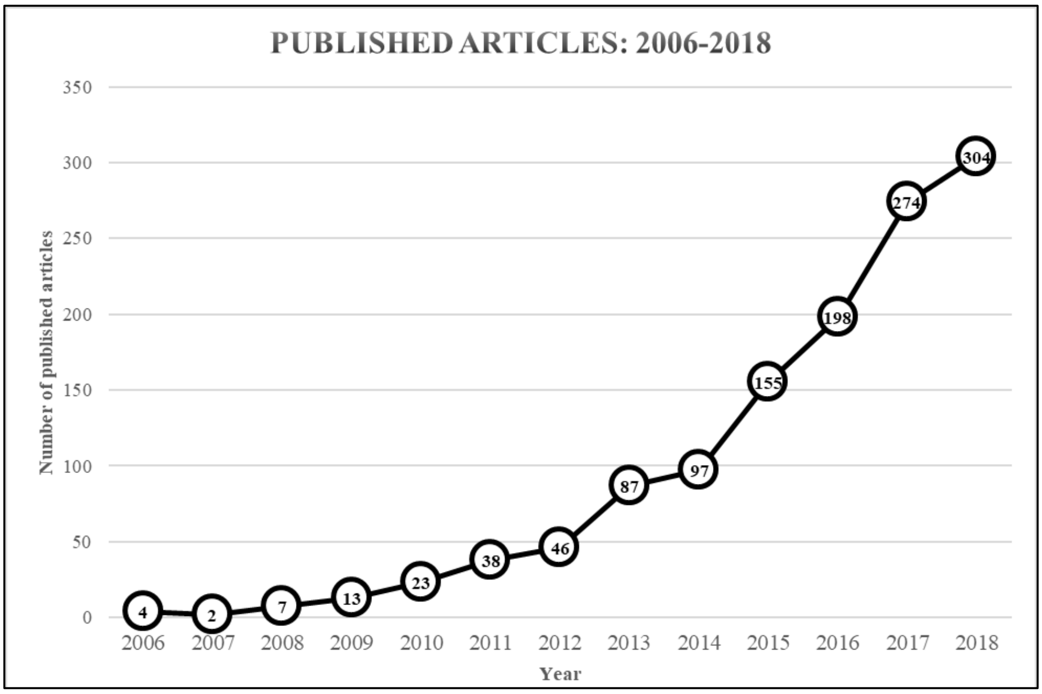


Figure 1 - BIM papers published between 2005-2018

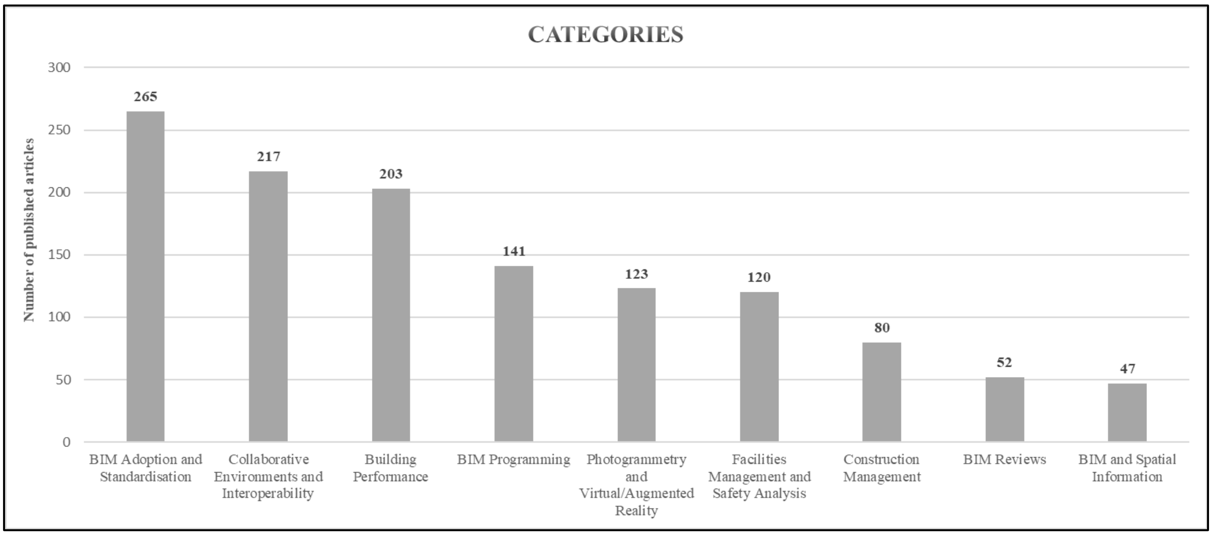


Figure 2 - BIM Categories

BIM Adoption and Standardisation (Table 1) is the category with the highest number of published papers, being an area that has been explored since the early phases of BIM research. The topics covered by this category are: (i) BIM Adoption; (ii) BIM Benefits & ROI; (iii) BIM Training & Education; and (iv) Rule Checking & Standards. The first identifies the challenges of adopting BIM at national and at organisation level and studies how it could be promoted through procurement. The second covers a number of studies focused on the benefits of using BIM in projects and return on investment (ROI) analysis. The third explores the benefits of introducing BIM in training or academic courses. At last, the fourth covers studies that promote the automation of rules checking and analysis of standards.

Table 1 - BIM Adoption and Standardisation Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
BIM Adoption and Standardisation	*0*	*0*	*2*	*2*	*8*	*6*	*9*	*20*	*14*	*37*	*39*	*64*	*64*	**265**	21.2%
BIM Adoption	0	0	0	2	5	3	2	10	4	16	19	38	34	**133**	10.7%
BIM benefits & ROI	0	0	1	0	0	1	4	4	5	7	4	14	15	**55**	4.4%
BIM training & education	0	0	0	0	1	1	3	4	4	7	11	9	10	**50**	4.0%
Rule Checking & Standards	0	0	1	0	2	1	0	2	1	7	5	3	5	**27**	2.2%

Collaborative Environments and Interoperability (Table 2) is the category with the second most papers published, covering the following sub-categories: (i) Interoperability & IFC; (ii) Collaborative Environments; (iii) Semantic BIM and Ontology, and (iv) Knowledge & Information Management. The first sub-category covers several works that have been done on the improvement of the interoperability between BIM tools for different applications. The second focuses on the benefits of BIM regarding team collaboration. The third covers the study on BIM semantics and ontology (i.e. identification of concepts and their relationship in a specific domain). The recent interest was probably encouraged by the increasing adoption of BIM throughout the world, by the increase of existing standards, and by the development of BIM data dictionaries. The last focuses on the exchange and management of information and knowledge within the BIM environment.

Table 2 - Collaborative Environments and Interoperability Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
Collaborative Environments and Interoperability	*1*	*2*	*0*	*3*	*7*	*7*	*8*	*17*	*9*	*31*	*35*	*51*	*46*	*217*	*17.4%*
Interoperability and IFC	1	2	0	1	2	1	3	6	5	7	10	10	17	**65**	5.2%
Collaborative Environments	0	0	0	1	3	1	3	3	0	6	6	23	15	**61**	4.9%
Semantic BIM and Ontology	0	0	0	1	0	2	0	5	2	16	11	10	5	**52**	4.2%
Knowledge and Information Management	0	0	0	0	2	3	2	3	2	2	8	8	9	**39**	3.1%

Building performance (Table 3) is increasingly becoming one of the most crucial targets for building in the EU, with environmental performance and energy efficiency at the forefront of this trend. Hence, the identified sub-categories are: (i) Energy Performance; (ii) Environmental Performance; and (iii) Indoor Quality Performance. The first covers studies on renewable energy potential (e.g. use of photovoltaics), automation of energy analysis, and also the study of the impact of human behaviour on energy consumption. The second includes works that assess the environmental impacts of construction products or whole buildings, different environmental assessment methods, or green certification. The last sub-category groups the works that aim to improve the indoor conditions such as the thermal conditions and daylighting analysis.

Table 3 – Building Performance Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
Building Performance	*0*	*0*	*0*	*1*	*0*	*8*	*7*	*13*	*21*	*22*	*28*	*49*	*54*	*203*	*16.3%*
Energy Performance	0	0	0	1	0	4	3	7	11	7	16	15	20	**84**	6.7%
Environmental Performance	0	0	0	0	0	3	2	4	5	11	7	20	29	**81**	6.5%
Indoor Quality Performance	0	0	0	0	0	1	2	2	5	4	5	14	5	**38**	3.0%

Most papers in the BIM Programming category (Table 4) deal with the area of BIM tool development. Even though this field began to be explored in 2006, it is still developing, which seems to indicate that, whilst it is not a new trend, it still has a lot of potential. As a result, this category includes the following sub-categories: (i) BIM Tool Development; (ii)

Cloud Computing; and (iii) Parametric Modelling. The first grouped works that focused on the development of BIM tools for the optimisation and process automation. The second included articles that studied the benefits of internet-based computing integration with BIM applications. At last, Parametric Modelling covers studies that focus on the benefits of information manipulation of BIM objects.

Table 4 - BIM Programming Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
BIM Programming	***3***	***0***	***1***	***5***	***4***	***4***	***6***	***10***	***11***	***15***	***27***	***23***	***32***	***141***	***11.3%***
BIM Tool development	2	0	1	4	2	2	4	5	8	12	23	18	24	**105**	8.4%
Cloud Computing	0	0	0	0	2	1	1	2	3	2	3	4	3	**21**	1.7%
Parametric Modelling	1	0	0	1	0	1	1	3	0	1	1	1	5	**15**	1.2%

The Photogrammetry and Virtual/Augmented Reality (Table 5) category provides some insight into the research work carried out in the fields related to image processing and improvement. The sub-categories are the following: (i) Laser Scanning; (ii) Augmented and Virtual Reality; and (iii) Image Processing. The articles that focus on the automatic BIM model generation based on the point cloud by using 3D laser scanning technology were grouped in the first sub-category while studies that cover the integration of BIM with Augmented Reality (AR) and Virtual Reality (VR) technology were grouped in the second sub-category. Lastly, works that focused on the image analysis and BIM (e.g. use pictures to either monitor as-constructed or as-built projects) were grouped in the last sub-category.

Table 5 - Photogrammetry and Virtual/Augmented Reality Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
Photogrammetry and Virtual/Augmented Reality	***0***	***0***	***0***	***1***	***2***	***3***	***3***	***10***	***12***	***15***	***20***	***13***	***44***	***123***	***9.9%***
Laser Scanning	0	0	0	0	2	1	1	5	6	11	14	8	24	**72**	5.8%
Augmented and Virtual Reality	0	0	0	0	0	1	1	4	4	2	3	2	12	**29**	2.3%
Image Processing	0	0	0	1	0	1	1	1	2	2	3	3	8	**22**	1.8%

Facilities Management (FM) and Safety Analysis (Table 6) is one of the categories with the lowest number of papers. However, in the past three years it has attracted the interest of several researchers. The analysis of this category led to the definition of the following sub-categories: (i) Safety Management; and (ii) Building Management and Maintenance. In the first it is possible to find numerous studies that focus on different aspects of safety analysis, as fire safety, safety during construction works, prediction of possible collisions due to changes in the construction schedules, or even enhance tower crane planification. The other sub-category covers studies that explore the maintenance processes and automatic processes to support building management (e.g. potential of using sensors to improve the monitoring of constructions).

Table 6 - Facilities Management and Safety Analysis Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
Facilities management and Safety Analysis	***0***	***0***	***0***	***0***	***0***	***3***	***3***	***6***	***9***	***13***	***22***	***31***	***33***	***120***	***9.6%***
Safety Management	0	0	0	0	0	3	2	4	6	9	10	16	16	**66**	5.3%
Building Management and Maintenance	0	0	0	0	0	0	1	2	3	4	12	15	17	**54**	4.3%

Registering an inconsistent growth in recent years, the Construction Management category (Table 7) has attracted increasing attention lately mainly due to research done in Schedule Management. This category is made up of the following sub-categories: (i) Schedule Management; (ii) Quantity Take-off; and (iii) Cost Estimation. The earlier studies focused mainly on the area of Schedule Management (also known as 4D BIM), with authors focusing on schedule improvements through BIM-based frameworks and applications, optimisation methods, and benefits of automation. The other sub-category is Cost Estimation, with some authors developing automatic tools or processes for building cost estimation (5D BIM) that either focus on the traditional cost estimation of construction projects or on a life cycle perspective, in which life cycle costing (LCC) methods are used. The last sub-category encompasses works that specifically focus on the improvement of BIM's automatic quantity take-off.

Table 7 - Construction Management Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
Construction Management	***0***	***0***	***3***	***0***	***2***	***0***	***7***	***6***	***12***	***5***	***9***	***22***	***14***	***80***	***6.4%***
Schedule Management	0	0	3	0	0	0	3	4	9	4	4	15	4	**46**	3.7%
Cost Estimation	0	0	0	0	1	0	4	1	2	1	5	5	10	**29**	2.3%
Quantity Take-off	0	0	0	0	1	0	0	1	1	0	0	2	0	**5**	0.4%

BIM and Spatial Information (Table 8) is the category that has the fewest papers in the analysed literature (not considering the BIM Review category). The sub-categories identified were based on two major subjects: (i) Geographical Information System (GIS); and (ii) Space Syntax. The first field to be explored in this category by researchers was the integration of BIM with Geographical Information System (GIS), with authors using BIM-GIS for a range of purposes such as emergency responses, BIM-based schedule management (in which potential suppliers near the construction site are identified), operation and maintenance stages or for urban management. The other sub-category that was identified is Space Syntax, a domain that makes use of spatial configurations (e.g. topological) to predict movement patterns and human behaviour.

Table 8 - BIM and Spatial Information Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
BIM and Spacial Information	***0***	***0***	***1***	***0***	***0***	***4***	***2***	***3***	***3***	***3***	***11***	***10***	***10***	***47***	***3.8%***
Geographical Information System (GIS)	0	0	1	0	0	2	0	1	1	3	9	6	9	**32**	2.6%
Space Syntax	0	0	0	0	0	2	2	2	2	0	2	4	1	**15**	1.2%

The category of BIM reviews collects all the articles that reviewed BIM literature in a specific field (e.g. rule checking systems, construction safety, structural design, sustainability) or generally (Table 9).

Table 9 - BIM Reviews Category

Category and Sub-categories	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	%
BIM Reviews	***0***	***0***	***0***	***1***	***0***	***3***	***1***	***2***	***6***	***14***	***7***	***11***	***7***	***52***	***4.2%***

The analysis of existing BIM literature revealed that the subjects that can be considered as new trends or as having potential are: i) the development of BIM-based tools; ii) BIM adoption (in which underdevelopment countries are only now publishing the challenges of BIM implementation); iii) Semantic BIM & Ontology; iv) Laser Scanning technologies; v) Safety Management; vi) Energy Performance; and vii) Sustainable Performance. Despite the considerable amount of literature on BIM tools development, researchers are expected to continue to explore new synergies with BIM, as BIM-based tools will always be required to automate most of the processes. Also, Interoperability & Industry Foundation Classes (IFC) will continue to be studied in the near future, as the interoperability and potential of new software/tools will need to be carefully assessed. Another topic that incorporates the knowledge in tool development and interoperability is the study on semantics and ontology. In contrast, a number of gaps were identified in BIM literature as well, namely: a) analysis and comparison of international/national BIM standards; b) assessment of BIM adoption over Europe; c) development of semantic rich BIM libraries to incorporate objects with useful information for automatic analysis; and d) use of Big Data methods to handle information that could be used in predictive analyses. Also, fields such as geographic information system (GIS), space syntax (set of theories that focus on the relationships between spatial layout and real life phenomenon, often researched in urban planning studies), and quantity take-off are not receiving much attention from researchers, particularly BIM-GIS integration, which offers new opportunities in urban planning and construction operations with low visibility [88].

2.3. Literature review on the role of BIM in the Sustainable Construction

Focusing specifically on one of the major trends in the literature of BIM, this research aims to improve the role of BIM in the Sustainable Construction (SC) field. According to Figure 3, the first journal article on this subject was published in 2008 [89]. Since then, the number of published scientific works on BIM-based SC registered an exponential growth.

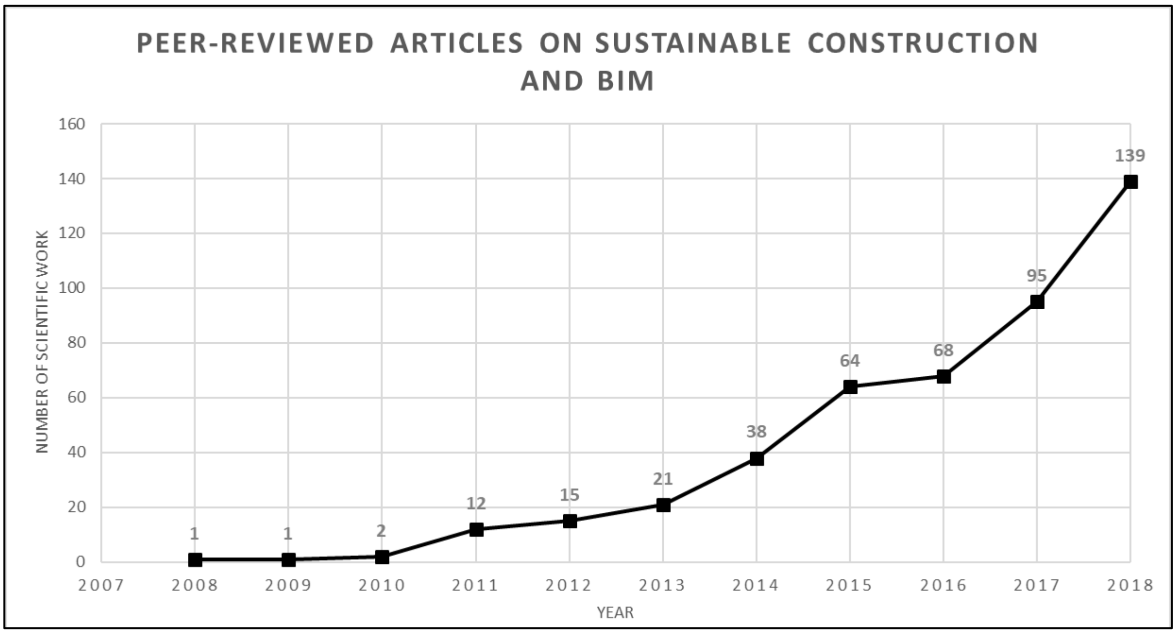


Figure 3 - Published scientific works on BIM-based sustainable construction

Similar to the methodology followed in [63], a content analysis of the scientific literature on the role of BIM in the sustainable construction was performed [64]. Additionally, the peer-reviewed articles (collected from the Web of Science database) were grouped into categories that represented the three dimensions of sustainability and their linkage.

2.3.1. Social Dimension

The most researched topic on this subject is safety analysis during construction activities. Hu and Zhang [90] wrote one of the most influential articles on this topic, integrating BIM with schedule management (also known as 4D BIM) and safety analysis for the first time. By integrating geometric information with schedule, materials, and dynamic safety analysis (based on historical data), their study unveiled the potential of BIM to quickly identify potential work sequence errors and clashes (i.e. conflicts between BIM models). The importance of historical data to improve safety analyses was one aspect that was later confirmed by several researchers, in which BIM played a pivotal role to assist in the identification of the most common accidents [91-93]. Zhang, S. and Teizer, J., two of the most productive and influential authors on sustainable construction and BIM, developed their work on this particular aspect of construction. They researched mostly on automatic safety analysis based on rule checking [94-96], safety hazards that may come from the use of scaffolding [97, 98], real-time location systems [99, 100], and more recently, hazard situations near heavy equipment [101, 102]. In their initial articles, the authors used BIM to provide geometric information of the project, visualise safety hazards in construction schedules, and estimate the bill of materials considering safety equipment and scaffolds as well. Later, the benefits of using sensors in worker helmets to improve safety management were explored and can be considered as a new trend in this field. Once again, the potential of BIM as a visualisation tool was demonstrated. Their comprehensive work showed that BIM can be used effectively to visualise the real-time location of workers/equipment and required spaces for construction activities, thus mitigating potential workspace conflicts among different crews or heavy equipment. Nonetheless, BIM models are not expected to solve all potential hazards during the construction phase (e.g. weather effect on construction site), and further research is required for identifying safety hazards and their severity during construction activities, in which it is foreseen that historical data should be used to draw lessons from past projects. Others have also worked on the reduction of safety hazards using BIM-based hazard identification, location detectors, and a cloud-based platform [103-105]. For instance, in Park, Kim, and Cho's study [103], BIM was used to pinpoint potential hazard locations, which allowed users to improve the reliability of safety management by 97.5% when combined with sensor data.

Other topics covered by this category were the fire protection and emergency planning studies. The first article on this topic explored the potential of BIM integration with geographic information systems (GIS) for fire response management [89], unveiling one of the most relevant topics of this literature. Based on geometric and semantic information contained in BIM models, the authors developed a tool that showed the shortest route from the fire station to the site. However, as argued by Chen, Wu, Shen, and Chou [106], a fire event is a dynamic situation, and some circumstances might change in an instant (e.g. the position of fire trucks). Instead of relying on a static model as in [89], Chen *et al.* developed an interactive three-dimensional environment to simulate the operation of ladder trucks. Focusing on the training of personnel, Ruppel and Schatz [107] developed a BIM-based game engine that enabled an interactive simulation of fire events. Their article significantly contributed to later research on the potential of virtual reality applications for personnel training and the use of BIM for fire prevention [108-110].

Focusing on user comfort and evaluation of building performance, Welle, Rogers, and Fischer [111] were amongst the first to study the potential of BIM for the daylighting simulation during the design phase. They calculated the building's daylighting performance based on the geometric information contained in the BIM model and reduced up to 79% of the simulation time. Currently, 19 out of 200 solar design and daylighting simulation tools are already integrated with BIM tools [112]. Regarding the operation phase of a building, it was observed that BIM and GIS can be used to evaluate the comfort of occupants [113]. The authors found that their approach allowed the identification of causes of discomforts more intuitively by examining the spatial distribution of user satisfaction, thus contributing to the improvement of building performance.

The use of BIM during the operation phase of buildings has been demonstrated in the studies of cultural heritage (also known as historical building information modelling (HBIM)) [114-117], representing a recent topic in literature. Biagini, Capone, Donato, and Facchini [114] used laser scanning technology to create an as-built BIM model of historical buildings and analysed cadastral documents to evaluate the actual condition of the building. However, despite the contribution of BIM models to the creation of national databases of cultural heritage, the authors indicated that further work was required on the development of historical national BIM libraries (e.g. containing objects with historical and geographical data) to improve the automation of analysis. Furthermore, the inherent limitation of laser scanners in analysing the interior composition of elements does not exclude a physical inspection to identify its current strength [118]. Another gap in this topic is the inexistence of an ontology-based model for the representation and management of cultural heritage information, in which BIM could be used to store geometric and semantic information of the built environment [115]. Rea, Pelliccio, Ottaviano, and Saccucci [119] explored the use of low-cost technologies to monitor cultural heritage buildings and reduce maintenance costs. A drone equipped with a laser scanner and camera was the solution found by users, because mechatronic systems were more economical than traditional approaches (based on human surveys) and reached zones with difficult access. The robot performed laser scanning of the cultural building, enabling the creation of an as-built BIM model, which could be used to assist in the development of an accurate maintenance plan. The use of aerial drones for cheaper creation (when compared with traditional approaches) of as-built models have also been studied [120]. Although the use of drones to generate as-built models during operation phases is currently an important matter (e.g. create as-built models of cultural heritage and identify thermal hot spots), there is still a gap in literature when it comes to the use of drones during the construction phase. It is expected that in the future, researchers will explore the potential use of drones for the monitoring of construction activities and generate as-constructed models for quality control.

Finally, literature on sustainable construction that focused on the use of BIM in the training of professionals or university students showed that BIM provided a less-expensive and more comprehensive learning tool, compared with traditional approaches [121-124]. It was also shown that students are becoming more aware of the advantages of acquiring BIM skills to improve their employment success [125].

2.3.2. Environmental Dimension

The second most studied aspect of sustainability in literature is the environmental impact of constructions. With it, the life cycle assessment (LCA) studies using BIM tools was a compelling question on this subject. A comprehensive and frequently cited article was published by Basbagill *et al.* [126], which explored the potential of BIM-LCA integration in early phases of the project. By extracting geometric information from BIM models and exporting it to LCA tools, the authors developed an approach that can assist decision makers in the selection of eco-friendly products. This approach was later replicated in other studies [127-129]. Nonetheless, it was recently argued that further work in exploring the workflow between BIM tools and LCA was necessary [127, 130]. With a similar approach, Jrade and Jalaei [129] used the quantity take-off generated by BIM tools to feed an LCA tool to obtain the environmental impacts of a building. However, their goal was to understand the potential of BIM tools to support the assignment of certification scheme credits, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM), which is another trend that is currently being further explored [131-136]. Their findings showed that the use of BIM contributed to the achievement of 57 LEED points with faster calculations than traditional approaches. Another study showed that BIM could automatically assess seven BREEAM and eight LEED criteria [134]. To improve the capacity of BIM tools for the assessment of certification schemes, Ilhan and Yaman [135] developed a tool to assist designers in the documentation necessary for the green building certification. By adding the required IFC properties, the authors demonstrated that it would be possible to conduct automatic certifications within a BIM-based environment if objects contained sufficient information. Once again, the lack of BIM libraries hindered advances in the field of BIM and sustainable construction. Nonetheless, recent studies have been focusing on the integration of environmental information (e.g. CO_2 emissions) in BIM objects [137, 138]. Still, these approaches only insert environmental indicators in elements but not in the materials and the BIM model is only used for the assessment of modules A1-A3 of the LCA framework (i.e. products' manufacturing).

The energy analysis based on BIM models is another matter of current interest that was observed in this review, in accordance with other reviews [57]. It was demonstrated that it was possible to save up to 30% of the energy consumption (thus contributing to the reduction of environmental impacts of buildings) if the behaviour of people was considered in the energy simulation [139]. More recent studies focused on the quantification of embodied energy [140-142]. For example, Shadram *et al.* [141] incorporated parameters in materials that represented their embodied energy and used BIM to quantify the volume of all materials. Their findings showed that BIM can be used to select suppliers of environmentally friendly materials. Nonetheless, the lack of a standardised format for the Environmental Product Declarations (EPDs) (e.g. IFC) limited the automation of their process, because it was necessary to manually input all the information contained in EPDs in the database. Therefore, further work is expected in the digitalisation of EPDs compatible with BIM tools.

The contribution of BIM for waste treatment and water distribution systems [56, 143-145] was another aspect considered. Bilal *et al.* [143] used BIM models as information repositories (e.g. gross floor area and material specification) for the assessment of construction waste. The novelty of this approach was its use of big data methods to predict the volume of waste generated. Moreover, it showed that currently, most wastes are classified as mixed waste, representing an obstacle to minimising impacts of waste materials. Moreover, Howell *et al.* [145], working with big data methods, proposed an ontology to describe concepts as smart homes, smart metering, and GIS, thus integrating distinct systems into a single domain. This new trend seems to indicate that the use of machine learning and artificial intelligence for automating analyses (e.g. LCA and LCC) using both the information in the BIM model and its integration with GIS tools (e.g. synchronisation of BIM models to represent the whole neighbourhood data) should potentially lead the research on smart and sustainable cities over succeeding years (i.e. digital models and or platforms that represent a city and the data useful for its management). Another aspect that should contribute to this innovative field is the use of sensors to improve the monitoring of the energy consumption of buildings. At last, the use of

BIM integrated with the circular economy paradigm has recently been studied [56], in which BIM models are used to automatically quantify the materials that can be salvaged after the demolition.

2.3.3. Economic Dimension

One of the most frequently cited researchers and author of several articles on BIM and sustainable construction is Love, PED, who significantly influenced this specific aspect of sustainability. Love authored articles that targeted design error reduction using BIM tools that undoubtedly can have a great impact on project costs [146] and on the financial benefits because of the use of BIM for asset owners [147, 148]. More recently, Love has focused on the potential of BIM in procurement processes to future-proof assets, particularly in rail infrastructure [149-151]. These studies highlighted that BIM alone was not adequate to prevent the occurrence of design errors, because there was a significant involvement of the human component as well. Furthermore, return on investment (ROI) analysis was indicated as an inappropriate method to assess expenses on BIM tools and training, because it does not provide an acceptable measure of BIM cost–benefits. The substantial discrepancy among ROI results obtained from other studies can also justify this argument [152-155]. Moreover, the capacity of BIM to withhold the life cycle information of projects makes it a unique tool to measure the performance over the life cycle of an asset (e.g. operation and maintenance costs). Thus, the inclusion of BIM in procurement processes became highly relevant for future-proofing (i.e. safeguarding an asset's value) of projects and for performance measurements throughout their life cycles; arguments that were supported by other studies [156, 157].

One aspect that was often studied (thus considered as a crucial subject) was the time and cost–benefits of the adoption of BIM [158-165]. Based on the empirical study of Lu *et al.* [159], it was found that BIM-based projects required an extra effort of 46% in the design phase (and corresponding costs) but reduced the construction cost by 9%, which represented substantial cost savings by the end of the project. Furthermore, BIM-based cost estimation greatly differs from traditional cost estimation, as shown in [166]. It was shown that although traditional methods required lesser efforts than BIM-based cost estimation did, their results were less precise (e.g. the unit cost overestimates costs) and detailed. It was also observed that BIM tools can be used to predict and improve the productivity of a project based on the compromise between time and cost analysis [160, 162, 165]. By monitoring the productivity of workers based on schedule management and correlating that information with the bill of materials extracted from BIM, the authors were able to predict possible delays of construction tasks.

Another relevant matter and a new trend in this domain is the development of ontologies for cost estimation. As results of these studies, Lee, Kim, and Yu published two comprehensive articles [167, 168], where they proposed a new ontology to automate the extraction of information (e.g. building element and quantity, finishing thickness, and room usage) from the project, thus enhancing the work accomplished by cost estimators. This research was then improved later [169].

Focusing on the life cycle thinking paradigm, researchers explored the potential use of BIM tools for the assessment of the life cycle costs of materials used in the project [53, 170-173]. Kehily and Underwood [53] integrated LCC information with the quantity information extracted from BIM models in a spreadsheet file. Not only were materials and elements considered, but also operational activities (e.g. cleaning and energy consumption). This study also showed that it would be more appealing if BIM objects contained data that could be used for LCC calculations, instead of using external databases. This challenge is in accordance with the limitations identified in previous studies, which seems to indicate that it is a multidisciplinary problem.

2.3.4. Environmental and Economic Dimensions

The first article that focused on this aspect showed the trade-offs between specific heat loss and life cycle costs of retrofit solutions [174]. By extracting the quantity information from the BIM model, the author estimated that retrofitting can save 51% of the energy and carbon emission, on average, which is in accordance with other studies [175, 176]. With a similar approach, Shin and Cho [177] developed a framework to improve the integration of BIM with LCA and LCC methodologies, generating faster results than traditional approaches. However, as previously noted, the lack of libraries with LCA or LCC information hindered the automation of such analyses; a limitation that was mentioned several times in literature but remains unresolved. Nonetheless, researchers are intensely exploring the integration of BIM with LCA and LCC, which is currently a matter of interest in this field [175, 178-181].

The use of BIM for the automatic assessment of certification schemes and its related costs has also been recently studied. Jalaei and Jrade [182] showed that BIM tools can be connected to external databases (containing materials with LEED parameters) to calculate the number of LEED credits of a project. With a similar approach, Akcay and Arditi [183] used BIM tools and LCC databases to calculate LEED credits in the energy and atmosphere category with minimum costs. Because this integration is a recent trend, it still has several constraints (e.g. not all LEED credits can be automated with BIM), which means that future work is expected in this field.

The end-of-life phase is another aspect that is currently explored in literature. For instance, Cheng and Ma [184] presented a BIM-based system for the estimation and management of construction and demolition wastes. The authors developed a tool that could read quantity information from BIM models and consider cost data to assess environmental and economic impacts of building demolitions. Their findings showed that BIM can contribute to the creation of a more accurate waste treatment plan. From a different perspective, Ajayi *et al.* [185] focused on identifying possible strategies to reduce the waste intensiveness of construction. In their study, BIM integration with integrated project delivery (IPD) methods and interoperability between BIM and waste management tools were highlighted as potential solutions for the reduction of material waste. It was also argued that recycling is not a solution to effectively reduce the end-of-life impacts of construction, because demolition waste requires transportation to waste treatment facilities (aside from the waste treatment processes themselves). Therefore, it is expected that future studies will promote the reusability of materials (e.g. adopt modular construction systems and avoid fixed connections) to avoid waste generation. In view of this, the use of new technologies and new waste treatment paradigms (e.g. circular economy) can offer a more appropriate solution than traditional approaches (e.g. adoption of a circularity index for each material within BIM projects). Finally, it is necessary to change public policies and legislation in order to promote reusability and recycling of materials starting from the procurement phase (e.g. develop suitable IPDs), because currently, it is perceived that it is cheaper to transport waste to landfills than to treat it.

Other authors explored the environmental and economic aspects of BIM-based SC, focused on the material instead of the project level [186, 187]. For instance, Akanmu, Asfari, and Olatunji [187] developed a decision support system that evaluates material suppliers based on their product cost and carbon emissions. Nonetheless, the considerable amount of information manually inputted to the model (e.g. list of nearby suppliers) is among the limitations of the proposed approach. To overcome this constraint, future research is expected to explore the integration of BIM with GIS tools to improve the automation of analyses.

2.3.5. Environmental and Social Dimensions

A recent study on this topic showed that existing standards and guidelines infrequently focus on these two dimensions [188]. To overcome this gap, the authors proposed a set of criteria to support the integration of social principles with environmental assessment methods using BIM tools, thus contributing to the improvement of existing standards. It was found that when environmental studies were implemented, the occupants (i.e. tenants) were usually excluded from decision-making processes. In this sense, Pan, Qin, and Zhao [189] conducted a comprehensive research on the use of BIM for the assessment of environmental impacts and thermal comfort of users. The authors concluded that the influence of user behaviour on the energy performance of buildings remains unclear, thus requiring more studies in the future. Another aspect that was observed was that interoperability problems between BIM and energy analysis tools persisted, which meant that existing open BIM schemas (e.g. IFC) still required improvement; an argument also shared by other authors [190]. Therefore, existing studies on this topic focused on the use of BIM tools to extract geometric and material information, and thereafter export it to energy and environmental analysis tools [190-193]. Once more, the enhanced visualisation of retrofitting solutions and communication between stakeholders were indicated as some of the benefits that come from the use of BIM tools. It is also argued that BIM tools offer a great potential for the energy and environmental monitoring of buildings [191]. Therefore, it is expected that future research will focus on the monitoring of these indicators rather than on their assessment (e.g. use of sensors as demonstrated in [192] and sharing of social responsibilities between owners and tenants).

With a different focus, Ding, Zhou, and Akinci [194] analysed the existing literature on the application of BIM in safety and environmental management. According to the study's finding, the authors argued that safety and schedule management must be controlled for both to ensure protection of workers. Furthermore, the authors calculated CO_2 emissions of materials based on the 4D BIM model, demonstrating that the schedule management has a potential application for other domains as well.

Finally, the demonstration of a BIM application in the environmental assessment was also shown in pedagogical courses [195, 196]. In these studies, the authors evaluated the success of adopting BIM in a university course and its synergy with sustainable construction principles (e.g. use BIM-based simulations). At the end of the course, the authors concluded that there was an increase in the students' self-confidence on their BIM skills and on the energy performance quality of their green design.

2.3.6. Economic and Social Dimensions

Focusing on on-site safety, Zhang and Hu [197] explored the potential of BIM for the economic impact of constructions because of changes in the schedule of construction activities and its influence on safety hazards. Their approach showed that a dynamic management was required to avoid possible collisions during construction tasks.

Other authors focused on the assessment of the indoor comfort of users and respective costs to improve it [198-200]. For instance, Kim and Park [198] extracted the information contained in the BIM model (e.g. material, cost, and geometry) to estimate the cost and thermal performance of refurbishment solutions in the early phases of the project. However, because BIM objects (e.g. walls and doors) did not have economic information, the authors had to manually input it, highlighting the fact that there is a lack of standardisation on parameters of BIM objects. The same problem was observed in the study of Woo, Peterson, and Gleason as well [199]. The authors used BIM to select the most cost-effective refurbishment solution to improve the energy performance of a building. To improve the automation of cost and energy analysis, shared parameters were added to the model to store energy-related information from sensors.

2.3.7. Sustainability Dimension

This last category covers studies that focus on all dimensions of the sustainability concept. One comprehensive article that focused on a major trend on this subject was written by Wong and Kuan [201]. Building on the study of Azhar *et al.* [131], an exploratory study on the potential use of BIM to obtain the 'BEAM Plus' sustainability certification was conducted. The authors developed a framework to enable the BIM-BEAM Plus approach by adding the necessary information to the model by using Revit's shared parameters. They observed that BIM's greatest potential for this field lay in the quantification of materials.

More recent studies focused on the use of BIM-based tools (e.g. energy analysis of Revit) for the reduction in energy consumption, thermal discomfort, CO_2 emissions, and cost [202-205]. Whereas in [202] it is claimed that the reduction in the energy consumption of buildings can bring significant environmental and economic benefits and improve conditions of its users, in [203] it is argued that this might not always be the case. In their study, Migilinskas *et al.* [203] concluded that for buildings with high performance because of the use of more thermal insulation, CO_2 emissions saved from energy consumption will not outweigh the embodied CO_2 emissions. Therefore, further research on the integration of these indicators is expected in the future, in which BIM tools have already proven their worthiness in sustainable assessments of buildings.

According to the literature, LCA and LCC are the most common methods used to assess the environmental and economic impacts of a project's life cycle, representing a new trend in this domain. For instance, Yung and Wang [206] developed a methodology to extract quantity information from a BIM model and connect it with external databases to enable the assessment of building sustainability using LCA and LCC. Ahmadian *et al.* [40] proposed a framework that can be used for the assessment of the sustainability of the supply chain management of materials used in constructions. The LCA methodology was used by the authors, and instead of simply using environmental categories, economic (e.g. manufacturing and maintenance costs) and social (e.g. safety and indoor air quality) categories were also considered, similar to [207]. Finally, different variables were weighed to generate a single indicator of sustainability, enabling the ranking of solutions, which was an approach also followed in [40]. These studies showed that the local producers have lower environmental and economic impacts, but data should be properly collected during the construction phase to improve the assessment of the sustainability of projects [40]. Therefore, it is necessary to collect national data that focus on environmental burdens and costs of products, and social factors (e.g. working conditions and workers' salaries) of regional and national manufacturers. It is fundamental that obtained data are interoperable with BIM-based tools to improve the automation of sustainable assessments of construction projects. For that purpose, open BIM schemas, such as IFC, should be used to exchange information between manufacturers and BIM models. However, IFC still lacks properties useful for the sustainable assessment of buildings (e.g. reusability of materials) [135].

2.3.8. Observed synergies between the dimensions of sustainability

As observed in the content analysis of the literature, the older articles on the role of BIM in the sustainable construction focused solely on a single aspect of the sustainability concept. In these articles, BIM was mostly used because of its automatic quantity take-off and visualisation potential. However, the synergies within this domain increased in the past years. Researchers began to use BIM not only as an auxiliary tool but more as a fundamental methodology and technology to achieve higher levels of performance and automatic simulations. This maturation of the literature demonstrates that the role of BIM in this field has not only increased the use of sustainability principles in the construction industry but also improved the quality of the sustainability analyses.

2.4. Trends and gaps in the literature

Has the potential behind BIM methodology and technology changed how the sustainability of the built environment is perceived? Building on the findings of this review, the use of BIM has not changed the fundamental concept of sustainability. However, the potential of BIM and disruptive technologies changed how business around sustainable construction and assessment is conducted. A better access to information, how it is exchanged, and its transparency, are without question the biggest contribution that the digitalisation brought to the construction industry, particularly to the field of sustainability.

In summary, the main challenges and gaps identified were (i) interoperability problems between BIM tools and sustainability tools; (ii) lack of ontologies across the fields of sustainable construction; (iii) lack of standards and public incentives for the adoption of BIM within a sustainable construction industry and (iv) lack of BIM libraries with semantic-rich objects. On the other hand, the main trends and crucial topics in literature are (a) use of LCA and LCC methods integrated with BIM; (b) BIM role in the automatic assessment of certification scheme credits; (c) automatic quantity take-off for the economic and environmental assessment of projects; (d) use of sensors to monitor construction sites and indoor air quality, and (e) BIM-GIS integration. Finally, it is believed that further research will be performed in the following fields: (1) the use of virtual and augmented reality to improve the training of professionals before construction activities or emergency responses; (2) the use of rule-based checking for the automatic analysis across several domains; (3) the use of mechatronic systems (e.g. drones) integrated with photogrammetry and laser scanning technologies to contribute to cultural heritage preservation; (4) the development of semantic-rich BIM libraries; (5) the use of big data methods to treat and extract knowledge from historical data is also expected, and combined with the use of sensors, can significantly improve the real-time monitoring of building performance; (6) the potential BIM-GIS integration with big data methods for research on smart and sustainable cities, and (7) the promotion of material reusability (e.g. by the adoption of circularity index and public incentives).

A particular aspect that must be addressed in the near future is the identification of information (e.g. environmental impact categories and circularity index of materials) that could be incorporated in BIM objects to improve simulations performed within a BIM-based environment. Researchers have extensively used BIM tools solely for the automatic extraction of material quantities [53, 111, 129, 206], mainly because BIM objects lack useful semantic information. Thus, it is argued that if digital objects contained data required for different analyses (e.g. environmental), then BIM models would truly incorporate the useful life cycle information of assets (e.g. building and relevant equipment inside it). In this sense, BIM models would become real data repositories that could be used by facility managers to easily monitor assets or plan refurbishments by simply replacing necessary objects. This would expedite the transition from building information modelling to building information management. Nevertheless, the inclusion of information in BIM objects should be done using non-proprietary formats (e.g. IFC), otherwise the information interoperability would be reduced. Therefore, further effort should be done in the improvement of open BIM schemas to cover sustainable-related information.

This research focuses on a specific topic in the literature on BIM and sustainable construction, which is the enhancement of BIM-based LCA and LCC analyses to promote the sustainable construction principles.

2.5. Existing analytical models for LCA and LCC integration

The integration of LCA and LCC is a topic that has been studied even before these two methods were standardised. Norris were amongst the first scholars to study this integration, arguing that there are two types of LCA/LCC integration approaches [208]. The first approach consists in a non-traditional LCA (e.g. dynamic LCA), in which the time variable is considered during the LCA analysis and costs functions are added to each physical flow, providing environmental and economic information of the studied alternatives. The second approach is based on an LCC analysis that includes costs from life cycle inventory (LCI) data imported from LCA studies. So, based on Norris arguments and depending on the purpose of the study, one must first select the main analysis method and then complement it with data from the other method. However, based on a literature review of life cycle analysis (LCA, LCC, and social LCA) conducted by Kloepffer in 2008, there are two other possibilities for integration [209]. Either experts should perform individual life cycle studies (and, in the end, the three sustainability indicators are summed in a single indicator) or use a single LCI database for the economic, environmental, and social studies (although this database does not yet exist). More recently, Gundes [210] argued that the integration of LCA with LCC can be done either by converting LCA results into costs (e.g. environmental LCC) or simply by conducting a separate analysis and interpret the results independently.

Based on the arguments described in the literature, the integration of LCA with LCC can vary considerably. In this sense, the purpose of the study (i.e. which aspect is more relevant to the client?) and the result of the study (i.e. the client prefers the results in a single indicator or in separate indicators?) will greatly determine how the integration will be done. This also raises the question of "how much subjectivity one should add to the analyses?". For instance, if experts conduct separate analysis, each with its own indicators, the subjectivity of the results will depend on the data used in each analysis (e.g. quality and representativeness of databases). However, if the goal of the study is to present a single indicator, then experts must rely on weighting methods to integrate the different aspects, being aware that the weights used to represent the importance of each aspect will undoubtedly influence the result. Thus, this type of integration should only be done by experts in the field and the used weights should be properly justified (either according to the client's priority or based on existing scientific literature).

The earlier studies on the integration of LCA with LCC focused on this last approach (i.e. use of weighting methods to present a single indicator) and it is possible to find several examples in the literature [211-216]. On the other hand, more recent literature explores the other approach (i.e. separated indicators for each analysis) [217-222]. This evolution shows that the research and concepts about the sustainability in the construction industry are likely becoming more transdisciplinary.

Regardless of how LCC and LCA are integrated, the life cycle thinking paradigm and its inclusion in sustainability analysis is increasingly growing. In this sense, the EU Commission is incorporating the life cycle thinking in several sectors to increase the chances of success to achieve their ambitious sustainability targets for 2020 and beyond [50]. Hence, the construction sector must adapt and begin to use methods such as LCA and LCC. However, the most significant limitations identified in the literature regarding both methods were how time consuming and data demanding they can be. To overcome this limitation, several authors have argued that BIM integration with LCA and LCC can greatly reduce the time spent in collecting the initial inputs required to perform the life cycle analysis [57, 63, 223].

2.5.1. The role of BIM in the integration of LCA with LCC

In the literature on BIM integration with LCA and LCC there are three main approaches. The first one resorts to several programmes to conduct the LCA and LCC analyses, while the second one connects the quantity take-off generated by a BIM model with external databases to obtain the total impacts of a project [223-226]. A third approach was suggested by Antón and Díaz, which argued that the inclusion of LCA information in BIM could represent an initial step towards an environmental integration, being more suitable for material comparison than solely use BIM for material/quantity extraction [224, 225]. However, researchers only began to study the potential of this approach very recently [137, 138].

Wang *et al.* [227] were amongst the first ones to follow the first approach. The authors explored the BIM-LCA potential to evaluate the environmental impact of a building. In the end, the authors identified the most sustainable solutions (e.g. materials and building orientation) by using Ecotect [228]. Other authors used a similar approach [126, 220, 229, 230]. An example of how cumbersome this approach can be is the study of Basbagill *et al.* [126], where seven tools were used (DProfiller, eQUEST, SimaPro, Athena EcoCalculator, CostLab, Excel, and ModelCenter) to perform an LCA study of a building.

Studies that follow the second approach are more recent, mostly owning to the advances in the BIM technology and market demand for more automatic analyses. A study that followed this approach was developed by Jrade and Jalaei [129], which used an integrated three module framework (BIM, LCA, and certification and cost module) to obtain the environmental impact of a building. The BIM model is used to generate and export a quantity take-off that connects with an external database developed by the authors, which contains environmental data (from Athena Impact estimator tool), cost data, and potential LEED points for building components. Similarly, Oti and Tizani [179] created a tool that integrated life cycle costs, ecological footprint (based on the agricultural potential of the land), and CO_2 emissions to assess multiple design alternatives. The developed tool extracts the materials' bill of quantity from the BIM model and connects with external databases that have the necessary information to perform the three analyses (i.e. LCC, ecological footprint, and CO_2 emissions). Another study was published by Kehily and Underwood [53], which extracted quantity information from the BIM model to a spreadsheet that contained LCC data for different types of elements and materials. Moreover, the approach was reviewed by a set of professionals and one of the observations was that it would be interesting to integrate LCC data within BIM objects instead of using external databases. With a similar approach, Shin and Cho [177] first identified which data is necessary to conduct an LCA and LCC analysis and then proposed a framework that integrated these two methodologies with BIM tools. In the end, BIM models were used to export quantity information (materials' type, volume and weight) to feed a spreadsheet that conducts the LCA and LCC analysis. Likewise, Kreiner, Passer, and Wallbaum [178] used the bill of quantities extracted from the BIM model to optimise the sustainable performance of buildings. With a different purpose, Liu, Meng and Tam [175] resorted to the particle swarm optimization (PSO) algorithm to identify the trade-offs between LCC and life cycle carbon emission (LCCE). Focusing on the three pillars of sustainability, Yung and Wang [206] performed the quantity take-off from a BIM model and connected with an external database to evaluate the building's sustainability. The originality of this study was the use of 4^{th} dimension of BIM (i.e. schedule management) to estimate the number of employers working in the construction as a social impact parameter.

Despite the novelty in this domain, current approaches still have a few limitations. The limitations of the first approach are more obvious, consisting mainly in interoperability issues between different programmes, licence costs, and human-made error that exponentially increases with the number of tools to be used. Although more advantageous, the second approach is heavily dependent on the flexibility of the database itself (i.e. the possibility to include and or edit information). In this regard, the type of LCA data (specific, average, or generic) has a considerable impact on how representative the results can be. Another limitation is that all LCA and LCC data is not stored in the BIM model, which should serve as a centralised data repository. This also means that the data available in these databases will never be owned, since every time the users intend to run an LCA or LCC analysis will need to have a valid license to connect to the BIM model and to the databases.

Considering the existing literature and the potential of BIM, should BIM-based tools only be used for the extraction of quantity take-offs? By doing so, is BIM's true potential in information management and projects' assessments not being overlooked? As noted in the literature, the lack of information within BIM models not only leads to ineffective decision-making but also prevents automatic simulations of the project in several domains [58-62]. For example, Iacovidou, Purnell, and Lim [60] argue that BIM "*offers an effective way of modelling and managing*" the project's information "*while also permitting design changes to be made in a quick, effortless and reliable manner; forming a reliable basis for decision-making*". Moreover, the lack of useful information within BIM models greatly hinders its use for operational and maintenance activities, causing "*significant costs and rework*" for this phase of construction [61]. Hence, instead of accepting the current approaches, where BIM is mostly used for geometric and material extraction, efforts should be made to push forward the inclusion of useful information in the model.

In this regard, a recent study identified the potential of BIM as an information management tool to promote smart and sustainable cities [62]. Business that require information management (e.g. facilities management) will greatly benefit from the integration of project's information in the BIM models, which could contain all relevant data. For example, if there is a need to refurbish an office building and if the respective BIM model already contains LCA/LCC information, then the facilities managers just need to update the model with the new elements and quickly run a new analysis. In this regard, recent studies are focusing on the inclusion of environmental information (e.g. CO_2 emissions) in BIM objects [137, 138]. Still, the addition of information in objects is limited only to the elements (thus, not materials) Furthermore, the integration of economic and environmental information for an LCA/LCC analysis within a BIM-based environment still remains unexplored, a limitation that has also been identified by other authors and professionals in the industry [53, 231]. BIM should act as a supply chain integrator, allowing a more collaborative information flow, in which every stakeholder could add information to the same model.

2.6. Concluding remarks

A literature review on the role of BIM in the sustainable construction was performed in this chapter. This analysis contributed to the understanding of the evolution of literature on this subject and its development according to dimensions of sustainability, namely in the integration of BIM with LCA and LCC. As noted, scholars that researched the application of LCA and LCC in the built environment and its integration argue that the use of building information modelling (BIM) tools can ease the work done by designers, mainly due to its automatic quantity take-off. Moreover, this review identified three existing approaches for the integration of BIM with LCA and LCC: i) use of several programs for the LCA and LCC analyses; ii) connect the bill of quantities generated by BIM tools with external databases; and iii) incorporate environmental and economic information within the BIM model for automatic simulations.

This research will focus on the third approach, which still lacks exploration. The next chapter will detail the research design that will be followed throughout the investigation.

Chapter 3 – Research Design

The research questions and hypotheses of this research are formulated in this chapter, building on the reviewed literature presented in the previous chapter. Moreover, the development of a suitable approach for a BIM-based LCA and LCC analysis is proposed, based on the existing LCA and LCC frameworks and on the models for the integration of BIM with LCA and LCC. This framework was published in the 'Automation in Construction' journal [232]. At last, the methodology used in this research is presented.

3.1. Research Questions

As observed in the previous chapter, to facilitate and promote the use of LCA and LCC in the construction industry, many authors argued that BIM-based tools should be used during the design phase, primarily due to their capacity to automatically extract materials' quantity, saving time and reducing human errors. Nonetheless, existing approaches and tools still have some limitations (e.g. interoperability issues, use of non-editable databases, etc.). Building on the gaps identified in the previous chapter, the questions that this research aims to address are the following:

Q1: Which information could be incorporated in BIM objects to enable a BIM-LCA/LCC analysis?

Q2: Which processes and exchange of information are necessary for a framework that implements an LCA and LCC analysis within a BIM-based environment?

Q3: How has an automatic BIM-LCA/LCC analysis to be conducted if the necessary information is incorporated in objects?

To properly answer these questions, it is necessary to review the LCA and LCC methodologies and, subsequently, develop a suitable BIM-LCA/LCC framework.

3.2. Framework for the LCA and LCC analyses

3.2.1. LCA methodology

Life Cycle Assessment (LCA) methodology is described as a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"*, according to ISO 14040:2006 [233]. Although LCA's framework first appeared at SETAC symposium, in 1991, only in 1997 it would be officially acknowledged, with the International Organization for Standardisation (ISO) publishing the 14040 and 14044 standards. The framework is standardised by ISO 14040:2006 (Figure 4) and is based on four main phases [233]: i) the aim and scope definition for the LCA; ii) the life cycle inventory analysis phase (LCI phase); iii) the life cycle impact assessment phase (LCIA); and iv) the life cycle interpretation.

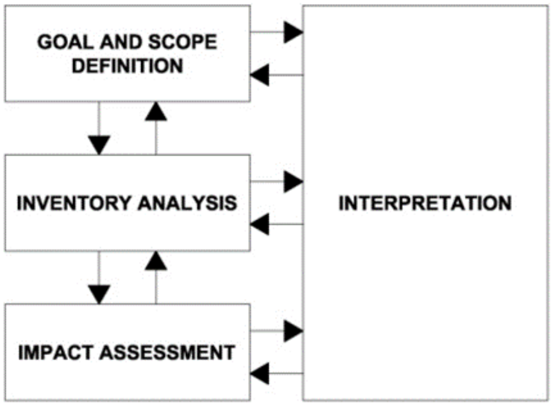


Figure 4 - LCA methodology phases [233]

The definition of the goal and scope is the first phase of an LCA study. In this initial phase, the experts outline the subject and the intended use of the study. Moreover, the boundary of the study and the functional unit are defined in this phase as well. The boundary has a great influence in the time and money spent in the study, as the wider it is the more data is required and, consequently, more time will be needed to process and model the data. The functional unit "*defines the quantification of the identified functions (performance characteristics) of the product*" (e.g. impacts per m^2 of a door with 100,000 opening and closing operations) [233]. It is only possible to compare different LCA studies if they both share the same functional unit. In this regard, it is equally important to determine the reference flow that fulfils the function, i.e. the amount of inputs that are needed to accomplish the function. However, as buildings can have different functions throughout their life cycle, the functional equivalent can be used instead on that case, and corresponds to the "*quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison*" [234]. The functional equivalent of a building should include the following aspects: building type; required service life; relevant technical and functional requirements; and the pattern of use [234]. Other aspects that should also be covered in the goal and scope definition phase are the identification of the life cycle stages covered by the study, the environmental impact assessment methods to be used, the assumptions made, and the data quality requirements, amongst others.

The Life Cycle Inventory (LCI) represents the second phase of an LCA study. It is in this phase that the expert collects the necessary data according to the assumptions made in the first phase. After the data is collected, the expert will then model the whole product system, quantifying its inputs (e.g. energy, raw material, and other physical inputs) and outputs (waste, air emissions, etc.). It is also in this phase that the allocation procedures must be clearly defined so that only the necessary input is selected. ISO 14044:2006 defines allocation as "*partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems*" [235]. As most processes result in more than one product, the experts must use allocation procedures (e.g. physical properties, economic value, etc.) to remove unrelated products from the study. At the end of the LCI phase, a table listing the material and energy balance of the product's system should be presented.

Subsequently, the next phase is the Life Cycle Impact Assessment (LCIA). In this phase, the potential environmental impacts of a product throughout its life cycle are evaluated. The results of the LCI are assigned (classification) to the environmental impact categories selected in the goal and scope phase. These categories are based on environmental impact assessment methods (EIAM), and can either have a problem oriented approach (midpoint), which focuses on the source of environmental problems, or a damage oriented approach (endpoint), which focuses on the damage that a product will cause to the environment [236]. It is the selection of the environmental impact assessment method used in the LCA study (e.g. CML 2001, ReCiPe, TRACY 2.1, Eco-Indicator 99, etc.) that will determine the results of the study. Hence, the potential environmental impacts are calculated (characterisation) based on the EIAM that was defined in the goal and scope of the study.

In the end, the results of LCI and LCIA will be analysed in the Interpretation phase and presented in the form of a report or recommendations. In this phase, it is recommended to perform sensitivity analysis, consistency checks, and contribution analysis to validate the accuracy of the results and its consistency with the goal of the study, as well as the identification of alternatives with less impact. The most significant results are identified and opportunities to reduce the environmental impacts of the products are also evaluated. The findings in the Interpretation phase will provide key information that can be used for decision-making processes and to compare the impacts of different products that share the same function.

Although LCA is more oriented to the environmental assessment of products, it can also be used in the built environment. In this sense, the EN 15978:2011 applies the LCA principles to the building sector, providing a framework to evaluate the environmental impact of new and existing buildings [234]. The evaluation process is very similar to the one described in the EN 14040:2006. Initially, the experts identify the purpose of assessment, covering the goal of the study and its intended use. The following step is the specification of the object of assessment, i.e. the building or part of the building. It is in this phase that the functional equivalent, i.e. the representation of the required technical features and functionalities of the building, is defined. Also, the reference study period (RSP) is another aspect defined in this phase. The RSP is not necessarily equal to the required service life (ReqSL) of the building. When the RSP/ReqSL is lower than 1, i.e. only a portion of the building's life cycle will be studied, the environmental impacts of the use stage of the building are multiplied by the resulting factor. However, when the RSP/ReqSL is higher than 1, this means that scenarios for refurbishment or demolition and construction of a new building must be developed. In this situation, the environmental impacts of the previous building will be added to the environmental impacts of the new building. Finally, the system boundary and the building model are both defined in this phase of the study. Regarding the system boundary, the experts must define which processes are considered in the building's assessment. This follows the modularity principle, i.e. the processes that influence the environmental performance of the building during its life cycle are assigned to the module in its life cycle where they occur (Figure 5).

The Product stage (A1-A3 modules) covers the impacts of the materials used at that stage, from the extraction of raw material (A1) and transportation between the extraction site and manufacturing plants (A2) to the manufacturing process itself (A3). The Construction Process stage (A4-A5 modules) considers the impacts due to the transportation of products from manufacturing plants to construction site (A4) and the construction activities as well, until the completion of the project (A5). The period between the completion of the construction and the demolishing operations is the Use stage (B1-B7 modules). This stage covers a wide range of impacts due to: normal use of building's components, as the release of substances from the facade, roof or floor (B1); maintenance (B2), repair (B3), and replacement (B4) of building's components; refurbishment of building (B5); and finally, the operational energy (B6) and water (B7) use. The last stage of a building's life cycle is the End of Life (EOL) stage (C1-C4 modules). This occurs when it is deemed that the building will no longer have any further function, starting with the buildings de-construction (C1) and the transportation of waste to disposal sites (C2). However, there is also the scenario when the waste generated from the demolition is reused, recovered or recycled (C3). If not, the environmental impact due to the final disposal of materials (e.g. neutralisation, incineration, and landfilling) will be quantified in the C4 module. There is another module beyond the building's life cycle, the module D, which comprises the benefits due to the reuse, recovery or recycling scenario (C3). In this regard, different approaches can be followed depending on the modules that are covered in the LCA study [237, 238]:

- Cradle-to-Grave: full LCA from extraction to disposal phase (modules A-C);
- Cradle-to-Gate: assessment of a partial lifetime of the product. In the architecture, engineering, and construction (AEC) sector, can represent the manufacturing stage (e.g. A1-A3);
- Cradle-to-Cradle: special kind of Cradle-to-Grave method, where the end-of-life (EOL) disposal is replaced by the product recycling process (modules A-D);
- Gate-to-Grave: partial LCA that evaluates only one phase of the whole process (e.g. modules A4-C).

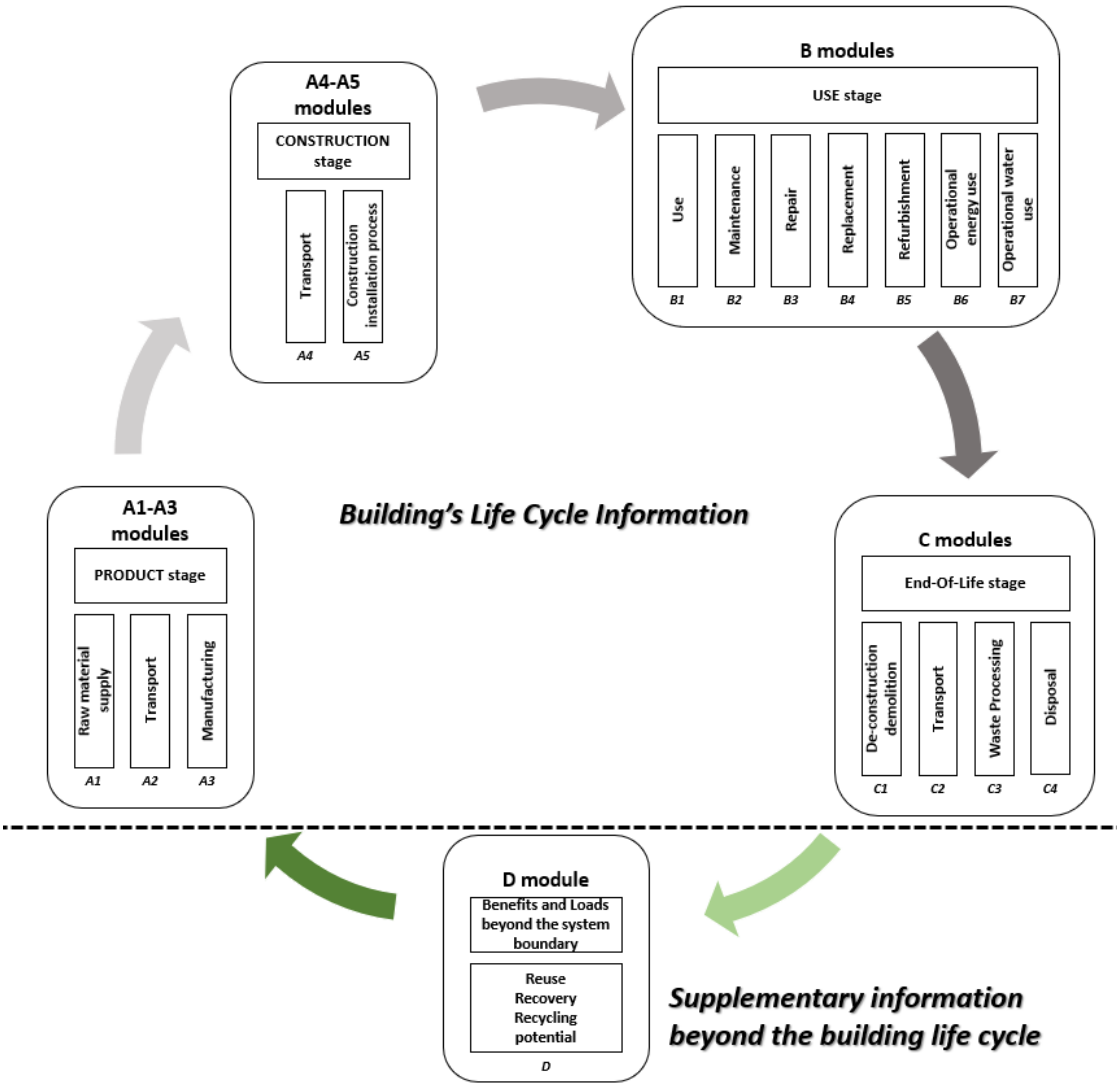


Figure 5- Building's life cycle Information (based on [234])

Lastly, the building model is defined, where the expert describes the purpose and information needed for the study (the used data can be generic, average or specific) and identifies the physical characteristics of the building (from the product level to the building element level).

The following step consists in the definition of scenarios for the building life cycle, which will be used in models for the different stages, from A to C modules. In this step it is required that more specific information is added to the model, e.g. use of Environmental Product Declarations (EPDs), and the limitations of their application in the building's life cycle must be indicated as well. The next task consists in the assessment of the building's environmental impacts during its life cycle, based on the information provided in the previous steps. The materials used in the project and the operational energy and water are quantified. Additionally, the type of data to be used is defined because it affects the degree of confidence of the results. It is only after the steps mentioned above that the expert is now able to calculate the environmental indicators (e.g. Global warming potential, Acidification potential, Eutrophication potential, etc.) caused by the building throughout its life cycle. Finally, the last steps consist in the elaboration of the report and verification of the results, based on consistency checks (e.g. consistency between goal and results).

Nowadays, the comprehensiveness of LCA's framework and its applicability to the built environment is fairly covered not only by standards, as the ones mentioned above, but also by scientific literature. However, despite the acknowledged comprehensiveness of the LCA method, it is often criticised due to its: i) high costs for complex products (i.e. with a considerable amount of inputs and processes); ii) significant subjectivity of the analysis as, depending on the experts, it is possible to obtain different results for the same product; iii) possibility to overview relevant data due to poorly defined boundaries; and iv) lack of macroeconomic perspective [239-241]. To cover some limitations of the traditional LCA method, commonly known as process-based LCA, scholars either integrate it with other methodologies (e.g. BIM, LCC) or use hybrid LCA approaches.

3.2.1.1. LCA tools

To perform the environmental assessment of products, the experts resort to LCA tools that conduct a computational analysis of all the inputs and outputs of a specific product. According to Trusty and Horst [242], there are three levels of LCA tools with distinct purposes [26, 243-246]:

- **Level 1 LCA tools:** these tools focus on the analysis of individual products of assemblies (e.g. frame of windows or doors), i.e. at the material level. They are also used to compare the environmental impact of products with the same functional unit, being suitable for the design stage. However, as level 1 LCA tools are product-oriented, their usefulness is related to the amount and quality of the LCA databases that are included in these tools;
- **Level 2 LCA tools:** these types of LCA tools are used to analyse the environmental impact of the whole building or building assemblies and compare different design options, providing valuable insight for decision-making processes, from early stages of the project until the design stage. Level 2 LCA tools generally comply with existing standards as ISO. Furthermore, they can also provide valuable data to level 3 LCA tools;
- **Level 3 LCA tools:** type of LCA tools that are more oriented to the whole building assessments based on a set of prearranged criteria, covering a wider range of environmental, economic, and social aspects, using data of level 2 LCA tools (e.g. energy mix). There is also a higher subjectivity inherent to these tools, as they use weighting methods in their results. Another aspect of level 3 LCA tools is that they can be used for certification purposes (e.g. LEED and BREEAM), promoting green building design. However, it is arguable that most of level 3 LCA tools are in fact LCA tools as they are not used to generate newer LCA data. Instead, they use already existing data from other LCA tools to provide more comprehensive results in a wider range of aspects.

In Table 10 it is possible to find a list of useful LCA tools for the construction industry based on their level and purposes [26, 230, 243-262].

Table 10 - List of LCA tools

LCA tool	Description
Level 1 LCA tools	
(US) BEES	BEES is a web-based application that focuses mostly on the construction industry. It also performs LCC studies.
(Germany) GaBi	One of the most recognised LCA tools in the market, GaBi is normally used in engineering applications, providing not only LCA reports but also supporting LCC studies and the development of EPDs.
(Germany) OpenLCA	Unlike other level 1 LCA tools, OpenLCA is an open source software with a considerable number of databases for a wide range of fields. It also has an LCC module and some social indicators from the PSILCA database [262].

LCA tool	Description
(Netherlands) SimaPro	SimaPro is also one of the most used LCA programs worldwide, being suitable for industrial processes. It also contributes to produce EPDs.
(France) TEAM 5.2	TEAM is used in a wide range of fields as agriculture, construction and waste management.
(Germany) Umberto	Umberto not only performs the traditional LCA studies but also allows users to perform LCC studies. It can also be used to elaborate EPDs and Product Environmental Footprints (PEF).
Level 2 LCA tools	
(Canada) ATHENA Ecocalculator	A version of ATHENA that is more suitable for parts of buildings (assemblies).
(Canada) ATHENA Impact Estimator	Performs the environmental assessment of the whole building, or part of it, from cradle-to-grave. However, it only uses North American datasets.
(Sweden) EcoEffect	The EcoEffect is only available in Swedish and besides the environmental performance it also conducts a life cycle costing study of buildings. However, it is still under development.
(Netherlands) Eco-Quantum	Financed by the Dutch government, Eco-Quantum tool allows engineers and architects to measure the environmental impact of their projects, using SimaPro data. However, it is available only in Dutch.
(Sweden) ELP	Unlike other LCA tools, the ELP performs the environmental impact of the whole neighbourhood, instead of working at the building level, providing socio-economic results. However, it is focused on the Swedish market and is still being further developed (ELP-s is the most recent version) [256]
(Germany) LEGEP	Based on national standards and databases, LEGEP tool assists designers in the evaluation of the environmental and economic performance of buildings from cradle-to-grave. It can also be used for sustainable certification, covering German and Austrian rating systems.
(France) novaEQUER	The recent version of EQUER, novaEQUER performs the LCA of buildings from cradle-to-grave using the Ecoinvent database. It also has a comparison tool that allows users to compare different design options. An advantage of novaEQUER is that it allows to import gbXML files, which contain building models from BIM-based programs.
Level 3 LCA tools	
(UK) BREEAM (US) LEED (Hong Kong) BEAM Plus (Portugal) LiderA (International) SBTool	International classification systems based on sustainability criteria. The assessed buildings are then categorised and certified based on a ranking system. Usually, these classification systems are domestic market-oriented, however, it is possible to apply them in other countries if enough adaptations are made.

LCA tool	Description
(China) Three Star System (France) HQE (Canada) Green Globes	
(France) eveBIM-ELODIE	Based on BIM models, the eveBIM-ELODIE quantifies the environmental impact of buildings by importing the quantity take-off from an IFC file and connecting with INIES database. However, this tool is oriented for the French market.
(UK) IMPACT	Like eveBIM-ELODIE, the IMPACT tool also imports the necessary information from BIM files, using Industry Foundation Classes (IFC) format, and gives the environmental and economic performance of buildings using British databases [260]. The results provided by IMPACT can also be used for BREEAM certification.
(Australia) LCADesign	Similar to eveBIM-ELODIE and IMPACT, LCADesign uses BIM-based information to evaluate the environmental impact of buildings. However, it is oriented towards the Australian market.
(Norway) One-Click LCA	A cloud-based plugin for Autodesk Revit (BIM-based program) that recognises automatically the materials used in the project to conduct the LCA of the construction. It not only uses its own LCA database but it also has incorporated several worldwide EPDs. Furthermore, its results contribute to certification schemes such as LEED and BREEAM.
(US) Tally	Another plugin for Revit that connects with GaBi database to perform the LCA of the whole project.

3.2.1.2. LCA databases

As mentioned above, the precision and quality of the results of level 1 LCA tools are dependent on the amount and quality of the used data for the inputs and outputs of a product's system. For that purpose, it is necessary to spend time and resources to develop LCA databases that contain energy and mass flows information. Similar to LCA tools, the LCA databases can also be grouped into three distinct groups, listed in Table 11 [245, 263-278]:

- **Group 1 of LCA databases:** comprises the inputs and outputs that are part of materials' manufacturing (e.g. glass, steel), the involved processes (e.g. steelmaking), and upstream (e.g. energy) and downstream processes data (e.g. landfill);
- **Group 2 of LCA databases:** cover the environmental information of products' components (e.g. assemblies). These LCA databases are very useful for LCA tools that are

oriented towards the construction industry, allowing the comparison of different products with the same function;

- **Group 3 of LCA databases:** contain operational and performance data (e.g. energy mix or water consumption).

Table 11 - LCA databases

Databases	Description
Group 1 - materials and processes	
(Australia) Aluminium LCA	Developed by the Australian Aluminium Council, contains data related to the production of aluminium.
(USA/ Canada) APC/EPIC	Developed by the American Plastics Council (APC) and by the Environment and Plastics Institute of Canada (EPIC), contains data related with the North American plastic industry.
(Australia) BHP Steel LCA	Developed by Broken Hill Proprietary Company (BHP), contains environmental data of over 65 steel materials.
(Sweden) CPM LCA	Developed by the Swedish Life Cycle Center, the CPM LCA database contains data to assist the environmental assessment of the Swedish industry.
(France) DEAM	Database used in the French LCA tool TEAM.
(Switzerland) Ecoinvent 3.5	Funded by the Swiss Federal Institutes of Technology (ETH Domain) and the Swiss Federal Offices, Ecoinvent is a non-profit association since 2013. It is one of the most used databases worldwide, covering LCI data from industrial processes mostly from Switzerland and Western Europe. The newest version of Ecoinvent distinguishes itself from the previous versions by introducing activities and product information (before it only covered processes) and by adding global coverage for activities through a global dataset. As a result of this new version, Ecoinvent can also be considered as a group 2 LCA database.
(European) Eco-profiles	Developed by the PlasticsEurope, covers data related with the European plastic industry as well as EPDs.
(European) ELCD	Funded by the European Commission, the ELCD (European Life Cycle Database) was an open access LCI database with information from European business associations (e.g. materials, energy carriers, transport, and waste management). It was recently discontinued but it is still available online [278].
(Switzerland) EMPA	Developed by the Swiss Federal Laboratories for Materials Science and Technology, EMPA database contains the information of the Swiss energy mix and industrial processes.
(European) EUROFER	Developed by the European Steel Association (EUROFER), this database contains information of steel products from EU manufacturers.
(Germany) GaBi	Database developed by the same producers of the GaBi LCA tool, containing data of energy supplies and production of a wide range of materials.

Databases	Description
(UK) ICE version 2.0	The Inventory of Carbon and Energy (ICE) is a British database with embodied energy and carbon data of building materials (e.g. bricks, glass or timber).
(Netherlands) IDEMAT 2016	Developed by the Delft University of Technology, the (Industrial Design & Engineering MATerials) IDEMAT database contains data of materials and processes from several existing databases (e.g. Ecoinvent) and from Delft University research (e.g. textile processing).
(UK) IMPACT	Database used in the British LCA tool IMPACT.
(Finland) KCL-EcoData	Database with environmental data of wood-based products.
(Australia) RMIT	An Australian LCA database with environmental data of national energy mix, fuel, construction materials, etc.
(Netherlands) SimaPro	SimaPro database was developed by PRé Consultants, the producers of SimaPro LCA tool and contains data of energy supplies and production of a wide range of materials.
(US) US LCI database	Developed by the National Renewable Energy Laboratory (NREL) and other partners, the US LCI contains data that are suitable for the environmental assessment of materials, components, or assemblies made in the US.
Group 2 – components	
(Canada) Athena	Database used in the level 2 LCA tools ATHENA Impact Estimator and ATHENA Ecocalculator, containing environmental data of structural and envelope elements, as well as energy flows.
(Spain) BEDEC	Developed by the Institut de Tecnologia de la Construcció de Catalunya, the BEDEC database has environmental and economic data of several products used in the construction industry.
(European) Eco-platform (Germany) IBU-EPD (Portugal) DAPHabitat (Germany) ÖKOBAUDAT (International) The International EPD System (UK) GreenBookLive	List of national and international databases with EPDs of a wide range of products, from furniture to building products.
Group 3 - operational and performance data	
(Finland) Lipasto	Finish database with emissions from vehicle traffic.

3.2.1.3. LCA Environmental Impact Assessment Methods (EIAM)

Another aspect that influences the results of an LCA study, beside LCA tools and LCA databases, are the environmental impact assessment methods (EIAM). The EIAM includes the environmental impact categories, category indicators, and environmental mechanisms (i.e. set of effects that, together, can damage human health or ecosystems) by using the information from LCI phase [245]. Furthermore, the EIAM can either be based on midpoint indicators (problem-oriented approach) or endpoint indicators (damage-oriented approach) [236, 245]. Midpoint indicators (e.g. Acidification, Global Warming, Eutrophication) represent the links of the cause-effect mechanism prior to the endpoints (e.g. Human Health, Resources Depletion), reflecting the relative importance of the environmental impacts [279]. It is argued that midpoint indicators are more accurate than endpoint indicators but can have a lower significance for the decision-making processes, with some experts considering that both indicators should be made available [26, 279]. Hence, depending on the purpose of the LCA study, the expert must use, and properly justify, the most suitable EIAM. The most common EAIM are displayed in Table 12 [245, 280-285].

Table 12 - List of EIAM

EIAM	Description
Midpoint indicators (problem-oriented approach)	
(US) BEES 4.0	Developed by the National Institute of Standards and Technology (NIST), BEES method is used in the LCA tool with the same name. However, although it uses midpoint impact categories, BEES method combines the categories into a single environmental performance score. It also performs an economic evaluation based on initial and future costs, which are merged in a single economic performance score. In the end, based on a weighting method, BEES will provide users with an overall score (environment plus economic scores).
(Netherlands) CML-IA	CML-IA (also known as CML 2001, which replaced CML 1992) was developed by the Institute of Environmental Sciences (CML) of Leiden University, and groups the environmental impacts in midpoint categories. Its newer version was updated in August 2016.
(Denmark) EDIP 2003	The Environmental Design of Industrial Products (EDIP) method was developed by the Institute for Product Development of the Technical University of Denmark. The EDIP 2003 version has 19 different impact categories and a more damage-oriented approach than the previous version, EDIP 97.
(Sweden) EPD 2013	As a method designed specifically for the elaboration of Environmental Product Declarations (EPDs), EPD was developed by the Swedish Environmental

EIAM	Description
	Management Council (SEMC). Furthermore, the impact categories used in this method were taken directly from the CML-IA method.
(Switzerland) IMPACT 2002+	Developed by the Swiss Federal Institute of Technology Lausanne (EPFL), IMPACT 2002+ is a combination of IMPACT 2002, Eco-indicator 99, CML-IA, and IPCC methods. It allows users to evaluate the environmental impact of products through a combined problem-oriented and damage-oriented approach, resulting in 14 midpoint categories summed up to 4 endpoint categories.
(International) IMPACT World+	Developed by several international institutions, IMPACT World+ combines IMPACT 2002+, EDIP, and LUCAS into an assessment method that can be used worldwide, without the regional limitations of other methods. Hence, IMPACT World+ method provides factors for each continent. Like IMPACT 2002+, it has 10 midpoint impact categories and 3 endpoint impact categories.
(European) ILCD 2011	The International Reference Life Cycle Data (ILCD) method was developed by the Institute for Environment and Sustainability in the European Joint Research Centre (JRC) and funded by the European Commission. Based on the analysis of several EIAM, the current version, ILCD 2011, groups the environmental information into 16 impact categories.
(Japan) LIME	Based on the Eco-indicator method, the Life-cycle Impact assessment Method (LIME) was developed by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). LIME, like other methods, uses a combined midpoint/endpoint approach, with 11 midpoint categories that are grouped into 4 endpoint categories. In the end, LIME generates a single score.
(Canada) LUCAS	The LCIA method Used for a Canadian-Specific context (LUCAS) was developed in 2005 by the Interuniversity Reference Center for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services (CIRAIG) of the École Polytechnique de Montréal. The goal was to develop an EIAM that was suitable for the Canadian context, using the characterisation models of EDIP 2003, IMPACT 2002+, TRACI, and LIME methods. LUCAS is a method that is based on a midpoint approach, with regional impact categories.
(European) MEEUP	Funded by the European Commission, the Methodology study for Eco-design of Energy-Using Products (MEEUP) method was developed in order to verify the eligibility criteria of products that aim to obtain the Conformité Européene (CE) marking and its accordance with the Ecodesign Directive and Energy Using Products (EUP) Directive. This method is oriented towards energy-using products and has a midpoint approach, with a total of 14 impact categories.
(Netherlands) ReCiPe 2008	With a goal to harmonise and integrate the endpoint approach of Eco-indicator and the midpoint approach of CML-IA methods, the ReCiPe method was developed by RIVM, CML, PRé Consultants, and Radboud Universiteit Nijmegen. As such, the

EIAM	Description
	ReCiPe method combines midpoint/endpoint approach, with 18 midpoint impact categories that are summed up to 3 endpoint impact categories.
(US) TRACY 2.1	Developed by the U.S. Environmental Protection Agency, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) is a method that was designed specifically for the US context, with a total of 10 impact categories.
(International) USEtox 2.0	Developed under the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), USEtox method assesses the environmental impact of chemical emissions of products. Mostly used in industrial LCA studies, USEtox is based on a midpoint approach and the characterisation factors are expressed in comparative toxic units (CTU) per kg of emission.
	Endpoint indicators (damage-oriented approach)
(Netherlands) Eco-indicator 99	Developed by the Dutch Ministry of Housing, the Eco-indicator 99 (which replaced Eco-indicator 95) focuses on the environmental consequence of products. One particularity of this EIAM is that it only generates a single score based on the weighting of human health, on the ecosystems quality and on resource impact categories.
(Sweden) EPS 2000	Developed by the Chalmers University of Technology, the Environmental Priority Strategies in product design (EPS) method uses a damage-oriented approach, with four impact categories that represent the damage on humans and ecosystems. It is based on the ‘willingness to pay’ principle, i.e. it considers the economic cost due to environmental damage. The results of EPS are represented by damage costs for emissions and use of natural resources, and are expressed as Environmental Load Units (ELU), with one ELU corresponding to one Euro of environmental damage cost.
(Switzerland) IMPACT 2002+	As mentioned above, IMPACT 2002+ combines a midpoint/endpoint approach.
(International) IMPACT World+	As mentioned above, IMPACT World+ combines a midpoint/endpoint approach.
(Japan) LIME	As mentioned above, LIME combines a midpoint/endpoint approach.
(Netherlands) ReCiPe 2008	As mentioned above, ReCiPe combines a midpoint/endpoint approach.
(Switzerland) Swiss Ecopoints	Also known as Ecoscarcity Method, the Swiss Ecopoints method was developed by the Federal Office of the Environment, Forests and Landscape and last updated in 2013. The Swiss Ecopoints method considers the European legislation on the environment and applies it to the Swiss context, based on an endpoint approach. It uses eco-factors to measure the environmental impact of emissions or resource

EIAM	Description
	extraction activities, providing the results in the form of eco-points (EP=UBP) per unit of quantity.

3.2.1.4. LCA Environmental Impact categories

According to ISO 14040:2006, impact category is considered as a "*class representing environmental issues of concern to which life cycle inventory analysis results may be assigned*" [233]. The results of the LCI and LCIA phases (i.e. category indicators) are assigned (classification process) to environmental impact categories, either at the midpoint or endpoint level. Then, the category indicators, i.e. the "*quantifiable representation of an impact category"*, are converted into a common unit using characterisation factors that are provided by the characterisation model, and grouped into environmental impact categories [233, 235]. For instance, the characterisation factor of methane gas (CH_4) for the global warming potential category over a period of 100 years (GWP_{100}) is equal to 25, while the characterisation factor of carbon dioxide (CO_2) is equal to 1 [286]. This means that one unit of CH_4 contributes 25 times more to global warming than one unit of CO_2. Another aspect is that a single category indicator can contribute to more than one impact category (e.g. nitrogen oxides (NOx) contribute to acidification and eutrophication as well, as seen in Figure 6).

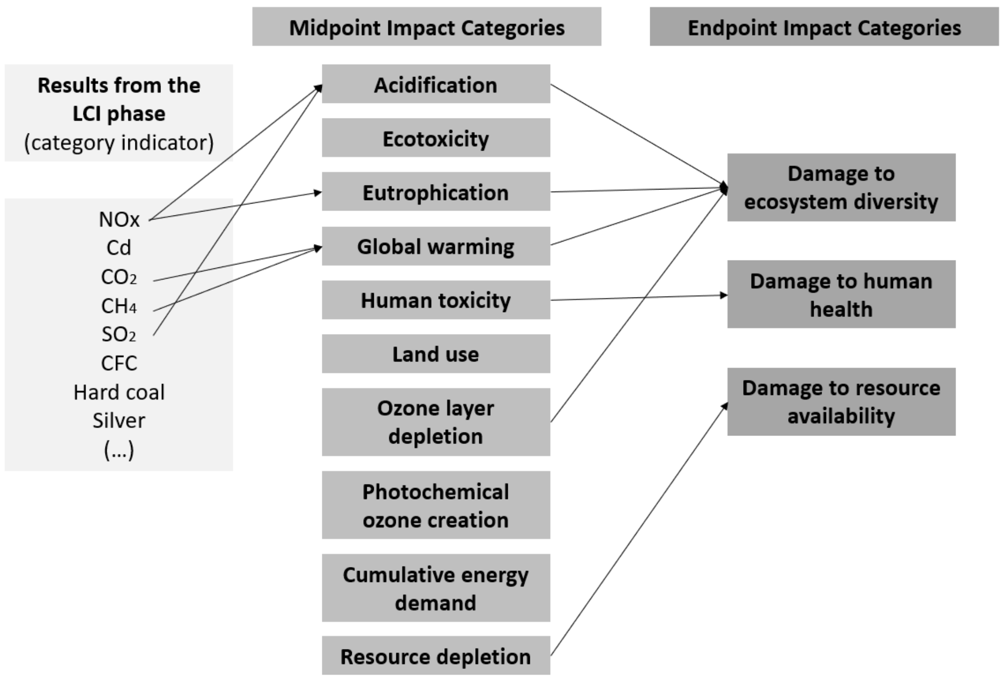


Figure 6 - Environmental mechanism: from category indicators to midpoint/endpoint categories (adapted from [236])

In the end of the characterisation process, each impact category has a corresponding numerical indicator result (e.g. in the Global Warming impact category all greenhouse gas emissions are converted into CO_2 equivalents, CO_2eq). Furthermore, the environmental impact categories can be global, regional, or local based on their scale and influence (e.g. global warming or ozone depletion are global impact categories, while acidification and eutrophication can be global, regional, or local), and midpoint impact categories can be grouped into endpoint categories, as done by some EIAM. Figure 6 shows the environmental mechanism mentioned above, i.e. the environmental processes related to the characterisation of the impacts. Also, the most common environmental impact categories are described in Table 13 [245, 285, 287-291].

Table 13 - Environmental Impact Categories

Impact Categories	**Description**
Midpoint categories	
Abiotic Depletion	The abiotic depletion category considers the consumption of natural resources, such as mineral, and fossil resources. The extraction rate and the natural deposits of a resource allow to understand the consequences of its depletion. However, abiotic depletion is a debatable category, as there is no scientific method to define the characterisation factors. It is also possible to split the abiotic depletion category into two: abiotic resource depletion – fossil fuels (ADPE) and abiotic resource depletion - non-fossil fuels (ADPM). The antimony element (also known as stibium - Sb), as the first element of the alphabet that has available the necessary data, is generally used as the reference element of the ADPM, and its unit is the antimony equivalent, Sbeq. The ADPE is represented in megajoules (MJ).
Acidification	The burning of fossil fuels generates anthropogenic emissions (e.g. sulphur dioxide (SO_2) and nitrous oxides (NOx)) that contribute to the decrease of water's pH, i.e. acidification of the water. This leads to phenomena known as acid rains that destroy forests, increase of fish mortality by acid, and contamination of water sources. The Acidification Potential (AP) is often represented as sulphur dioxide equivalent, SO_2eq.
Cumulative Energy Demand	The cumulative energy demand (CED) is often used as a measure of the primary energy demand (PED) throughout the life cycle of the product. CED does not correspond to an impact category according to ISO standards, as any kind of energy demand cannot be considered as a category. However, Dutch EIAMs (e.g. Eco-indicator 99) usually considers the CED as a category, as the energy demand is easily determinable with low uncertainty. CED can also provide information for two energy-based categories: Primary energy consumption using renewable sources (PE-

Impact Categories	Description
	Re) and Primary energy consumption using non-renewable sources (PE-NRe). CED, PED, PE-Re, or PE-NRe are all represented in megajoules (MJ).
Ecotoxicity	Chemical, biological, or physical pollutants can have an impact on organisms and ecosystems, such as starvation of species due to organ lesions, disruption of hormone levels, and change in biodiversity. There are EIAMs that distinguish different types of ecotoxicity, resulting in terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FAETP), and marine ecotoxicity (MAETP). The Ecotoxicity Potential can be represented by the bioconcentration factor ($BCF = C_{\text{pollutant X in the organism}}/C_{\text{pollutant X in the surrounding medium}}$).
Eutrophication	Represents the impacts of the oversupply of nutrients (e.g. Nitrogen and Phosphorous) in the ecosystems. This is caused by the massive growth of plants or algae that leads to the increase of oxygen consumption due to biomass degradation which, in turn, will change the quality of water and species composition. In Eutrophication, the distinction is often made between Aquatic Eutrophication (freshwater and marine) and Terrestrial Eutrophication (due to overfertilisation impacts such as change of nutrients' amount in the soil). The Eutrophication Potential (EP) can be represented by phosphate equivalent, PO_4^{3}-eq.
Global Warming	Probably the most known environmental impact category, global warming is caused by greenhouse gas emissions (e.g. CO_2, CH_4) that trigger the greenhouse effect process. There are several global and local consequences from the increase of global temperature, as the melting of glaciers, rise of sea water level, and, consequently, the increase of flooding disasters and submerge of coastal land areas. There are authors and EIAMs that, instead of global warming, refer to this category as Climate Change, Carbon Footprint, or Radiative Forcing. The Global Warming Potential (GWP) is represented by the carbon dioxide equivalent, CO_2eq.
Human Toxicity	Even though Human Toxicity covers the toxicological impacts on humans, it is a controversial category as there are a wide number of different impact mechanisms that lead to carcinogenic, non-carcinogenic, and respiratory diseases. The difficulty in quantifying the effects on human health of chemical products is also another issue. The Human Toxicological Potential (HTP) can be represented by the unit m^3fU^{-1}, which indicates the risk potential of emissions according to the MAK-values[1].
Land Use	Depending on the study's goal, land use can be based on its sink potential or preservation soil potential, i.e. its potential to absorb anthropogenic gases. Land Use Potential can be represented by area x time (e.g. m^2 x year).

[1] MAK - Maximale Arbeitsplatz-Konzentration (in German) or Maximum Workplace Concentration (in English)

Impact Categories	Description
Ozone Layer Depletion	Since the Chlorofluorocarbons (CFC) were banned, the impacts of anthropogenic gases in the ozone layer have far decreased. The more recognisable consequence of the ozone layer depletion (or stratospheric ozone depletion) is the 'Ozone Hole', where a high number of ultraviolet rays are able to reach the Earth's surface. The Ozone Layer Depletion Potential (ODP) represents the amount of ozone destroyed by a gas over its lifetime relative to that due to the emission of the same mass of CFC-11. It can be represented by CFC-11eq or R-11eq (i.e. Refrigerant 11).
Photochemical Ozone Creation	The photochemical oxidation is caused mainly by road traffic, solar radiation, and poor geographical conditions for air flow, contributing to the ozone creation. It is also called summer smog due to the high concentration levels of ozone at low heights after long sunny days. This can damage human health and ecosystems, as well as contribute to the greenhouse effect. The Photochemical Ozone Creation Potential (POCP) can be represented in ethylene equivalent, C_2H_4eq.
Endpoint categories	
Damage to ecosystem diversity	This endpoint category comprises all the midpoint categories (mentioned above or others) that have an impact on the ecosystem diversity, such as: global warming, ecotoxicity (terrestrial and marine ecotoxicity), land use, eutrophication, and acidification.
Damage to human health	Comprises all the midpoint categories that have an impact on the human health, such as: ozone layer depletion, human toxicity, photochemical ozone creation, and global warming.
Damage to resource availability	Comprises all the midpoint categories that have an impact on the resource availability, such as abiotic depletion, land use, and cumulative energy demand (as fossil fuels are used to generate energy).

3.2.2. LCC methodology

Life Cycle Costing (LCC) has its origins in systems engineering [292, 293] and was first mentioned in the 1967's report on life cycle costing in equipment procurement [294]. Since then, US Department of Defence issued several guides on procurement based on life cycle costing [295], and after 1974 some states published legislation that made LCC mandatory for all new public buildings [296].

According to Dhillon [295], life cycle cost is "*the sum of all costs incurred during the life span of an item or system (i.e. the total of procurement and ownership costs)*". Hence, LCC considers the acquisition costs (delivery, installation, and insurance), operating costs (energy and water use and maintenance), and end-of-life costs (decommissioning or disposal) of a product [297]. Furthermore, in LCC analysis (LCCA) it is necessary to consider the time variable, i.e. make use of interest and inflation rates to determine the time value of money (difference between future value and the present-day value). This means that, unlike in traditional LCA studies where the environmental impacts are summed up, in LCC studies this is not possible as the costs occur in different periods of time [298]. By using economic-based methods such as discounted cash flow and net present value, all the costs associated with the product during its life cycle are factored (using discount rates) and expressed in current time value.

In 2008, a common methodology for the application of LCC in the construction industry was published by ISO [299]. Also, the European Commission published a set of reports on the application of LCC in the construction industry that is in accordance with ISO 15686-5 [300-302]. In this sense, LCC is becoming more relevant in the procurement processes by public authorities [297], with the recent European Directive on public procurement 2014/24/EU stating that "*the most economically advantageous tender from the point of view of the contracting authority shall be identified on the basis of the price or cost, using a cost-effectiveness approach, such as life cycle costing*" [45].

3.2.2.1. LCC methods

Before the most common LCC methods are discussed, it is important to highlight three economic indicators that are often used in LCC methods: the discount rate, the inflation rate, and the escalation rate [299, 300].

Discount rate – it is the "*factor or rate reflecting the time value of money that is used to convert cash flows occurring at different times to a common time"* [299]. The discounting technique is used when the purpose of the study is to compare the cost of a product over different periods of time [300]. It is guided by the principle that a certain amount of money in the present is more valuable than the same amount of money in the future. Hence, discount rate takes into consideration the inflation and possible change in earning power (i.e. the ability to generate income) in the future, enabling the comparison of products from different periods of time. The selection of a suitable discount rate is extremely important for the success of an LCC analysis and differs from private to public sector. While in private sector the discount rate depends on the cost of capital, expected risk, and opportunity cost of capital (i.e. the cost of alternative investments), in the public sector it ranges from 3% to 5% and is usually fixed by national ministries of finance [300]. High discount rates usually favour projects with a quick return on investment instead of projects with further benefits in the future [303]. However, if the discount rate is zero, the product or service will always have the same cost regardless when it was purchased and is only used in public sector investments with a lasting life expectancy.

Inflation/deflation – it is the "*sustained increase/decrease in the general price level*" [299]. A discount rate that accounts for the effects of inflation when predicting future costs is named 'nominal discount rate', otherwise it is named 'real discount rate'. It is common practice to neglect the inflation from LCC analysis when all costs have the same rates, therefore, the real discount rate is used in these cases. On the other hand, if products or services are subject to different inflation rates (e.g. from different countries), it is not possible to exclude the effects of inflation, thus, the nominal discount rate is used. However, it is recommended to use real costs and, consequently, real discount rates in LCC studies in the construction industry, due to the long service life of buildings.

Escalation rate – it is the "*positive or negative factor or rate reflecting an estimate of differential increase/decrease in the general price level for a particular commodity, or group of commodities, or resource*" [299]. So, a product with an escalation rate of 0% will maintain the price over the time. Although escalation rate and discount rate might look similar, they are not the same. If the discount rate is higher than the escalation rate (i.e. the product is being discounted at a higher rate than it is escalating), this means that the same product will have a lower present value than its costs. If both rates were equal, then that material would have a present value equal to its present cost. Moreover, the escalation rate differs from the inflation as the last is equal to all goods and services while the first is specific to each good or service.

The most used methods in LCC analysis are thoroughly explained bellow [299, 300, 304-306].

Net Present Value (NPV) or Net Present Cost (NPC)

As a standard economic evaluation method in LCC analysis, the NPV is the sum of the discounted future cash flows, considering both costs and profits. The NPC is very similar to NPV but it only considers the future costs. It can be used in all construction investments, from set of assemblies to individual components. The net present value X_{NPV} can be determined using the equation (1):

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

In the above equation:

C_n is the cost (i.e. net cash flow) in year n;

d is the discount rate;

p is the period of analysis.

If the inflation rate was to be taken into consideration, the NPV formula should be determined using the nominal discount rate, according to equation (2):

$$X_{NPV} = \sum_{n=1}^{p} C_n \times \left[\frac{(1+i)}{(1+d)}\right]^n \qquad (2)$$

In the above equation:

i is the inflation rate per annum;

Payback (PB)

The payback period is the length of time that it takes to recover the cost of an investment and is often used to evaluate alternative options. There are two kinds of payback period; the simple payback and the discounted payback. While the simple payback uses real values for future costs, the discounted payback uses present values. Although it is a simple method to assess the merit of an investment, payback ignores the time value of money, unlike the NPV. A project with a low payback period might not always be a better option than a project with a higher payback period. As such, it should be used only as an additional method to evaluate the value of an investment. Payback period can be calculated using the following equation (3):

$$Payback\ period = \frac{Cost\ of\ Investment}{Annual\ Net\ Cash\ Inflows} \qquad (3)$$

In the above equation:

$Cost\ of\ Investment$ is the initial investment;

$Annual\ Net\ Cash\ Inflows$ is the annual revenues of the investment.

Net Savings (NS)

Net Savings is the present value of savings minus the present value of additional investments. It is used to measure the cost-benefit of a project, i.e. a project is cost-effective if its net savings value is greater than zero. It is often used to compare investment options, in which the option with the greatest net savings is considered the most economically viable. Net savings can be calculated using the following equation (4):

$$NS = \sum_{n=1}^{p} \frac{S_n}{(1+d)^n} - \sum_{n=1}^{p} \frac{\Delta I_n}{(1+d)^n} \tag{4}$$

In the above equation:

S_n is the savings in year n;

ΔI_n is the additional investment costs in year n;

d is the discount rate;

p is the period of analysis.

Savings to Investment Ratio (SIR)

Savings to Investment Ratio expresses the ratio between savings and investment costs in the present value. In other words, while Net Savings provided a value that represents the difference between savings and costs, the SIR represents the ratio of savings and costs. Hence, a project is considered a good investment if its SIR is greater than 1 (i.e. its savings are greater than the cumulative investments costs). It is also used to prioritise investment options through a ranking system based on SIR order. However, projects with the highest SIR might not always be the ones that have the lowest LCC. For instance, when choosing between insulations with different thickness/layers, while a single layer of insulation will have a higher SIR the thickest one will probably have a lower LCC. The SIR value is determined by the following equation (5):

$$SIR = \frac{\sum_{n=1}^{p} \frac{S_n}{(1+d)^n}}{\sum_{n=1}^{p} \frac{\Delta I_n}{(1+d)^n}} \tag{5}$$

Adjusted Internal Rate of Return (AIRR)

The Adjusted Internal Rate of Return is the compound rate of interest that measures the annual percentage yield of a project over the period of analysis. Like NS and SIR, the AIRR is another method that measures the cost-effectiveness of a project and allows economists to determine the discount rate that produces an NPV of zero. Hence, an investment is only considered viable if the AIRR is greater than the discount rate. To determine the AIRR in a simplified manner it is possible to use the following equation (6):

$$AIRR = (1 + d)(SIR)^{\frac{1}{n}} - 1 \quad (6)$$

In the above equation:

d is the discount rate;

SIR is the Savings to Investment Ratio;

n is the number of years between the base date and the occurrence of the cost.

Annual Cost (AC) or Annual Equivalent Value (AEV)

The Annual Cost or Annual Equivalent Value is a uniform annual amount of money that is equivalent to the total net cost of the project, considering the time value of money over the period of analysis. As such, an investment option with the lowest AEV represents the option with the lowest total cost. Furthermore, when discounted, the AEV is equivalent to the NPV. The annual equivalent value is calculated with the following equation (7):

$$X_{VAE} = \frac{C_n}{(1 + d)^n - 1} \quad (7)$$

In the above equation:

C_n is the cost in year n;

d is the discount rate.

3.2.2.2. LCC tools

To perform the LCC analysis it is possible to use LCC tools that, depending on the complexity of the study, could range from simple Excel spreadsheets to industry-oriented tools. Despite LCC has emerged sooner than the LCA, there are considerable fewer tools available on the market. Furthermore, unlike the complex and comprehensive LCA programs with massive databases, most LCC tools are simple spreadsheets with a straightforward approach. Some of these are identified and described in Table 14 [255, 258, 297, 307-318].

Table 14 - LCC tools

LCC tool	Description
(Austria) ABK LEKOS	In accordance with Austrian standards, the ABK LEKOS tool includes a database with costs that can be used for early design stages. However, it is not suitable for later stages.

LCC tool	Description
(Sweden) BELOK LCC	Resulting from the cooperation between the Sweden’s Energy Agency and Sweden's largest property owners, the BELOK LCC is a web-based tool that estimates the costs associated with the energy efficiency of products during their life cycle. However, it is only available in Swedish.
(UK) BLP Life Cycle Costing tool	Funded by the Homes and Communities Agency, the Building LifePlans (BLP) developed an LCC tool in 2009. Their tool has its own database with cost information on construction and components and is compliant with the British Standards (BSI).
(Germany) DGNB/BNB building certificate	Developed by the German Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety, the BNB certificate is based on five pillars: economic, ecologic, social, technical and process quality. One of the indicators used in the German system corresponds to the LCC analysis, with the BNB website providing an excel-based LCC tool that uses the NPV method.
(Israel) D-LCC	Developed by the Advanced Logistics Development (ALD), the Decision by Life Cycle Cost (D-LCC) is a flexible tool that can be used in a wide range of sectors. It estimates the life cycle costs of products using the NPC method and allow users to perform cost-effectiveness analyses and sensitivity analyses.
(European) EU LCC tool	The EU LCC tool is currently under development and is being funded by the European Commission in order to encourage the use of LCC in public procurement processes. This tool will also consider environmental impact based on the ReCiPe method.
(UK) IES LIFECYCLE and IES IMPACT Compliant Suite	IES developed a module named LIFECYCLE that performs the life cycle costing of the whole building, which can be integrated with the IMPACT tool. It also has developed a similar tool, the IES IMPACT Compliant Suite, which integrates LCC with LCA.
(European) LCC-CO2 tool	Developed by the Ecoinstitut Barcelona and Öko-Institut e.V. and funded by the Intelligent Energy Europe program (SMART-SPP), the LCC-CO2 is an excel-based tool and was designed to assist public authorities in the assessment of LCC and CO_2 emissions of products and services. It can also be used to compare different solutions in tender phase.
(Sweden) LCP - kalkyl för energisparåtgärder	Developed by the Swedish Svenska Bostäders, the LCP is an excel-based tool that focuses solely on the life cycle costs related to energy consumption. However, it is only available in Swedish.
(Germany) LEGEP	LEGEP tool was developed by a research project in the field of sustainable construction, providing an integrated environmental and economic analysis. In accordance with German, Austrian, and Danish standards, it allows the user to conduct an LCA and LCC analysis of the full life cycle of the project. For that purpose, the LEGEP tool includes a set of individual modules, each with their own databases, with environmental and economic information of over 700 products.

LCC tool	Description
(US) RSMeans Life Cycle Costing tool	RSMeans developed an online life cycle costing tool that allows users to conduct LCC analysis of their assets. It is a tool that is oriented towards facilities management, containing several databases with historical cost data related with residential, commercial, and industrial buildings.
(Germany) SMErobot LCC tool	The LCC tool developed by the SMErobot company focuses on the life cycle costs for robots and industrial services, allowing users to compare different solutions.
(Denmark) TCO tool	Developed by the Danish Environmental Protection Agency (EPA), the Total Cost of Ownership (TCO) tool focuses on lighting fixtures and electronic equipment. However, total cost of ownership analysis is only a partial LCC analysis that focuses on the product's user perspective.
(Sweden) The National Agency for Public Procurement LCC tools	Developed by the Swedish National Agency for Public Procurement, the excel-based LCC tools available on their website are based on the NPV method and allow users to conduct the LCC analysis of products and compare different solutions. It also considers the environmental impact due to energy consumption.
(Germany) Umberto	Another German tool that allows users to conduct environmental and economic life cycle assessments of products.
(Sweden) WCM LCC calculator	Developed by the World Class Manufacturing (WCM) company, the LCC calculator can be accessed on their website or downloaded as a spreadsheet.

3.2.2.3. LCC databases

As mentioned above, the LCC tools are mostly excel-based, without having their own databases, i.e. users must introduce in the spreadsheets all the cost information related to the product to be analysed. As such, the number of available LCC databases is much smaller when compared with LCA databases. Another aspect that influences this seemingly shortage of LCC databases is that each country has specific costs (e.g. product prices, workers' salary, taxes), unlike some LCA databases that can be adapted to national markets (using national energy mix, for instance). Hence, the collection of LCC databases can be hindered by this issue, since it is highly unlikely that non-English countries have cost information in English. This issue can be observed in Table 15, which lists some of the existing LCC databases and documents with cost information [307, 316, 318-321].

Table 15 - LCC databases

LCC databases	Description
(Germany) BKI-Baukosten	An exhaustive set of documents with cost information of construction elements, statistical costs based on type of buildings, tendering and awarding processes, accessibility, etc. It was last updated in the beginning of 2017. However, it has

LCC databases	Description
	some disadvantages, as it is only available in German, does not have a digital version, and is oriented towards the German market (although it can be adapted to the Austrian market).
(UK) BLP database	The BLP LCC tool has its own database, with cost information of more than 40.000 construction components.
(International) Compass International	Compass International publishes every year a set of books that compile the global costs of a wide range of sectors (e.g. construction, manufacturing, industry/commercial schedules, offshore). It collects real cost data from worldwide sources, as government agencies, development banks, national trade agencies, EU Commission reports, etc. Thus, it is a valuable source of cost data from over 100 countries, which allows readers to compare costs internationally. However, it is only available in paper or pdf format and does not consider the full life cycle of the products (only acquisition and maintenance).
(Portugal) LNEC-*Fichas de Rendimento*	Developed by the Portuguese National Laboratory for Civil Engineering (LNEC), *Fichas de Rendimento* is a document with estimated costs for construction elements and construction processes. It has a few disadvantages, as it focuses on the Portuguese market, it is only available in paper, contains only costs for the construction stage, and its last update was done in 2013.
(US) RSMeans	The company RSMeans has developed a set of national databases with life cycle cost data of different type of buildings, construction works and elements.
(Germany) SIRADOS Baudaten	It is one of the databases used in the LEGEP program. It contains data that is used for cost estimation, tendering, and calculations for the built environment. However, it is only available in German.

As argued before, the exploration of the LCA and LCC methodologies enables a more comprehensive understanding of the information and processes required for a BIM-based LCA and LCC analyses. Thus, the frameworks, methods, and information indicated in this sub-section contribute to the development of a BIM-LCA/LCC framework, which is detailed below. This framework is expected to answer the first research question, i.e. which information can be integrated in the BIM model?

3.3. Proposed framework for the BIM-LCA/LCC analysis

3.3.1. Identification of environmental and economic information required for the BIM-LCA/LCC analysis

Building on the literature on BIM integration with LCA and LCC, it is argued that if the digital objects had the necessary information, the LCA and LCC analysis of buildings using BIM-based tools could become more automatic and faster. To do so, it is necessary to (i) identify which information must be included in objects, (ii) propose a conceptual framework for BIM-LCA/LCC analysis that will be based on that information, (iii) develop a methodology that could handle the information exchange required to perform the LCA and LCC analysis within a BIM-based environment, and (iv) develop a tool that could perform the LCA and LCC analysis based on the proposed framework.

Firstly, in order to overcome some of the limitations of the existing approaches and promote the use of BIM as an information repository that can be used for information management, the required information to be included in the BIM models (e.g. using BIM objects) and a suitable framework for a BIM-based LCA and LCC analysis must be identified. In this sense, it is hypothesised that:

H1: For LCA, products with Environmental Product Declarations (EPDs) can have the LCA results and service life incorporated in the objects, while, for LCC, products can have the corresponding acquisition costs, service life, and density.

Secondly, the identification of the information required for the LCA and LCC analysis within a BIM-based environment facilitates the understanding of how it can be inserted in the model in a manner that allows an automatic analysis. In this regard, academics are frequently developing new frameworks to improve the synergy between BIM and interdisciplinary domains. By formally specifying the processes and relationships between the required variables to perform analyses (e.g. environmental, economic, information management, etc.), researchers have been proposing BIM-based ontologies and semantics [115, 322-325]. While ontologies focus on the definition of the relationship between concepts, the semantics identifies the concepts within a domain [326]. The development of ontologies and semantics are very often connected with the development of information delivery manuals (IDM) and model view definitions (MVD). The IDMs are used to link the processes performed throughout the lifecycle of the buildings with the specific information required by these processes. These processes and information exchanges are then converted into data schemas, the MVDs. More detailed examination is presented in the next chapter. Therefore, it is hypothesised that:

H2: It is expected that the use of methodologies such as information delivery manual (IDM) and model view definition (MVD) would contribute to the identification of the processes and exchange of information required for a BIM-based LCA and LCC analysis.

Thirdly, the development of IDMs and MVDs are enabling the development of new BIM-based applications (e.g. Revit APIs). These applications contribute to the information management within BIM models and semi-automatic and automatic simulations, thus reducing human-made errors and workload of designers [327-329]. However, not all information can be added into the BIM model and human interpretation and analysis is required [328, 330]. The information added to the models can often be used for simpler analyses but such approach might not be possible for more comprehensive analyses. Therefore, it is hypothesised that:

H3: Although a streamlined LCA/LCC analysis could be done automatically, considering just the production phase (A1-A3 modules), a complete LCA/LCC analysis cannot.

As stated above, before proposing a BIM-LCA/LCC framework, the information required for the LCA and LCC analyses must first be identified and incorporated into the BIM model. This will provide the answer to the first research question, and parametric modelling can offer an adequate solution. Through parametric modelling, it is possible to incorporate the information regarding different specialties in a single object, as well as to define parametric relationships and constraints [331].

3.3.1.1. Required information for BIM-LCA integration

According to a European research project named 'EeBGuide' that wants to "*support LCA practitioners in obtaining comparative results from their works*", experts can conduct three different types of LCA studies: screening, simplified, and complete [332]. A screening LCA can be used for an initial assessment of the environmental impacts of buildings or products. The simplified LCA study is similar to the screening LCA, but it is usually done in a more advanced stage and with more data. A complete LCA study corresponds to the framework proposed in ISO 14040: 2006, with a comprehensive assessment of the environmental impact of the building/product and covering its entire life cycle. Another European research project named 'ACADEMY' [333] promoted a fourth type of LCA study based on the Streamlined LCA approach proposed by the Society of Environmental Toxicology and Chemistry (SETAC) in 1999 [334]. The Streamlined LCA is an *ad hoc* version of the standard LCA approach in which the expert selects the most suitable boundaries and environmental categories for their study. This approach is recommended for the assessment of different products using the LCA methodology when quantitative data of the system is not readily available, being an ideal approach to be applied at early stages of the project. Considering the existing literature on LCA and BIM, it is possible to conclude that, if the BIM models also contains information regarding the environmental impact of materials, at least an automatic Streamlined LCA analysis of the whole project would be possible. However, for a complete LCA analysis it would be necessary to manually insert specific information of the project (other than the one incorporated in each material). To include such information in a structured way, several aspects must be considered, namely the system's boundary, the type of LCA data, and the environmental impact assessment method used.

Even though there are several important aspects to consider in an LCA analysis (please refer to [234] for further information), it is fundamental to define the system boundary, in which the experts outline which processes will be covered in the building's assessment. According to [234], the building's life cycle is split into three main modules (A, B, and C), as seen in Figure 5. There is another module beyond the building's life cycle, the module D, that comprises the benefits from reuse, recovery or recycling (C3). In contrast to previous modules, module D can include positive environmental impacts, i.e. the avoided impacts from the use of recycled materials instead of raw materials.

The data used for the LCA study can be from three different types: generic, average or specific [335]. Whereas generic data uses information from different manufacturers to provide decontextualised results (e.g. Ecoinvent), specific data uses information from a single product collected at the manufacturer's production site (e.g. EPDs, a scheme that structures and harmonises the manufacturers' product's information [336]), and average data is compiled using information provided by different manufacturers but with the same declared unit (e.g. average EPDs) [335]. Another aspect that must be considered in an LCA study is what type of output is intended from the study, i.e. does the expert intend to identify the problem or the damage caused by the building's environmental impact? For that purpose, either the LCA study has a problem-oriented approach (midpoint) or a damage oriented approach (endpoint) [236]. It is the selection of the environmental impact assessment method used in the LCA study (e.g. CML 2001, ReCiPe, TRACY 2.1, Eco-Indicator 99, etc.) that will determine the categories used to express the results of the study.

Based on these aspects, if parametric modelling is used to add information to BIM objects, the most suitable data to be incorporated in the objects to perform an automatic environmental analysis is specific information from each product (e.g. EPDs). However, in the early stages of the project (i.e. level of development (LOD) [337] lower than 300), only generic and average LCA data can be inserted in the objects, using the average data of each material (e.g. for LOD 200 of concrete columns, the information used to perform an LCA study can be the average of all EPDs available in LCA databases). Only for later stages of the project (i.e. LOD 300 or above), EPDs can be used as a source as products/materials are known in this phase [57].

For a complete LCA study, beside the information contained in BIM objects (that should be provided by manufacturers), there is other information that only designers can provide. For the A4-A5 modules, the designer must provide the type of transportation of the products from suppliers to the construction site (e.g. truck, train, ship, etc.), transportation distances, and utilities used (e.g. electricity consumption) and waste generated during construction. For the B modules, the designer must know the products' service life to determine the environmental impact of replacement activities and provide energy and water consumption during the operational phase of the building. For the C modules, the designer must indicate the type of transportation of the products from the demolition site to waste treatment/disposal facilities (e.g. truck), transportation distances, and the most probable waste scenarios (e.g. reuse, recycle, incineration, landfill). In addition to this information, the designer must provide the service life of the building and its location (e.g. Belgium) as well, as each country has its specific energy mix (e.g. coal, hydro, wind, solar, nuclear), that will affect the outputs generated (e.g. CO_2 emissions). Furthermore, for the A4 and C modules specifically, the density of products must be known, as the material/element weight influences the transportation and waste treatment.

Regarding the environmental impact assessment method, the CML 2001 method (midpoint) and the cumulative energy demand (CED) will be used to categorise the LCA results [287, 338], as European EPDs provide LCA results of products based on these methods and are already recognised in other European standards [339]. Usually, EPDs only provide environmental impacts of A1-A3 modules (mandatory) of products but might contain environmental information on the A4-A5, B and C modules as well. However, the data from A4-A5, B and C modules of products should not be used in the environmental assessment of a building, as it is based on one probable scenario defined by the producer (i.e. it is not site specific) [340]. Hence, a BIM object should contain the impacts for the following environmental categories (A1-A3 modules): acidification potential (AP); global warming potential (GWP); eutrophication potential (EP); abiotic depletion potential of materials (ADPM); abiotic depletion potential for fossil fuels (ADPE); photochemical ozone creation potential (POCP); ozone depletion potential (ODP); renewable energy (PE-Re); and non-renewable energy (PE-NRe). It is also required that each product (i.e. BIM objects) contains the expected service life. The necessary environmental information that needs to be integrated in the BIM model to permit the Streamlined and Complete LCA analysis and that needs to be used throughout the development of the project is listed in Table 16.

Table 16 - Information required for Streamlined and Complete LCA analysis

STREAMLINED LCA analysis	***BIM objects***	Generic LCA data (ADPE; ADPM; AP; EP; GWP; ODP; POCP; PE-NRe; PE-Re)
	Project details	---
COMPLETE LCA analysis (LOD 300 or above)	***BIM objects***	Durability; Density; EPD LCA results (ADPE; ADPM; AP; EP; GWP; ODP; POCP; PE-NRe; PE-Re)
	Project details	Building's service life; Transportation type; Transportation distance; Utilities used and Waste generated during construction; Estimated utilities used during operational phase; Possible waste scenarios for each material

3.3.1.2. Required information for BIM-LCC integration

According to ISO 15686-5:2008 and European Commission's report developed by Davis Langdon, one of the most common LCC methods in the construction industry is the Net Present Value (NPV) [299, 300]. The NPV is the sum of the discounted future cash flows, considering both costs and profits, and can be determined using equation (1). One important variable that is part of the NPV method (and other LCC methods) is the discount rate as the "*factor or rate reflecting the time value of money that is used to convert cash flows occurring at different times to a common time"* [299]. Discounting techniques are used when the purpose of the study is to compare the cost of a product over different periods of time [300]. It is guided by the principle that a certain amount of money in the present is more valuable than the same amount of money in the future. Hence, the discount rate considers inflation and possible changes in earning power (i.e. the ability to generate income) in the future, enabling the comparison of products from different periods in time.

If the same modules from the LCA analysis are considered for a streamlined LCC analysis (i.e. A1-A3), then the BIM object only needs to include acquisition cost information (that should be provided by the manufacturer). In the case of a complete LCC analysis of the project (i.e. LOD 300 and above), the designer must insert additional information, e.g. the service life of the building and discount rate. Following the LCA framework, for the A4-A5 modules, the designer must provide the type and distance of the transportation used to move products from suppliers to the construction site based on the distance (transportation price will be calculated based on that data and on products' density), the consumption of utilities during construction (utilities cost will be calculated based on that data), and the cost of all the construction activities tasks. For the B modules, the designer must provide the energy and water consumption during the operational phase of the building. Similar to the LCA analysis, BIM objects should also contain the durability (i.e. estimated service life), to determine the replacements' costs. For the C modules, the designer must provide the type and distance of the transportation of products from the demolition site to waste treatment/disposal facilities. In these modules, the designer must also indicate the waste treatment according to different scenarios (e.g. reuse, recycle, incineration, landfill). Therefore, the proposed framework and future tools that support it must consider all this information (i.e. BIM objects, information provided by the user, and databases that contain cost information).

The necessary economic information to be integrated in the BIM model to permit a Streamlined and Complete LCC analysis and to be used throughout the development of the project is listed in Table 17.

Table 17 - Information required for Streamlined and Complete LCC analysis

STREAMLINED LCC analysis	***BIM objects***	Acquisition cost
	Project details	---
COMPLETE LCC analysis (LOD 300 or above)	***BIM objects***	Acquisition cost; Durability; Density
	Project details	Building's service life; Discount rate; Transportation type; Transportation distance; Utilities used during construction; Construction activities costs; Estimated utilities used during operational phase; Possible waste scenarios for each material

3.3.2. BIM-LCA/LCC framework

Building on the framework proposed by Shin and Cho [177] and using the environmental and economic information previously identified, the framework that supports the environmental and economic assessment of a project by using LCA, LCC, and BIM is shown in Figure 7 and is supported by equations (8-17).

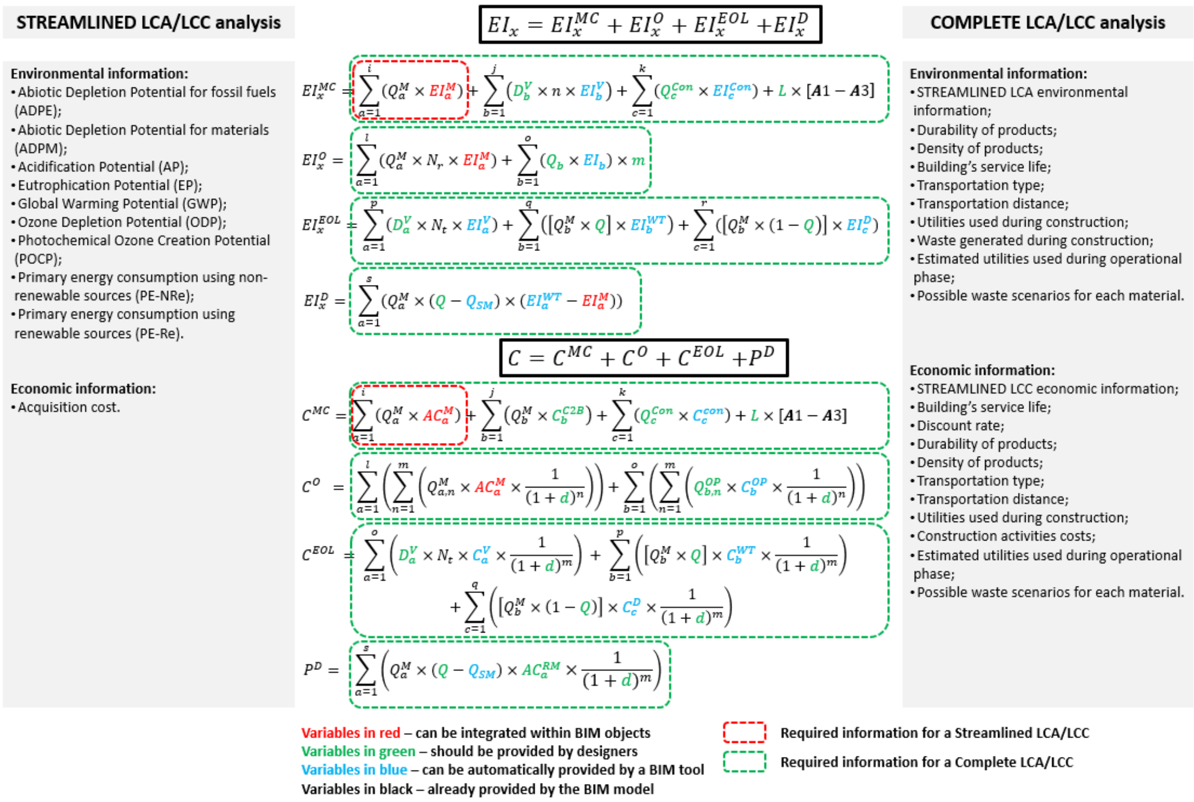


Figure 7 – BIM-LCA/LCC analysis framework

All the variables that can potentially be incorporated into a BIM-based tool to support this framework and increase the automaticity of these analyses are identified in Figure 7 (highlighted in blue). An important differentiating aspect between the proposed framework and Shin and Cho's framework is that, instead of just considering CO_2 emissions as the unique LCA indicator, the proposed framework considers a wide range of environmental indicators based on the CML 2001 method. Moreover, the environmental impacts due to materials' replacement (B2-B4 modules), material processing/disposal of the demolition waste (C2-C4 modules) and use of reused/recycled/recovered materials (module D) were also considered. The costs resulting from the utilities consumed during construction (A5), and transportation costs in C modules, were also considered in this framework.

3.3.2.1. Quantification of the environmental impacts based on the LCA methodology

The environmental impacts of the project, until and throughout the construction phase (A1-A5 modules), can be determined according to equation (8).

$$\underbrace{EI_x^{MC} = \sum_{a=1}^{i}(Q_a^M \times EI_a^M)}_{\text{A1-A3}}^{\text{STREAMLINED LCA}} + \overbrace{\underbrace{\sum_{b=1}^{j}(D_b^V \times n \times EI_b^V)}_{\text{A4}} + \underbrace{\sum_{c=1}^{k}(Q_c^{Con} \times EI_c^{Con}) + L \times [\mathbf{A1-A3}]}_{\text{A5}}}^{\text{COMPLETE LCA}} \quad (8)$$

In the above equation:

EI_x^{MC}	Environmental Impact of category x resulting from manufacturing and construction phase (A1-A5 modules);
i, j, k	Number of existing materials i, transportation j, and construction utilities k;
Q_a^M	Quantity of material a;
EI_a^M	Environmental Impact (of category x) of material a;
D_b^V	Distance from the supplier to the construction site multiplied by the number of travels (n);
EI_b^V	Environmental Impact (of category x) of transportation b;
Q_c^{Con}	Consumption of utility c throughout the construction (e.g. electricity (kWh), gas (MJ), water (m^3));
EI_c^{Con}	Environmental Impact (of category x) of utility c;
L	Percentage of wasted materials during the construction phase (as a percentage of the materials used in the Product stage, i.e. the $[A1-A3]$ modules).

The environmental impacts of the project during operation phase (B modules) can be determined according to equation (9).

$$\overbrace{\underbrace{EI_x^{O} = \sum_{a=1}^{l}(Q_a^M \times N_r \times EI_a^M)}_{\text{B2-B4}} + \underbrace{\sum_{b=1}^{o}(Q_b \times EI_b) \times m}_{\text{B6-B7}}}^{\text{COMPLETE LCA}} \quad (9)$$

In the above equation:

EI_x^{O}	Environmental Impact of category x resulting from operation phase (B modules);
l, o	Number of existing materials to be replaced l and utilities o;
Q_a^M	Quantity of material a;

EI_a^M	Environmental Impact (of category x) of material a;
N_r	Number of replacements during use phase (i.e. operation phase) based on materials' durability (not considering repairs);
Q_b	Consumption of utility b during use phase per year;
EI_b	Environmental Impact (of category x) of utility b;
m	Period of analysis (in years).

The environmental impacts of the project at the end-of-life phase (C modules) can be determined according to equation (10).

$$EI_x^{EOL} = \overbrace{\underbrace{\sum_{a=1}^{p}(D_a^V \times N_t \times EI_a^V)}_{\textbf{C2}} + \underbrace{\sum_{b=1}^{q}([Q_b^M \times Q] \times EI_b^{WT})}_{\textbf{C3}} + \underbrace{\sum_{c=1}^{r}([Q_b^M \times (1 - Q)] \times EI_c^D)}_{\textbf{C4}}}^{\textbf{COMPLETE LCA}} \quad (10)$$

In the above equation:

EI_x^{EOL}	Environmental Impact of category x resulting from end-of-life phase (C modules);
p, q, r	Type of transportation p, and number of materials to be treated q or disposed r;
D_a^V	Distance from the demolition site to waste facilities, multiplied by N_t;
EI_a^V	Environmental Impact (of category x) of transportation a;
N_t	Number of travels between the demolition site and waste treatment facilities;
Q_b^M	Quantity of material to be treated;
Q	Percentage of materials to be treated (e.g. reused, recycled);
EI_b^{WT}	Environmental Impact (of category x) due to the waste treatment of material b;
EI_c^D	Environmental Impact (of category x) due to the disposal of material c;

The benefits and loads beyond the system boundary (D module) can be determined according to equation (11).

$$EI_x^D = \overbrace{\underbrace{\sum_{a=1}^{s}(Q_a^M \times (Q - Q_{SM}) \times (EI_a^{WT} - EI_a^M))}_{\textbf{D}}}^{\textbf{COMPLETE LCA}} \quad (11)$$

In the above equation:

EI_x^D	Environmental Impact of category x resulting from beyond the system boundary (D module);
s	Number of existing materials to be reused, recycled or recovered;
Q_a^M	Quantity of material a obtained from the demolition site;
Q	Percentage of materials to be treated (e.g. reused, recycled);
Q_{SM}	Percentage of secondary material to be used in the manufacturing process (i.e. the percentage of material recovered from other systems to replace primary materials);
EI_a^{WT}	Environmental impacts due to the waste treatment (recycle/recover) processes of material a;
EI_a^M	Environmental impacts due to the manufacturing processes of material a, in which only primary materials (i.e. not recycled) are used.

Therefore, the total environmental impacts can be obtained using equation (12):

$$EI_x = EI_x^{MC} + EI_x^{O} + EI_x^{EOL} + EI_x^{D} \qquad (12)$$

3.3.2.2. Quantification of the economic impacts based on the LCC methodology

The economic impacts of the project, until and throughout the construction phase (A1-A5 modules) can be determined according to the equation (13).

$$C^{MC} = \overbrace{\underbrace{\sum_{a=1}^{i}(Q_a^M \times AC_a^M)}_{\textbf{A1-A3}}}^{\textbf{STREAMLINED LCC}} + \overbrace{\underbrace{\sum_{b=1}^{j}(Q_b^M \times C_b^{C2B}) + \sum_{c=1}^{k}(Q_c^{Con} \times C_c^{con}) + L \times [\boldsymbol{A1 - A3}]}_{\textbf{A5}}}^{\textbf{COMPLETE LCC}} \qquad (13)$$

In the above equation:

C^{MC}	Costs resulting from manufacturing and construction phase (A1-A5 modules);
i, j, k	Number of existing materials i, j and construction utilities k;
Q_a^M, Q_b^M	Quantity of materials a or b used in the construction;
AC_a^M	Acquisition cost of material a;
C_b^{C2B}	Cost to build/assemble construction elements (e.g. cost to apply 1 m^2 of mortar);
Q_c^{Con}	Consumption of utility c throughout the construction;
C_c^{Con}	Cost of utility c;
L	Percentage of wasted materials during construction phase.

The economic impacts of the project during operation phase (B modules) can be determined according to equation (14).

$$C^{O} = \overbrace{\underbrace{\sum_{a=1}^{l}\left(\sum_{n=1}^{m}\left(Q^{M}_{a,n} \times AC^{M}_{a} \times \frac{1}{(1+d)^{n}}\right)\right)}_{\textbf{B2-B4}} + \underbrace{\sum_{b=1}^{o}\left(\sum_{n=1}^{m}\left(Q^{OP}_{b,n} \times C^{OP}_{b} \times \frac{1}{(1+d)^{n}}\right)\right)}_{\textbf{B6-B7}}}^{\textbf{COMPLETE LCC}} \qquad (14)$$

In the above equation:

C^{O}	Costs resulting from operation phase (B modules);
l, m, o	Number of materials replaced during the use phase of the building l, period of analysis m (in years), and consumed utilities o;
$Q^{M}_{a,n}$	Quantity of material a to be replaced in year n during the use phase of the building;
AC^{M}_{a}	Price of material a;
n	Year of analysis;
d	Discount rate;
$Q^{OP}_{b,n}$	Consumption of utility b in year n during operation phase;
C^{OP}_{b}	Cost of utility b.

The economic impacts of the project during disposal phase (C modules) can be determined according to equation (15).

$$C^{EOL} = \overbrace{\underbrace{\sum_{a=1}^{o}\left(D^{V}_{a} \times N_{t} \times C^{V}_{a} \times \frac{1}{(1+d)^{m}}\right)}_{\textbf{C2}} + \underbrace{\sum_{b=1}^{p}\left(\left[Q^{M}_{b} \times Q\right] \times C^{WT}_{b} \times \frac{1}{(1+d)^{m}}\right)}_{\textbf{C3}}}^{\textbf{COMPLETE LCC}} \qquad (15)$$

$$\underbrace{+\sum_{c=1}^{q}\left(\left[Q^{M}_{b} \times (1-Q)\right] \times C^{D}_{c} \times \frac{1}{(1+d)^{m}}\right)}_{\textbf{C4}}$$

In the above equation:

C^{EOL}	Costs resulting from end-of-life phase (C modules);
o, p, q	Number of transportations o, and materials to be treated p or disposed q;
D^{V}_{a}	Distance from supplier to construction, multiplied by N;

C_a^V	Cost of transportation a;
N_t	Number of travels between demolition site and waste treatment facilities;
m	Last year of the period of analysis;
d	Discount rate.
Q_b^M	Quantity of material to be treated and to be disposed;
Q	Percentage of materials to be treated (e.g. reused, recycled).
C_b^{WT}	Costs owing to the waste treatment of material b;
C_c^D	Costs owing to the disposal of material c;

The economic benefits beyond the system boundary (D module) can be determined according to equation (16).

COMPLETE LCC

$$P^D = \sum_{a=1}^{s} (Q_a^M \times (Q - Q_{SM}) \times AC_a^{RM} \times \frac{1}{(1+d)^m}) \qquad (16)$$

D

In the above equation:

P^D	Profits resulting from the reuse, recycle or recovery of materials
s	Number of existing materials to be reused, recycled or recovered s;
Q_a^M	Quantity of material a obtained from the demolition site;
Q	Percentage of materials to be treated (e.g. reused, recycled);
Q_{SM}	Percentage of secondary material to be used in the manufacturing process (i.e. percentage of material recovered from other systems to replace primary materials);
AC_a^{RM}	Profits resulting from the reuse/recycle/recover material a;
m	Last year of the period of analysis;
d	Discount rate.

Therefore, the total life cycle costs of the project can be obtained using equation (17).

$$C = C^{MC} + C^O + C^{EOL} + P^D \qquad (17)$$

3.4. Methodology

As referred in section 1.2, to answer the research questions and verify the hypotheses, a quantitative approach will be followed, as the goals of the research are inherently related with the empirical investigation of mathematical and computational techniques and based on quantitative data. These quantitative data represent the independent variables to be used throughout this research, i.e. the environmental and economic indicators (indicated in the proposed BIM-LCA/LCC framework). As the main goal of this research is the assessment of the environmental and economic impact of constructions, the dependent variable is the sustainability of construction.

The methods that will be used to achieve the research goals are the systematic review; data mapping; computer simulation; secondary data collection; and pilot case study. As observed in the previous chapter, a systematic review of the literature was conducted to identify existing gaps and trends in this field. This review contributed to the formulation of the questions this research aims to address and for the hypotheses to be tested. After the literature review, the identification of the required variables and their relationship was performed, based on the data mapping principles. This process resulted in the development of a framework to support the research (the BIM-LCA/LCC framework). The mathematical framework will then be converted into computer language, building on the development of an IDM and MVD for the BIM-LCA/LCC analysis. Based on computer simulation principles (i.e. conversion of a complex system to a mathematical model), the framework and IDM/MVD will contribute to the development of a BIM-based application (explained in later chapters). At last, a pilot case study will be used to refine and validate the proposed approach and framework. Unlike the typical case studies, the pilot cases studies are used to test approaches that were never tested before. The project selected for the pilot case study will represent a non-residential building located in the Netherlands, where the use of sustainability methodologies (e.g. LCA), certifications (e.g. BREEAM), and environmentally-friendly materials are already usual. As there are more requests for environmental studies of materials manufactured in these countries, it will be easier to have access to more detailed and comprehensive LCA results (e.g. EPDs or generic databases), when compared with countries from the Southern Europe. Furthermore, the Western Europe countries are more prone to request sustainability certifications and LCA studies of materials and buildings (as this is one of the criteria under evaluation) [341, 342]. At last, a non-residential building was selected because most of the case studies discussed in the literature are non-residential buildings, thus it would be easier to compare the results. Hence, the research will focus on a project located in a country that promotes the use of LCA and LCC methodologies.

By following the methods identified above, the results obtained in this research are expected to contribute to the achievement of the following goals:

- Assessment of the environmental and economic impact of buildings by using LCA and LCC methods;
- Identification of the required information to conduct an LCA and LCC study either at initial or later stages of the projects;
- Development of a framework that can intuitively be used for the environmental and economic assessment of the project;
- Contribution to the background knowledge on BIM-LCA/LCC integration and provide outcomes that can be used by BIM software developers for the development of dedicated applications.

3.5. Concluding Remarks

Building on the gaps and trends identified in the previous chapter, the formulation of pertinent questions that still remain unanswered was possible. These questions reflect the importance of the BIM methodology in the field of sustainable construction, particularly in its integration with the LCA and LCC methodologies. However, in order to understand how these questions can be properly addressed, it was necessary to review the existing LCA and LCC frameworks.

The necessary steps to conduct an LCA study of a project were described, in accordance with international legislation. Furthermore, the different environmental impact assessment methods (EIAM) and environmental impact categories were discussed. Some of the most common LCA tools and databases were identified. Similarly, the steps to perform an LCC analysis were also presented, including the suitable economic assessment methods (e.g. NPV) and variables (e.g. discount and inflation rate), as well as LCC tools (mostly Excel-based) and databases.

For the development of a suitable BIM-based LCA and LCC integration, the identification of the required information to be inserted in BIM objects was performed. It was observed that, if manufacturers include environmental and economic information in the digital representation of their products, a simple LCA/LCC analysis could be done in an automatic fashion. This can be achieved if manufacturers include some of the data that are listed in EPDs within BIM objects. Unfortunately, there is no tool that automatically converts the information contained in the EPDs (that are in portable document format (PDF)) into digital objects (e.g. in IFC or proprietary formats). To avoid the need of manual tasks, further work is required in this domain.

However, for a complete LCA/LCC study, some specific data can only be provided by the designer (e.g. site-specific details). The mapping of the required data was then used to propose the BIM-LCA/LCC framework. In this regard, two different levels of calculations were considered, one for a streamlined and another one for a complete LCA/LCC analysis.

In the end, the methodology and methods were indicated. The methods to achieve the research goals are the systematic review; data mapping; computer simulation; secondary data collection; and pilot case study. As a systematic review has been performed in chapter 2 and the mapping of data used to support the proposed framework was done in this chapter, the next chapter will focus on the identification of the processes required for a BIM-based LCA and LCC analyses. Hence, the development of an information delivery manual (IDM) and a model view definition (MVD) will be explored in the next chapter.

Chapter 4 – Use of IDM/MVD and IFC-schema for the information exchange in the BIM-LCA/LCC analysis

New information delivery manuals (IDMs) and model view definitions (MVDs) are currently being developed to improve the knowledge in specific domains and identify the required exchange of information that enables different types of building analysis (e.g. sustainability analysis and structural analysis). However, a gap in the state-of-the-art that focuses on the development of an information schema that enables the LCA and LCC analysis within a BIM-based environment still remains. Therefore, the BIM-LCA/LCC framework proposed in the previous chapter is used in the development of an IDM/MVD for the BIM-LCA/LCC analysis. This methodology contributes to the identification of the processes and exchange of information necessary for the LCA and LCC analysis. For this purpose, industry foundation classes (IFC) is selected as the information schema to be included in the IDM/MVD documents. The work presented in this chapter was published in the 'Automation in Construction' journal [232].

In order to improve the background knowledge on BIM-LCA/LCC integration within the BIM user community, the next step was to describe the processes and exchange of information necessary for the LCA and LCC analysis within a BIM-based environment. For that purpose, the IDM/MVD methodology was used to develop an IDM based on the framework described in chapter 3. An IDM's goal is to "*provide the integrated reference for process and data required by BIM by identifying the discrete processes undertaken within building construction*" [343]. The IDMs are very useful for BIM users to understand the processes behind the analysis of different fields in the construction sector (e.g. sustainable assessment), as well as for providing detailed specifications of the information required for the analysis. This information is then "translated" into an appropriate data schema by an information exchange framework, resulting in an MVD. An MVD is "*the set of information from the information model that can be supported by a type of software application*" [343]. Moreover, to support open IDM/MVD, the Industry Foundation Classes (IFC) schema is often used as the information exchange format. The development of the IFC was started in 1994 by the International Alliance for Interoperability (IAI), currently known as buildingSmart International [344]. Since then, the IFC schema underwent several transformations before being published in 2013 as the international IFC standard, ISO 16739:2013 [345]. According to buildingSmart, the IFC data model can be considered as a neutral and open object-based file format [346], and is structured in four independent layers: resource, core, interoperability, and domain [344]. The *Resource layer* provides the resource schema used by classes in other layers; the *Core layer* contains Kernel, which provide basic concepts of objects (*IfcObject*), relationships (*IfcRelationship*), definitions (*IfcPropertyDefinition*), and Core Extensions that are specialisations of the Kernel classes *IfcProcess*, *IfcControl*, and *IfcProduct* (examples of a core extension are the subclasses *IfcElement* and *IfcSpatialStructureElement* of the Kernel class *IfcProduct*); the *Interoperability layer* provides a set of modules that promote the interoperability between domains; and the *Domain layer* contains modules for specific domains in the architecture, engineering and construction (AEC) sector, such as architecture, mechanical, electrical, and plumbing (MEP), structural engineering, energy, etc. [344, 347, 348].

In the last years, several studies were published that researched the significance of IDM/MVD for the information exchange. Sanguinetti *et al.* [349] proposed a system architecture to improve the analysis of spaces, energy consumption and preliminary costs considering the architectural design. For that purpose, the authors developed their research by building on the IDM/MVD framework and previous research [350], and identifying the required processes to automatize the analysis of the model. Other works on MVD were published by Venugopal *et al.* [323, 351], where the authors argued that the IFC schema lacked a formal definition of its entities (i.e. concepts within the IFC schema, such as *IfcRoof*) and attributes (i.e. properties within each entity). To fill this gap, the authors developed an object-oriented mechanism known as MVD concepts to add semantic meaning into the model views. Also focusing on the improvement of MVD, Lee, Park, and Ham [352] proposed the xPPM method to improve the reusability of some elements within an MVD. By developing a tool that stores the information regarding exchange requirements (ER) and functional parts (FP) in the XML format, instead of a document file format, the authors provided a solution that allows for easier maintenance and tracking of the information contained in the IDM and MVD documents. To obtain strictly the necessary information from a model, Jiang *et al.* [353] queried an MVD file using the 'QueryGenerator' tool. By specifying the elements (e.g. doors, walls) and constraints on selected attributes (e.g. height greater than 2 meters), the users are able to query the information they desire directly from an MVD. Pinheiro *et al.* [329] proposed an IDM/MVD framework that improves the information exchange from IFC to energy analysis tools. The IfcDoc tool, developed by buildingSMART international [354] and used in other recent studies [329, 355-359], assisted in the IFC MVD development and in the diagram generation. In the end, the authors verified that the IFC schema lacks the properties required to perform a suitable heating, ventilation, and air conditioning (HVAC) analysis, therefore, 49 IFC PropertySets were added to the MVD documentation. Another study that focused on the IDM/MVD for energy analysis was published by Andriamamonjy, Saelens, and Klein [358]. In this study, the authors not only proposed an IDM/MVD suitable for the needs of existing energy analysis tools but also developed a plugin that is able to convert the information in an IFC file into an energy analysis tool based on the proposed MVD.

Currently, although fields as precast concrete and energy analysis have been comprehensively explored in IDM/MVD development, there is a gap in the state-of-the-art regarding a model view in which the integration of BIM with LCA and LCC is mapped and modelled. Therefore, an IDM/MVD that supports the proposed BIM-LCA/LCC framework was developed in this research whose details are described below.

4.1. Development of IDM/MVD for the information exchange using the IFC-schema

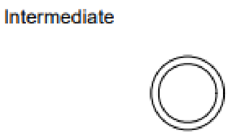
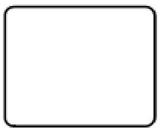
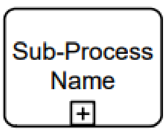
The architecture of an IDM required to support the BIM-LCA/LCC integration framework must include the following components [43]: (i) process map (PM); (ii) exchange requirements

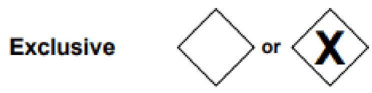
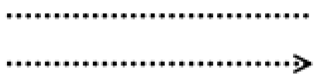
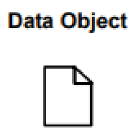
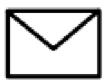
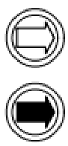
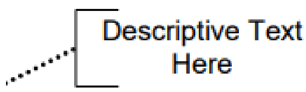
(ER); (iii) functional parts (FP); and (iv) business rules (BR). The scope of the IDM for the BIM-LCA/LCC integration is based on the framework proposed in the previous chapter. In that regard, the required classes of information for the LCA and LCC analysis must cover the environmental and economic features of a project, and this information should be incorporated in the BIM objects. The chosen development approach is based on the process discovery and data mining. The first step is the discovery process, in which experts in the field collaborate and exchange knowledge to determine the business process (i.e. the processes required to perform a specific task) within the scope of the IDM. A process map should be developed and improved based on iterative evaluations of all involved human resources. The purpose of a process map is to describe the flow of information among the actors involved in the scope of an IDM. It also sets the boundary of a specific topic which, in this case, is the environmental and economic assessment of a BIM project. Furthermore, the actors (i.e. person who perform a specific role) and processes conducted by them are identified and described as well. It is also during this step that the exchange requirements necessary to support this business process are identified. An exchange requirement represents the information exchanged among processes and actors at a stage of the project. It should have enough detail so that the reader of the IDM and software developers are able to understand the information exchanged, however, it should not contain technical terms. The next step is to identify the exchanged information in each exchange requirement, which will contribute to the development of the functional parts as technical components of the process map (e.g. an attribute that represents the eutrophication potential impact of a material), as well as business rules. A functional part is designed to be reusable, thus it can be used in different exchange requirements. Furthermore, they can be broken down into other functional parts as well. Regarding the business rules, their main goal is to tailor a specific business need for a particular purpose, providing enough flexibility to the information schema of the IDM without the need to change the schema (e.g. functional parts) itself. An example of a business rule in the BIM-LCA/LCC domain would be the definition of a minimum service life of the building, i.e. it could not be negative. After the process map, exchange requirements, and functional parts are identified, the resources (i.e. the authors) should formally create these components, using the guidelines specified in [43, 343] and templates on the buildingSMART website [343].

4.1.1. Process Map for the BIM-LCA/LCC analysis

In accordance with the [343], the preferred approach to develop a process map within IDM is the Business Process Modelling Notation (BPMN). The table below (Table 18) lists the most common BPMN elements used in IDMs [360]:

Table 18 - Common BPMN elements in IDMs

	The **Pool** represents a participant or role in a process. It can contain processes within it or not, in which in this case it represents a "black box".
	A **Lane** is a sub-part within a Pool with the same extension. These are used to structure the tasks to be performed throughout the Pool (i.e. processes in the IDM framework).
	An **Event** is an occurrence that arises throughout the processes. These usually have a cause and an impact in the flow of information and are represented by circles with open centres. The **start event** indicates when a process will start.
	Opposite to the start event, the **end event** represents the end of a process.
	**Intermediate events** can occur between the start and end of a process, i.e. between a start event and an end event. Although they do not start or terminate a process, they affect the flow of the process.
	An **Activity** represents a task to be performed during a process.
	A **Send Task** is represented by a rounded corner rectangle and includes a filled envelope marker. These types of activities have at most a single input.
	A **Receive Task** is a rounded corner rectangle and includes an unfilled envelope marker. These types of activities indicate that, as soon as a message is received by a participant, the indicated task will begin.
	A **Sub-process task** has a "plus" sign in the lower-centre of the rectangle and indicates that the activity contains lower level of detail that are not visible in the diagram.

	A gateway is used to control the sequence flows in a process. Internal markers will indicate whether there is a branching or merging of paths. An **Exclusive Gateway** is used to indicate that alternative flows are possible within a process.
	**Parallel Gateway** fork affects both the incoming and outgoing flow and can be used to create and synchronize parallel flows. It is used to create parallel paths or to merge all incoming flows before triggering the next process.
	**Inclusive Gateway** can be used to create alternative but also parallel paths within a Process flow. Unlike the exclusive gateway, all expressions are evaluated.
	A **Sequence Flow** is used to indicate the order in which Activities will be performed in a Process.
	A **Message Flow** shows the flow of information (i.e. message) among two Participants (or roles in the IDM framework).
	An **Association** is used to associate specific information and artefacts (e.g. data objects) with other elements of the BPMN. The arrowhead indicates the direction of flow.
	**Data Objects** represent a singular or multiple object and provide information about what is needed to perform an Activity or what they create. In the IDM framework, data objects can either be Exchange Requirements or not.
	A **Message** represent the information exchanged between two Participants.
	An **Off-Page Connector** indicate when a Sequence Flow leaves a page and when it restarts on the next page, being usually used for printing.
	**Text Annotations** are used to provide additional information about a task or process.

Therefore, a process map using the BPMN approach was developed to operationalise the proposed framework and is detailed in Figure 8 and Figure 9.

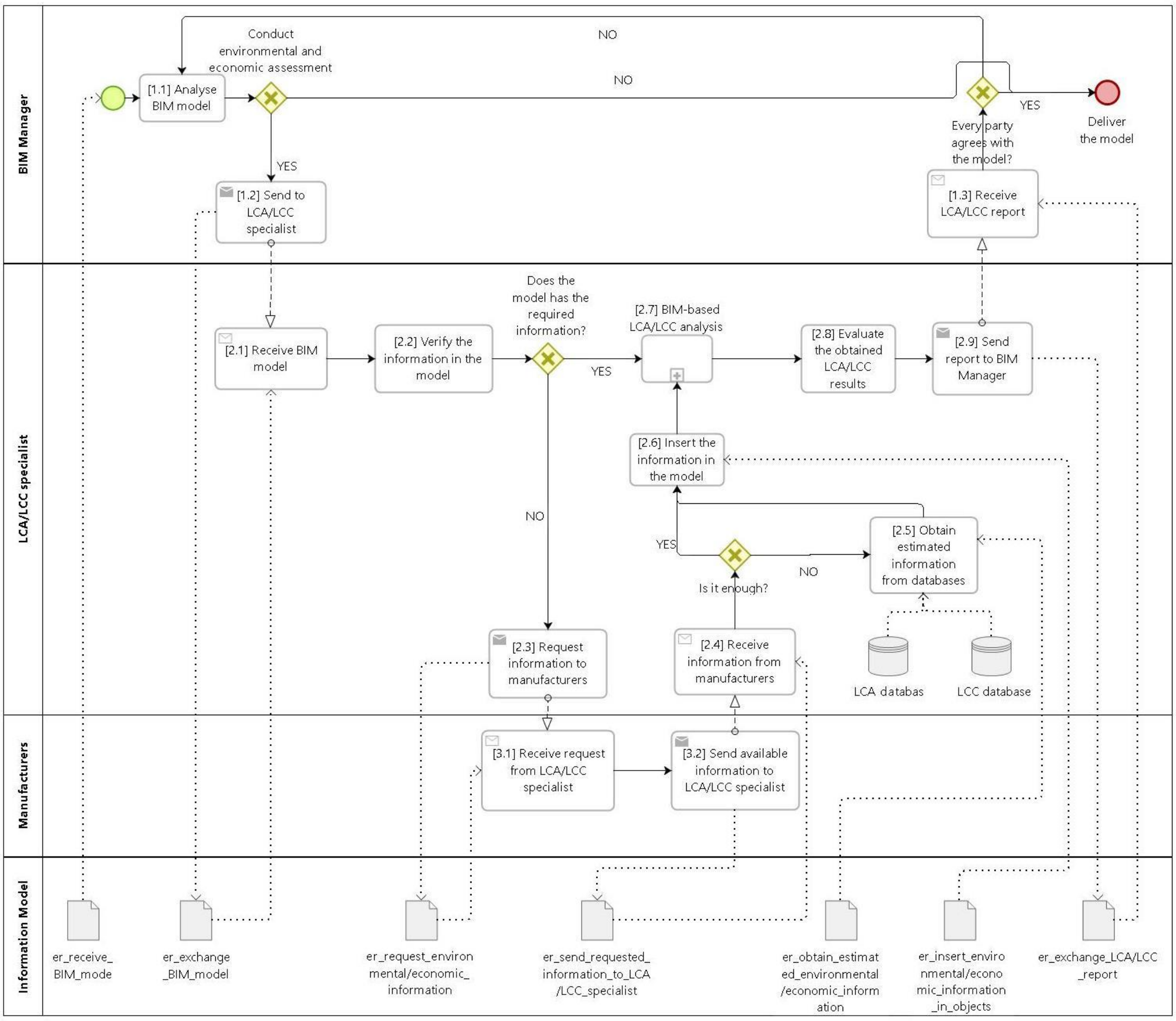


Figure 8 - Process map of the IDM for the BIM-LCA/LCC analysis

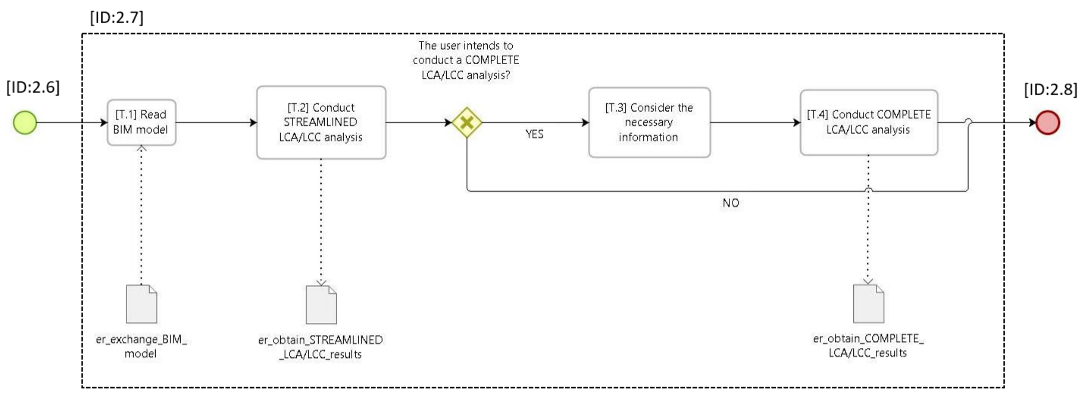


Figure 9 – Sub-process for the [ID:2.7] BIM-based LCA/LCC analysis

As observed, this schema considers three roles (shown as lanes in the Figure 8): BIM Manager; LCA/LCC specialist; and manufacturers. Furthermore, the life-cycle stages covered by this schema are: design (corresponds to the A1-A3 modules), production (A4-A5 modules), maintenance (B modules), and demolition (C modules) based on the ISO 22263:2008 [361], as well as benefits beyond the system boundary (module D). Each process and exchange requirement identified in the process map was thoroughly detailed in the IDM document created during the development of this research and that is provided in Annex A.1.

In the first task (*start event and task 1.1*), the BIM Manager (or Coordinator, i.e. the person responsible for the project within a company) should assemble and merge the BIM models of all specialties (e.g. structural, architectural, MEP) and detect possible clashes. After all the clashes are identified, the BIM Manager must contact the affected specialties (e.g. structural engineer) so that the necessary changes to the model are made. In the end, the BIM Manager should have all models free of clashes. Afterwards, it is up to the BIM Manager to send the models to an LCA/LCC specialist so that an environmental and economic analysis is conducted (*first gateway*). If the decision is negative, then the BIM model will be proposed to the client as it is. Otherwise, the next task is to send it to the specialist that will verify the information in the model (*task 1.2 and task 2.1*). The specialist must read the information (i.e. parameters) contained in the model and in each element/material (*task 2.2*). The information that the specialist must look for, either within the elements (BIM objects) or materials, is detailed below:

- the **type** of the element (e.g. Wall, Floor);
- the **name** of the element (e.g. ExteriorWall#1);
- the **thickness** of the element (if a Wall, Floor or Roof);
- the **area** of the element (if a Wall, Floor or Roof);
- the **volume** of the element (if a Wall, Floor, Roof, Foundation, Column or Beam);
- the **density** of the element (in kg/m^3);
- the **lifespan** of the element (in years);
- the **quantity** of the element (if Window or Door);
- the abiotic depletion potential for fossil resources (**ADPE**) of the element (in MJ);
- the abiotic depletion potential for non-fossil resources (**ADPM**) of the element (in kg Sb-eq);
- the acidification potential (**AP**) of the element (in kg SO_2 eq);
- the eutrophication potential (**EP**) of the element (in kg PO_4^{3-} eq);
- the global warming potential (**GWP**) of the element (in kg CO_2 eq);
- the ozone depletion potential (**ODP**) of the element (in kg R-11 eq);
- the photochemical ozone creation potential (**POCP**) of the element (in kg C_2H_4 eq);
- the use of non-renewable primary energy (**PE-NRe**) of the element (in MJ);

- the use of renewable primary energy (**PE-Re**) of the element (in MJ);
- the **acquisition cost** of the element (in euros).

If the BIM model already contains the necessary environmental and economic information (*second gateway*), then it is already possible to conduct a streamlined LCA and LCC analysis. Otherwise, if the products to be used in the construction are known then the specialist must contact the manufacturers of the materials/elements that do not have information and request the missing information (*task 2.3*). If the products are not known, then values from LCC databases can be used. The specialist should request all or some of the information listed below:

- the results of the LCA study of the product (i.e. material/element), in the format of an Environmental Product Declaration (EPD). The EPD contains the LCA analysis of a product based on the CML 2001 environmental impact assessment method;
- the market price of the product;
- estimated maintenance costs and/or periodic maintenance of the product;
- density of the product;
- durability of the product.

In this regard, if the manufacturer does not have the EPD of the product, he can request that service to an external organisation (*task 3.1*). If the information provided by the manufacturer of a product is not enough (*task 3.2*, *task 2.4, and third gateway*), the LCA/LCC specialist should consult existing LCA and LCC databases to fill that gap, as these can contain estimated values for similar products (*task 2.5*). After consulting the databases, the specialist can then proceed with the next task, i.e. insert the information in the model (*task 2.6*). For that purpose, the specialist has to directly add the information in the model, either in the elements or in the materials used in each element. It is of extreme importance that the specialist inserts the environmental and economic information in each element/material using the same functional unit.

On one hand, it is expected that the specialist inserts all the required information in the model for the first time this process is used. On the other hand, if the specialist works within the same company as the BIM Manager, it is advisable to draw guidelines on how the involved parties (e.g. structural engineer, architect) could create the BIM model. Usually, the companies use the same variety of materials and building assemblies. These could be represented as families (i.e. products) or part of the materials' library. Therefore, every time a new family is developed, or a new material is added to the project, companies can upload it in a '*green BIM* *library*'. If companies use families from a '*green BIM library*', which contain all the elements and products that already have environmental and economic information, then it would only be necessary to import these families to the BIM projects, thus enabling an automatic streamlined LCA/LCC analysis. The above-mentioned guidelines could be part of the company's BIM Execution Plan (BEP). After the specialist adds the required information, he/she now should proceed to the next step, i.e. conduct a streamlined and or complete LCA/LCC analysis (*task 2.7*).

For a streamlined LCA/LCC analysis (*task T.2*), an assessment of the environmental and economic impacts of the A1-A3 modules (i.e. the impacts from the products manufacturing process alone) is made. To obtain the results for a streamlined analysis, the indicators (i.e. environmental impact category or acquisition cost) should be multiplied by the elements' quantity. Moreover, this first analysis can be automatic if the model already contains the necessary information. After running this analysis, the specialist can proceed to the next task, if whished (*fourth gateway*).

For a complete LCA/LCC analysis (*task T.3 and task T.4*), in which the modules A4-A5, B2-B4, B6-B7, C2-C4, and D are also considered, it is necessary to consider site specific information. For that purpose, a tool to handle all the necessary information within a BIM-based environment was developed and described in the next chapter (*task T.3*). For the A4 module, which covers the impacts from the transportation of products from suppliers to construction site, the specialist should either consider a predefined transportation and distance or consider a transportation for each material, as well as the corresponding distance. For the A5 module, which covers the impacts during the construction phase, the specialist should consider an estimated value for the energy, water, and natural gas consumption. Furthermore, the waste generated during construction should be indicated as well. If the specialist decides to include the utilities consumption in A5 in the study, then he/she should include the environmental impacts and costs for each utility based on the location of the project. For the operation impacts (B2-B4 + B6-B7), it is necessary that the specialist defines the lifespan of the asset, the discount rate, and the initial costs of the project. The first two variables are used for the quantification of the number of replacements the materials require and for the LCC calculations, using the NPV method. The last information to be analysed in these modules are the estimated utilities consumption (i.e. electricity, water, natural gas), also using the same information as in the A5 module (B6-B7). For the C modules, the specialist should define the type of transportation to be used for the disposal phase and the distance between the construction site and the waste treatment facilities (C2), similar to the A4 module. Furthermore, the specialist has to define the type of waste processing and disposal for each material used in the project (C3-C4). At last, the benefits beyond the system boundary (module D) are obtained based on the avoided impacts due to the recycled/recovered/reused materials. Therefore, the specialist must provide the estimated percentage of materials (i.e. materials resulting from demolition waste) that are going to be treated and their estimated price (e.g. the price of a recycled material). After all the above-mentioned information is filled in, the specialist can now perform the complete LCA and LCC analysis of the project.

After the LCA/LCC specialist obtains the environmental (LCA) and economic (LCC) analyses of the project, it is possible to evaluate the results and generate a report (*task 2.8*). The information contained in the report should cover:

- total environmental impacts of the project per category (LCA analysis) (**mandatory**);
- total economic impact of the project (LCC analysis) (**mandatory**);
- list of environmental impact of each material used in the project, as well as the corresponding functional unit and estimated durability (**mandatory**);
- list of all variables used for the calculations of the LCA and LCC of the project, either given by the BIM Manager (e.g. initial costs, lifespan of the building) or estimated by the specialist (i.e. discount rate) (**mandatory**);
- list of possible scenarios for waste treatment (**optional**);
- set of pictures of the BIM model in which the elements (e.g. walls, windows) are grouped based on their environmental and economic impacts, by using a colour scheme (**optional**);
- BIM model with environmental and economic information (**optional**).

Afterwards, the report must be forwarded to the BIM Manager (*task 2.9 and task 1.3*). The information contained in the report will help the BIM Manager in the decision-making process (*fifth gateway*). If the BIM Manager decides to change some of the materials/elements used in the project, the corresponding specialties should be contacted in order to verify if such option is feasible (e.g. how the structural analysis is affected by that change). Based on those contacts, the BIM Manager will have to re-analyse the BIM model (e.g. perform clash detections) and send it back to the LCA/LCC specialists. Otherwise, if the BIM Manager is pleased with the report's results and with the model as it is, all BIM models can finally be submitted to the client (*end event*).

4.1.2. Functional Parts of the IDM for the BIM-LCA/LCC analysis

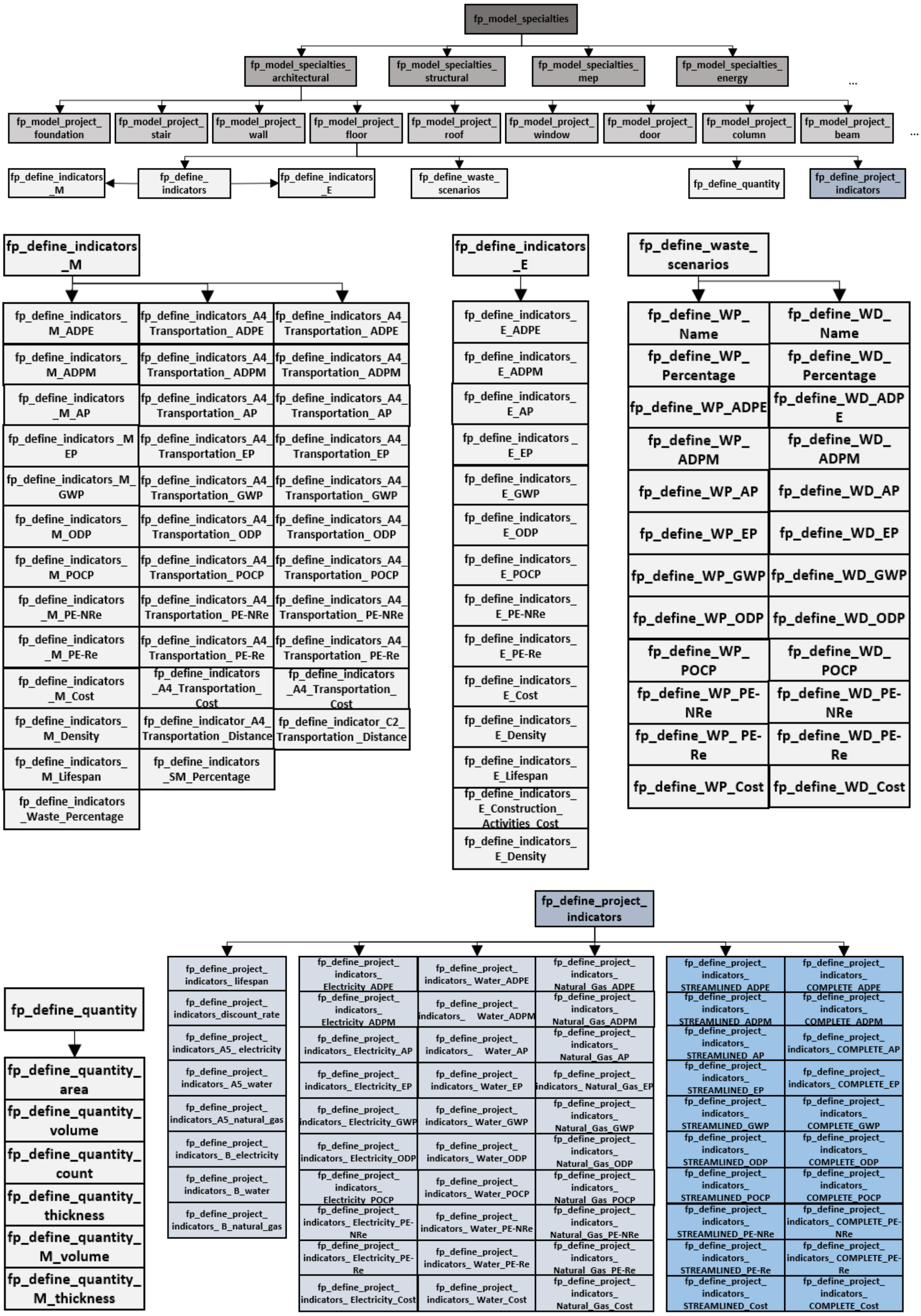


Figure 10 - List of functional parts required for the BIM-LCA/LCC IDM

As mentioned above, each exchange requirement contains one or more functional parts, which should provide enough information on an individual action performed within the process map. The list that contains all functional parts within the proposed process map is shown in Figure 10 and has a tree-shaped diagram, similar to the relationships observed in IFC schemas.

Furthermore, each functional part should comprise a list of technical concepts, their description and the list of IFC entities and properties (i.e. *IfcPropertySet*) that are covered by each concept. Each concept contains a list of the required units of information with a corresponding IFC entity/property, as shown in Figure 11. An IFC PropertySet defines a property that can be used either in BIM objects (through the *IfcObject* or *IfcElement* entities) or in Materials (through the *IfcMaterial* entity) and can be easily identified because of their prefix '*Pset_*'. Additionally, the level of importance of each unit of information for the functional part was indicated (e.g. mandatory (MAN), recommended (REC), optional (OPT), or if it must not be stated at all (NOT)).

Information Needed	Entity/Pset/Functional Part	MAN	REC	OPT	NOT
Specify the Environmental Impact 'abiotic depletion potential for non-fossil resources' (ADPM) of the element *The ADPM impact of an element is necessary to conduct a BIM-based LCA/LCC analysis. It represents the consumption of natural resources (non-fossil fuels).*	*Pset_EnvironmentalImpactIndicators. ResourceDepletionPerUnit → IfcMassMeasure* *OR* *Pset_EnvironmentalImpactIndicators. ResourceDepletionPerUnit → fp_define_indicator_E_ADPM*	✓			
Specify the Environmental Impact 'acidification potential' (AP) of the element *The AP impact of an element is necessary to conduct a BIM-based LCA/LCC analysis. It represents the contribution of anthropogenic emissions for the decrease of water's or soil's pH, i.e. acidification of the water.*	*Pset_EnvironmentalImpactIndicators. AtmosphericAcidificationPerUnit → IfcMassMeasure* *OR* *Pset_EnvironmentalImpactIndicators. AtmosphericAcidificationPerUnit → fp_define_indicator_E_AP*	✓			
Specify the Environmental Impact 'eutrophication potential' (EP) of the element *The EP impact of an element is necessary to conduct a BIM-based LCA/LCC analysis. It represents the impacts of the oversupply of nutrients (e.g. Nitrogen and Phosphorous) in the ecosystems which, in turn, will change the quality of water/soils and species composition.*	*Pset_EnvironmentalImpactIndicators. EutrophicationPerUnit → IfcMassMeasure* *OR* *Pset_EnvironmentalImpactIndicators. EutrophicationPerUnit → fp_define_indicator_E_EP*	✓			

Figure 11 - Example of information exchanged within Functional Parts using IFC schema

Throughout the development of the IDM for the BIM-LCA/LCC analysis, it was observed that the newest IFC schema (IFC4) contains a set of properties that were specifically designed for the LCA analysis. However, several more properties are required if one intends to conduct an LCA and LCC analysis within a BIM-based environment. Table A.1 (in annex) summarises the list of all *PropertySet* that already exist and the ones that need to be added (in ***bold***) either at the project, object, or material level.

As observed, 15 out of 137 properties already are preconised in the IFC4 schema (mostly at the object level) for the LCA/LCC analysis. Thus, 58 properties at the project level, 17 properties at the element level (in which 13 already are contemplated by the IFC4), and 62 properties at the material level (in which two already exists) are necessary. Hence, the IFC4 schema can be used only if a streamlined LCA/LCC analysis was to be conducted within a BIM-based environment and if only the information within the elements was considered (ADPE is the only category that is missing a *PropertySet*). However, to conduct a complete LCA/LCC analysis, the IFC schema needs considerable improvement, mainly at the material level (*IfcMaterial*) and at the project level (*IfcBuilding*). Moreover, out of the 137 proposed properties, only 10 are mandatory if a streamlined LCA/LCC analysis is intended and considers the elements alone (nine corresponding to the results of each environmental impact category and one to the economic impact), or 20 if elements and materials are both to be considered. If a complete LCA/LCC analysis is required, then at least 26 properties are mandatory (besides the ones mentioned above, it is also necessary to consider the durability and density of elements and materials, as well as the estimated lifespan of the building and discount rate to be used in the LCC study), while the remaining 111 are optional (Figure 12). The more information is considered, the more representative the LCA/LCC study will be.

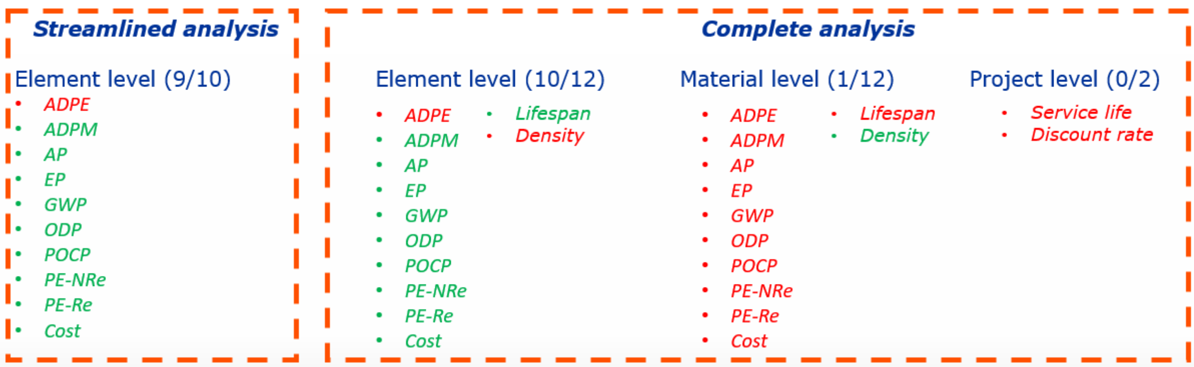


Figure 12 - Environmental, economic, and physical information required for a Streamlined and Complete BIM-LCA/LCC analysis

After the creation of the IDM, an MVD was proposed as the last step to improve the knowledge on BIM-LCA/LCC integration (now focusing on software developers). Whereas the IDM focuses on the identification of the processes and exchange of information necessary for the LCA and LCC analysis within a BIM-based environment, the MVD focuses on the software developers instead. Therefore, the IDM components were used to develop an MVD for the BIM-LCA/LCC analysis. The IfcDoc [354], a tool that is often used by researchers, was used to develop the MVD and include all the IFC entities and properties that are relevant for the analysis (i.e. exchange requirements and functional parts previously identified). Figure 13 displays the exchange requirements table automatically generated by the IfcDoc tool based on the information provided by the BIM-LCA/LCC framework and corresponding IDM, containing the entities and concepts to be exported in the MVD for the BIM-LCA/LCC analysis.

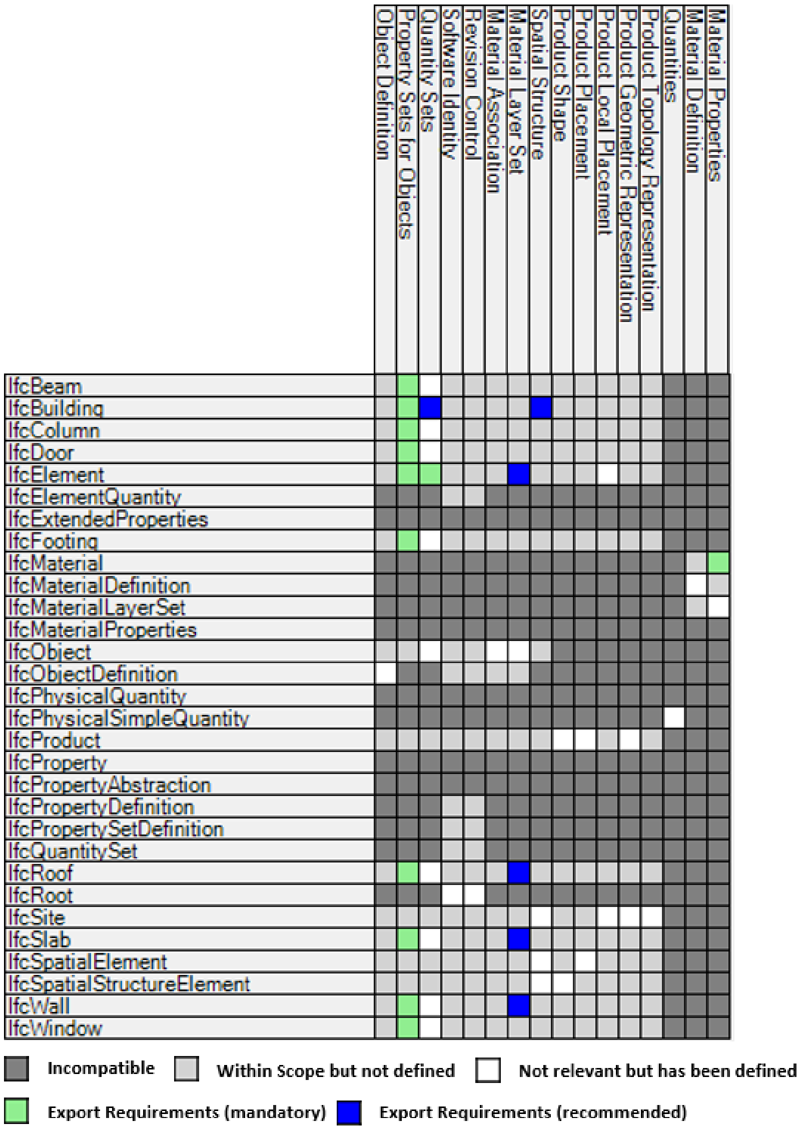


Figure 13 - Entities and Concepts to be exported in the MVD for the BIM-LCA/LCC analysis

Each concept (top part of the matrix) "*defines a graph of entities and attributes, with constraints and parameters set for particular attributes and instance types*" (left part of the matrix) [354]. All the IFC entities shown on the left part of the Figure 13 contribute directly or indirectly to the IDM/MVD for the BIM-LCA/LCC analysis. Furthermore, the relationship between the concepts shown at the top of the matrix and the IFC entities shown on the left is also identified in Figure 13, where dark grey corresponds to an incompatible relationship within this MVD, light grey means it is not relevant for this MVD, white indicates that they are both compatible but not relevant, and green indicates that these attributes must be exported while blue export requirements are only recommended.

After the IDM components are "translated" into the MVD, the IfcDoc automatically generates a set of documents that contains the IFC entities, attributes, properties and concepts that were specified in the information exchange necessary for an LCA and LCC analysis within a BIM-based environment. These documents can then be used by software developers to create a tool that allows an environmental and economic analysis using the framework proposed in the previous chapter and that respects the relationships identified in this chapter.

Based on the findings presented in the previous and current chapters, it is demonstrated that BIM-LCA/LCC tools require more information than is usually contained in BIM models to properly conduct an LCA and/or LCC analysis within a BIM-based environment (i.e. within the BIM software itself). Furthermore, these findings allowed to understand if the IFC4 schema already contains the required IFC properties to store and analyse the LCA and LCC data of elements (BIM objects) and materials. Although the IFC4 schema added new properties to the schema in the field of LCA studies, when compared with IFC2x3, only the elements were addressed (*Pset_EnvironmentalImpactIndicators* contained in *IfcElement*). It has been shown that greater detail is required at the material and project levels. At the material level, two properties focused on physical aspects of the materials (durability and density), two properties focused on a quantity aspect (i.e. thickness and volume), 10 properties focused on the environmental impacts of its manufacturing, 22 properties focused on transportation impacts (for both A4 and C2 modules), and 26 properties focused on the waste treatment of materials. At the project level, two properties focused on the lifespan of the asset and used discount rate, 30 properties were related with the environmental impacts and costs of each utility (i.e. electricity, water, and natural gas), six properties representing the utilities consumption during construction and operation phases, and 20 properties to store the results of a streamlined and complete LCA/LCC analysis. Therefore, it is possible to conclude that the existing schema still needs to be improved to allow an LCA/LCC analysis within a BIM tool.

Another aspect that was observed is that there is not a suitable property (i.e. *IfcValue*) to store the values of the environmental impact categories. Most of the environmental impacts are expressed in kg-eq (e.g. kgCO_2-eq), being represented using the *IfcMassMeasure* as it is a property that stores values whose units are in kilograms (kg). The only categories that are not represented by *IfcMassMeasure* are the primary energy consumption using non-renewable (PE-NRe) and renewable (PE-Re) sources, which are represented as *IfcEnergyMeasure* in megajoules (MJ). On the other hand, the IFC schema already contains a suitable property for the LCC data, which is represented as *IfcMonetaryMeasure* (in the selected currency).

The advantage of the proposed BIM-LCA/LCC framework and IDM/MVD is that two different types of LCA/LCC analysis were considered: Streamlined and Complete. This provides sufficient flexibility to be adapted to the background knowledge of the users, because they can conduct a quick analysis (just considering the products' manufacturing) or a comprehensive analysis (considering a project's full life cycle) within a BIM-based environment. In this regard, while for a streamlined analysis the IFC4 schema already contains most of the necessary properties (nine properties within *IfcElement*), for a complete LCA and LCC analysis it still requires a considerable improvement (26 mandatory properties, in which eleven already exist, and 111 optional properties). The use of BIM models as permanent and updated data repositories, in which the users are able to edit or add any information, is also another advantage of the proposed approach. If the asset owner wishes to perform a retrofit or refurbishment of the construction, it is only necessary to update the environmental and economic information of the new material/element within the BIM model as the LCA and LCC analysis will be done automatically afterwards. This also means that if the new materials' manufacturers are able to provide their products' environmental information, it is not necessary to acquire licenses for the LCA databases, as the user can insert that information directly in the BIM model.

On the other hand, a limitation of the proposed IDM and MVD is that it can only be applied to the BIM-LCA/LCC framework described in the previous Chapter. Another limitation is that the proposed IDM/MVD focused on the architectural and structural domain but not on other domains (e.g. MEP). Although the proposed framework can be applied to any domain, the IDM/MVD shown in this Chapter did not consider MEP elements. Therefore, it still requires further development in the IDM/MVD to conduct LCA and LCC analysis for that domain and others (e.g. HVAC systems).

4.2. Concluding Remarks

Building on the BIM-LCA/LCC framework developed in the previous chapter, an IDM/MVD for the BIM-based LCA and LCC analyses was proposed, based on the IFC data schema. It was verified that, to comply with the proposed framework, 137 IFC properties are required. Out of the 137 properties, the IFC4 schema already contains 15 properties; (i) 13 at the element level: eight for the environmental impact categories (in which the ADPE category is missing), one for the economic impact, the lifespan, and the area, volume, and quantity, (ii) two at the material level: density and thickness. For a Streamlined LCA/LCC analysis, the IFC schema does not require significant improvement, in contrast with the Complete analysis. In this case, the IFC schema should cover additional 15 mandatory properties apart from the previous eleven (mostly at the material level), and 111 optional properties (at the material and project levels). It was also observed that the IFC schema does not have suitable properties to store the type of information required by each environmental impact category. Even though *IfcMassMeasure* stores values in kilograms (kg), the same property is not appropriate to estimate all environmental impact categories. Therefore, the use of *IfcValue* type in each category is proposed.

It is expected, that with this approach (i.e. BIM-LCA/LCC framework and IDM/MVD), stakeholders will achieve higher levels of efficiency. In this regard, the workflow within organisations will be indisputably influenced. As observed in Figure 8 and Figure 9, the BIM Manager (or BIM Coordinator) must select which models will be sent to the LCA/LCC specialist, i.e. which specialties will have an LCA and LCC study. It is advisable that the BIM Manager merges all the models into a single BIM model and removes any duplicated element. This would allow the LCA/LCC specialist to compare the environmental and economic impact of all the elements and materials used in the project, even if they belong to different specialties (e.g. structural or architectural elements). Furthermore, it is highly important that the model to be sent to the specialist is as representative as possible of the real project. As the specialist will be working with the information contained in the model, the materials' quantities must be precise. Only in these conditions it is possible to conduct an accurate and representative LCA and LCC study of the project. Afterwards, it is the specialist's responsibility to insert the environmental and economic information. For that purpose, the specialist must contact all the suppliers of the project's materials to request the EPDs of their products (if the products to be used in the project are known, otherwise generic information contained in LCC databases could be used). If these documents are not available, then it is up to the specialist to find the most similar materials based on existing LCA databases. This process could ultimately lead to the creation of a BIM objects' library tailored to each organisation, as each organisation usually works with the same products/materials. In the end, the proposed approach promotes the use of materials with environmental information (thus benefiting manufacturers whose products have EPDs), identifies the information that should be inserted in BIM objects to enable automatic LCA and LCC analysis, and promotes the development of organisation-specific BIM libraries that contain BIM objects with environmental and economic information, which can be used in different projects. Moreover, this approach can be followed in early stages of the project, throughout the design stage, or even during the life cycle of the project. In this respect, the more information is known (e.g. products used in the project) the more comprehensive and representative the results will be. Hence, while in early stages of the project generic data can be used to obtain an early estimation of the project's impacts, in later stages specific data should be used to achieve a representative result.

In summary, the proposed IDM/MVD identified the information exchange required for the LCA and LCC analysis within a BIM-based environment. It also provided the background knowledge for solution providers to develop a BIM tool to perform the LCA and LCC analysis based on the framework proposed. By knowing which information (i.e. the 137 IFC properties) that must be exchanged among the stakeholders (i.e. BIM manager, LCA/LCC specialist, and Manufacturers), the software developers (and other stakeholders) will be able to create a suitable MVD that can be used to exchange information on sustainability among different software, thus promoting the use of open BIM for the LCA and LCC analysis. Consequently, a prototype tool to support the framework proposed in the last Chapter and building on the IDM/MVD proposed in this chapter was developed and is described in the next chapter.

Chapter 5 – Development of the BIM-based Environmental and Economic Life Cycle Assessment (BIMEELCA) tool

Building on the BIM-LCA/LCC framework proposed in chapter 3 and on the IDM/MVD proposed in chapter 4, a prototype tool to support the decision-making process during early phases of a project is developed and detailed in this chapter. This tool will be used to validate the BIM-LCA/LCC framework and to verify the feasibility to conduct LCA and LCC analyses within a BIM-based environment. Therefore, the framework's mathematical model was converted into computer language. This results in a simulation model of the environmental and economic impact of the built environment. In the end, guidelines for the adjustment of BIM Execution Plans (BEP) are proposed, in order to include the required information for the BIM-based LCA/LCC analysis and for the BIMEELCA tool. The work presented in this chapter is based on the framework published in the 'Automation in Construction' journal [232] and on an article entitled 'Development of a BIM-based Environmental and Economic Life Cycle Analysis tool', still under development.

The Autodesk Revit software was the selected BIM-based environment, as it is the most used BIM tool in the market, particularly for sustainability-related simulations [362, 363]. The existing literature on Revit-based applications is vast, with researchers using the application programming interface (API) [364, 365] or Dynamo plug-in [366, 367] to develop *ad-hoc* tools. Although both interfaces are used, they have different approaches and serve different purposes.

Revit Dynamo [368] is a visual programming tool, i.e. users' resort to visual programming language (VPL) to develop their applications. In this sense, there is no need to write full scripts (i.e. sequence of programming instructions) when using VPL-based tools, as these already contain "blocks" with pre-defined functions. In order to develop a simple application, users construct their *ad-hoc* script by dragging-and-dropping the blocks [369]. It is also possible to develop their own code/functions while using VPL-based tools (e.g. develop their own code blocks). Visual programming tools are very useful to introduce computational modelling as there is no need to have a deep understanding of the computational processes behind the development of applications [369, 370]. However, the release of new versions of VPL-based tools might change the definitions of some code blocks. This means that a code in Dynamo might no longer work (or work as it should) in a newer version.

In contrast, the Revit API consists in a platform that is "*accessible by any language compatible with the Microsoft .NET Framework*" (e.g.: C#, Python, Visual C#, Visual Basic .NET) [371]. These languages are based on object-oriented programming (OOP), i.e. they resort to objects, the main component of an OOP code, to perform specific actions and interact with other components of the script [372]. In this regard, the 'objects' of a Revit API can represent a wide range of instances such as BIM objects (e.g. walls, windows, doors), materials, views, etc. Moreover, the script developed using Revit API platform can be represented in two types of applications: Command (i.e. *IExternalCommand*), which consists in a single operation (like a Macro), or Application (i.e. *IExternalApplication*), which can perform different operations between its start and end. Furthermore, every command that can be used in the normal Revit application can be replicated in the Revit API.

Throughout the development of this research, it was observed that, for complex and multi-purpose operations (i.e. to perform different operations to achieve a common goal), the Revit API can be more flexible and comprehensive when compared with Dynamo, although less intuitive and with a steeper learning curve. Therefore, the Revit API platform was selected to develop a BIM-based Environmental and Economic Life Cycle Assessment (BIMEELCA) tool. Furthermore, the C# language was used in its development, mainly because the available Revit API user's guide is based on the same language [371]. The programming language C# (pronounced *'C sharp'*) was developed by the Microsoft company, being first released in 2000 as part of the .NET Framework initiative. Its first version, C# 1.0, was released in 2002, and was continually improved throughout the years, recently reaching the C# 7.0 version [373]. Currently, it is internationally approved by the standard ISO/IEC 23270:2018 [374].

In order to develop and test C# applications, the users must rely on integrated development environment (IDE) programs. In this regard, most users resort to Visual Studio, an IDE that specifically focuses on C# [373]. Therefore, the software Visual Studio Community 2017 (version 15.5.2) was the IDE used for the development of the BIMEELCA tool as well. Furthermore, the windows presentation foundation (WPF), an application model that resorts to extensible application markup language (XAML) [373], was also used in the development of the tool. The WPF was needed because the graphical user interface (GUI) generated by the Revit API was not flexible enough to allow multiple operations and interact with the user (e.g. store data provided by the users).

The purpose of this chapter is to present the developed BIMEELCA tool and its usefulness for a BIM-based LCA and LCC analysis. Consequently, the operations available to the users of the BIMEELCA tool (i.e. LCA/LCC specialists or designers with a strong background in sustainable construction) are summarised in Figure 14 and detailed below. To simplify the explanation, a project template and random values are used.

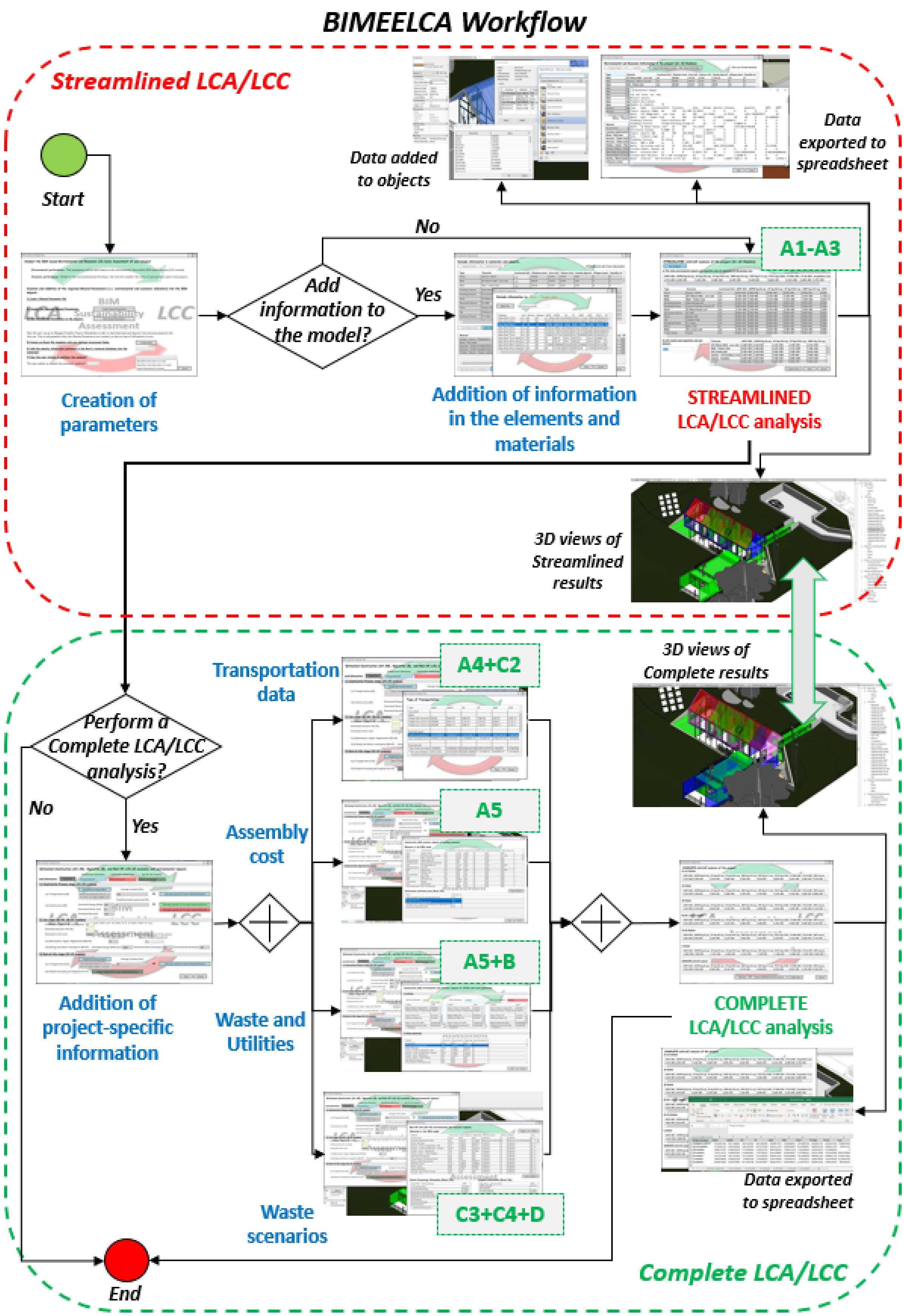


Figure 14 - BIMEELCA's workflow

5.1. BIMEELCA Part One: Read data from the BIM Model

The BIMEELCA command is located in the ‘Add-in’ ribbon, as seen in Figure 15. The initial window contains a few options that must be addressed before running an LCA and LCC analysis (Figure 16). The first required step is the creation of the shared parameters (i.e. each parameter will correspond to an environmental impact category and acquisition cost) that will be used in the LCA and LCC analyses. These should then be added to all elements that will have a significant contribution to the environmental and economic impacts of the project. In this regard, the parameters will be added to the project general information, materials, ceilings, curtain walls, doors, floors, roofs, walls, windows, structural framing (i.e. beams), structural columns, structural foundations, and stairs. Following the same reasoning of the BIM-LCA/LCC framework previously proposed, the tool will not consider mechanical, electrical and plumbing (MEP) elements.

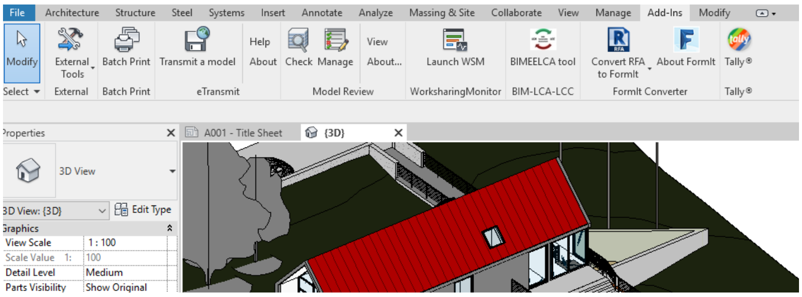


Figure 15 - BIMEELCA command in the Add-in ribbon

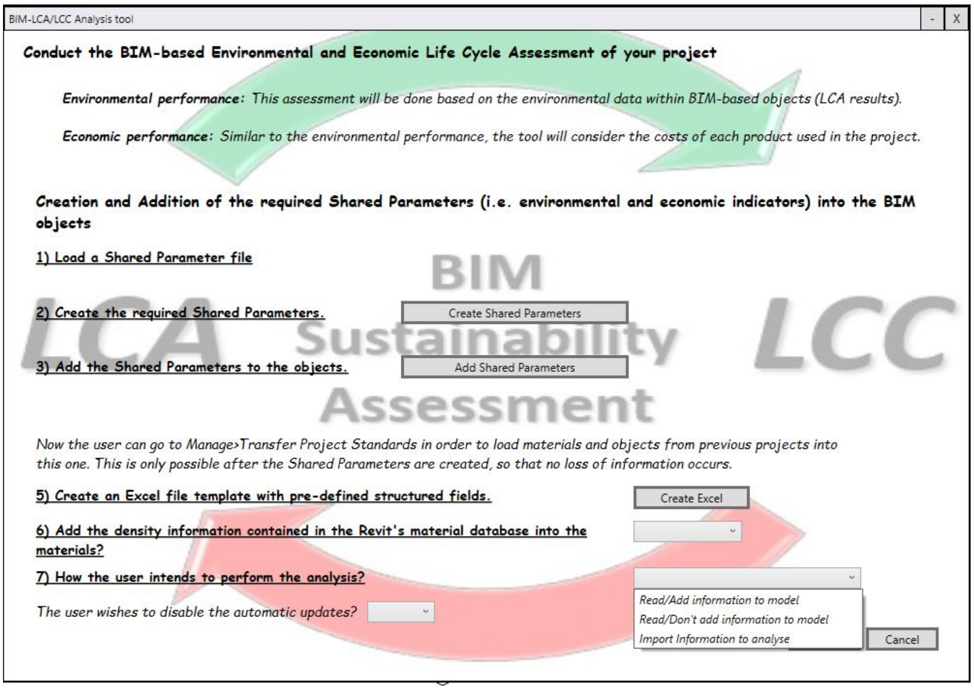


Figure 16 - Initial window of BIMEELCA tool

The next step consists in the creation of a template spreadsheet, which can be used by the users to insert the environmental and economic impacts of the materials and elements they often work with. This step is important because the tool will read the information contained in a spreadsheet, meaning that the order in which the information is structured in the spreadsheet must be the same as in the tool (e.g. the first column corresponds to the name of the material).

At last, the BIMEELCA tool was developed to have different options to perform the LCA and LCC analyses (three options are shown at the 7) step in Figure 16). The first option means that the tool will read the information contained in the model (i.e. the quantity take-off of materials and elements, as well as the values contained in the parameters added before) and add information into it. In this option, the user will be able to edit the BIM model by adding or changing the environmental and economic information contained in the materials and elements. In the second option, the tool will read the information contained in the model but not add any into it. This means that the user will only "virtually" insert the information in the elements, i.e. it will look the same as in the first option but no information is actually added to the model. This option was added to the tool in case the user does not desire to edit the model or increase its size. The last option allows the users to read a file (also generated by the tool) that already contains all the information of a BIM model, including bill of quantities and impacts in each material or element (this will be later explained). This option is suitable for the users that already have performed a Streamlined LCA and LCC analysis (i.e. impacts due to the A1-A3 modules of the LCA framework) and intends to perform a Complete LCA and LCC analysis.

After selecting the options, the user will visualise a second window that contains the information about the elements and materials inserted in the model, as well as all the information that can be useful to perform the analyses (Figure 17). In case the user selected the third option (i.e. import information to analyse), a different window will appear (explained later and shown in Figure 26). The window in Figure 17 displays all the elements that have a physical representation in the model and verify if they have information or not (upper right side of the window). All the elements or materials that have environmental or economic information will be highlighted in bold. Furthermore, the type of elements, name of elements, functional unit per element, thickness (if applicable), area (if applicable), volume, quantity (if applicable), density, lifespan (i.e. service life of the product), environmental indicators (based on the CML 2001 environmental impact assessment method, same as in the BIM-LCA/LCC framework), and acquisition cost are listed.

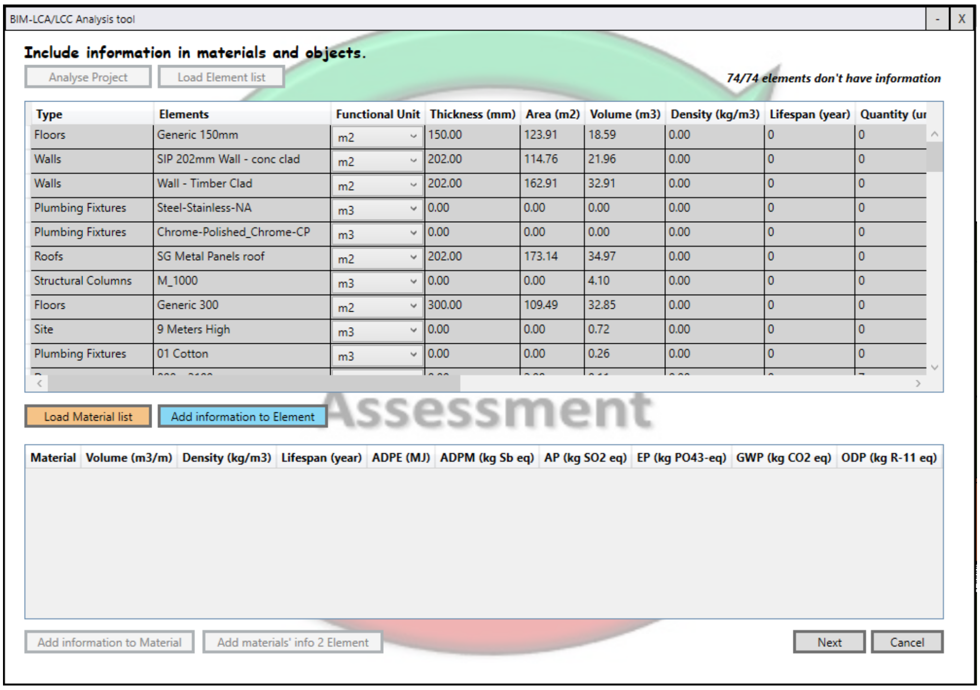


Figure 17 – List of elements contained in the model

The user will also be able to add the environmental, economic, and physical properties into the elements and materials (Figure 18). For this purpose, it is possible to directly add the information in the element 'X' ('Add information to Element' option) or by adding the information to each material contained in the element 'X' ('Add information to Material' option).

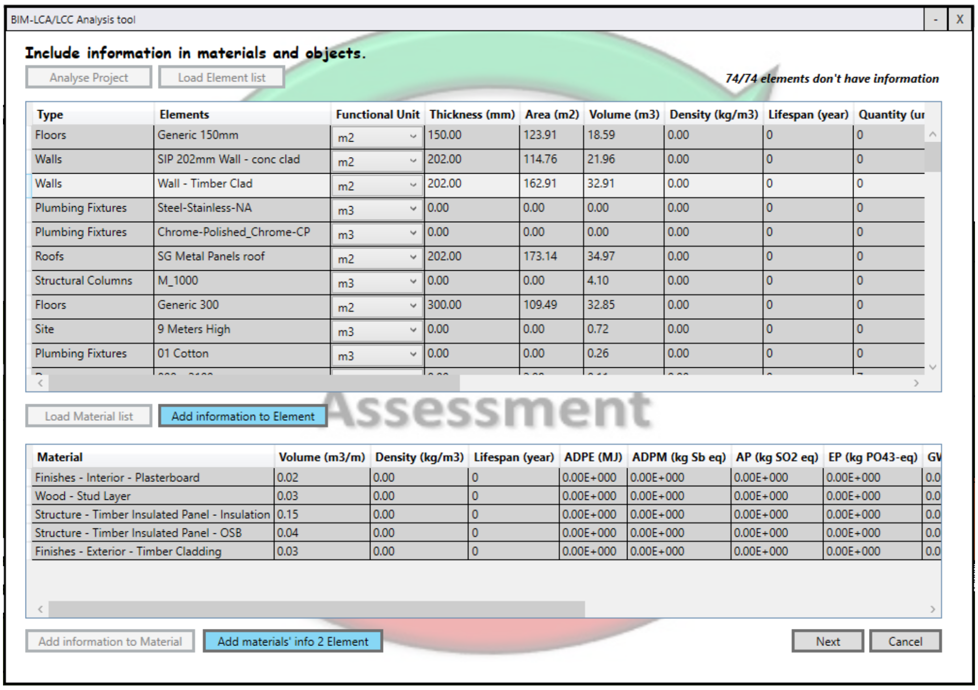


Figure 18 - List of materials contained in each element

If the user chooses the first option, then a window like the one shown in Figure 19 will appear, where it is possible to open a spreadsheet that contains the indicators required for the LCA and LCC analyses.

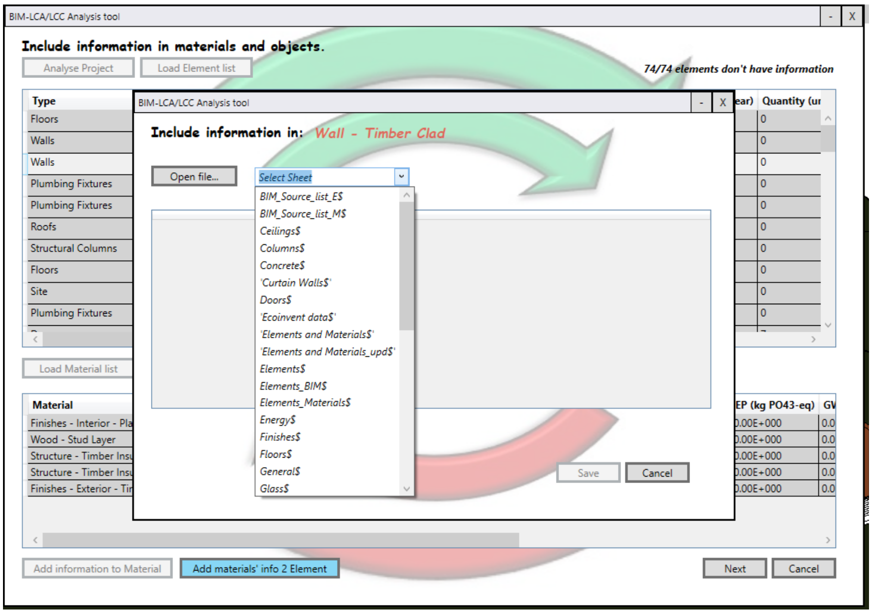


Figure 19 – Reading of a spreadsheet that contains the indicators required for the analyses

After selecting the sheet that holds the information to be added, the user can then select the cells that contains the indicators of the element under analysis, as shown in Figure 20 (the name of the element is highlighted in red, at the top of the window).

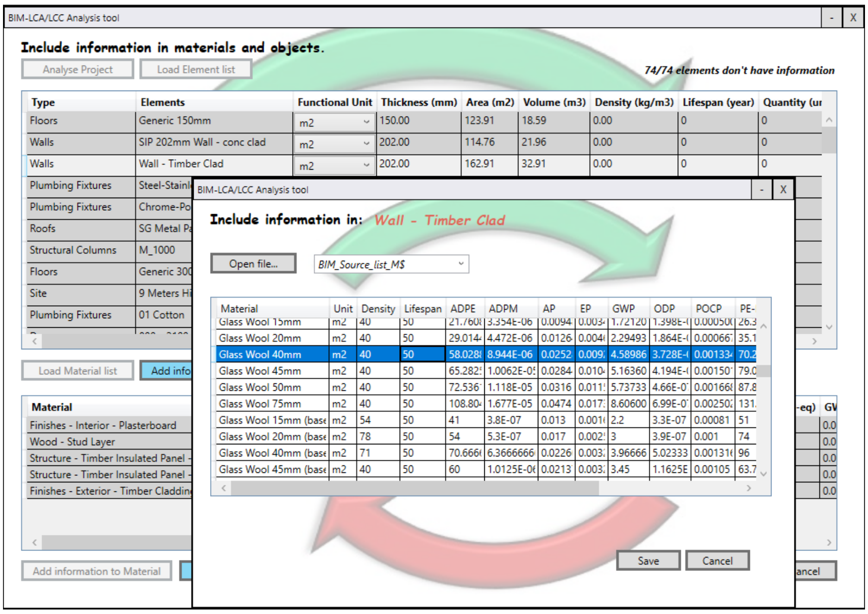


Figure 20 - Information contained in the spreadsheets to be added to the material or element

This information is then saved into the corresponding element in the BIM model (Figure 21). The user is able to immediately know if the information was successfully added to the element in the model if the number of elements that do not have information decreased (top right corner of Figure 21).

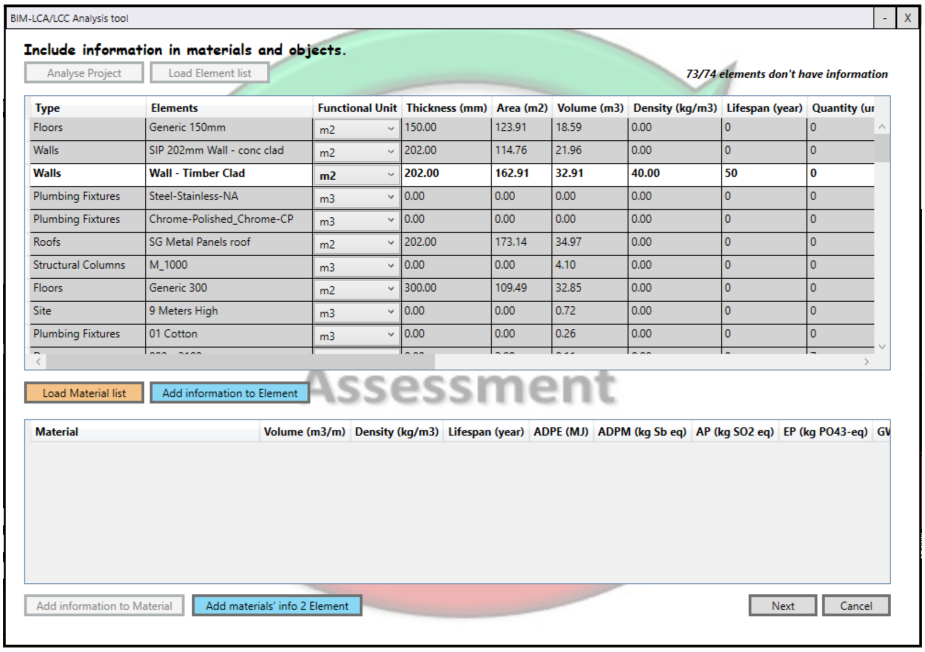


Figure 21 - Information added to the element

Although the tool allows the users to add information in the materials or elements, it does not allow the users to create new instances (i.e. elements or materials) in the model. The same procedure can also be done for the materials (Figure 22) (again, the name of the material is highlighted in red). In this case, the user inserts the information in the material(s) instead of in the element. If the user adds the impacts to the materials, it is then possible to sum the corresponding impacts into the element itself. Moreover, the density of the element is based on equation (18).

$$\rho_E = \frac{\sum_{i=1}^{n} \rho_{M,i} \times t_{M,i}}{t_E} \qquad (18)$$

In the above equation:

n	Total number of materials i in a single element;
ρ_E	Element's density (i.e. wall, roof, ceilings, or floor) in kg/m^3;
ρ_M	Material's density in kg/m^3;
t_E	Element's thickness in m;
t_M	Material's thickness in m;

$$and \sum_{M} t_M = t_E$$

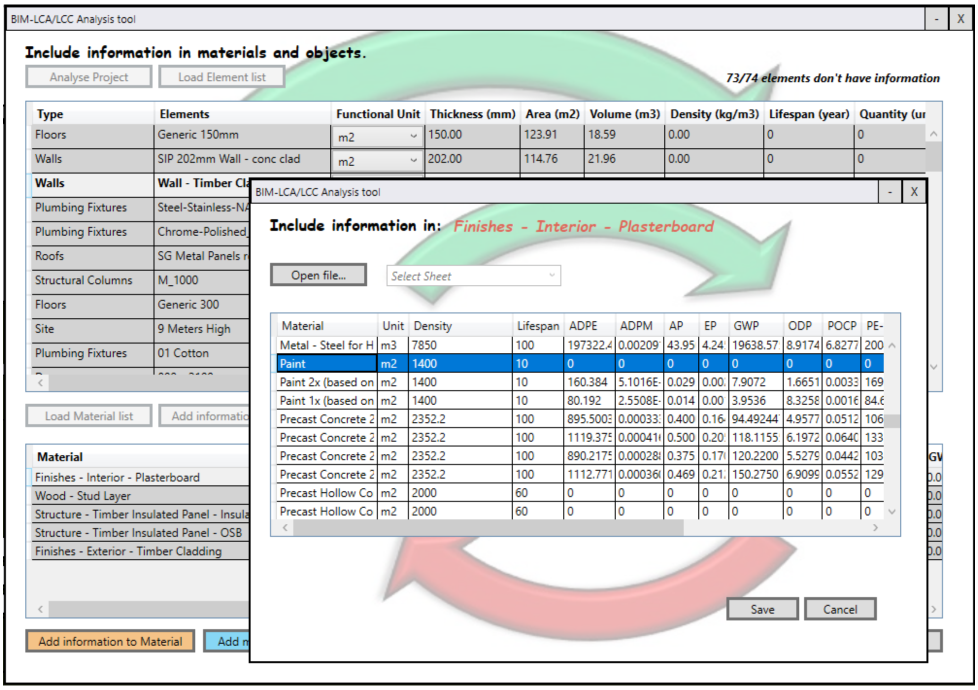


Figure 22 – Information to be added to the material

However, this will only work for elements that have the thickness information (i.e. walls, roofs, ceilings, or floors). The other elements do not have this information due to the way that Revit itself reads the information (e.g. the thickness of windows or doors' frames varies according to the thickness of the walls). Therefore, this operation will work best for the type of elements mentioned above. For the other type of elements that have more than one material, it is advisable to add the impacts and physical properties directly in the element (Figure 21). Furthermore, the tool recognises all the materials that are part of an element but not the number of times they are used in the element (e.g. two layers of Glass Wool 20mm). This lack of recognition is another limitation of the tool. However, this can easily be surpassed if the users duplicate the material's layer using different names (e.g. Glass Wool 20mm #1 and Glass Wool 20mm #2). Hence, if an element has more than one layer of the same material and the users expect to obtain the corresponding impacts based on the information contained in each material, they must give a different name for each material layer, even if they are the same.

At last, the lifespan of the element will be the same as the lowest lifespan of all materials part of that element. Therefore, if the users know the expected lifespan of an element (e.g. a service life of 25 years), it is advisable to add the information directly in the element, instead of summing the materials' information into the element itself (e.g. minimum of 5, 10, and 25 years). The users will be able to see if the information was successfully added to the elements or materials if they check their properties in the Revit's GUI (Figure 23 and Figure 24).

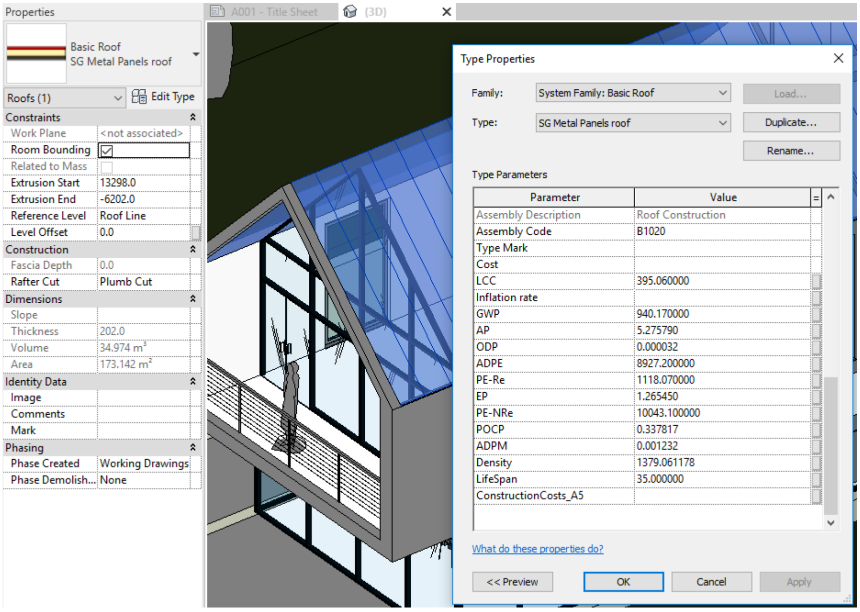


Figure 23 - Element's properties

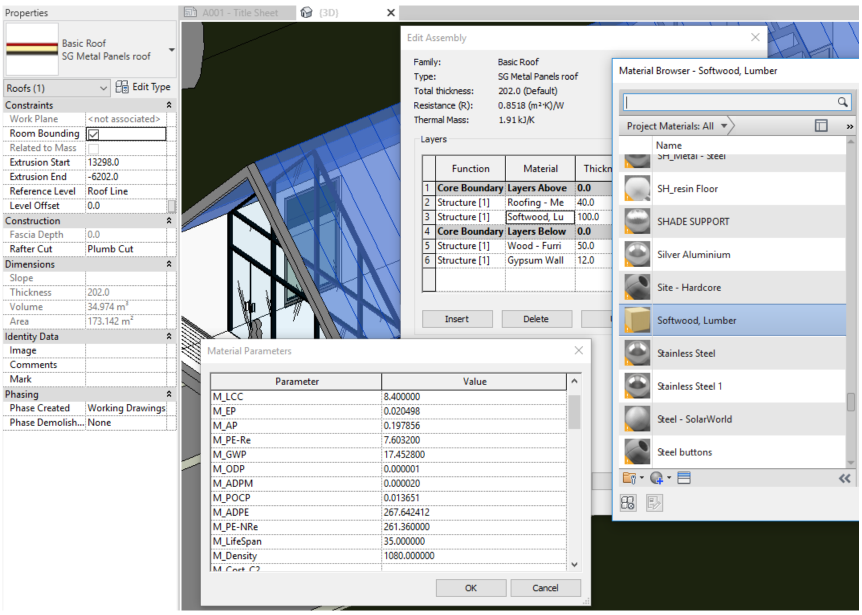


Figure 24 - Material's properties

For the last step, the user must select the functional unit that will be used in the environmental and economic assessment of each element. For that purpose, the user can select the most suitable functional unit from a pre-defined list as shown in Figure 25.

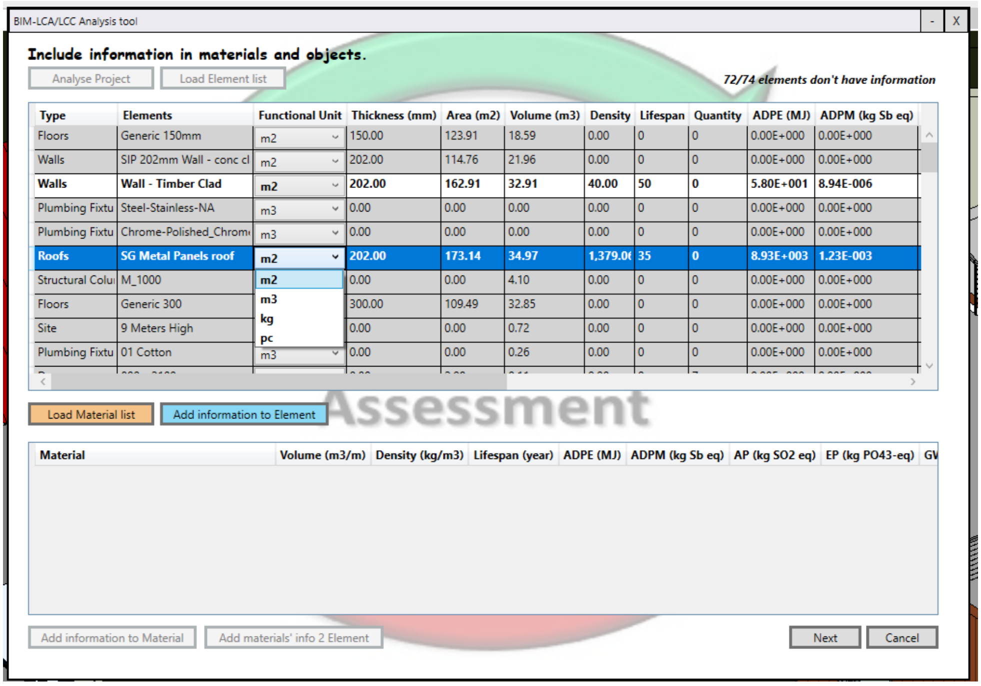


Figure 25 - Selection of the functional unit per element

The selection of the functional unit will determine how the impacts of each element will be quantified in the Streamlined LCA/LCC analysis. If the users select 'm^2', the impacts will be multiplied by the area of the element. However, if they select 'm^3', 'kg', or 'pc', the impacts will be multiplied by the element's volume, weight (the element's density is required for this case, as the weight is equal to the density multiplied by the volume), or quantity, respectively. Furthermore, the users must select a functional unit that matches the functional unit of each material that is part of the same element. For example, if a wall has a functional unit per m^2, then the impacts of all materials part of that wall must have the same functional unit. Moreover, the users must also be aware that even though the same material can be used in different elements, it can have different functional units or thicknesses (thus, different impacts). Firstly, if the same material is used in different elements and with different thicknesses, then the users must 'duplicate' the materials in order to match the different thicknesses (e.g. Glass Wool 20mm and Glass Wool 30mm). Secondly, if a material is used in an element that has a functional unit per m^2, it cannot be used in an element with a different functional unit (e.g. m^3). How the information is used (i.e. selection of functional unit) is extremely important to maintain the representativeness and accuracy of the LCA and LCC analyses.

After finishing these steps, the *task T.1* identified in the Sub-process 'BIM-based LCA/LCC analysis' in the IDM/MVD proposed in the previous chapter is completed.

5.2. BIMEELCA Part Two: Export the information that was added to the BIM Model

After the user adds the information to the model (either using the first or second option of step 7) in Figure 16), the BIMEELCA tool conducts a second verification to check if the data was successfully added (Figure 26). As soon as the verification is done, the tool can export the elements and materials' quantity list (as seen in the tool's window) to Excel format or to text format. This can be seen in Figure 27, Figure 28, and Figure 29.

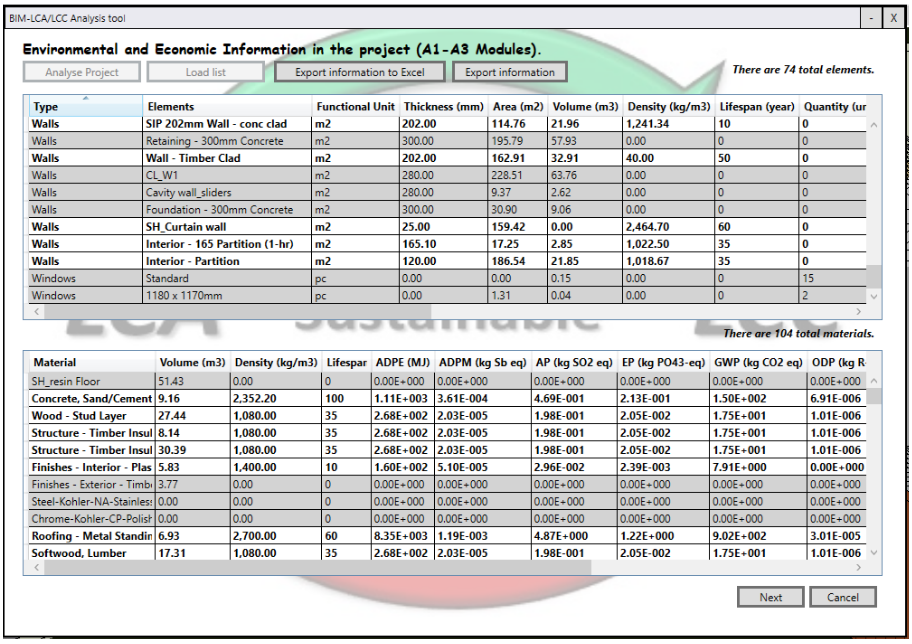


Figure 26 – Environmental and Economic information in the BIM model

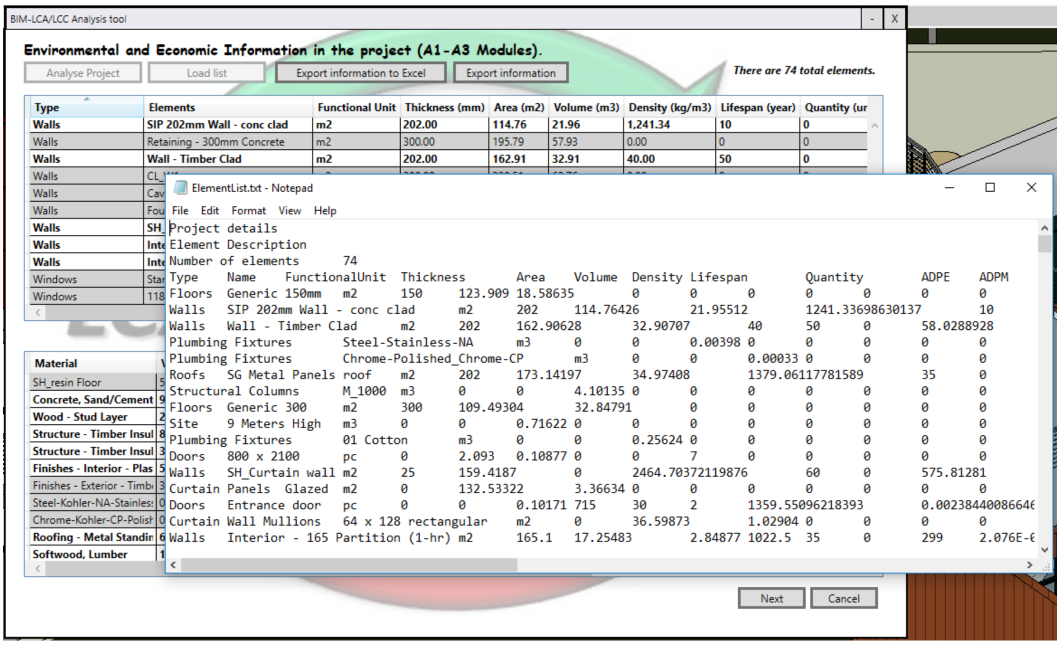


Figure 27 - Elements and Materials' information exported to a text file

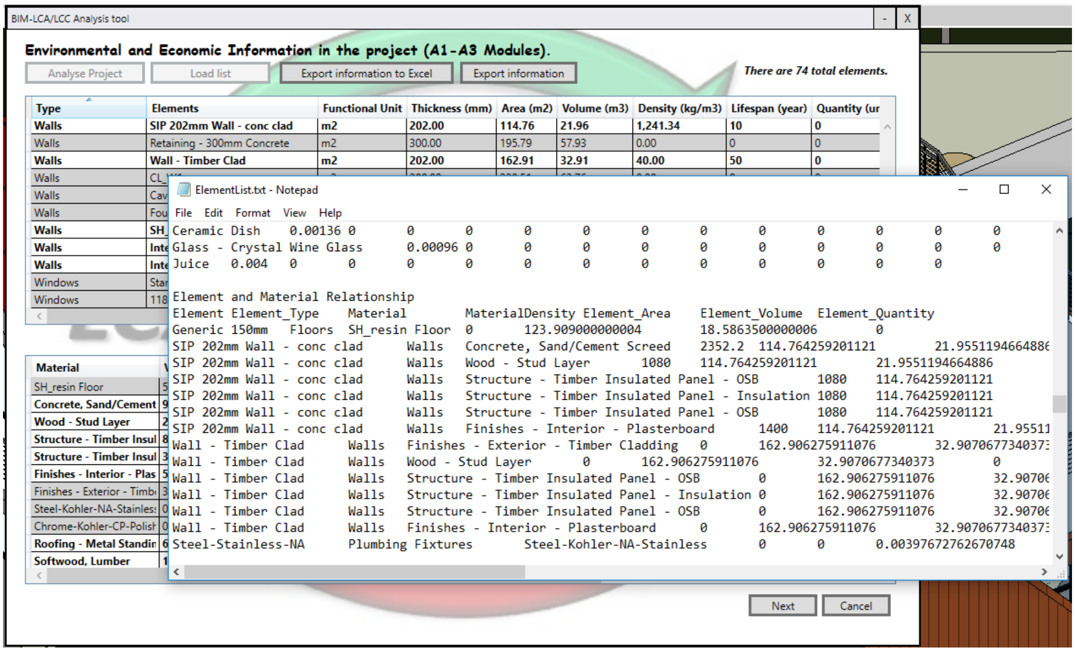


Figure 28 – Elements composition exported to a text file

As visualised, the tool not only exports the quantities but also the environmental, economic, and physical (i.e. density and lifespan) properties of each element and material. Moreover, the tool also exports the composition of each element, as shown in Figure 28. This information is important for future operations (e.g. the tool has two options for the automatic quantification of the materials' replacements: i) consider all materials' layers or ii) just replace the external layers of the walls, roofs, and floors (e.g. paint, tiles)).

	Name of element	Type of element	Density (kg/m3)	Lifespan (years)	ADPE	ADPM	AP	EP	GWP	ODP
2	Generic 150mm	Floors	0	0	0	0	0	0	0	0
3	SIP 202mm Wall - conc clad	Walls	1241.336986	10	2074	0.0004729	1.0926	0.27689	210.41	9.94002E-06
4	Wall - Timber Clad	Walls	40	50	58.0288928	0.000008944	0.02528	0.009264	4.58986992	3.728E-07
5	Steel-Stainless-NA	Plumbing Fixtures	0	0	0	0	0	0	0	0
6	Chrome-Polished_Chrome-CP	Plumbing Fixtures	0	0	0	0	0	0	0	0
7	SG Metal Panels roof	Roofs	1379.061178	35	8927.2	0.00123177	5.27579	1.26545	940.17	0.000032482
8	M_1000	Structural Columns	0	0	0	0	0	0	0	0
9	Generic 300	Floors	0	0	0	0	0	0	0	0
10	9 Meters High	Site	0	0	0	0	0	0	0	0
11	01 Cotton	Plumbing Fixtures	0	0	0	0	0	0	0	0
12	800 x 2100	Doors	0	0	0	0	0	0	0	0
13	SH_Curtain wall	Walls	2464.703721	60	575.81281	0.000165	0.353	0.075	51.659488	0.00000507
14	Glazed	Curtain Panels	0	0	0	0	0	0	0	0
15	Entrance door	Doors	715	30	1359.550962	0.002384401	0.22552213	0.043590792	-11.35225442	8.93736E-06
16	64 x 128 rectangular	Curtain Wall Mullions	0	0	0	0	0	0	0	0
17	Interior - 165 Partition (1-hr)	Walls	1022.5	35	299	0.00002076	0.2029	0.02144	19.7	0.000001069
18	Interior - Partition	Walls	1018.666667	35	299	0.00002076	0.2029	0.02144	19.7	0.000001069
19	Standard	Windows	0	0	0	0	0	0	0	0
20	Curtain Wall Dbl Glass	Doors	715	30	986.1393768	0.001729506	0.163580667	0.031618231	-8.234266614	6.48264E-06
21	1180 x 1170mm	Windows	0	0	0	0	0	0	0	0
22	Pad 2	Pads	0	0	0	0	0	0	0	0
23	CL_W1	Walls	0	0	0	0	0	0	0	0

Sheet1 | Elements_BIM | Materials_BIM | Elements_Materials

Figure 29 - Elements and Materials' information exported to an Excel file (e.g. sample of the elements' information represented in the project)

The exported text file (shown in Figure 27 and Figure 28) can then later be used in the third option shown in Figure 16. In this case, the tool will not read the model that is currently opened but rather the information contained in the text file, so that the users can perform a Streamlined or Complete LCA/LCC analysis of the current model or an old model. This is very useful to users that have already performed the steps described before and only intend to run a Complete LCA/LCC analysis based on the data contained in the text file only.

5.3. BIMEELCA Part Three: Run a Streamlined LCA/LCC analysis

After reading the information in the model and allowing the users to export that information to a spreadsheet or text file, the BIMEELCA tool will automatically conduct a Streamlined LCA/LCC analysis based on that information (Figure 30). The tool also allows the users to visualise the environmental and economic impacts per type of element. The third part of the BIMEELCA tool focuses on the *task T.2* identified in the Sub-process 'BIM-based LCA/LCC analysis' in the IDM/MVD proposed in the previous chapter.

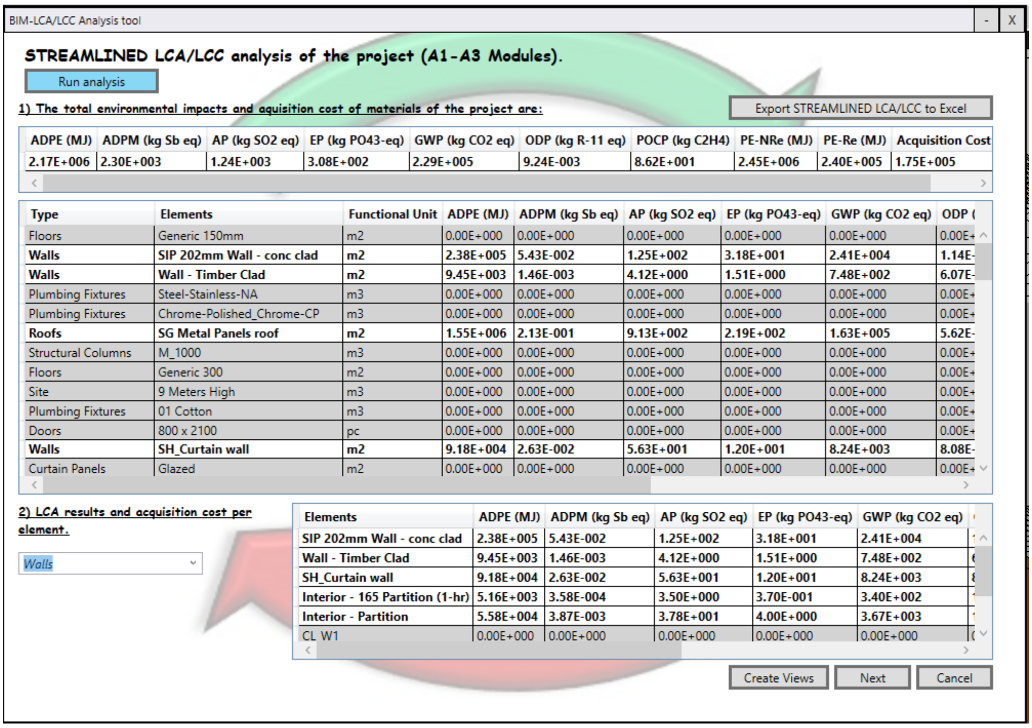


Figure 30 - Streamlined LCA/LCC analysis (based on the A1-A3 modules)

The automatic generation of 3D views for the visualisation of the environmental and economic results from the Streamlined LCA/LCC analysis is another operation enabled by the tool. In this regard, the tool generates a 3D view with a colour scheme per categorisation (i.e. the environmental impact categories identified in the BIM-LCA/LCC framework and the cost information), as seen in Figure 31.

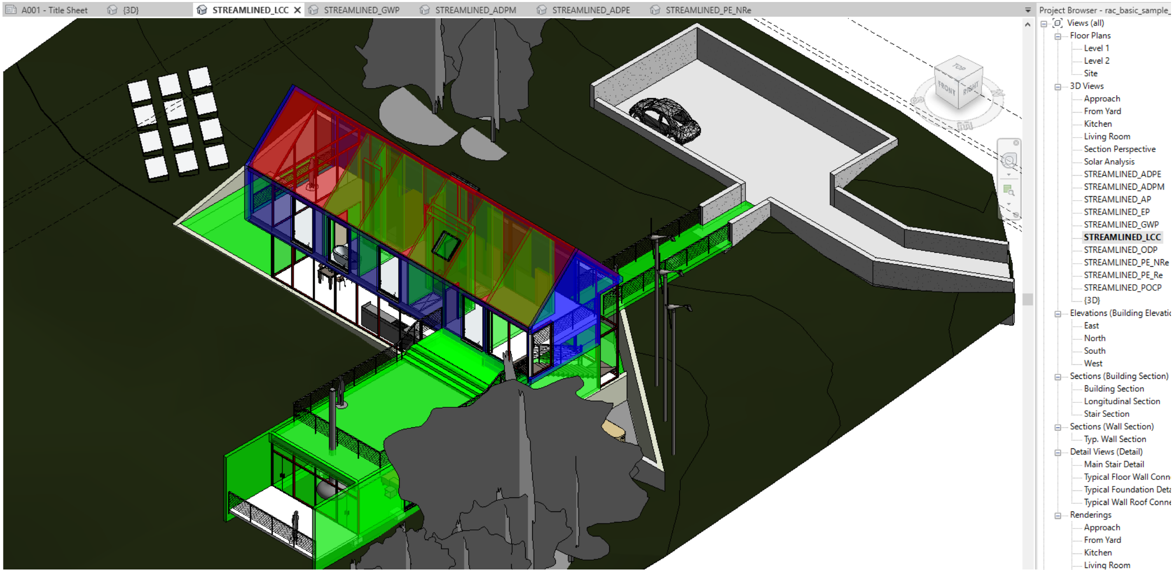


Figure 31 - Visualisation of the impacts per categorisation (e.g. LCC)

For each category, the tool identifies the elements with maximum and minimum contributions (disregarding the elements with empty indicators) and assign the red, orange, purple, blue, and green colour to the elements that have impacts higher than 80% of the maximum contribution, 80-60%, 60-40%, 40-20%, and lower than 20%, respectively. Therefore, the element with the highest contribution will always be highlighted in red and the one with the lowest in green. Moreover, the tool will disregard all the elements that do not have a value in a specific category, i.e. their colour will remain unchanged (i.e. the appearance of the element will not change). By visualising the results of the Streamlined LCA/LCC analysis, the users will be able to instantaneously identify which elements contributes the most to the impacts of the manufacturing stage (A1-A3 modules). Nonetheless, elements that apparently are environmentally friendly, based on this analysis, might not be if the full life cycle of a project is considered. For that purpose, it is very important to conduct a Complete LCA/LCC analysis as well.

5.4. BIMEELCA Part Four: Run a Complete LCA/LCC analysis

The last part of the BIMEELCA tool focus on the performance of the Complete LCA/LCC analysis of the model. Therefore, the steps presented in this part will address the *task T.3* (insert project-specific information) and *task T.4* (run a Complete LCA/LCC analysis based on the data provided by the users) identified in the Sub-process 'BIM-based LCA/LCC analysis' in the proposed IDM/MVD. The main window that presents all the required information to perform a Complete LCA/LCC analysis is shown in Figure 32. Although the users are given a multitude of fields to fill, only the estimated lifespan of the project, discount rate and how the estimated replacement of the interior layers of walls/floors/roofs will be done are mandatory. The first two variables are always a requirement for a full life cycle analysis of a project while the third only asks the users if they prefer to consider all the layers in the walls, floors, and roofs or just the exterior layer. This last option is given to the users in case only superficial interventions are foreseen, i.e. only the outer layers are to be repaired (e.g. paint, floor tiles).

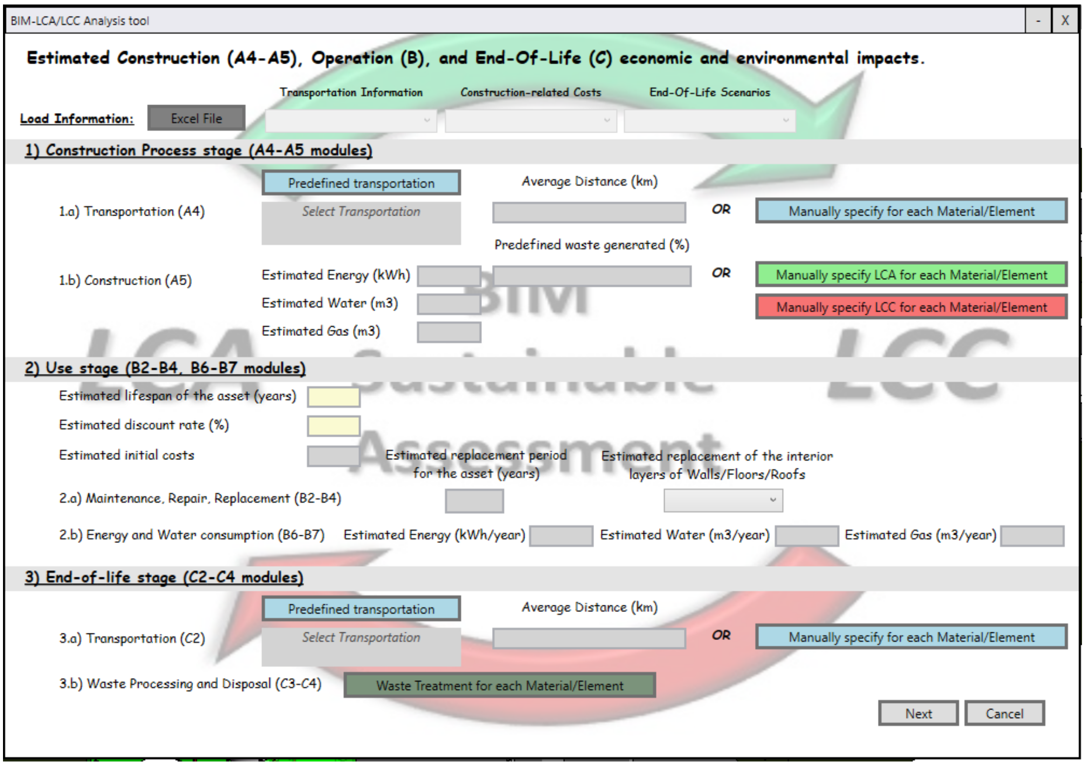


Figure 32 – Main window for the Complete LCA/LCC analysis

The load of a spreadsheet that contains project-specific information is the first step in case the users intend to perform a Complete LCA/LCC analysis. This is required because the tool itself does not contains any data. As soon as that information is loaded into the tool, the users will be able to select the sheets that contain the information relative to transportation, construction-related costs, and end-of-life scenarios (Figure 33).

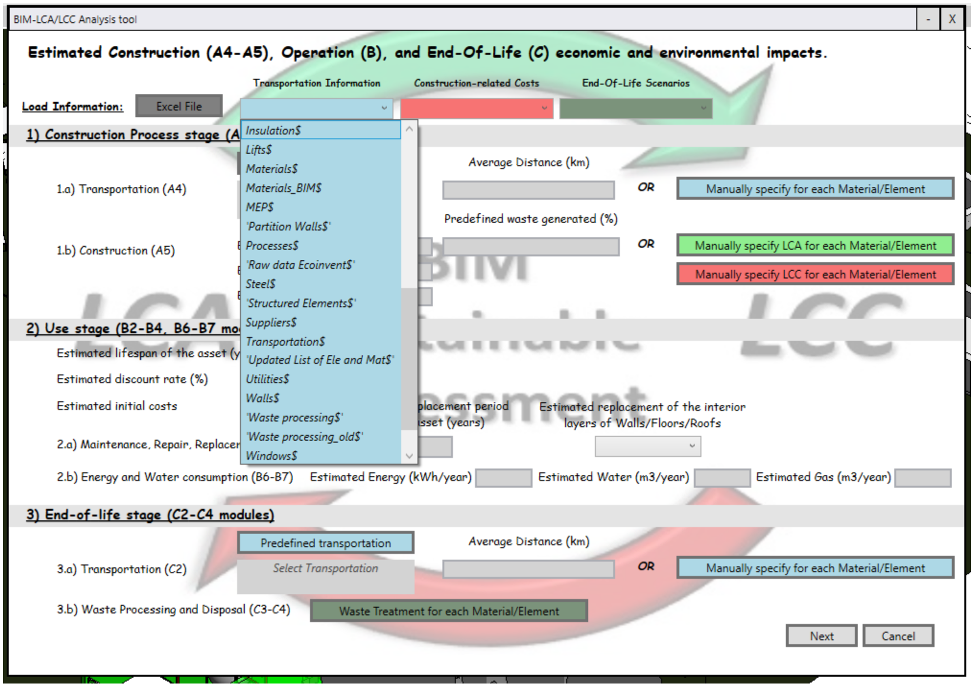


Figure 33 – Load project-specific information from spreadsheet

The left-most drop-down menu is used for the definition of the transportation used by the suppliers, as shown in Figure 33 and Figure 34. The users can then select a pre-defined transportation and distance between construction site (1.a)) and supplier/waste treatment facility (3.a)) to be used in the A4 and C2 modules or manually specify the type of transportation and distance for each material (Figure 35).

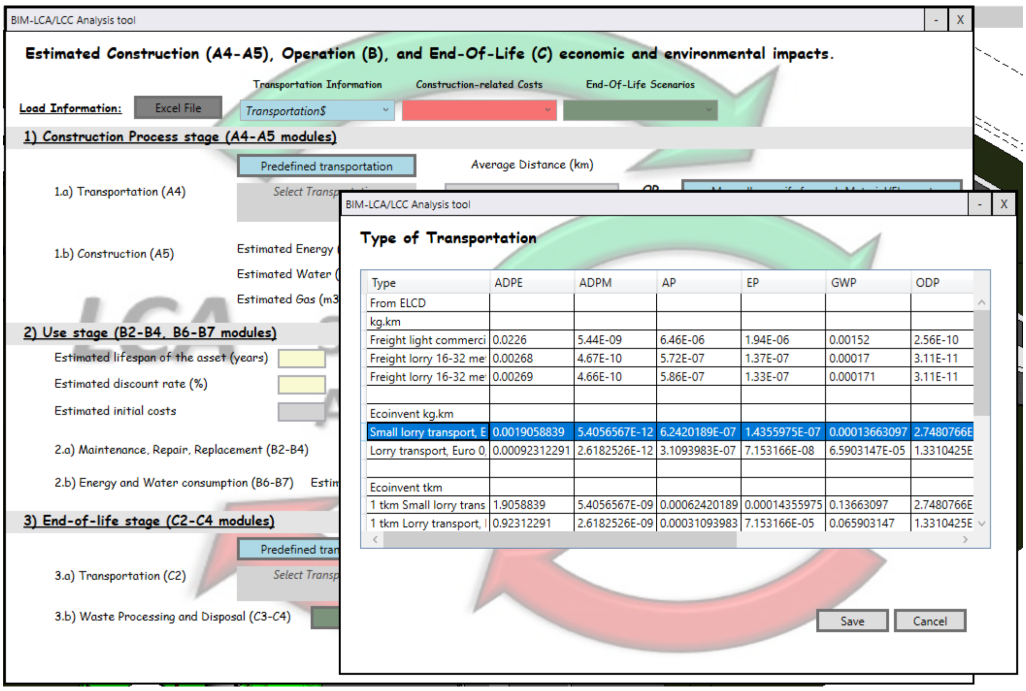


Figure 34 - Selection of the type of transportation (modules A4 and C2)

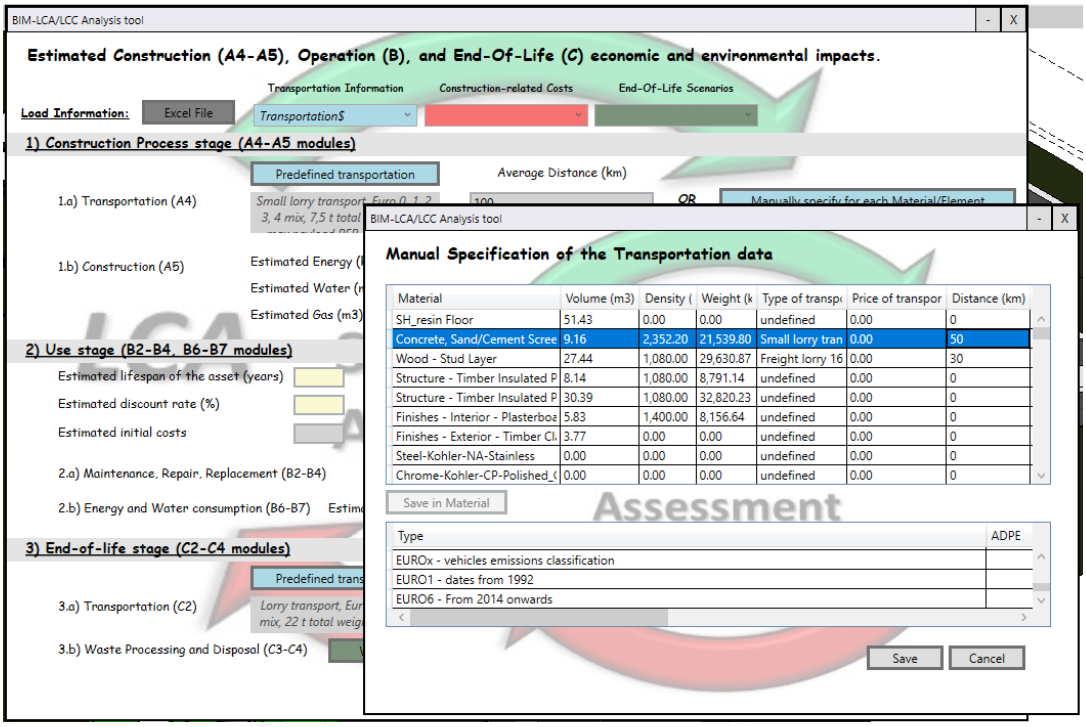


Figure 35 - Manual specification of the transportation data

For the calculation of the environmental and economic impacts due to these modules, it is necessary that the materials have their corresponding density values (in kg/m^3). The weight of each material will be determined based on the multiplication of its density with its total volume. Subsequently, the impacts of the transportation (i.e. per kg.km) will be multiplied by the weight of a material and the distance between its supplier and the construction site.

The next step is the definition of the impacts due to the construction activities (i.e. A5 module). For this purpose, the users are able to insert the utilities consumed during the construction stage of the building (i.e. electricity, water, and natural gas) as seen in Figure 36, as well as the estimated waste generated in this stage and the price for each construction activity task (e.g. assembly cost). Regarding the last, if the cost previously inserted in the materials (or elements) already reflects the assembly costs, then the users should not insert the costs relative to assembly tasks in this step, to avoid double counting (Figure 37). The same applies for the transportation costs, i.e. if the products' cost already covers its transportation then the costs of A4 should be disregarded.

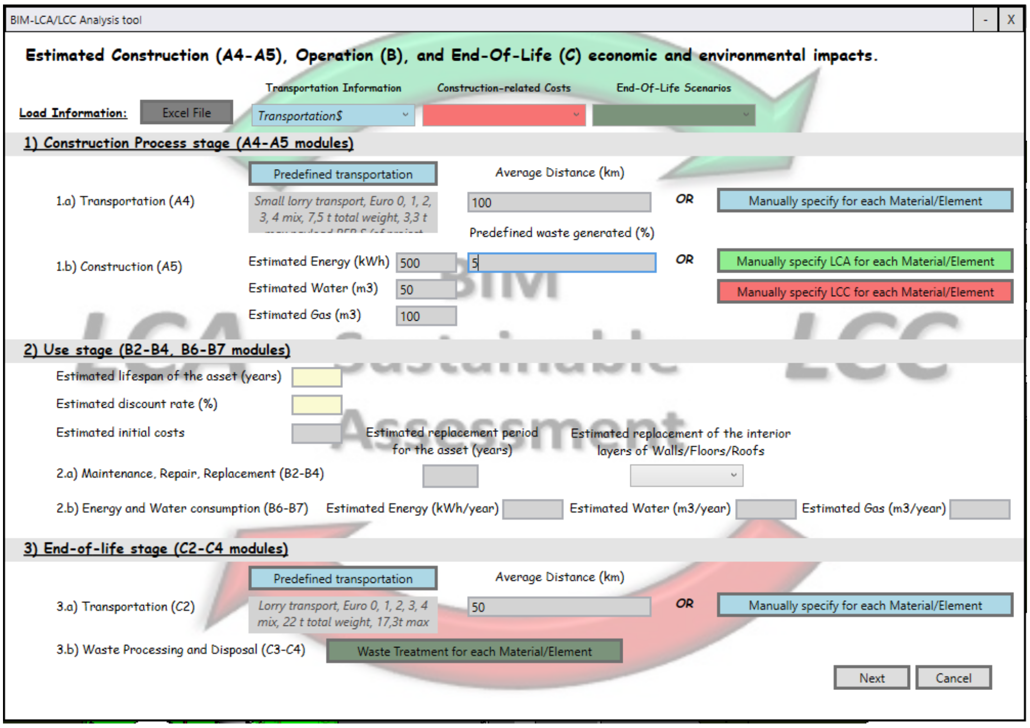


Figure 36 - Specification of the information required for construction activities (A5 module)

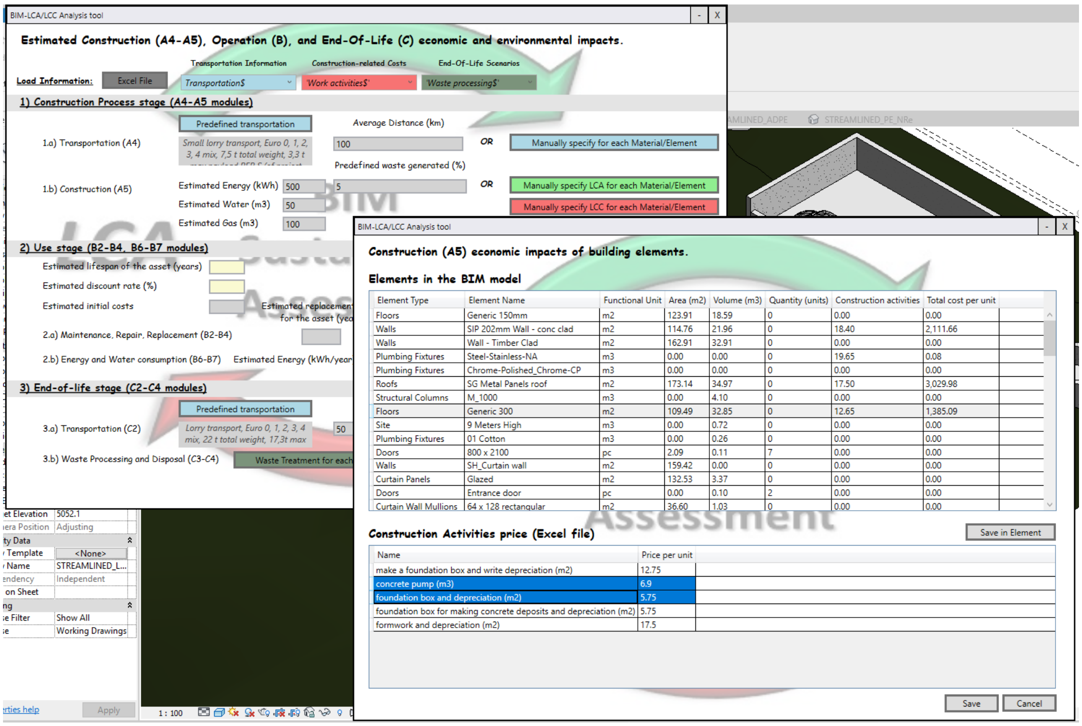


Figure 37 - Assignment of costs related to construction tasks

For the definition of the impacts due to the utilities' consumption or manual specification of each material's waste (these have a pre-defined value of zero), the users must open a different window (Figure 38). Once more, the users will have to select which sheets contain the impacts for the electricity, water, and natural gas consumption (based on the energy-mix of each country). These impacts will be multiplied by the consumption that the users indicated in the main window displayed in Figure 32. Moreover, the users are able to specify the waste generated for each material. In this regard, the calculations for the impacts of waste generated in the A5 module are represented by the multiplication of the material's weight by its impacts. However, it is noted that if the users only inserted information in the elements previously (e.g. walls, roofs, doors) and not in the constituting materials (Figure 22), then this operation will not generate the impacts for those materials.

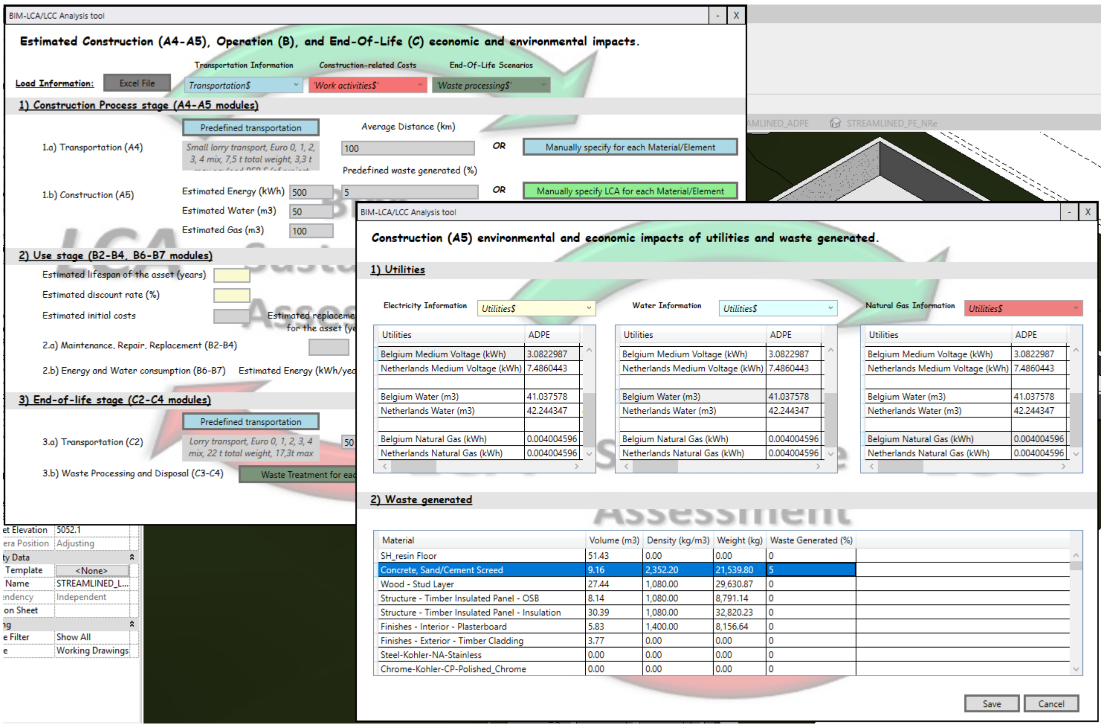


Figure 38 - Assignment of impacts due to utilities and waste generated in the A5 module

Once the data required for the A modules are filled, the users can now specify the estimated data for the operation stage (modules B), as shown in Figure 39. The computational complexity for the algorithm behind the environmental and economic impacts due to the B modules is much higher when compared with the remaining modules, despite its seeming simplicity in the GUI.

As mentioned before, the users must insert the estimated lifespan of the asset (i.e. the service life) and a discount rate suitable for the type of construction and location. These variables will influence the sensitivity analysis that experts often perform in LCA and LCC analyses, as well as the number of estimated replacements.

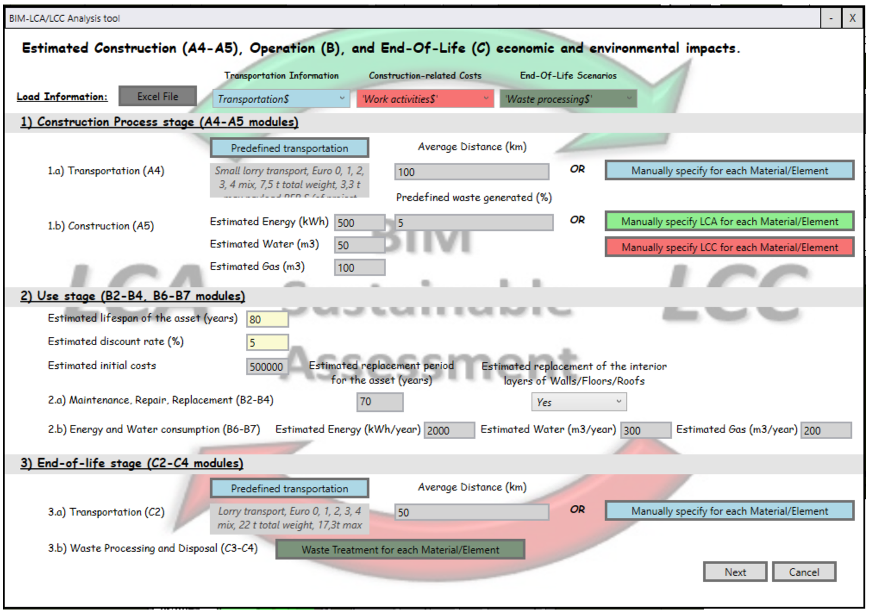


Figure 39 - Assignment of project-specific information based on estimated values

If desired, the users can also indicate initial costs in the main window (e.g. land acquisition) so that all initial costs are taken into consideration. The user must not insert the cost obtained in the Streamlined analysis in this field, to avoid double counting. For the calculation of the maintenance, repair, and replacement phases (B2-B4 modules), the users can indicate the maximum replacement period for the asset, i.e. there will only be replacements until this age. Moreover, as explained before, the users can also indicate whether the interior layers of walls, roofs, and floors are replaced or not. If the last option is selected, then only the outer layer will be considered.

Regardless of the selected option, the replacements will be determined based on the functional unit that was initially selected for each element. Therefore, for materials that are part of elements with a functional unit of ‘m^2’, ‘m^3’, or ‘kg’, the number of replacements will be multiplied by the hosting element’s quantity and by the materials’ environmental impacts. However, the same does not apply for the materials in elements with a functional unit of ‘pc’ (i.e. unitary). If the functional unit of an element is ‘pc’, then the replacement of the constituting materials will be calculated based on the multiplication of their environmental impacts by the element’s quantity. For the sake of simplification, the tool considers that all the elements that have a functional unit of ‘pc’ will be replaced on the entirety. Hence, the users should use the same environmental and economic information that was inserted in the element and add it to a single “dummy” material. This dummy material would represent the same impacts of the element. Consequently, if an element has more than a single material, the users must insert the information in only one of the materials while the others must remain empty. For example, if

Door#1 contains Glass and Wood as materials, then the user should insert the impacts of Door#1 in the wood material (to act as the dummy material) and leave glass material empty. At last, the environmental impacts due to the utilities' consumption (B6-B7 modules) will be obtained by multiplying the environmental impacts of each utility with the estimated consumption.

The life cycle costs calculations of the B modules are based on the Net Present Value (NPV) presented in the proposed BIM-LCA/LCC framework. This method was used to quantify the costs due to the materials' replacement, utilities' consumption and initial costs. The last information that can be inserted in the GUI of the tool corresponds to the end-of-life (C modules) operations. Like in Figure 34, the users can insert the transportation data for the C2 module. For the definition of waste treatment (C3-C4 modules), the tool allows the users to insert different scenarios for each type of material, as shown in Figure 40, as well as export or import it to a text file (so that users are able to work with that list later).

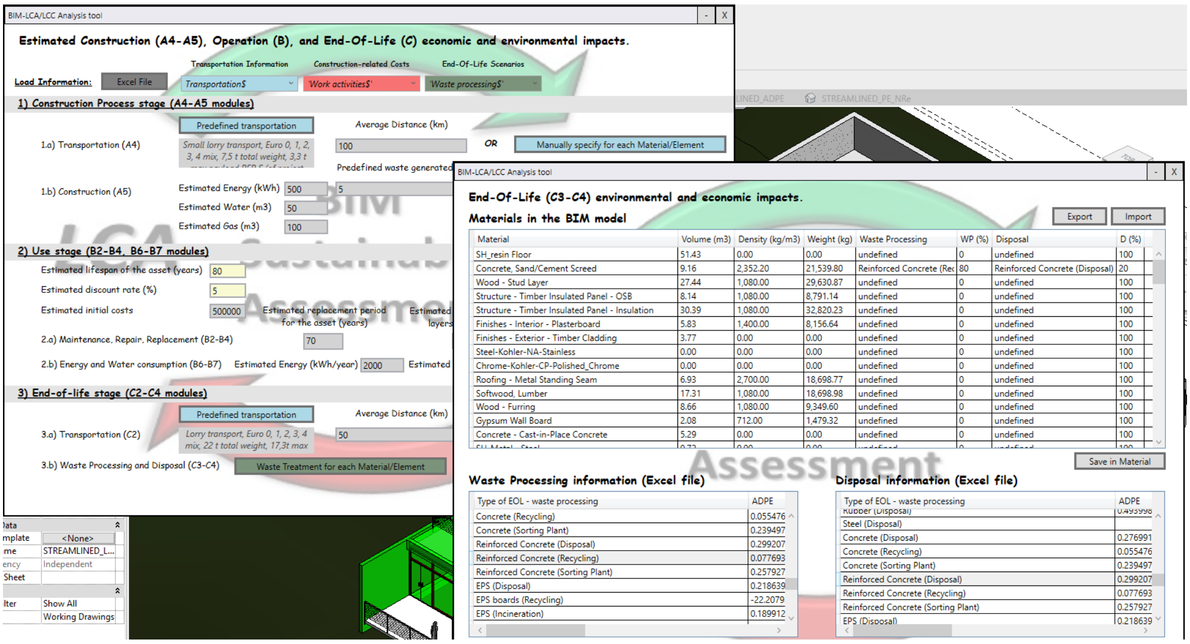
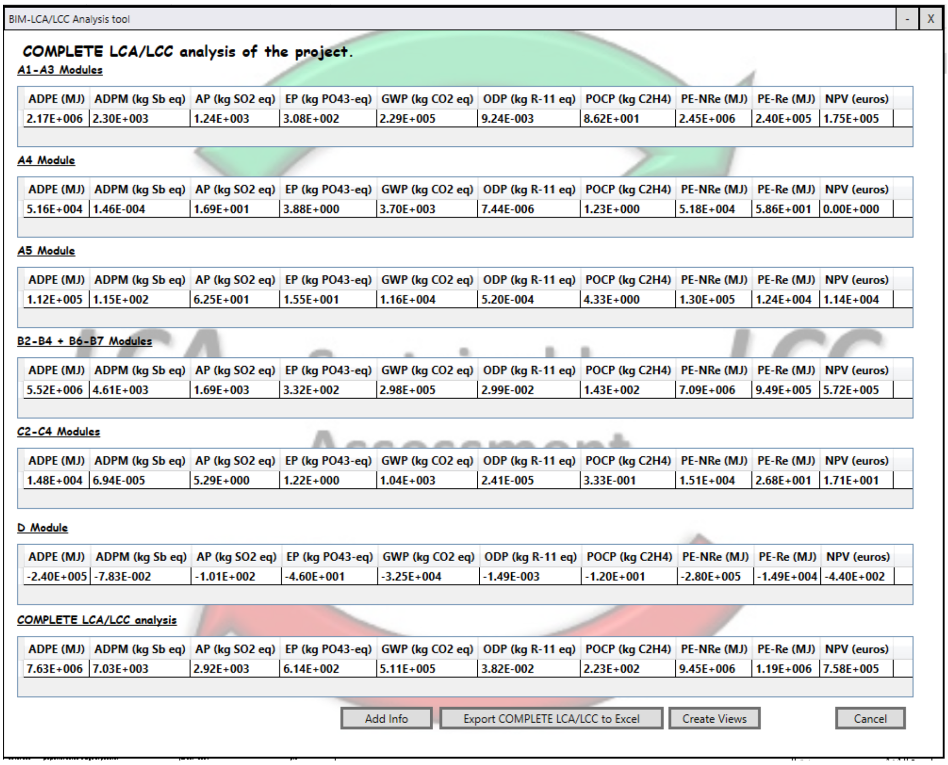


Figure 40 - Assignment of waste treatment scenarios per type of material: list of materials (top table); waste processing scenarios – C3 module (bottom-left table); and disposal scenarios – C4 module (bottom-right table)

The environmental and economic impacts due to the waste treatment are determined in a similar way as the impacts due to transportation, i.e. the weight of the materials is multiplied by the corresponding impacts. Consequently, the total impacts of modules C correspond to the sum of the transportation impacts (C2) and the waste treatment impacts (C3-C4). For the life cycle costs, the total cost of module C are based on the NPV method.

For the benefits due to the reuse, recovery or recycling scenario (module D), the impacts are based on the difference between the impacts of a recycled/reused material (C3) and the environmental and cost impacts of a new material (A1-A3). This means that the results of module D are almost always negative. Unlike previous modules that were considered as a burden to the society, module D is considered as a positive impact. Thus, the total impacts of a project will be reduced if this module is considered. Hence, in order for the tool to consider the impacts of module D, it is fundamental that the users not only add information to the elements but to the materials as well. Otherwise, the tool will only handle the data of the materials that have information contained in them. This is not a limitation of the tool itself but rather a constraint of the proposed BIM-LCA/LCC framework, i.e. the LCA and LCC data is specific for materials (and not elements) for a Complete analysis. At last, it is assumed that all waste scenarios with negative impacts (C3 module), i.e. beneficial to the environment, already cover the recycling and reuse benefits (module D). Therefore, to avoid double counting, all scenarios that fit this criterion will not be considered in the calculation of the module D's impacts. After the calculation of the impacts of all modules, the tool will display the total impacts for the Complete analysis and per module (Figure 41). Moreover, the users can export the results and all the calculations performed by the tool to a spreadsheet (Figure 42).


BIM-LCA/LCC Analysis tool

COMPLETE LCA/LCC analysis of the project.

A1-A3 Modules

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
2.17E+006	2.30E+003	1.24E+003	3.08E+002	2.29E+005	9.24E-003	8.62E+001	2.45E+006	2.40E+005	1.75E+005

A4 Module

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
5.16E+004	1.46E-004	1.69E+001	3.88E+000	3.70E+003	7.44E-006	1.23E+000	5.18E+004	5.86E+001	0.00E+000

A5 Module

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
1.12E+005	1.15E+002	6.25E+001	1.55E+001	1.16E+004	5.20E-004	4.33E+000	1.30E+005	1.24E+004	1.14E+004

B2-B4 + B6-B7 Modules

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
5.52E+006	4.61E+003	1.69E+003	3.32E+002	2.98E+005	2.99E-002	1.43E+002	7.09E+006	9.49E+005	5.72E+005

C2-C4 Modules

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
1.48E+004	6.94E-005	5.29E+000	1.22E+000	1.04E+003	2.41E-005	3.33E-001	1.51E+004	2.68E+001	1.71E+001

D Module

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
-2.40E+005	-7.83E-002	-1.01E+002	-4.60E+001	-3.25E+004	-1.49E-003	-1.20E+001	-2.80E+005	-1.49E+004	-4.40E+002

COMPLETE LCA/LCC analysis

ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO43-eq)	GWP (kg CO2 eq)	ODP (kg R-11 eq)	POCP (kg C2H4)	PE-NRe (MJ)	PE-Re (MJ)	NPV (euros)
7.63E+006	7.03E+003	2.92E+003	6.14E+002	5.11E+005	3.82E-002	2.23E+002	9.45E+006	1.19E+006	7.58E+005

Add Info | Export COMPLETE LCA/LCC to Excel | Create Views | Cancel

Figure 41 - Environmental and economic impacts of a project based on a Complete LCA/LCC analysis

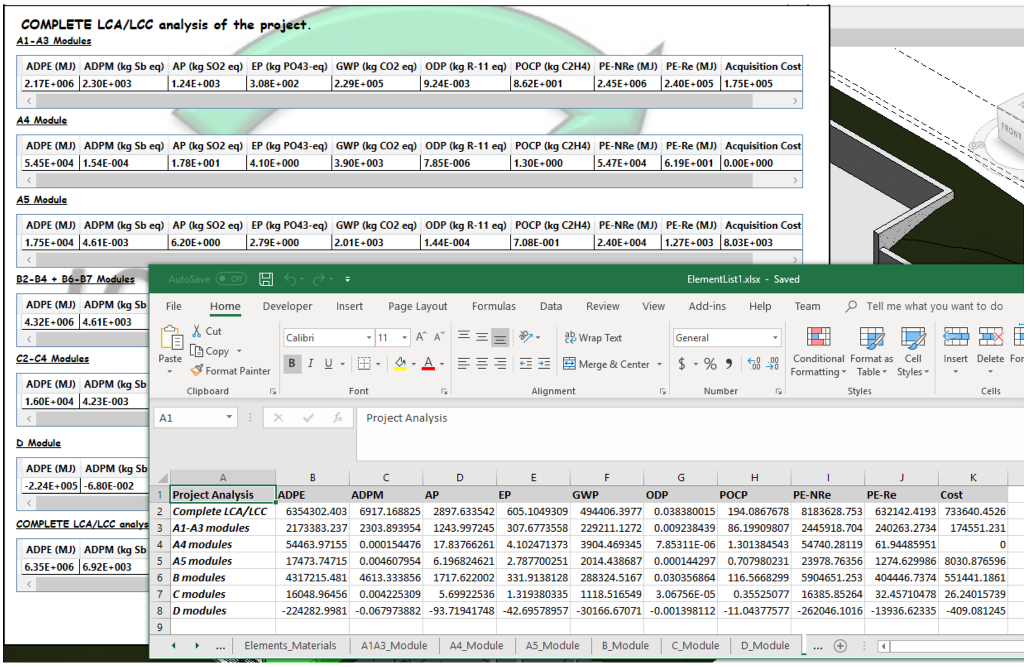


Figure 42 – Export the environmental and economic impacts of each element, material, and life cycle stage to an Excel file

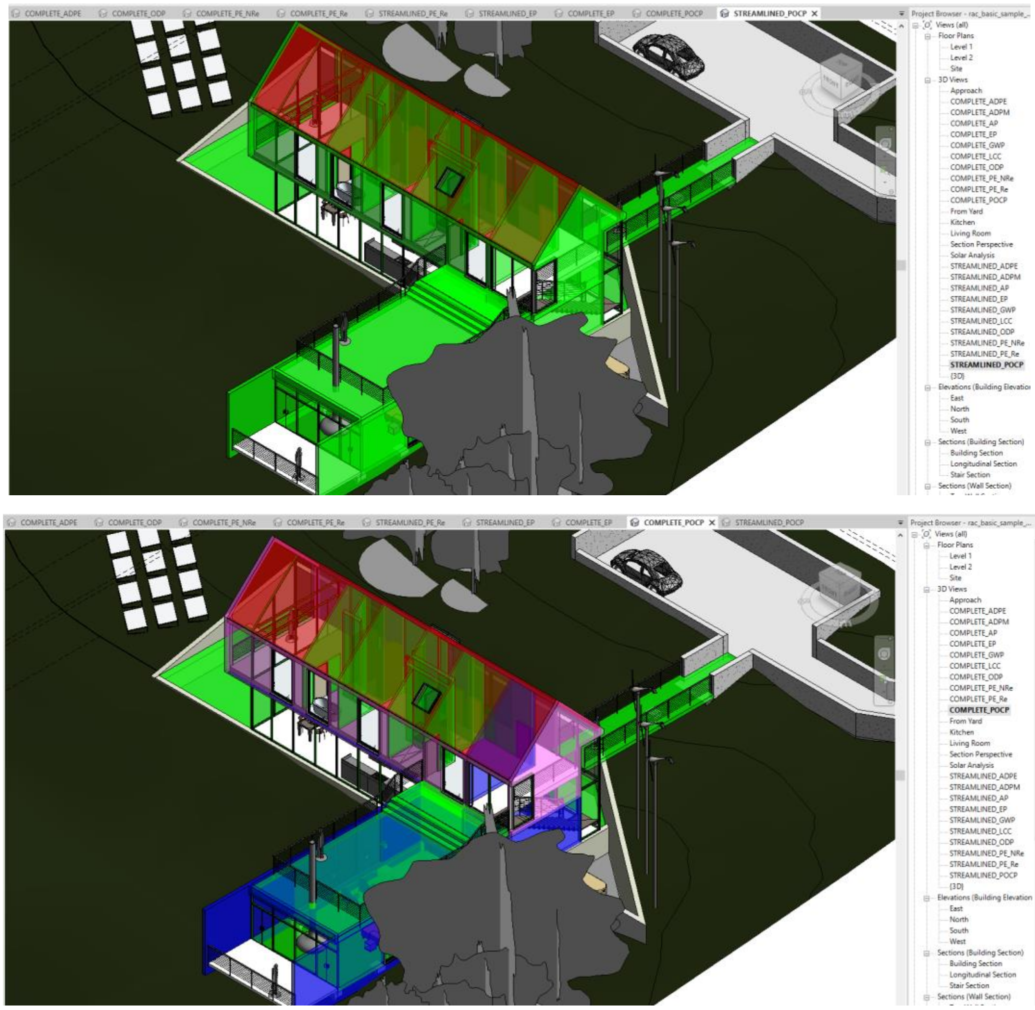


Figure 43 - Comparison between Streamlined and Complete analysis

At last, there is also an option to generate 3D views of the results of the Complete analysis with the same colour scheme as in the Streamlined analysis. This will allow the users to compare the results of both analyses and instantaneously identify the elements that contain materials that have higher impacts when considering the service life and discount rate they have indicated previously (Figure 43).

As observed in Figure 43 (top), it is possible that almost all elements have the same colour in the Streamlined or Complete analyses. This means that almost all elements might be in the same colour range even though their impacts are considerable different, because there is one (or more) that might have a very high impact when compared to the others (e.g. the roof in red). For example, if a single element greatly contributes to the total impacts of the project (an outlier), the colour range of the remaining elements will be substantially influenced as well. This is because the remaining elements will contribute much less to the total impacts when compared with the outlier. Therefore, if this situation occurs, it is advisable that the users identify the element with the outlier impact (which can easily be done by consulting the exported information) and remove the information contained within it (so that the tool disregards it in future analyses) before conducting a new analysis.

At last, the tool allows the users to automatically insert the results of the Complete LCA/LCC analysis at project, element and material level, as exemplified in Figure 44.

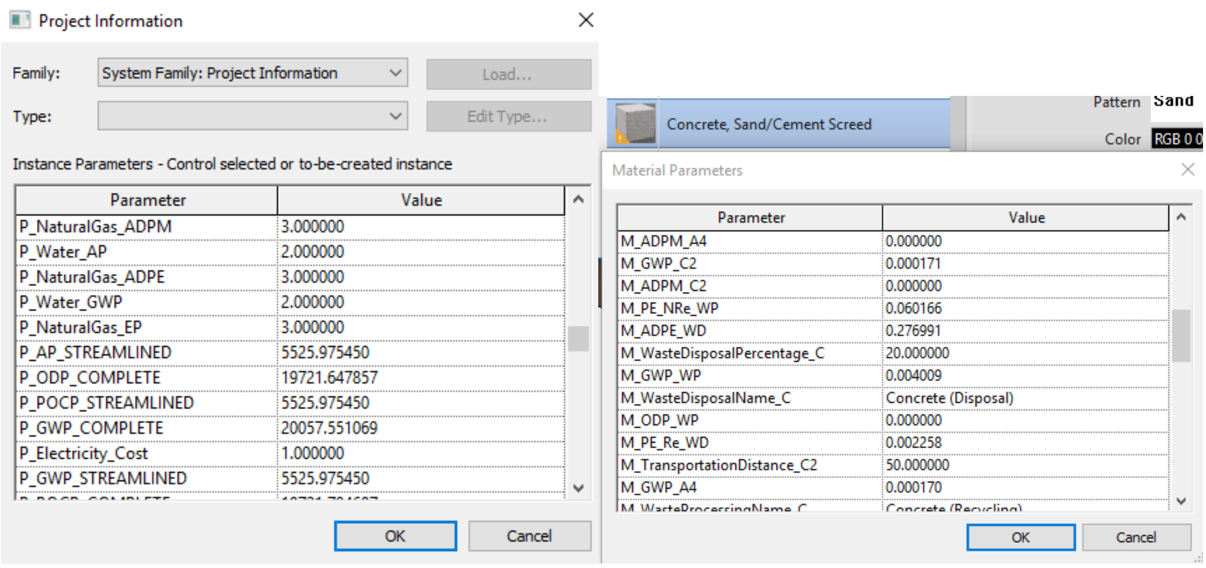


Figure 44 - Information added to the Project Information and Materials

At project level, the service life of the construction, discount rate, utilities consumption and respective impacts, and Streamlined and Complete results are inserted in the model. If the user added any cost in the A5 module (e.g. assembly costs), this value will also be inserted in the corresponding element. At the material level, the transportation distance and impacts due to transportation in both A4 and C2 modules, the waste percentage in the A5 module, the type of waste processing and disposal, and the recycled (C3) and disposed (C4) percentage and impacts are added as well (per unit). This automatic operation is in accordance with the proposed properties in the IDM/MVD for the BIM-LCA/LCC analysis, so that the model contains a comprehensive information about the variables used for an LCA and LCC analysis.

The information required by the BIMEELCA tool (i.e. project-specific data) could also be included in BIM Execution Plans (BEPs). A BEP is a plan that stipulates the information modelling aspects of a BIM project, the roles and responsibilities, the procedures and also details the project deliverables [69].

5.5. Guidelines for the inclusion of the information required by the BIM-LCA/LCC framework and the BIMEELCA tool in BIM Execution Plans

The guidelines presented in PAS1192-2:2013 [68] (that was superseded by ISO 19650-1:2018 [69]) and in the AEC (UK) BIM protocol [70] contributed to the development of BEPs specific to the needs of national markets and companies. Since the publication of PAS1192-2, several BEP templates were made available worldwide which are often used in the information management of a BIM project [375].

According to the guidelines presented in [68, 69], a BIM project starts with the CAPEX stage that can represent a project with no pre-existing information (e.g. new building) or a project with pre-existing information on an existing asset (e.g. facilities management). It is also in this stage that the employer's information requirements (EIR), i.e. a set of information required by the employer (i.e. owner) and that is aligned with the project’s goals, should be addressed and included in the tender documentation by the suppliers (e.g. contractor). The suppliers must then include their supply-chain approach and how they will carry out the project in their initial BIM execution plan (also known as pre-contract BEP).

A pre-contract BEP should include a project implementation plan (PIP) and a project information model (PIM), as well as the project’s goals and milestones. A PIP consists in a document created by the supplier that allows the employer to assess the competence and capability of the supplier to deliver the information required in the EIR. This document should include the following: the supplier building information management assessment form, the supplier information technology assessment form, and the supplier resource assessment form. A PIM, also known by design intent model, contains a federated BIM (i.e. a set of linked BIM models of different domains), non-graphical information and other documentation that might be relevant to the project.

Once the contract is awarded, after the procurement stage, a more in-depth BEP is developed (known as post-contract BEP). This BEP shall contain, amongst others, the master information delivery plan (MIDP), the task information delivery plan (TIDP), the standards and procedures followed throughout the project, and the roles and responsibilities of the stakeholders. The MIDP focuses on the deliverables that should be provided throughout the project (e.g. BIM models, drawings, specifications) and stipulates when the project information should be prepared and by whom. The TIDP consists in a set of documents designed by each specialty and must contain the deadlines and responsibilities that were agreed in the contract.

Therefore, if the employer wishes to include in the project the required information for the BIM-based LCA/LCC analysis and for the BIMEELCA tool, thus obtaining a digital model with semantically rich objects, this should be specified in the BEP. In this sense, it should be stipulated in the BEP that the manufacturers and or suppliers should provide the specific environmental information of their products (e.g. in the format of an EPD) whenever they have it available. If not, it should be stipulated in the contract who is responsible to collect the generic data (and from which database) and who is responsible to insert this information in the model. All this should be indicated in the section that covers the project goals for collaboration and information management in the pre-contract BEPs, according to PAS1192-2 Clause 6.2.

Regarding the post-contract BEPs, the procedures required for the BIM-based LCA/LCC analysis and for the BIMEELCA tool should be further detailed. Firstly, the roles of the actors identified in the IDM/MVD must be included in the BEP, i.e. the BIM Manager, the LCA/LCC specialist, and the manufacturers/suppliers. This can easily be done if a matrix of responsibilities is included. Besides the Who, this matrix could also include the level of development/detail that the models should respect in order to perform the LCA and LCC analyses. For early stages of the project, only low LODs would be required (lower than 300), but as soon as the products that will be used in the project are known (e.g. products/materials) then higher LODs should be used. To meet the proposed approach indicated in the BIM-LCA/LCC framework, the use of generic data for projects with LODs lower than 300 and the use of specific data for projects with LODs higher than 300 should be specified in the BEP, as well as who is responsible for the data collection for both cases (the LCA/LCC specialist). The indication of the required information and how it is exchanged (i.e. the format) could be part of the TIDP, i.e. the manufacturers/suppliers should agree to exchange the sustainable-related information (i.e. the environmental and economic indicators) in the format of a digital object and or in text (e.g. spreadsheet, pdf) whenever they have that information. On the other hand, the LCA/LCC specialist should agree to create a semantically rich BIM model based on the information provided by the manufacturers/suppliers or based on generic databases. In the end, the TIDP, the responsibility matrix and the project's milestones should be grouped in the MIDP.

Although not comprehensive, the guidelines presented in this subsection are meant to be used in the development of pre-contract and post-contract BEPs in order to cover the required procedures to adopt the BIM-LCA/LCC framework and implement the use of the BIMEELCA tool in BIM-based projects.

5.6. Concluding Remarks

The comprehensive tool described in this chapter was developed between September 2017 and May 2018, being regularly debugged and improved until February 2019. This tool was developed for a specific type of end-users, the LCA/LCC specialists. However, it can also be used by designers (e.g. architects, engineers) with a strong enough background in sustainable construction so that the results obtained are properly understood. The BIMEELCA tool has some advantages when compared with other tools in the market. Existing tools connect geometric information and material and or element information with external databases, but never add information to the model itself, unlike the developed tool. This means that if the model is exchanged with other stakeholders, they will either need to acquire the proprietary license of the same LCA/LCC tools and or even need to redo the same procedure in order to perform the LCA/LCC of the project.

In contrast, if BIMEELCA tool is used to add information to the model, non-proprietary applications will be able to read that data and perform LCA and LCC analyses. Furthermore, the addition of information in the model leads to other opportunities. In this regard, if the designer wishes to perform a refurbishment of a project and if the model already has LCA/LCC data, it will only be necessary to add the information on the new elements to perform a new LCA/LCC analysis of the project. Moreover, the tool is able to import information from an excel spreadsheet. Thus, users can work with a tool that they are familiar with (i.e. Excel) to insert the information they desire. In contrast, existing tools only allow users to select the information contained in their databases (e.g. Tally, One-Click LCA). Furthermore, that information cannot be edited as well, meaning that the users cannot adapt existing information to their needs. At last, the accuracy of the tool's quantity take-off was compared with Revit's quantity take-off (i.e. the materials' volume obtained by the tools was compared with the volume obtained by Revit itself). The obtained results were consistent, with a 1.8% maximum difference and an average difference of 0.09% between both approaches. However, the Revit's automatic quantity take-off did not recognise the materials used in the curtain wall mullions, unlike the tool.

BIMEELCA also allows the users to conduct LCA and LCC analyses based only on the information available in the model. For example, it is possible to obtain the impacts due to the use stage (B modules) or transportation (A4 or C2 modules) according to the needs of the users or purpose of the study. This can be useful for product comparison or if the energy performance of the building changes during its service life (e.g. due to a different pattern of use).

Nevertheless, the tool also has a few limitations. It only allows the users to automatically create or associate parameters to the elements indicated before (i.e. materials, ceilings, curtain walls, doors, floors, roofs, walls, windows, beams, columns, foundations, and stairs). If the users wish to analyse other types of elements, they will have to manually insert the shared parameters indicated in the beginning of this chapter in the categories they wish to cover (e.g. insert the environmental, economic, and physical indicators in the 'furniture' category). In this regard, as long as the tool recognises the element, it is still possible to consider them in the analysis (e.g. if the users add information in furniture objects, the tool will automatically recognise it and consider this category in the analysis). Furthermore, the tool is not able to recognise if a material is used twice or more in the same element (e.g. two layers of Glass Wool with 20 mm). To overcome this limitation, the user must make sure that each material layer has a different name. Moreover, the tool only uses the CML 2001 environmental impact categories (based on the BIM-LCA/LCC framework). However, the tool can easily be adapted to consider other methods.

More importantly, the BIMEELCA tool is not an LCA tool *per se*, but rather a tool that allows users to insert LCA and cost data in the model and perform a holistic assessment of the project based on those values (i.e. a level 3 LCA tool). Therefore, the users must obtain the environmental impacts of the elements beforehand (e.g. using LCA databases or EPDs).

In the near future, BIMEELCA tool is expected to be shared with external users to further explore the potential of the tool and obtain industry feedback. Furthermore, the source code should be uploaded in development platforms such as GitHub for bug identification and improvement of the software architecture. Presently, there are no plans regarding how this tool will be publicly shared in the future.

After the development of the BIMEELCA tool, based on the previous chapters, a pilot case study will be used to demonstrate the validity of the proposed BIM-LCA/LCC framework and compare it with existing approaches. This process will be described in the next chapter.

Chapter 6 – Validation of the BIM-LCA/LCC framework: A Case Study for Western Europe

The BIM-LCA/LCC framework proposed in this research is validated in this chapter. In this regard, an office building under construction in the Netherlands is used as a pilot case study. The BIMEELCA tool is used to support the validation of the framework. A Streamlined and Complete LCA/LCC analysis are performed and then compared with the results from traditional approaches. At last, the advantages and disadvantages of both approaches are discussed. The work presented in this chapter is based on the framework published in the 'Automation in Construction' journal [232] and on a submitted article entitled 'BIM-based life cycle assessment and life cycle costing of an office building in Western Europe'.

6.1. Methodological approach for the BIM-LCA/LCC analysis of a project

The pre-requisites to conduct a BIM-based LCA/LCC analysis are based on a six-step approach (Figure 45).

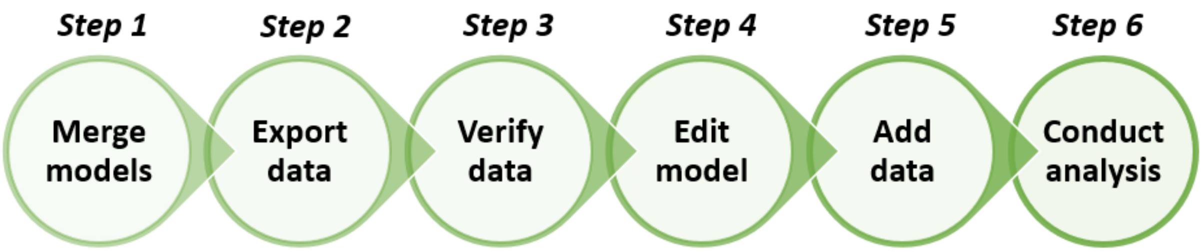


Figure 45 - Six-step approach for the BIM-LCA/LCC analysis

Firstly, all models to be analysed (e.g. Architectural and structural) should be merged together. This should be performed by the BIM Manager (as described in the BIM-LCA/LCC process map). Only by merging the models in a single model, it is possible to holistically compare the impacts of the construction solutions of all different specialties. Secondly, it is necessary to read the information contained in the BIM model. This task can be easily performed if the expert exports the information contained in the model (i.e. bill of quantities). Thirdly, the exported list must be checked in order to identify duplicates, i.e. identify same solutions but with different names. It is possible that the model contains distinct elements from the same family that have the same name or vice versa, i.e. the same elements but with different names. The fourth step addresses these issues, where it is advisable that the expert or designer homogenises the whole project so that the LCA/LCC tools (e.g. BIMEELCA) are able to correctly read the bill of quantities. Furthermore, the expert should also verify if the materials contained in the elements have no inconsistencies, based on the issues referred in the previous chapter (e.g. same material with different thickness have different impacts, thus it is necessary to define two materials). A new bill of quantities should be exported after the expert finishes editing the model, for consistency verification purposes. The fifth step focuses on the addition of environmental, economic, and physical information in the project. In this step, it is advisable that the expert creates a list (in a spreadsheet) that covers all the elements and materials contained in the project and insert in it the required information. Afterwards, the expert can use this list and import the information contained in it into the BIM model. At last, a Streamlined and Complete LCA/LCC analysis (sixth step) are performed based on this information.

Building on this six-step approach, the first steps to be addressed in this chapter are based on the analysis of the information shared by BESIX. This multi-national contractor company located in Belgium, France, and in the Netherlands provided a pilot case study that is used in this research to validate the proposed BIM-LCA/LCC framework. Hence, a Streamlined and Complete LCA/LCC analysis is conducted and described in this chapter, with the assistance of the BIMEELCA tool.

6.2. Environmental and Economic analysis of an office building located in the Netherlands

6.2.1. Description of the Case Study

This office building under construction will be the new headquarters of BESIX in the Netherlands, with a total surface area of 1,900 m² approximately (800 m² for the ground floor and 1,100 m² for the first floor). Steel and concrete are the main materials used in the building. The stairs (apart from the central stair, which is made out of steel with bamboo flooring) are made of reinforced concrete. Foundation beams of reinforced concrete (C30/37 concrete and B500B steel) and pile foundations were designed to support the vertical loads from the floors. Moreover, the floors are made of prefabricated hollow core slabs. A framework of diagonal steel columns and beams supports the first floor and roof.

The collaboration between the company and this research was based on the exchange of all the documents the contractor had regarding this project. These consisted of 1,500 files with an approximate size of 15 GBs, covering BIM models, contracts between suppliers, budget sheets, reports on fire safety and energy and environmental performance, etc. The BIM models (in Revit format) provided by the company contained the (Figure 46): (a) Architectural, (b) Structural, (c) Roof, and (d) MEP design. However, as mentioned in the previous chapters, only the architectural and structural models will be considered in this research. The architectural elements in the Roof model will also be considered but not the photovoltaics system. Furthermore, the BIM models contain some objects with LODs 400 (i.e. objects graphically represented in the model with an accurate size, shape, and detailing), such as the curtain walls, windows, and doors, but most of the objects are lower than LOD 300 (i.e. objects graphically represented in the model with an approximate size and shape but without specific information).

It was observed that the documents did not include any type of environmental information about the elements (e.g. doors, windows) or materials used in the project. Therefore, in the case of incomplete data, generic LCA databases (e.g. IBU, ÖKOBAUDAT, MRPI, Ecoinvent) or specific data (e.g. EPDs, market price) obtained from the supplier's websites were used.

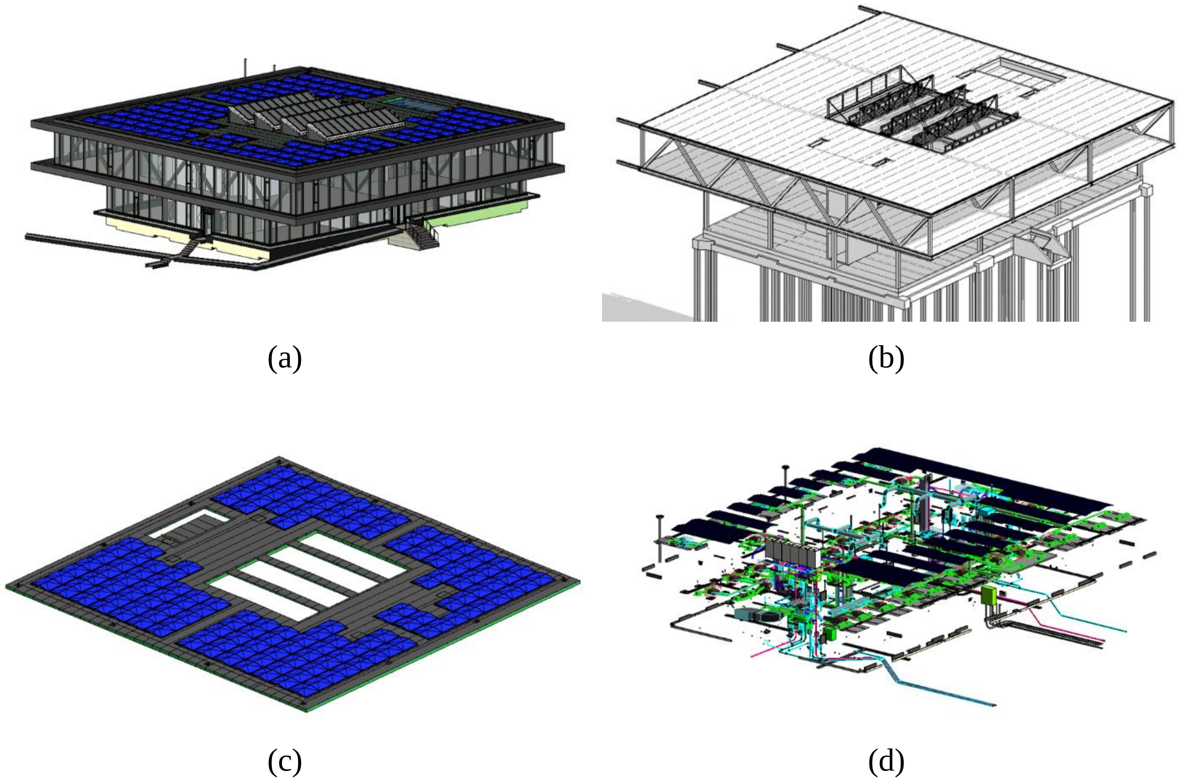
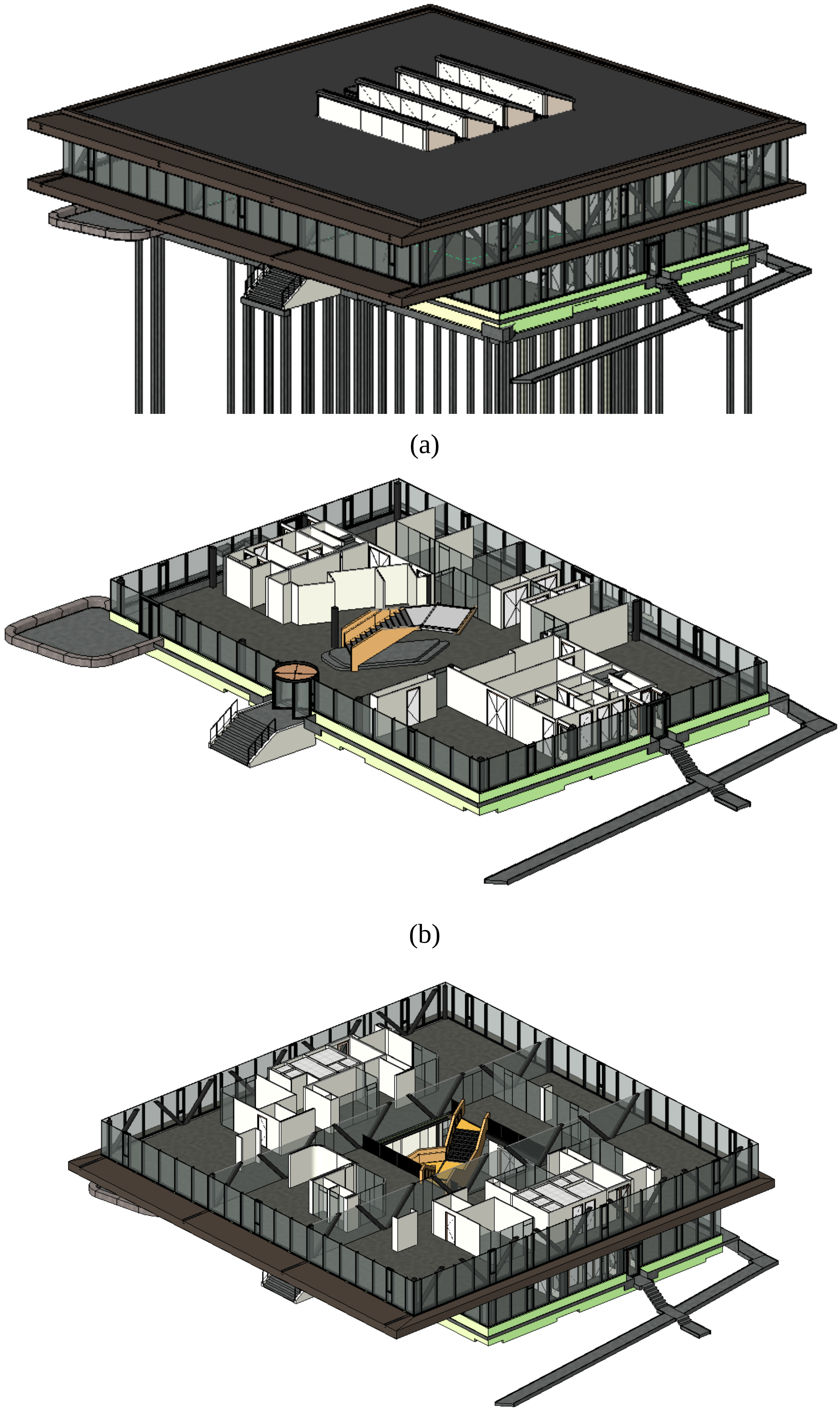


Figure 46 - BIM models shared by the company for the Case Study: (a) Architectural, (b) Structural, (c) Roof, and (d) Mechanical, electrical, and plumbing (MEP)

Focusing on the first steps indicated in the methodological approach, the architectural and structural models were merged in a single model. Afterwards, the bill of quantities of the model was exported and verified by performing a consistency check. While performing this step, the following obstacles were observed: i) the model contained families with unclear naming (or unclear nomenclature), so it was necessary to rename these to the corresponding English names; ii) several objects (e.g. doors, curtain panels) were the same (or close to) but had different names, so it was necessary to check the whole model and modify it in order to group all similar building assemblies within a common solution (e.g. Door 1 and Door 2 into Door); iii) it was necessary to check the materials used in every element and rename it, not only based on their type (e.g. glass wool) but also based on their dimensions (e.g. glass wool 15mm, glass wool 20mm); and iv) the elements and or materials that had different names but very similar solutions (e.g. reinforced concrete for walls or concrete for slabs), were considered as the same element and or material. In addition, the BIM model provided by the architectural office contained several partition wall solutions. However, when compared with the contractor's budget and contracts, some inconsistencies were observed (e.g. solutions that were in the model but not in the budget). In this case, only the solutions that were identified in the contractor's list were used. Therefore, it was necessary to adjust the BIM model, i.e. change the architectural solutions to the ones specified in the contractor's list.

Furthermore, other aspects should be taken into consideration when performing this type of simulations, regardless of the project's information. For example, if IFC models are to be used, one must be aware of the potential loss of information when converting IFC files into Revit format. Some types of elements might lose their category (e.g. roof is no longer recognised as a 'Roof' family) and the materials that are part of it. This will result in a non-identification of these elements for the LCA and LCC analyses, as it is not possible to have access to their original information. The lack of comprehensive detailing for some elements is another limitation of the Revit software. For instance, partition walls contain not only vertical layers (gypsum board and insulation) but also metallic frames. Concerning the last, it is not possible to consider the exact framework geometry when modelling the walls. Therefore, the environmental and economic information of such elements need to be considered in an additional layer. Moreover, the Revit software does not allow users to insert material layers with a thickness smaller than 0.8 mm, which proves to be insufficient for membranes with smaller thicknesses. This will result in a different value between the material's real quantity (provided by the supplier) and the digital quantity (provided by Revit). At last, the quality and representativeness of the LCA and LCC analyses will be as good as the level of detail of the BIM model. If the BIM model does not contain all the final elements and or exact amount of materials, the results will not be representative of the as-built project.

After merging the models and editing the objects in it (fourth step), it was now possible to extract the objects (i.e. elements) and materials' bill of quantities. The merged model is shown in Figure 47 of the (a) office building, (b) ground floor, and (c) first floor. Additionally, the elements and the materials that will contain information (i.e. will be covered in this study) are listed in Table A.2 and Table A.3, respectively. After the information is inserted in 102 elements and 48 materials, the tool automatically assesses the total impacts of the project for the A1-A3 modules. The remaining 30 elements and 28 materials are not covered by the BIM-LCA/LCC framework such as the mechanical, electrical, and plumbing (MEP) elements and furniture objects. Therefore, no information was added to these elements and materials and they were not included in the analysis.



(a)

(b)

(c)

Figure 47 – BIM model of the project in the Netherlands: (a) office building; (b) ground floor; and (c) first floor

At last, the composition of each construction element listed in Table A.2 is detailed in Table A.4, based on the BIM model. As previously explained, for the elements that have a unitary functional unit (i.e. piece – 'pc'), the BIMEELCA tool will only consider the impacts of a single material for the replacement of the whole element. Hence, only a single material of the element will have information (a 'dummy' material), while the others do not.

After merging the models and editing the objects in it, it was then possible to add the required information to perform a Streamlined and Complete LCA/LCC analyses (fifth and sixth step). By following the six-step approach described earlier, a semantically rich BIM model is obtained that can be used in the design stage of the project but also for asset management. In this research, the model will be used for the assessment of the impacts during the design stage of the project (i.e. for the identification of the elements that have higher impacts). However, this model can be later used by the facilities manager of the building in order to perform an updated LCA/LCC analysis if refurbishment works are to be done during the service life of the building.

6.2.2. Streamlined LCA/LCC analysis

For the incorporation of the environmental, economic, and physical information within the elements and materials, the BIMEELCA tool was used. A table with this information was first created in Microsoft Excel and used as data source by the tool.

The environmental information, density and lifespan of the elements and materials are based on specific data, i.e. on the EPDs of products/materials used in the project, or on average and generic data when specific data is not available (i.e. EPDs of similar products manufactured in Western Europe and Ecoinvent database). It is important to highlight that the quality of the obtained results is dependent on the quality of the input data. In this regard, a Pedigree matrix can be used to assess the quality of data sources. For example, this matrix was used to assess the quality of Ecoinvent v3.0 database according to different indicators. Because in this study Ecoinvent database is used when specific data is not available, the geographical representation of the data is very important. On this matter, the Ecoinvent database obtained a 4 out of 5 (5 being the worst) in the geographical correlation indicator, meaning that data from areas with slightly similar production conditions are used in its development [376]. This indicates that it covers only generic data, which is to be expected. Nonetheless, despite this limitation Ecoinvent is one of the most used LCA databases worldwide, being acknowledged as the largest and most comprehensive LCI database on the market [377]. At last, whenever the information about the lifespan of the materials was not available, the results presented in a comprehensive review on the impacts of construction materials were used [378]. The budget sheets provided by the contractor were used as source for the costs of the elements and materials (i.e. acquisition and assembly costs, whenever that information was available). The market price was also used whenever the company's documents were omissive about this information. The environmental and economic impacts of the elements and materials used in the pilot case study are listed in Table A.5 and Table A.6, respectively. These values only cover the impacts due to the manufacturing of the materials (A1-A3 modules). At last, the data listed in these tables were inserted in the BIM model using the BIMEELCA tool, as shown in Figure 48.

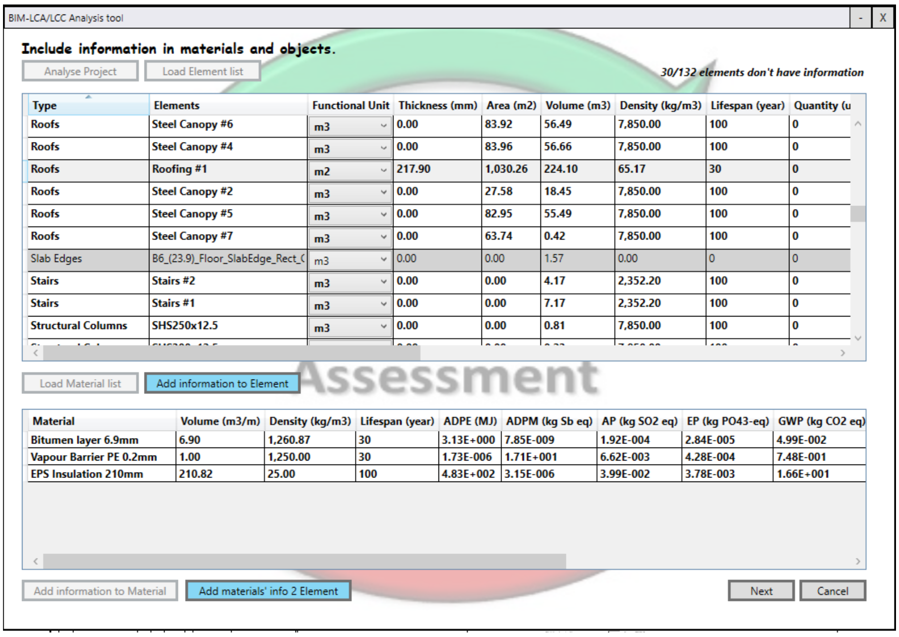


Figure 48 - Addition of the information required for the Streamlined LCA and LCC analysis

After the information is inserted, the tool automatically assesses the total impacts of the project for the A1-A3 modules. The total impacts per element and material are presented to the user (Figure 49), as well as the total impacts of the project (Figure 50 and Table 19).

Table 19 – Streamlined LCA/LCC analysis results

Streamlined	**ADPE (MJ)**	**ADPM (kg Sb eq)**	**AP (kg SO_2 eq)**	**EP (kg PO_4^{3} eq)**	**GWP (kg CO_2 eq)**	**ODP (kg R-11 eq)**	**POCP (kg C_2H_4)**	**PE-NRe (MJ)**	**PE-Re (MJ)**	**Cost (euros)**
	4.93E+7	1.77E+4	2.03E+4	1.18E+4	4.72E+6	2.56E-1	2.37E+3	5.56E+7	4.62E+6	1,777,321
Results per m² (1900 m²)	2.60E+4	9.31E+0	1.07E+1	6.20E+0	2.48E+3	1.35E-4	1.25E+0	2.93E+4	2.43E+3	935

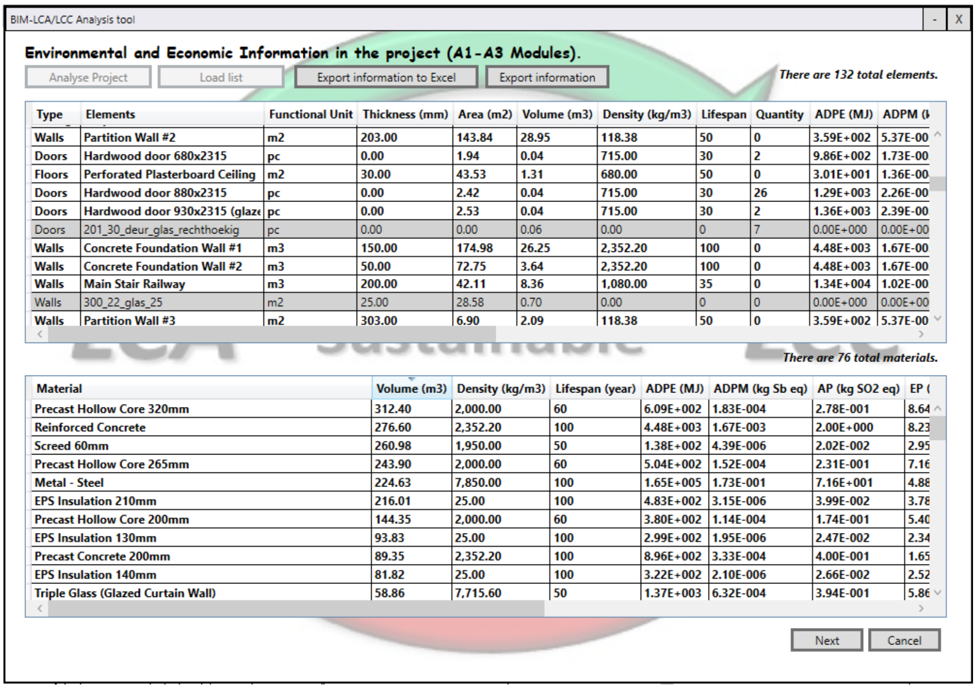


Figure 49 - List of information added to the BIM model

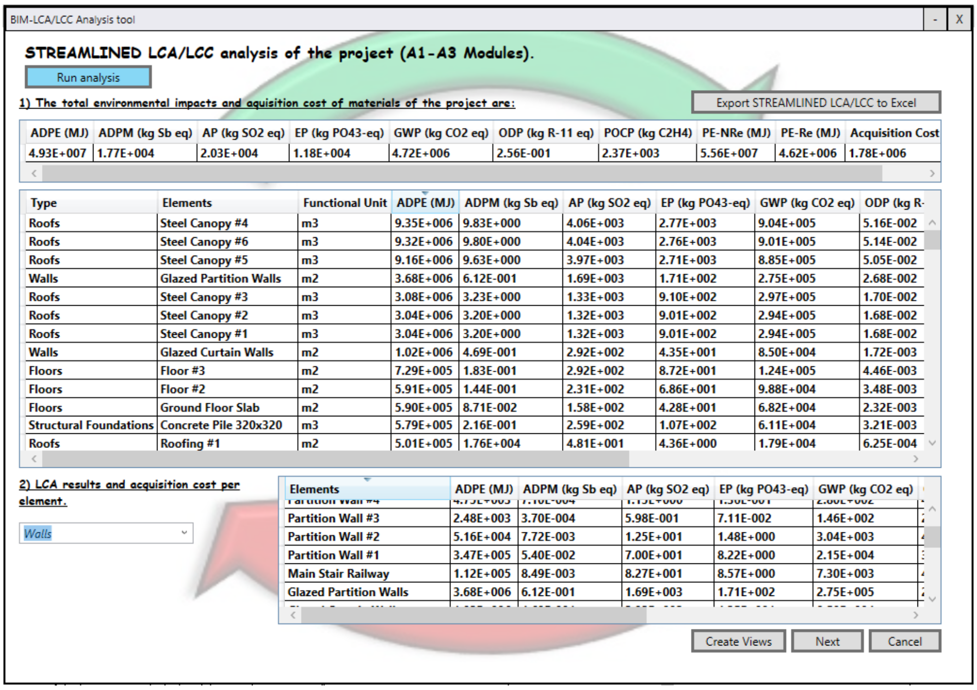


Figure 50 - Streamlined LCA and LCC analysis results

The results of the Streamlined LCA and LCC analyses can be visualized as well. Figure 51 shows the impacts per element in the LCC category. As visualized, most of the elements exhibit a green colour. In contrast, the glazed curtain walls (red), ground floor slab (orange), the roofing and EPS 140mm (purple), and the partition walls (blue) were the elements that had a different colour range, indicating that these were the elements that contributed the most to this category (in absolute terms).

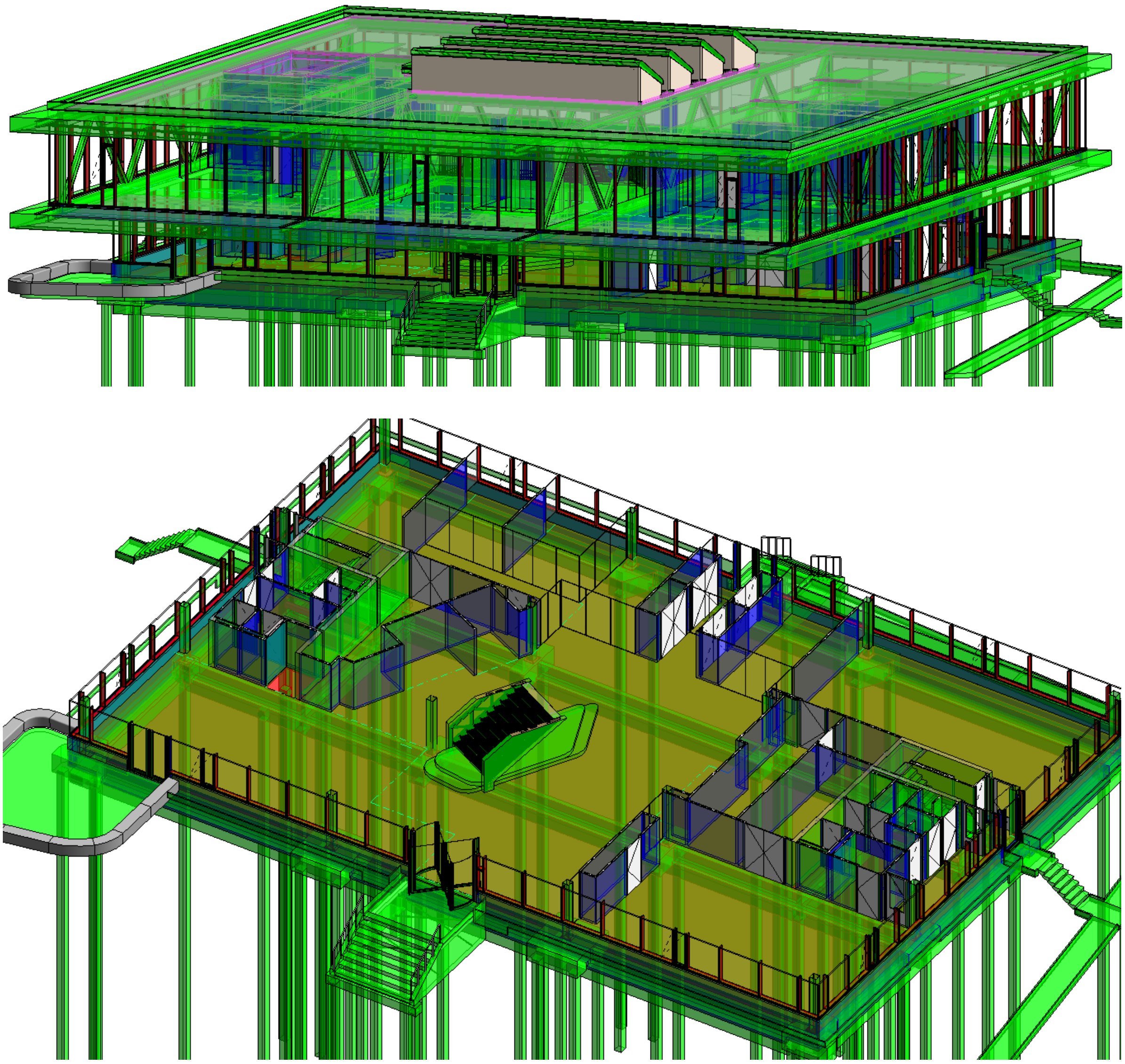


Figure 51 - Streamlined analysis results (LCC)

The global warming potential (GWP) and the cumulative energy demand (non-renewable) sources (PE-NRe) categories are also displayed in Figure 52 and Figure 53, respectively. In these examples, the canopy (i.e. the rectangular steel frame around the ground and first floor's ceilings) is the element that contributes the most to both categories because of the amount of steel (a high energy intensive material) used in its manufacturing.

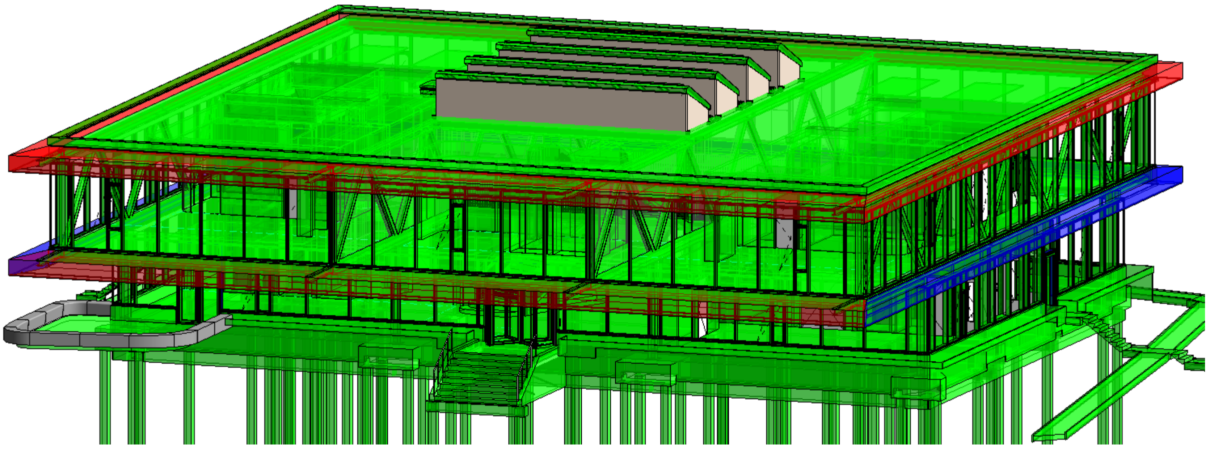


Figure 52 - Streamlined analysis results (GWP)

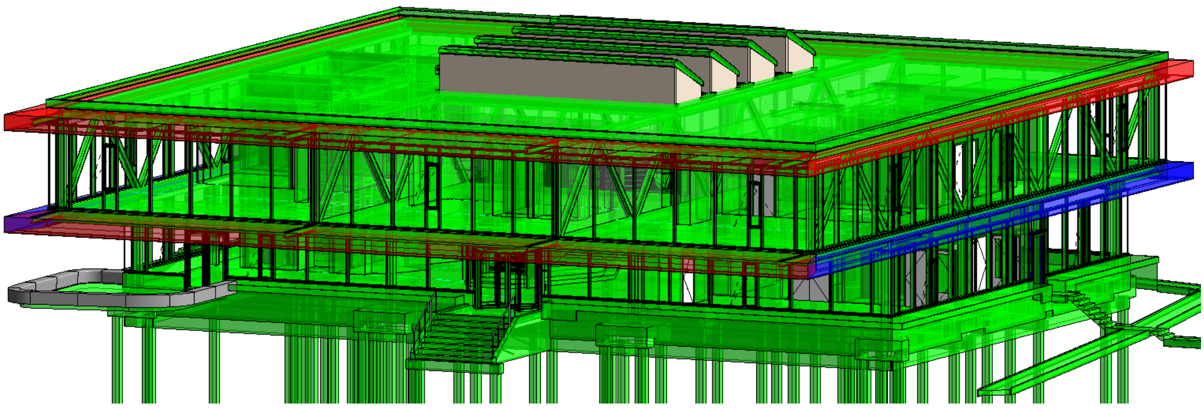


Figure 53 - Streamlined analysis results (PE-NRe)

Although extremely useful for the quick identification of the elements' impacts, this visual indication should be corroborated with the results exported to XLS format. As observed in Table 20, the glazed curtain walls and ground floor slab are the elements with the highest costs, corroborating the results displayed in Figure 51. The results listed in Table 20 validates the visualised results presented in the other categories as well. However, it is noted that these results only consider the A1-A3 modules, i.e. these impacts might not be representative of the full life cycle of the project. This can only be assessed with a Complete LCA/LCC analysis.

Table 20 - Top 10 elements with highest contribution to the Cost, GWP, and PE-NRe of the project (Streamlined analysis)

	Name of element	Cost (euros)	Name of element	GWP (kg CO_2 eq)	Name of element	PE-NRe (MJ)
1	Glazed Curtain Walls	2.8E+05	Steel Canopy #4	9.0E+05	Steel Canopy #4	1.1E+07
2	Ground Floor Slab	2.7E+05	Steel Canopy #6	9.0E+05	Steel Canopy #6	1.1E+07
3	Framing	1.8E+05	Steel Canopy #5	8.8E+05	Steel Canopy #5	1.0E+07
4	Roofing #1	1.2E+05	Steel Canopy #3	3.0E+05	Glazed Partition Walls	4.2E+06
5	EPS 140mm	1.1E+05	Steel Canopy #2	2.9E+05	Steel Canopy #3	3.5E+06

	Name of element	Cost (euros)	Name of element	GWP (kg CO_2 eq)	Name of element	PE-NRe (MJ)
6	Glazed Partition Walls	1.1E+05	Steel Canopy #1	2.9E+05	Steel Canopy #2	3.5E+06
7	Partition Wall #1	8.5E+04	Glazed Partition Walls	2.7E+05	Steel Canopy #1	3.5E+06
8	EPS Wall 140mm	7.2E+04	Framing	1.4E+05	Framing	1.4E+06
9	Foundations	6.0E+04	Floor #3	1.2E+05	Foundations	1.2E+06
10	Columns	5.1E+04	Foundations	1.1E+05	Glazed Curtain Walls	1.2E+06

6.2.3. Complete LCA/LCC analysis

After performing the Streamlined LCA and LCC analysis, the project-specific information was inserted in the BIMEELCA tool (Figure 54). A service life of 50 years (non-residential buildings) and a discount rate of 3% were selected for this case study, based on the recommendation of official Dutch documents and Eurocodes [379-381].

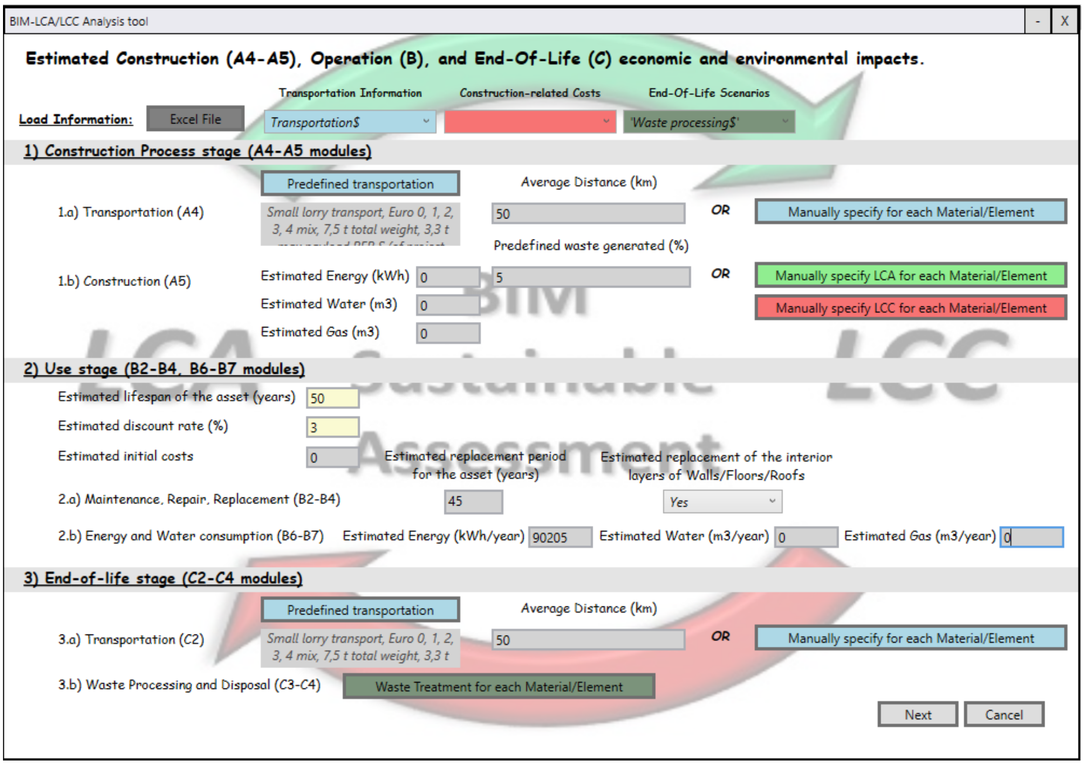


Figure 54 - Project-specific information on the pilot case study

Transportation Impacts (A4 and C2)

As seen in Figure 54, a small lorry (7.5 tons) was selected as the predefined mean of transportation for all the materials used in the project, and a transportation distance of 50 km was used, in accordance with Dutch documents [380]. The impacts of the transportation are listed in Table 21 and are based on ELCD database [278].

Table 21 - Transportation environmental impacts per kg.km, based on the Ecoinvent

Transportation	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
Small Lorry (7.5 tons)	1.91E-03	5.41E-12	6.24E-07	1.44E-07	1.37E-04	2.75E-13	4.55E-08	1.92E-03	2.17E-06	0

Furthermore, no costs were considered for these modules, as the elements and materials acquisition costs already cover their transportation to the construction site (A4). For simplification purposes also, no costs were considered for the transportation (C2) of the construction and demolition waste (CDW) but were considered in the waste treatment scenarios (C3-C4), i.e. companies usually provide a single price for the waste collection and treatment. Moreover, the literature on this subject has shown that these modules have no significant influence in the total life cycle assessment of projects [382].

Construction Impacts (A5)

Regarding the estimated utilities consumption during the construction phase, no data was inserted as no meters were installed at the construction site. Moreover, an average of 5% waste generated (e.g. material loss) during construction was considered as well, similar to other studies [383].

Operation Impacts (B)

The goal of this LCA and LCC study is to assess the impacts of elements and materials used in the project, not the additional costs for the construction (e.g. land acquisition). Therefore, no initial costs were considered in the pilot case study. Moreover, this variable will not influence the sensitivity analysis, as the company responsible to build the project will not change; therefore, the value would remain the same.

Concerning the B2-B4 modules, a period of 45 years was considered for the materials' replacement. As the replacement of materials in the last years of the service life of a building is not expected to occur, a 10% reduction of the total estimated life was considered. Thus, there will only be replacements during the first 45 years of the project (i.e. 10% of 50 years). Moreover, it is considered that the materials will be replaced regardless of their position within the elements.

At last, the company requested an energy performance study of the project to a third-party stakeholder. An electricity consumption of 90,205 kWh per year was estimated, but no information on the water and natural gas consumption was provided. Therefore, these were not considered in this study. The impacts and costs of the utilities were based on the Ecoinvent database, European data and Dutch sources [265, 384-386]. This information is listed in Table 22, and Figure 55 shows how it was added to the analysis.

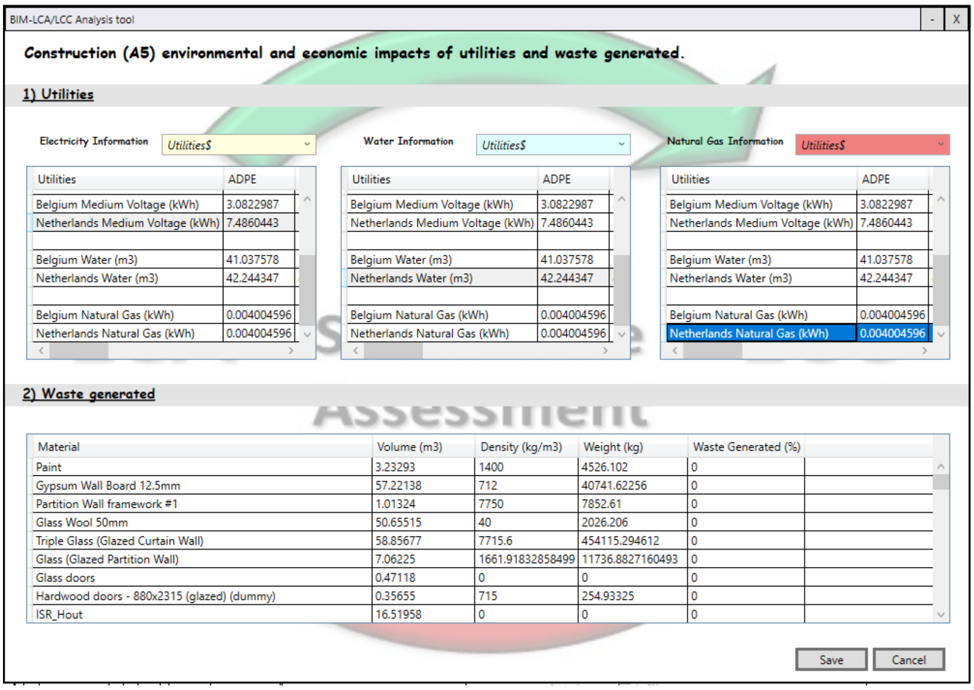


Figure 55 - Selection of the impacts due to the utilities' consumption

Table 22 - Utilities' environmental impacts and cost per kWh (electricity and gas) or m^3 (water), based on the Netherlands energy-mix

Utility	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
Electricity	7.49E+00	1.82E-07	9.52E-04	8.92E-04	5.99E-01	3.15E-08	4.39E-05	9.48E+00	9.18E-01	0.1706
Water	4.22E+01	8.72E-08	9.63E-04	1.36E-04	3.03E-01	2.52E-07	8.02E-05	4.69E+01	3.13E-02	1.1430
Natural Gas	4.00E-03	1.33E-09	1.90E-06	9.75E-07	3.69E-04	3.50E-11	1.16E-07	6.47E-03	7.74E-04	0.0800

End-of-life Impacts (C3-C4)

The impacts due to the waste processing (C3) and disposal (C4) were added to the materials identified in Table A.3, as shown in Figure 56. All the materials that had no information were disregarded in this process (e.g. as discussed before, doors and windows with several materials only contained a single 'dummy' material with information).

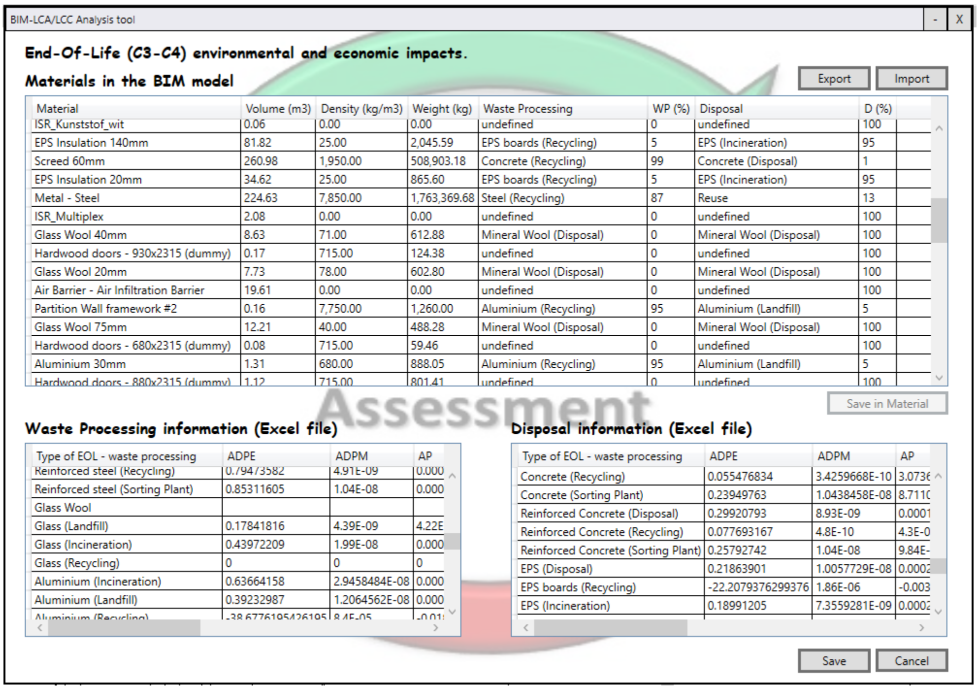


Figure 56 - End-of-life impacts of materials

The types of waste processing and disposal listed in Table 23 were considered in this study, based on Ecoinvent [265]. As observable, some materials do not have waste treatment scenarios, because Ecoinvent database does not contain information about them. Therefore, only materials that had suitable waste treatment scenarios were considered in the calculation of the C3-C4 modules' impacts. Regarding the costs of waste treatment, no information was available online or was provided by companies in the Netherlands. Hence, Belgian cost data was used for the CDW treatment costs [387]. Although Belgium CDW costs might not be representative of the Dutch reality, the lack of national data, the geographic proximity and the similarity in the purchasing power of both countries substantiated this decision [388]. Moreover, the end-of-life costs and impacts do not have a significant contribution to the total life cycle costs and impacts of the project [173, 383, 389]. At last, the percentage assigned to each waste scenario was based on the recycling rates identified in Dutch documents [380].

Building on the assumptions identified above, the environmental impacts and costs due to the waste treatment scenarios that were considered in this study, and the corresponding waste scenarios per material, are listed in Table 23 and in Table 24, respectively.

Table 23 - Environmental impacts and costs of the waste scenarios (per kg)

Waste Scenario	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
Aluminium (Landfill)	3.92E-1	1.21E-8	1.06E-4	3.07E-5	2.18E-2	4.26E-9	4.22E-6	5.27E-1	2.15E-2	0.1815
Aluminium (Recycling)	-1.86E-2	8.40E-5	-1.88E-2	-1.22E-3	-3.20E+0	-7.79E-8	-1.34E-3	-2.97E+1	-3.96E+0	0.0968
Concrete (Disposal)	2.77E-1	8.79E-9	8.89E-5	2.17E-5	1.41E-2	3.10E-9	2.90E-6	3.06E-1	2.26E-3	0.1815
Concrete (Recycling)	5.55E-2	3.43E-10	3.07E-5	7.17E-6	4.01E-3	4.99E-10	7.88E-7	6.02E-2	2.30E-4	0.0151
EPS (Incineration)	1.90E-1	7.36E-9	2.48E-4	5.51E-4	3.15E+0	1.73E-9	9.30E-6	2.30E-1	5.47E-3	0.0968
EPS boards (Recycling)	-1.07E-2	1.86E-6	-3.20E-3	4.81E-4	3.92E-1	1.22E-7	-2.10E-3	-3.41E+1	2.39E+0	0.0968
Glass (Landfill)	1.78E-1	4.39E-9	4.22E-5	1.03E-5	7.19E-3	2.13E-9	1.55E-6	1.97E-1	1.46E-3	0.1815
Gypsum (Disposal)	2.67E-1	8.73E-9	8.34E-5	2.04E-5	1.34E-2	3.01E-9	2.76E-6	2.95E-1	2.22E-3	0.1815
Gypsum (Recycling)	4.56E-2	5.59E-6	2.52E-5	5.89E-6	3.29E-3	4.10E-10	6.47E-7	4.94E-2	1.89E-4	0.0968
Mineral Wool (Disposal)	2.22E-1	8.45E-9	5.82E-5	1.45E-5	1.01E-2	2.60E-9	2.11E-6	2.45E-1	2.03E-3	0.1815
Reinforced Concrete (Disposal)	2.99E-1	8.93E-9	1.01E-4	2.45E-5	1.57E-2	3.30E-9	3.21E-6	3.30E-1	2.35E-3	0.1815
Reinforced Concrete (Recycling)	7.77E-2	4.80E-10	4.30E-5	1.00E-5	5.61E-3	6.98E-10	1.10E-6	8.43E-2	3.22E-4	0.0182
Reuse	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.0968
Rubber (Disposal)	4.94E-1	3.50E-8	3.63E-4	6.14E-4	3.14E+0	5.28E-9	1.56E-5	7.42E-1	4.03E-2	0.2481
Steel (Recycling)	-1.73E+1	1.48E-8	-7.18E-3	-2.40E-3	-1.75E+0	-8.29E-8	-1.29E-3	-1.85E+1	-2.75E-1	0.0968

Table 24 – Waste scenarios per material and respective percentage, based on [380]

Material	Volume (m^3)	Density (kg/m^3)	Weight (kg)	Waste Processing (C3)	Waste Processing (%)	Waste Disposal (C4)	Waste Disposal (%)
Aluminium 30mm	1.31	680.00	888.05	Aluminium (Recycling)	95	Aluminium (Landfill)	5
EPS Insulation 130mm	93.83	25.00	2345.76	EPS boards (Recycling)	5	EPS (Incineration)	95
EPS Insulation 140mm	81.82	25.00	2045.59	EPS boards (Recycling)	5	EPS (Incineration)	95
EPS Insulation 160mm	1.63	25.00	40.79	EPS boards (Recycling)	5	EPS (Incineration)	95
EPS Insulation 20mm	34.62	25.00	865.60	EPS boards (Recycling)	5	EPS (Incineration)	95
EPS Insulation 210mm	216.01	25.00	5400.24	EPS boards (Recycling)	5	EPS (Incineration)	95
Glass (Glazed Partition Wall)	7.06	1661.92	11736.88	Glass (Landfill)	0	Glass (Landfill)	100
Glass Wool 15mm	0.97	54.00	52.36	Mineral Wool (Disposal)	0	Mineral Wool (Disposal)	100
Glass Wool 20mm	7.73	78.00	602.80	Mineral Wool (Disposal)	0	Mineral Wool (Disposal)	100
Glass Wool 40mm	8.63	71.00	612.88	Mineral Wool (Disposal)	0	Mineral Wool (Disposal)	100
Glass Wool 45mm	4.50	40.00	179.80	Mineral Wool (Disposal)	0	Mineral Wool (Disposal)	100
Glass Wool 50mm	50.66	40.00	2026.21	Mineral Wool (Disposal)	0	Mineral Wool (Disposal)	100

Material	Volume (m^3)	Density (kg/m^3)	Weight (kg)	Waste Processing (C3)	Waste Processing (%)	Waste Disposal (C4)	Waste Disposal (%)
Glass Wool 75mm	12.21	40.00	488.28	Mineral Wool (Disposal)	0	Mineral Wool (Disposal)	100
Gypsum Wall Board 12.5mm	57.22	712.00	40741.62	Gypsum (Recycling)	5	Gypsum (Disposal)	95
Metal - Steel	224.63	7850.00	1763369.68	Steel (Recycling)	87	Reuse	13
Partition Wall framework #1	1.01	7750.00	7852.61	Aluminium (Recycling)	95	Aluminium (Landfill)	5
Partition Wall framework #2	0.16	7750.00	1260.00	Aluminium (Recycling)	95	Aluminium (Landfill)	5
Partition Wall framework #3	0.10	7750.00	773.84	Aluminium (Recycling)	95	Aluminium (Landfill)	5
Precast Concrete 200mm	89.35	2352.20	210176.03	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Precast Concrete 250mm	2.57	2352.20	6053.86	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Precast Hollow Core 150mm	4.16	2000.00	8325.00	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Precast Hollow Core 200mm	144.35	2000.00	288708.44	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Precast Hollow Core 265mm	243.90	2000.00	487794.18	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Precast Hollow Core 320mm	312.40	2000.00	624806.94	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Reinforced Concrete	276.60	2352.20	650626.42	Reinforced Concrete (Recycling)	99	Reinforced Concrete (Disposal)	1
Screed 46mm	1.63	1950.00	3176.08	Concrete (Recycling)	99	Concrete (Disposal)	1
Screed 50mm	1.39	1950.00	2705.63	Concrete (Recycling)	99	Concrete (Disposal)	1
Screed 60mm	260.98	1950.00	508903.18	Concrete (Recycling)	99	Concrete (Disposal)	1
Structural Steel	9.61	7850.00	75407.96	Steel (Recycling)	51	Reuse	49
Structural Steel - Hollow Sections	3.42	7850.00	26823.37	Steel (Recycling)	87	Reuse	13
Triple Glass (Glazed Curtain Wall)	58.86	7715.60	454115.29	Glass (Landfill)	0	Glass (Landfill)	100

As observed in Table 23, the reuse scenario has no impacts but has costs. While the costs for collecting and sorting of reusable materials were considered, the environmental emissions were not as no environmental data were found for this process.

Benefits due to the reuse, recovery or recycling of materials (D)

At last, the environmental benefits due to the recycling of materials are obtained based on the difference between the environmental impacts of recycling the material (C3, Table 23 and Table 24) and the environmental impacts of using a new material (A1-A3, Table A.6). For reuse, only the referred benefit is considered. The economic benefits due to the recycling of materials are based on the value payed at the recycling plant to receive the material. For reuse, only the negative equivalent of the acquisition cost of the same material is considered. However, all scenarios that were listed in Table 23 and in Table 24 covered both the C3 impacts as well as benefits due to reuse and recycling (D), based on Ecoinvent database. Thus, to avoid double counting, the impacts of these scenarios will not be considered in the calculation of the module D's impacts.

Results of the Complete BIM-based LCA and LCC analyses

After the project-specific data and estimated waste scenarios were considered, the BIMEELCA tool, which was developed building on the BIM-LCA/LCC framework, automatically calculated the total impacts of the project and per module, as seen in Table 25. Furthermore, the project-specific information and the materials' life cycle information that were highlighted in the IDM/MVD chapter were added to the BIM model as well (Figure 57).

Table 25 – Complete LCA/LCC analysis results

Modules	**ADPE (MJ)**	**ADPM (kg Sb eq)**	**AP (kg SO_2 eq)**	**EP (Kg PO_4^{3-} eq)**	**GWP (kg CO_2 eq)**	**ODP (kg R-11 eq)**	**POCP (kg C_2H_4)**	**PE-NRe (MJ)**	**PE-Re (MJ)**	**Cost (euros)**
A1-A3	4.93E+7	1.77E+4	2.03E+4	1.18E+4	4.72E+6	2.56E-01	2.37E+3	5.56E+7	4.62E+6	1.78E+6
A4	4.97E+5	1.41E-03	1.63E+2	3.74E+1	3.56E+4	7.17E-05	1.19E+1	5.00E+5	5.65E+2	0.00E+0
A5	2.47E+6	8.84E+2	1.02E+3	5.89E+2	2.36E+5	1.28E-02	1.19E+2	2.78E+6	2.31E+5	8.89E+4
B	3.55E+7	3.84E+3	4.95E+3	4.09E+3	2.80E+6	1.45E-01	2.53E+2	4.46E+7	4.37E+6	5.57E+5
C+D	-2.72E+7	9.01E-01	-1.13E+4	-3.77E+3	-2.74E+6	-1.30E-01	-2.06E+3	-2.90E+7	-4.75E+5	7.50E+4
Complete	6.06E+7	2.24E+4	1.51E+4	1.27E+4	5.05E+6	2.84E-01	6.98E+2	7.45E+7	8.75E+6	2.50E+6
Results per m^2 (1900 m^2)	3.19E+4	1.18E+1	7.96E+0	6.70E+0	2.66E+3	1.49E-4	3.68E-1	3.92E+4	4.60E+3	1.31E+3

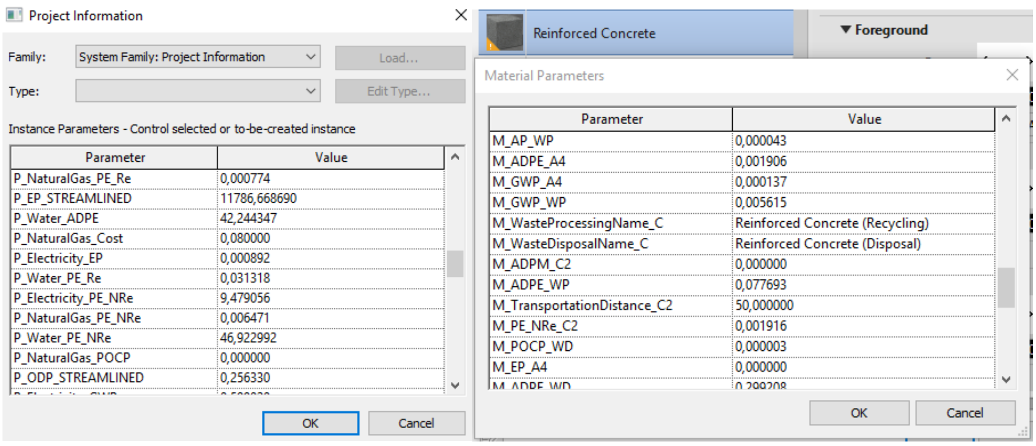


Figure 57 - Addition of project-specific information to the model and life cycle information to the materials

Summing up, the products' manufacturing (A1-A3) and operation phase (B) were the modules that contributed the most to the total environmental impacts and cost of the pilot case study, according to Table 25 and Figure 58.

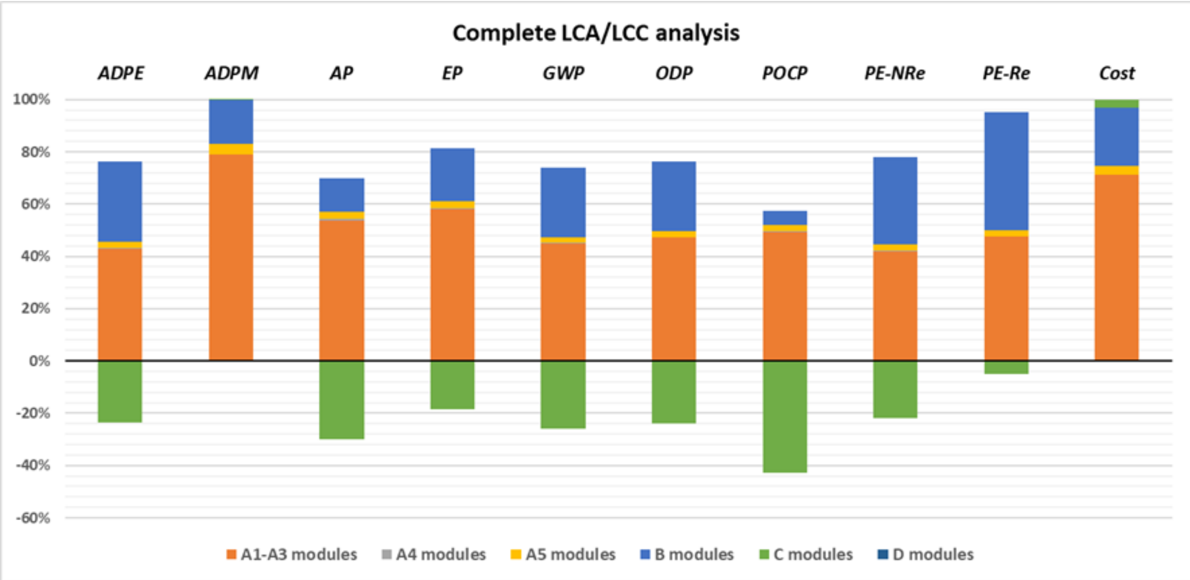


Figure 58 - Relative contribution of the impacts of the pilot case study, per module

As in the Streamlined analysis, the tool can generate three-dimensional views with the impacts for each module. Figure 59, Figure 60, and Figure 61 contain the results for the Complete LCA/LCC analysis for the same categories that were displayed before.

As observable in Figure 59, the glazed curtain walls (in red), the ground floor slab (in orange), the partition walls, roofing, and EPS 140 mm (purple), and the revolving door (blue) were the elements with highest life cycle costs. Although some still remain as the most influential elements in this category, others seem to have a bigger contribution to the total impacts when compared with the Streamlined results (e.g. revolving door and partition walls). This is because the materials used in these elements have a low service life. For example, the revolving doors have a service life of 20 years, meaning that it has to be replaced 2 times during the lifespan of the building (i.e. 45 years for the replacement period). Regarding the partition walls, every 10 years it is necessary to repaint these and replace the constituting materials according to their service life, which greatly contributes to their life cycle costs as well.

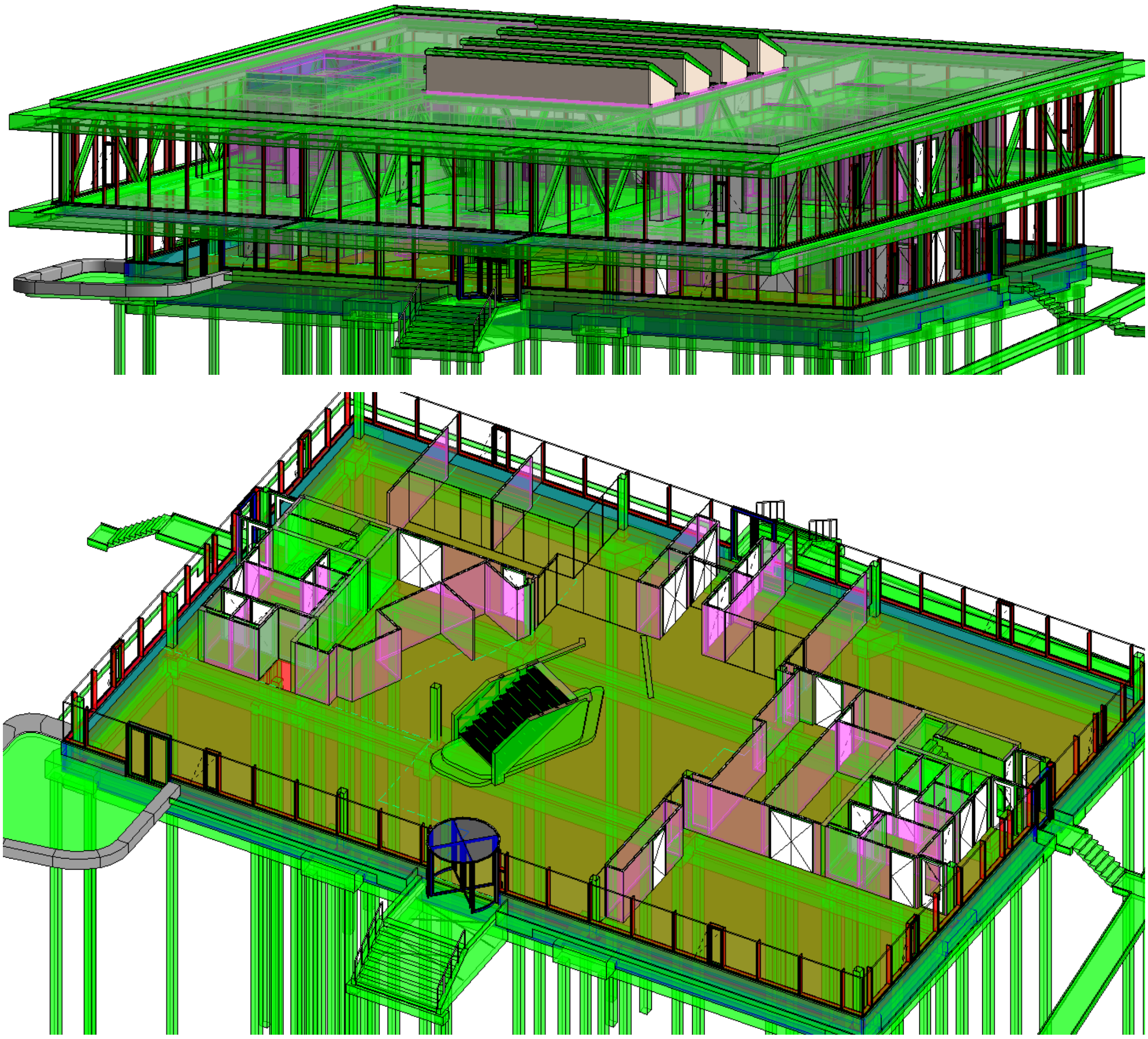


Figure 59 – Complete analysis results (LCC)

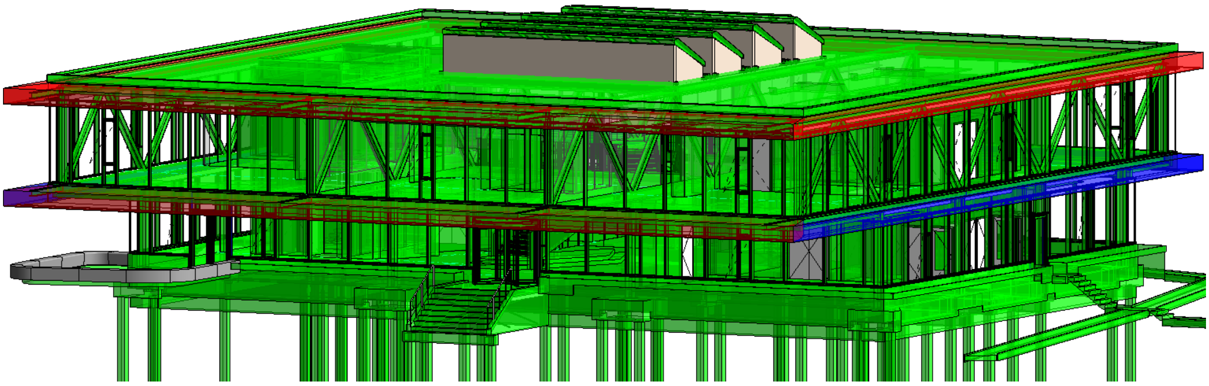


Figure 60 - Complete analysis results (GWP)

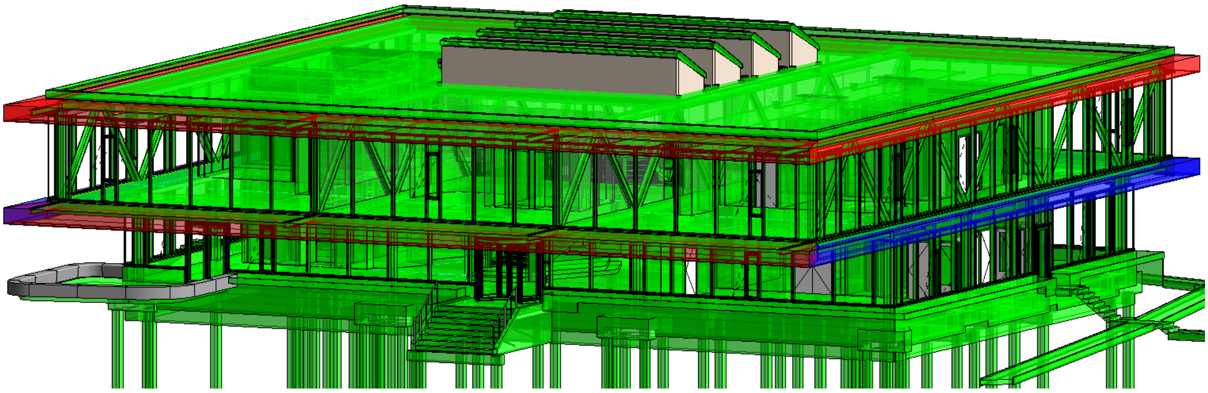


Figure 61 - Complete analysis results (PE-NRe)

On the other hand, almost all elements shown in Figure 60 and Figure 61 seem to be highlighted in green, unlike the steel canopy. Again, because the steel used in the manufacturing of the canopy is a high energy intensive material, these results were already expected. These results are very similar to the ones presented in the Streamlined analysis, suggesting that, for these categories, the impacts of the operation phase (module B) are likely not dominant during the life cycle of the project (if the utilities impacts are disregarded). This can also be observed in Figure 62 and Figure 63, in which the roof elements (such as the steel canopy) are the ones that have higher relative contribution to the total impacts in most categories. As observed, the elements that contribute the most to the environmental and economic impacts of this project, if only a Streamlined analysis is considered, are the roofs, floors, and walls (Figure 62), which is in line with existing literature [226].

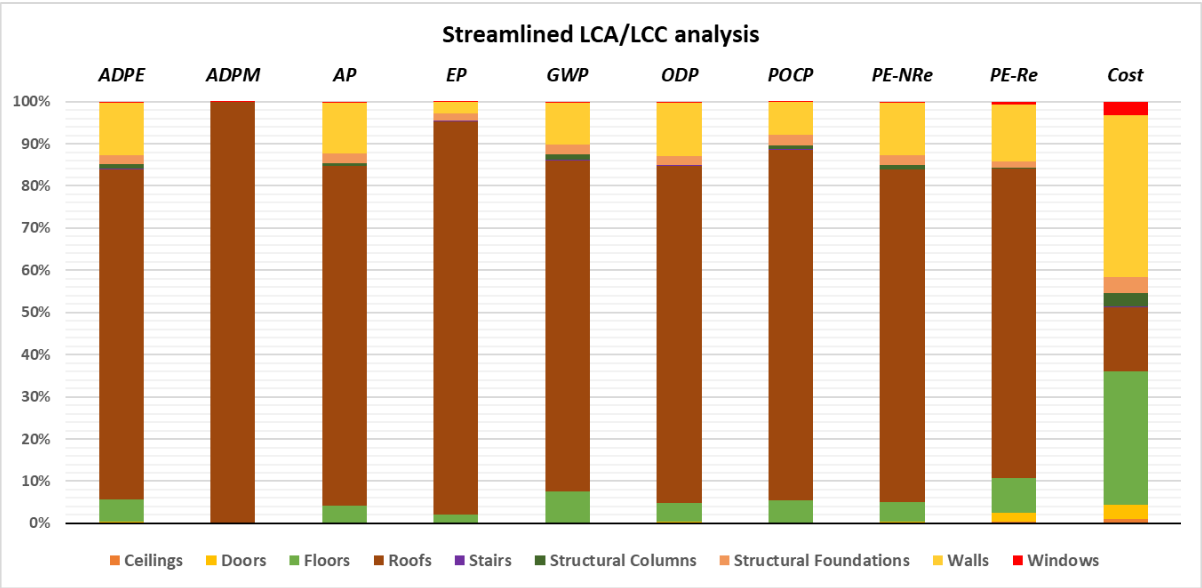


Figure 62 - Relative contribution of the building assemblies in the Streamlined analysis (per category)

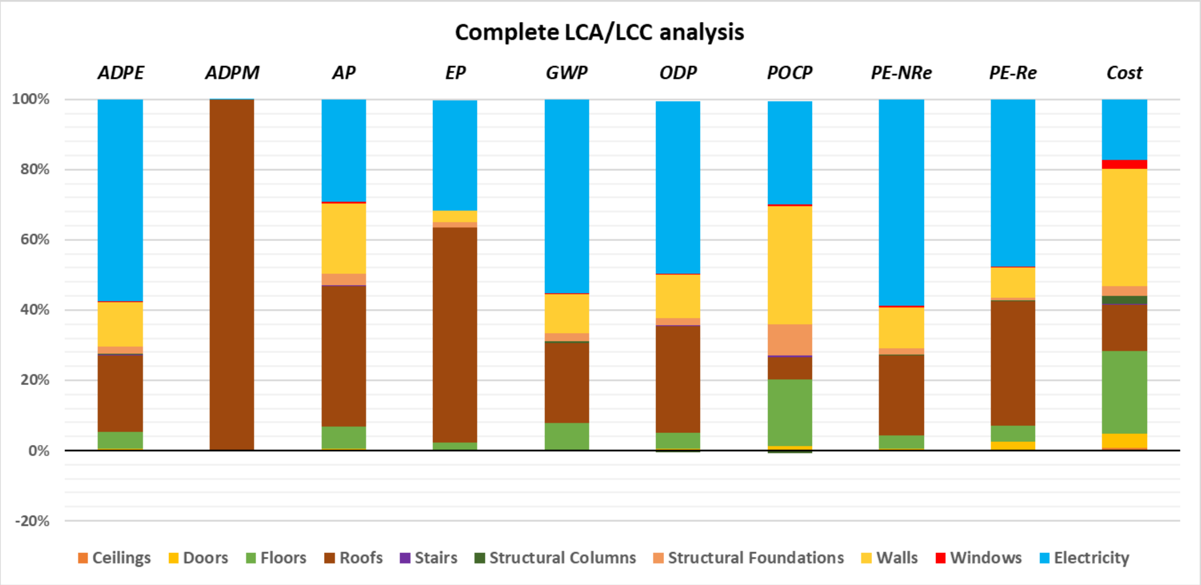


Figure 63 - Relative contribution of the building assemblies and utilities in the Complete analysis (per category)

If a Complete analysis is considered, a slight change in the relative contribution of each element is observed. The operational energy is now the most important contributor to almost all categories. In this regard, the energy-mix specific of each country will play an important role in the environmental impacts of the operational energy and water modules (B6 and B7). The more renewable sources are used in a country (e.g. hydraulic and solar energy), the less impacts the energy and water will have in the total life cycle of a building. In this case, 60% of the GWP impacts are due to electricity, which is in accordance with a study that focused on the LCA of buildings located in Germany [390]. Regarding the building assemblies, although the roof elements remain as the highest contributors on almost all categories, the relative contribution decreased (Figure 63). This is because walls have higher maintenance needs than roofs. For example, the walls and partition walls must be repainted every 10 years (which entails a considerable cost) and the bamboo rails used in the central stairs must be replaced once, a material that has a high environmental impact in the ADPE, AP, and POCP categories because it was manufactured in China and then shipped to the Netherlands.

At last, the results of a sensitivity analysis are displayed in Figure 64, with the discount rate varying from 1% to 10%. As observed, the values due to the A modules did not vary because these costs occurred in the first year. However, in B modules the values varied between -65% and 55%, and in modules C varied between -96% and 167% (when compared with the standard value of 3%). A negative value indicates that the LCC result obtained for a specific discount rate is lower when compared with the predefined discount rate. When the total life cycle costs of the project are considered, the selection of the discount rate can produce a variation between -17% and 17%. Hence, it is very important that the discount rate is carefully selected when LCC analysis are performed, an argument that has been often indicated in the literature.

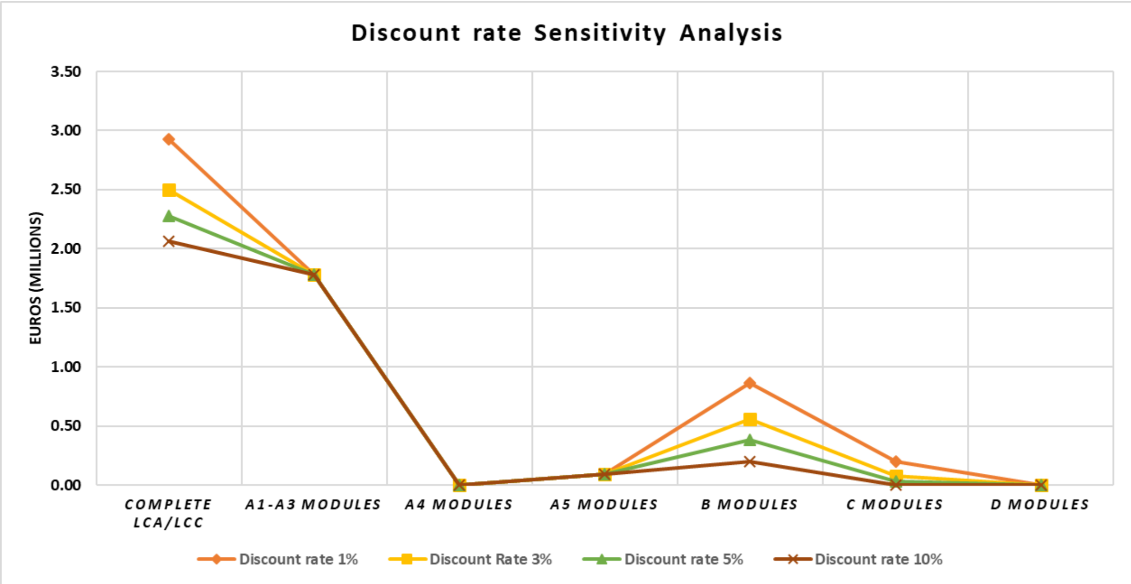


Figure 64 - Sensitivity analysis on the discount rate

6.3. Comparison of the proposed BIM-LCA/LCC framework with the traditional approach

The next step consists in the comparison of the LCA and LCC results using different approaches. As mentioned in the previous chapters, the other two approaches are i) use of a wide range of programs to perform the LCA and LCC analysis and ii) extract the quantity take-off automatically generated by the BIM tool and connect it to LCA databases or cost sheets. As the first approach is not often used nowadays (according to the literature on this subject), the BIM-LCA/LCC approach will be compared with the second approach. For this purpose, two other tools were used, Tally and ATHENA Impact Estimator [247, 248]. Whereas for the last it is necessary to export the bill of quantities to ATHENA software, this procedure is not necessary for Tally. The plug-in Tally is already integrated within a BIM-based environment (Revit); thus, it reads the materials' quantity information straight from the BIM model and connects it with an LCA database (GaBi). Although Tally seems more advantageous than ATHENA software, both approaches have disadvantages and advantages when compared with the BIM-LCA/LCC approach. These will be discussed in the next paragraphs.

6.3.1. Traditional approach based on a BIM-based LCA tool: Tally

The same BIM model was used in this approach for consistency purposes. The first task that is required is the definition of the materials used in each BIM object (i.e. element). The software reads the geometric information contained in the BIM model and connects it with an external LCA database, GaBi, that contains the most used materials in the US and North American (NA) markets [248].

In this regard, all the elements and materials that were identified in Table A.2 and Table A.3 were covered in this analysis as well. Regarding the materials' selection, the most similar materials were used in the study, even though Tally only focuses on the US/NA region. This information is listed in Table 26, based on the report automatically generated by the software.

Table 26 – Type of materials used in the pilot case study (based on Tally's database) and corresponding environmental impacts

Type of materials	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Non-renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)
03 – Concrete	**2.44E+03**	**1.50E+02**	**7.87E+05**	**-5.80E-04**	**4.59E+04**	**7.05E+06**	**5.35E+05**
Cast-in-place concrete; structural concrete; 4001-5000 psi	1.07E+03	5.13E+01	2.90E+05	-4.55E-04	1.69E+04	2.96E+06	2.12E+05
Precast concrete slab	3.73E+01	2.81E+00	1.41E+04	-1.49E-06	8.16E+02	1.15E+05	9.81E+03
Precast concrete structural panel	1.16E+02	8.44E+00	4.25E+04	-9.41E-06	2.47E+03	3.47E+05	2.75E+04
Precast concrete structural panel; hollow core	1.21E+03	8.71E+01	4.39E+05	-1.13E-04	2.56E+04	3.61E+06	2.85E+05
Stair; cast-in-place concrete	3.09E+00	2.03E-01	1.05E+03	-5.50E-07	6.11E+01	9.04E+03	6.98E+02
05 – Metals	**2.35E+04**	**1.01E+03**	**3.96E+06**	**1.09E-01**	**3.40E+05**	**5.22E+07**	**2.99E+06**
Aluminium; formed	4.72E+01	1.13E+00	1.08E+04	1.34E-06	4.70E+02	1.42E+05	3.36E+04
Steel; angle	1.63E+01	4.29E-01	3.72E+03	-1.57E-06	9.46E+01	4.87E+04	1.88E+03
Steel; deck	2.28E+04	9.86E+02	3.83E+06	1.08E-01	3.35E+05	5.06E+07	2.89E+06
Steel; HE section	8.37E+00	2.25E-01	1.67E+03	-7.98E-07	4.57E+01	2.14E+04	5.48E+02
Steel; HSS section	1.89E+02	9.31E+00	3.02E+04	1.10E-03	2.61E+03	4.66E+05	4.25E+04
Steel; IPE section	3.90E+02	9.11E+00	7.73E+04	-3.89E-05	2.06E+03	9.62E+05	2.28E+04
Steel; plate	1.31E+00	5.06E-02	4.92E+02	-1.77E-07	1.52E+01	6.04E+03	1.87E+02
07 - Thermal and Moisture Protection	**1.37E+02**	**1.02E+01**	**5.51E+04**	**-3.53E-07**	**2.78E+03**	**1.81E+06**	**2.88E+04**
APP modified bitumen; sheet	6.05E+01	3.25E+00	1.86E+04	1.28E-06	1.01E+03	7.90E+05	1.57E+04
Expanded polystyrene (EPS); board	6.70E+01	6.36E+00	3.39E+04	1.38E-06	1.67E+03	9.68E+05	9.63E+03
Glass wool; batt or blown	4.22E+00	3.14E-01	8.76E+02	1.85E-07	3.33E+01	1.25E+04	1.98E+03
Polyethelene sheet vapor barrier (HDPE)	4.92E+00	2.83E-01	1.74E+03	-3.20E-06	7.10E+01	3.69E+04	1.54E+03
08 - Openings and Glazing	**1.02E+03**	**5.50E+01**	**1.57E+05**	**7.08E-04**	**9.65E+03**	**2.26E+06**	**6.65E+04**
Curtainwall System (including glazing)	8.15E+02	3.04E+01	1.27E+05	7.20E-05	7.32E+03	1.87E+06	-1.52E+04

Type of materials	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Non-renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)
Door; exterior; glass	9.94E+00	1.83E+00	1.91E+03	8.12E-05	1.13E+02	2.70E+04	2.37E+03
Door; interior; wood; hollow core; flush	3.63E+01	1.26E+01	6.35E+03	4.19E-04	3.18E+02	7.29E+04	4.73E+04
Door; interior; wood; stile and rail	1.17E+01	3.67E+00	2.12E+03	1.36E-04	1.15E+02	2.65E+04	1.02E+04
Glazing; double pane IGU	1.32E+02	5.60E+00	1.68E+04	6.92E-09	1.63E+03	2.30E+05	1.23E+04
Window frame; aluminium	1.65E+01	8.39E-01	2.83E+03	3.34E-07	1.63E+02	3.51E+04	9.53E+03
09 - Finishes	**6.56E+02**	**5.41E+01**	**1.96E+05**	**5.03E-05**	**1.09E+04**	**2.36E+06**	**4.78E+05**
Acoustic ceiling system; mineral fiber board	3.46E+01	1.92E+00	6.15E+03	4.59E-05	3.33E+02	9.54E+04	1.04E+04
Flooring; solid wood plank	2.39E+02	2.83E+01	3.28E+04	4.49E-09	2.70E+03	3.42E+05	3.00E+05
Flooring; underlayment; cementitious	2.49E+02	1.79E+01	1.08E+05	2.50E-08	5.61E+03	1.10E+06	8.98E+04
Metal ceiling system; aluminium	4.74E+01	1.16E+00	1.08E+04	4.35E-06	4.75E+02	1.44E+05	3.29E+04
Paint	4.66E+01	2.43E+00	1.22E+04	6.75E-09	8.88E+02	2.70E+05	2.88E+04
Wall board; gypsum	3.93E+01	2.43E+00	2.63E+04	3.12E-09	8.90E+02	4.12E+05	1.65E+04
Operational Electricity	**3.17E+03**	**4.83E+02**	**2.48E+06**	**1.89E-06**	**6.04E+04**	**3.29E+07**	**7.80E+06**
Operational Electricity	3.17E+03	4.83E+02	2.48E+06	1.89E-06	6.04E+04	3.29E+07	7.80E+06
Operational Heating	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
Operational Heating	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Grand Total	***3.09E+04***	***1.76E+03***	***7.63E+06***	***1.09E-01***	***4.70E+05***	***9.86E+07***	***1.19E+07***

After selecting the corresponding materials, the software Tally allows the users to indicate some project-specific information, as shown in Figure 65. In this regard, the same means of transport (truck) and distance (50 km) were used in module A4, and the same electricity consumption was used in module B (90,205 kWh/year, with the energy-mix of the Netherlands).

In the end, a report is automatically generated by Tally, in XLS and PDF format. Similar to the materials' database, the only environmental impact assessment method available in the tool is US-oriented. The software uses the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (Tracy 2.1) method. Therefore, all the results displayed in the report are based on this method.

Figure 66 displays the results per life cycle stage for some impact categories and, in particular, for the global warming potential. As observed, the manufacturing stage (A1-A3 modules) contributes two times more than the operational stage (B modules) to the total GWP of the project. This is in accordance with the results of the Complete LCA/LCC analysis obtained by the BIMEELCA tool and based on the BIM-LCA/LCC framework. However, the results due to the end-of-life (C modules) and benefits (D) are very distinct.

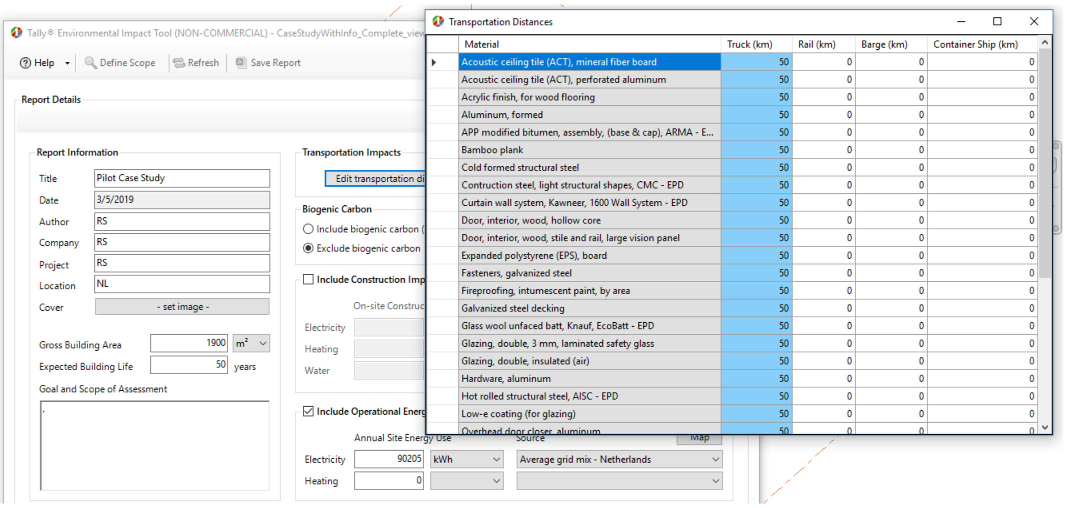


Figure 65 - Definition of project-specific information in Tally's GUI

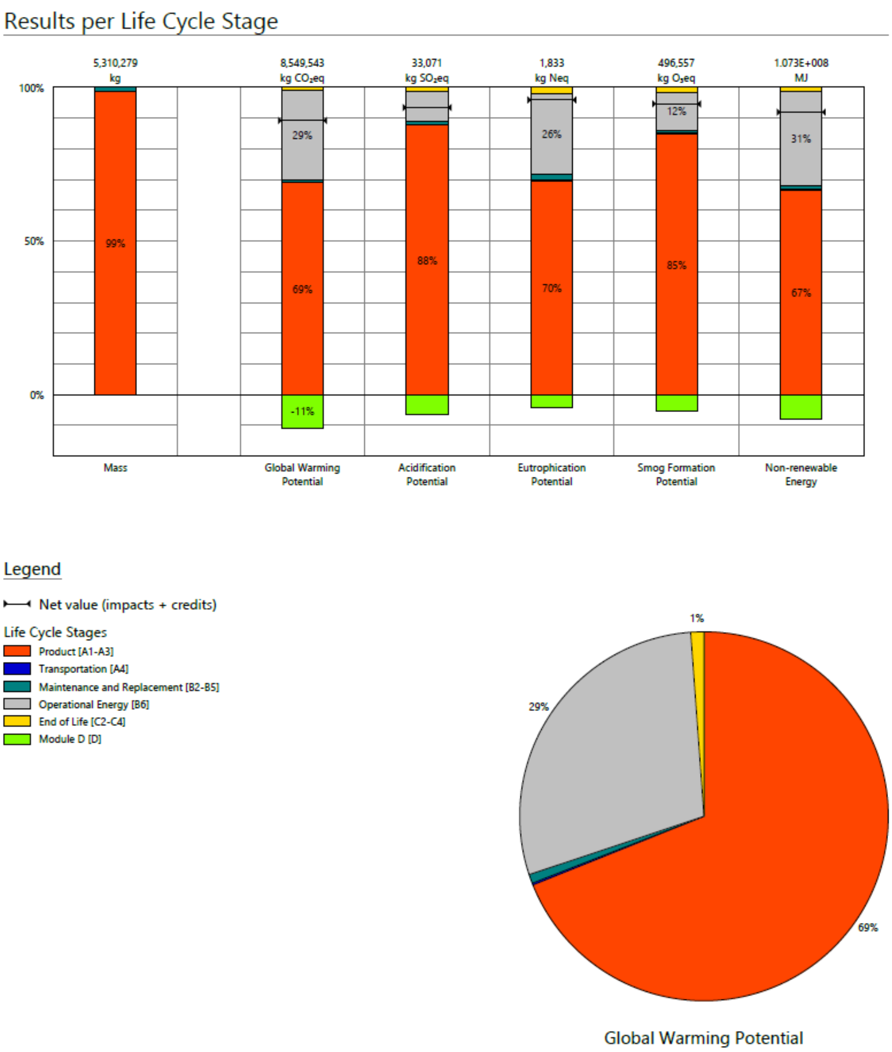


Figure 66 - Results of the LCA study per life cycle stage (Tally)

Furthermore, the impacts per type of material are shown in Figure 67. Once more, the results for the GWP category are in accordance with the results obtained in the BIM-LCA/LCC approach, i.e. the steel structure elements are the ones that contribute the most to the total impact of the project. The same can be observed in the non-renewable energy category (PE-NRe).

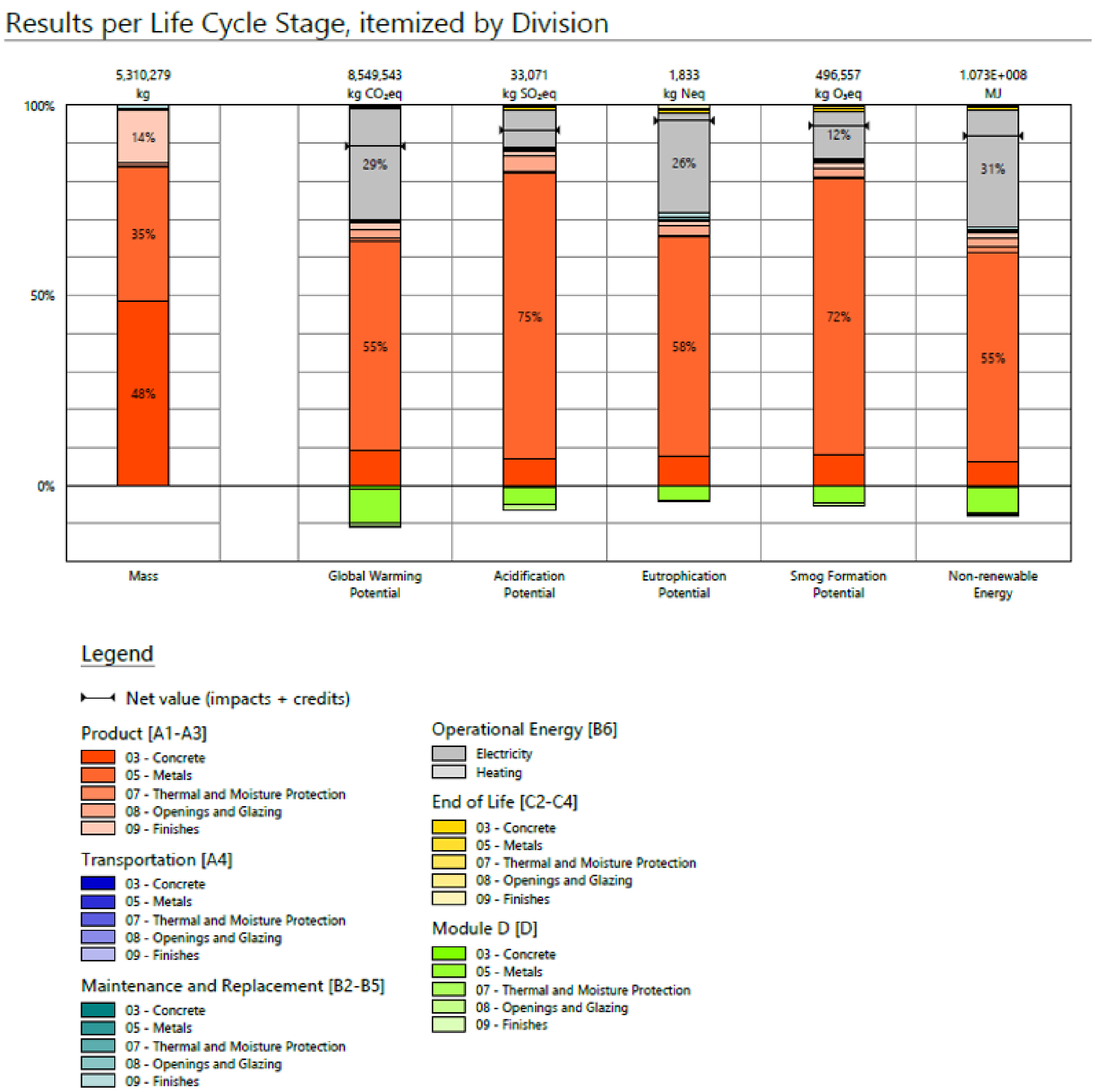


Figure 67 – Results of the LCA study per type of material (Tally)

At last, the LCA results of the pilot case study, based on the information indicated before, are listed in Table 27. However, as observed, the Tally software does not perform an LCC analysis of the project. Therefore, only the impact categories indicated in Table 27 can be compared with the approach proposed in this research.

Table 27 - Results of the LCA analysis of the pilot case study (Tally)

Modules	Acidification Potential ($kgSO_2eq$)	Eutrophication Potential (kgNeq)	Global Warming Potential ($kgCO_2eq$)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO_3eq)	Non-renewable Energy Demand (MJ)	Renewable Energy Demand (MJ)
Product (A1-A3)	2.90E+04	1.28E+03	5.89E+06	1.03E-01	4.21E+05	7.14E+07	3.72E+06
Transportation (A4)	6.62E+01	5.39E+00	1.42E+04	4.89E-10	2.19E+03	2.03E+05	5.02E+03
Maintenance and Replacement (B2-B5)	3.27E+02	3.18E+01	6.76E+04	3.16E-04	4.38E+03	1.24E+06	2.50E+05
Operational Energy (B6)	3.17E+03	4.83E+02	2.48E+06	1.89E-06	6.04E+04	3.29E+07	7.80E+06
End of Life (C2-C4)	4.80E+02	3.80E+01	9.86E+04	1.69E-08	8.58E+03	1.47E+06	1.04E+05
Module D	-2.18E+03	-7.50E+01	-9.22E+05	5.95E-03	-2.69E+04	-8.66E+06	2.00E+04
Grand Total	***3.09E+04***	***1.76E+03***	***7.63E+06***	***1.09E-01***	***4.70E+05***	***9.86E+07***	***1.19E+07***

6.3.2. Traditional approach based on an External LCA analysis: ATHENA Impact Estimator

Unlike in the BIM-LCA/LCC approach and Tally, the ATHENA Impact Estimator is not integrated within a BIM-based environment. Hence, it is necessary to export the bill of materials generated by a BIM-based software to the ATHENA software (Figure 68). In this regard, the materials' quantity listed in the Table A.3 will be exported to this software.

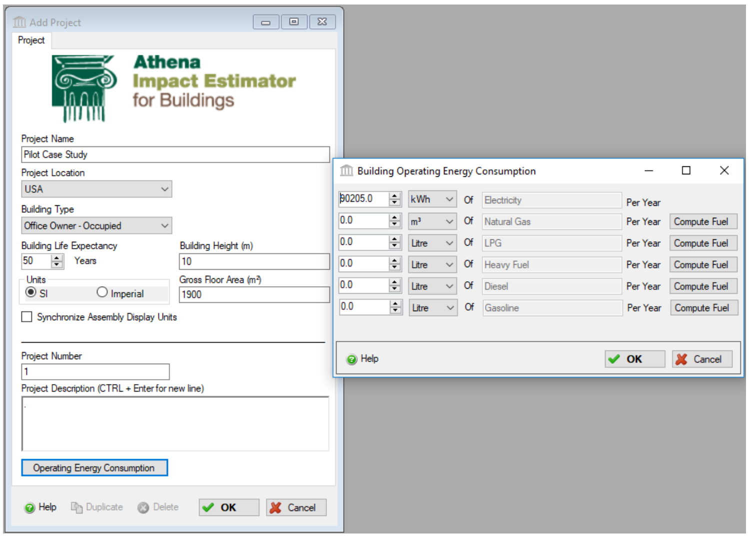


Figure 68 - Complete LCA analysis of the pilot case study (initial window of ATHENA)

After this information is successfully loaded into the program, it is necessary to connect the listed materials with the materials available in the ATHENA's database (Figure 69 and Table 28), similar to Tally's plug-in. Another aspect that these two tools share is the geographical representation of the database, i.e. the materials available in both tools are limited to the NA market, as well as the impact assessment method (Tracy 2.1).

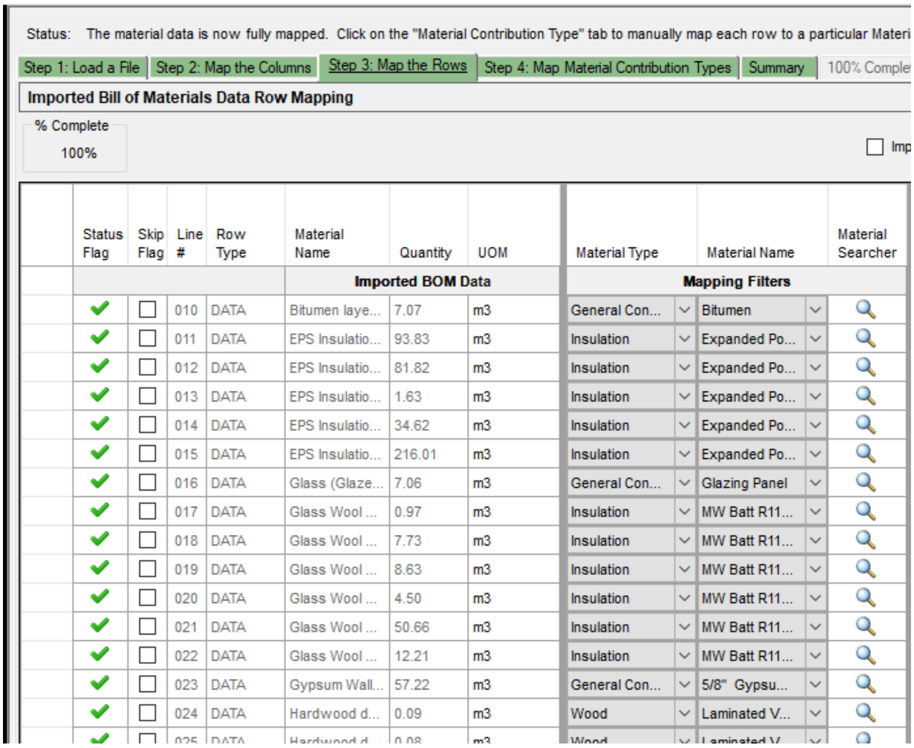


Figure 69 - Connection of the imported quantity take-off with ATHENA's database

Table 28 - Materials used in the pilot case study (ATHENA)

Material	Unit	Total Quantity
5/8" Gypsum Fibre Gypsum Board	m^2	566.48
Aluminum Cold Rolled Sheet	Tonnes	0.90
Aluminum Extrusion	Tonnes	0.87
Bitumen	Tonnes	8.91
Expanded Polystyrene	m^2 (25 mm)	280.82
Galvanized Decking	Tonnes	1,780.98
Glazing Panel	Tonnes	706.24
Hollow Structural Steel	Tonnes	27.12
Laminated Veneer Lumber	m^3	11.39
MBS Primary Frames	Tonnes	76.19
Mortar	m^3	303.60
MW Batt R11-15	m^2 (25 mm)	88.94
Polyethylene Filter Fabric	Tonnes	2.58
Precast Concrete	m^3	1,073.33
Solvent Based Alkyd Paint	L	46,124.40

At last, the ATHENA software calculates the environmental impacts of the project based on the selected materials. The total impacts are listed in Table 29. However, an LCC analysis was not performed by ATHENA, as this tool only focuses on the environmental dimension of buildings' performance, similar to Tally.

Table 29 – Results of the LCA analysis of the pilot case study (ATHENA)

LCA Measures	Unit	Product (A1 to A3)	Construction process (A4 & A5)	Use (B2, B4 & B6)	End of life (C1 to C4)	Beyond building life (D)	Total
Global Warming Potential	kg CO_2 eq	5.97E+06	3.11E+05	3.57E+06	1.61E+05	-1.51E+06	8.50E+06
Acidification Potential	kg SO_2 eq	3.23E+04	3.14E+03	2.88E+04	1.54E+03	-3.47E+03	6.23E+04
HH Particulate	kg $PM_{2.5}$ eq	2.54E+04	2.12E+02	1.28E+04	2.82E+02	-1.51E+03	3.72E+04
Eutrophication Potential	kg N eq	1.80E+03	2.06E+02	3.63E+02	7.22E+01	-1.77E+02	2.27E+03
Ozone Depletion Potential	kg CFC-11 eq	1.54E-02	3.63E-04	6.96E-04	4.65E-06	-2.39E-07	1.65E-02
Smog Potential	kg O_3 eq	4.88E+05	9.68E+04	1.58E+05	3.72E+04	-3.50E+04	7.45E+05
Total Primary Energy	MJ	7.59E+07	4.48E+06	5.21E+07	2.41E+06	-6.94E+06	1.28E+08
Non-Renewable Energy	MJ	7.54E+07	4.47E+06	4.98E+07	2.36E+06	-6.94E+06	1.25E+08
Fossil Fuel Consumption	MJ	6.16E+07	4.33E+06	4.31E+07	2.24E+06	-1.39E+07	9.74E+07

6.3.3. Comparison of the results and approaches

After conducting the LCA and LCC analyses based on the proposed BIM-LCA/LCC framework and two other LCA analyses based on other approaches (using Tally and ATHENA tools), a comparison of the results is made. In this regard, it is important to highlight that, even though the approaches share the same goal, they all have distinct features. The framework proposed in this research focuses on an environmental and economic assessment of a project, based on the CML 2001 method. Furthermore, this approach is region-free, i.e. does not depend on specific databases. In contrast, the BIM-based LCA analysis (Tally) and external LCA analysis (ATHENA) focus on the North American market and the addition of new materials is not possible. Consequently, the materials available in their databases are only representative of that market. Moreover, both tools use the Tracy 2.1 method. Hence, the results obtained by these tools can more easily be compared, unlike in the case of the BIMEELCA tool.

Therefore, the results obtained by these approaches can only be compared in the categories that were developed based on the same scientific model. Although CML and Tracy 2.1 being distinct methods, some of the categories that are covered by these methods follow the same model. In both methods, the global warming potential (GWP) category is based on the characterisation model of the Intergovernmental Panel on Climate Change (IPCC), while the ozone depletion potential (ODP) is based on the World Meteorological Organization (WMO). Regarding the acidification potential (AP), the Tracy 2.1 is based on a hydrogen ion

(H+) whereas in CML 2001 the H+ is converted into SO_2eq. Nonetheless, both Tally and ATHENA display the results of this category in SO_2eq. In the case of Non-renewable Energy (PE-NRe) and Renewable Energy (PE-Re), both methods share the same units. However, for the Eutrophication Potential (EP), the unit used in Tracy 2.1 is the Nitrogen (kg N eq) while in CML the unit is phosphate (kg PO_4^{3-}eq). Nonetheless, it is argued in the literature that it is possible to convert one unit to another, with 1 kg of N being equal to 0.42 kg of PO_4^{3-}eq [288]. Unfortunately, the remaining categories cannot be compared. For example, the Smog Formation (Tracy 2.1) was specifically developed for the US context, based on the Maximum Incremental Reactivity (MIR) method, while CML uses the Photochemical Ozone Creation Potential (POCP) method, with both methods having different units. Additionally, the Fossil Fuel Consumption indicator (a subtotal of the Primary Energy Consumption according to Tracy 2.1) includes all the energy used in the manufacturing stage of the products (e.g. transform or transport the raw materials), an indicator that does not have direct correspondence in the CML method. Thus, based on these observations, it is argued that the use of Tally and ATHENA tools is not advisable for projects located in Europe or any other region apart from North America. Moreover, the LCC indicator was not compared, as both Tally and ATHENA do not cover the economic impacts of projects.

Consequently, the categories that were compared were the AP, EP, GWP, ODP, PE-NRe and PE-Re. The pilot case study's compared impacts are listed in Table 30, relative to the results obtained by the BIMEELCA tool (based on BIM-LCA/LCC framework).

Table 30 - Comparison of LCA total impacts results (relative to the BIMEELCA tool)

Approach	**BIM-based LCA analysis**	**External LCA analysis**
Tool used	**Tally**	**ATHENA**
AP (kg SO_2 eq)	***104%***	***312%***
EP (Kg PO_4^{3-}eq)	***-94%***	***-93%***
GWP (kg CO_2 eq)	***51%***	***68%***
ODP (kg R-11 eq)	***-62%***	***-94%***
PE-NRe (MJ)	***32%***	***68%***
PE-Re (MJ)	***36%***	**---**

The lesser the difference, the closer the results are to the ones obtained by the BIMEELCA tool (e.g. 0% means that the results are the same while +100% means that the results are twice the values obtained by the BIMEELCA tool). It can be observed that the differences between impacts are very distinct for each category, ranging from -94% to 312%.

It is also visualised that the results of the BIM-based approach (Tally) are closer to the results of the BIM-LCA/LCC framework. Notwithstanding, there is a stronger similarity between Tally and ATHENA's results, when compared to the BIMEELCA, as both these tools use NA products. Nevertheless, upon closer examination, it is observed that the impacts in the production stage (A1-A3 modules) are similar in most of the compared categories (Table 31).

Table 31 - Comparison of LCA modules results (relative to the BIMEELCA tool)

Approach	**BIM-based LCA analysis**	**External LCA analysis**
Tool used	**Tally**	**ATHENA**
	A1-A3 modules	
AP (kg SO_2 eq)	43%	59%
EP (Kg PO_4^{3-}eq)	-95%	-94%
GWP (kg CO_2 eq)	25%	26%
ODP (kg R-11 eq)	-60%	-94%
PE-NRe (MJ)	28%	36%
PE-Re (MJ)	-19%	---
	A4-A5 modules	
AP (kg SO_2 eq)	-94%	166%
EP (Kg PO_4^{3-}eq)	-100%	-86%
GWP (kg CO_2 eq)	-95%	14%
ODP (kg R-11 eq)	-100%	-97%
PE-NRe (MJ)	-94%	36%
PE-Re (MJ)	-98%	---
	B modules	
AP (kg SO_2 eq)	-29%	481%
EP (Kg PO_4^{3-}eq)	-95%	-96%
GWP (kg CO_2 eq)	-9%	28%
ODP (kg R-11 eq)	-100%	-100%
PE-NRe (MJ)	-23%	12%
PE-Re (MJ)	84%	---
	C and D modules	
AP (kg SO_2 eq)	-85%	-83%
EP (Kg PO_4^{3-}eq)	-100%	-99%
GWP (kg CO_2 eq)	-70%	-51%
ODP (kg R-11 eq)	-105%	-100%
PE-NRe (MJ)	-75%	-84%
PE-Re (MJ)	-126%	---

If the EP and ODP categories are disregarded, the remaining categories are relatively similar despite the use of distinct LCA data. For example, the steel elements (one of the highest contributors to the total impacts of the case study) have a difference of 7%, 20%, and 13% in the GWP, PE-NRe, and PE-Re categories, respectively, when compared with Tally's results. Therefore, the discrepancy in the total results is mostly due to the impacts of the remaining modules.

In this regard, the transportation and construction impacts (A4-A5) modules have very distinct results in all approaches. As the fuels were produced in different regions (Europe and North America), it is likely that the corresponding impacts vary as well (the exact impacts due to the diesel mix used in the study are not available to the users of Tally and ATHENA). Furthermore, Tally's plug-in does not consider the potential waste generated during the construction stage, assuming that there is no loss of materials during the assembly of the construction solutions. Unlike Tally, that only covers the utilities consumption during the construction stage, both BIMEELCA and ATHENA addresses the impacts due to the construction and installation processes. Unfortunately, ATHENA does not show the impacts of the materials per functional unit (or service life), only the total value, hindering the comparison of the results with other tools.

In the operation stage (modules B), the categories have very different results as well, aside from the GWP and PE-NRe. This discrepancy can be justified by the use of different energy-mix, as well as different estimated service life of the materials used in the project. For example, in Tally's database the paint and EPS have a service life of 7 and 50 years respectively, while in the BIMEELCA tool (that used specific data) these values are of 10 and 25 years. However, the results between the BIM-LCA/LCC approach and the BIM-based approach are closer, when compared with the other approach. The possibility to select the country's energy-mix in Tally can explain these results. In contrast, ATHENA does not allow the users to select locations outside the NA region, which can potentially influence the representativeness of the LCA results of projects located outside this boundary (BIMEELCA – Dutch energy-mix provided by Ecoinvent; Tally – Dutch energy-mix provided by GaBi; ATHENA – NA energy-mix provided by Athena's database).

At last, the end-of-life impacts and benefits due to reuse, recovery or recycling of materials (modules C and D) are very distinct too. These results are greatly affected by the definition of the waste treatment scenarios and percentage of treated materials. Both Tally and ATHENA do not allow the users to define these (e.g. Tally's end-of-life scenarios are based on the Waste Reduction Model by the US Environmental Protection Agency). For example, the steel recycling rates are 98% in Tally, while in BIMEELCA tool it was assumed as 87%

and 13% reuse in accordance with Dutch documents [380]. Similar to module B, it is not advisable to compare the impacts of these modules because the waste scenarios and impacts are from different regions. Hence, the comparison of modules C and D between BIMEELCA and the other approaches might not be accurate.

6.4. Discussion

In this chapter, innovative BIM-based LCA and LCC analyses were performed and compared with existing approaches. According to Gundes [210], the integration of LCA and LCC analyses can be performed and interpreted distinctly. Building on this argument, the BIM-LCA/LCC framework uses the same input data (e.g. materials' quantity and impacts) but generates separate results, i.e. per indicator. Not only this process reduces the amount of time spent in conducting the analyses but also reduce human-made errors. Furthermore, different tools can have different approaches for the same aspects of the analyses (e.g. how waste during construction stage is quantified) or dissimilar flexibility in handling the data. Therefore, it is argued that sustainability analyses should use the same input data and tool, even if for different purposes (e.g. environmental and economic assessments). In this sense, this approach represents a special application of the LCA and LCC integration argued in Gundes's study [210], i.e. a single analysis was performed even though the results were analysed independently.

The BIM-LCA/LCC approach was built on Antón and Díaz's research, which argued that BIM models should contain environmental information to promote an automatic assessment of the project [224, 225]. Existing approaches either used several programs to conduct different analyses or solely used BIM to automatically extract the bill of materials to external databases [53, 220]. However, these approaches had a few limitations, as the interoperability issues between different software, license costs per software, human-made errors that exponentially increase with the number of tools to be used, flexibility of the databases, etc. Currently, the use of BIM to extract the bill of materials and connect it with external databases is the most used approach. Therefore, the BIM-LCA/LCC approach was compared with a BIM-based LCA tool (Tally) and with an external LCA tool (ATHENA), in order to compare their advantages and disadvantages.

In relation to the BIM-based LCA analysis, the main advantage is that all the calculations are performed within a BIM-based environment, like in the BIM-LCA/LCC approach. The tool used in this approach, Tally, is able to read the elements and materials used in the project (only the architectural and structural, not the MEP). Another advantage is that Tally allows a higher definition that BIM models currently do not have (e.g. define the type of materials for each composing element of the door such as the closer). Therefore, LCA and LCC analysis based only on the geometric information contained in the model (i.e. elements and materials' volume) might not address smaller components as well as LCA tools could. Based on the geometric information provided by the model, Tally's users are able to select the most suitable materials that are available in their database (GaBi) and make the correspondence between the Revit's material and the GaBi's material (but not insert environmental information in the model). This presents as a significant obstacle, because the database available in Tally only contains products that are representative of the US and North America regions. Furthermore, the tool is not flexible enough, preventing users from inserting the environmental data of the products they use in the project. Thus, the results generated by the tool can be very different than the European reality. Additionally, Tally uses the Tracy 2.1 method, which is specific for the NA region. Hence, if this approach is to be used in European projects, the users must use tools that not only use European methods (e.g. CML) but also European LCA databases. At last, waste scenarios and percentages are predefined in Tally, representing another limitation of the tool.

Considering the third approach, the extraction of the material's quantity take-off automatically generated by the BIM tool was required, unlike in the previous approaches. In other words, if a small modification to the project is necessary, the users will need to re-export the bill of quantities and conduct a new LCA analysis. This limitation is present in all tools that resort to this approach, i.e. that are not integrated within a BIM-based environment. Furthermore, the ATHENA tool was also developed focusing on the US/NA market, thus it shares all the regional limitations of Tally. Moreover, the users are also not able to edit existing environmental data or insert new data, another limitation that is shared with Tally.

The LCA and LCC analyses greatly depend on the representativeness of the source [335], i.e. are the environmental and economic data representative of the materials and elements used in the project? While the traditional approaches presented in this chapter (BIM-based LCA and External LCA analysis) does not allow users to add or edit the impacts' information within the materials, the BIM-LCA/LCC approach was specifically developed to address that issue. The main advantage of using the proposed approach is that users are able to freely insert only the information they want to use in the LCA and LCC calculations. Furthermore, this is expected to influence the construction industry and promote the development of digital information-rich objects, that contain sustainability impacts of the corresponding products. This effort should be addressed by the products' manufacturers. At last, both ATHENA and Tally did not address the life cycle costs of the project. These mutual but important limitations of existing approaches indicate that new approaches should be developed in order to conduct easy, automatic, and project-specific LCA and LCC analyses.

However, some issues were observed in the application of the BIM-LCA/LCC framework. One of these were related to the detailing level of the elements. For a precise analysis, an exact quantification of the materials used in the project is required. In this sense, the connections between elements and materials were mostly disregarded, and a more accurate model would be required. This high level of detailing would be crucial not only for a more accurate LCA and LCC analyses but also to promote the circularity in projects. Hence, it is necessary to know the amount and type of connections (e.g. nailed, bolted) to understand the reusability rate of the products used in the project.

Focusing on the developed BIMEELCA tool, one aspect that should be addressed in the future is how the results of the Streamlined and Complete LCA/LCC analyses are presented. At the moment, the results are based on the contribution of each element to the total impacts. However, the presentation of the impacts per type of functional unit or per type of elements (i.e. categories, such as roofs, walls, doors) are other possible options that could be addressed in future developments of the tool. Another aspect to be considered is the size of the file. Before the information was added to the model, it had a size of 108 MBs. After the Streamlined and Complete analysis, the model had 132 MBs (an increase of 22%). Notwithstanding their pertinence, these limitations do not affect the suitability of the BIM-LCA/LCC framework for a BIM-based LCA and LCC analyses.

In summary, the selection of the most reliable approach/tool greatly depends on the location of the project and on the purpose of the study. Firstly, the selected approach must allow users to select materials manufactured in the same geographic region of the project. Secondly, this decision is also depended on how the sustainable data is going to be handled, i.e. are the users only interested in obtaining the results of an LCA/LCC analysis or are they interested in having a semantically-rich BIM model that can be reused throughout the life cycle of the project? In this regard, the flexibility of the external LCA/LCC databases, how they are integrated with the BIM tools, and how the information within the BIM model can be reused are the aspects that influence the BIM-LCA/LCC integration the most. If the databases do not allow users to insert or edit information or if the users need to constantly export the bill of materials after modifications in the project, then this approach greatly hinders the automation of simulations and does not contribute to the promotion of sustainability assessments of projects. Moreover, the proposed framework aims to reduce the human-made error and time spent in doing sustainability assessments of the model, thus promoting the identification of the life cycle environmental and economic burdens of the construction. It also encourages companies to request digital objects with environmental and economic data from manufacturers, thus positively influencing the sustainability of the construction industry. Finally, this approach also promotes the use of BIM models as data silos, thus contributing to the decision-making processes and automatic simulations during the design and operation phase [58, 61, 62]. If BIM models contain semantic information, this could be used to perform an automatic analysis, as demonstrated in this chapter, not only to build sustainable constructions but also during refurbishments. In this regard, the facilities managers only had to insert the updated information and use the already existing information within the model to perform a new LCA or LCC analysis. Furthermore, the data-rich models could eventually be used to obtain historical data which could contribute to predictive analyses.

6.5. Concluding Remarks

The BIM-LCA/LCC framework, promoted by the BIMEELCA tool, was successfully validated in this chapter, with the help of a pilot case study, an office building located in the Netherlands. To support this approach, the BIMEELCA tool, which was detailed in the previous chapter, was used. Building on the proposed framework, a Streamlined analysis was conducted, demonstrating that an automatic LCA and LCC analysis is possible if the correct information is contained within the model. However, the user (e.g. designer, LCA/LCC expert) must provide project-specific information to perform a Complete analysis. Nonetheless, with the assist of the BIMEELCA tool, this process can become increasingly faster and intuitive after its use in other projects. As construction companies mostly use the same products in their projects, a green BIM library can be developed, comprising a list of materials and BIM objects (i.e. elements) semantically rich. This could enable a swift and automatic Streamlined

LCA/LCC analysis in a wide range of projects. Ultimately, the results of Streamlined and or Complete analyses can lead to the development of a benchmarking within the company.

The proposed approach and results were also compared with existing approaches. A BIM-based LCA analysis and an External LCA analysis tools were used for that purpose. It was observed that the integration of LCA and LCC analysis with BIM is greatly influenced by the databases' flexibility (i.e. capacity to add or edit information) and their integration with BIM tools. In this regard, the proposed approach promotes the use of specific data and is region-free, unlike the other tools (Tally and ATHENA). The use of open applications for the reuse of the information inserted in the BIM model is another advantage of the proposed approach, unlike existing tools that only handle proprietary data. By adding information within the model, other users could have access to the LCA and LCC data of the BIM objects, without the need of BIMEELCA tool or Excel spreadsheets, and reuse it for the same or different purposes. Moreover, it was observed that a higher level of detail is required in the BIM models in order to consider the amount and type of connections between elements. This aspect is particularly relevant if the principles of circularity are taken into consideration. For example, the capacity to automatically identify if a connection is bolted or not is fundamental to promote circular economy in construction. Despite these principles were not considered in this research, a further exploration of BIM's potential in this topic would prove to be useful for the promotion of the sustainability in the construction industry.

Finally, the proposed framework encourages the use of BIM models for a purpose other than the automatic quantity take-off. The potential use of BIM as data repositories and sources of historic data is benefited by the use of the proposed framework, which aims at the inclusion of environmental and economic data within the models. This can eventually lead to predictive analyses based on the buildings' performance. Moreover, the BIM-LCA/LCC framework promotes the use of sustainability-based methodologies during early stage, for the selection of green materials, as well as during the operation stage, for the selection of suitable products taking into consideration the remaining service life of the building. In the last case, as the model is already filled with useful information, the facilities managers are only required to replace the information of the elements and materials to be refurbished and run a new analysis within the BIM environment.

Chapter 7 – Conclusions

The main aim of this research is to enhance the integration of life cycle assessment (LCA) and life cycle costing (LCC) methodologies with building information modelling (BIM), as existing approaches still have some limitations (e.g. interoperability issues, use of non-editable databases). For that purpose, it was necessary to review the existing approaches for the integration of LCA/LCC with BIM, identify which information could be incorporated in the BIM models, which processes and exchange of information are necessary for a suitable BIM-LCA/LCC integration, and if an automatic LCA/LCC analysis is possible within a BIM-based environment. The work developed in this research is expected to contribute to the development of automatic sustainability simulations, creation of tailor-made BIM objects' libraries, and use of historical data contained within data-rich models for predictive analyses.

The work developed throughout this research intends to promote the sustainability of the construction projects (the dependent variable) based on the environmental and economic dimensions of the sustainability concept (the independent variables). For that purpose, state-of-the-art methodologies such as BIM were integrated with sustainability-related methodologies, such as LCA and LCC. In this regard, it is claimed that three approaches for the integration of LCA/LCC with BIM are discussed in the literature. The first approach, which was often used in the earlier BIM-based LCA/LCC integration research, focuses on the use of a wide range of programs, each with its own purpose. For example, BIM tools are used for modelling, LCA tools are used for environmental studies, LCC tools are used for economic studies, etc. More recently, a second approach focuses on the use of quantity take-off automatically generated by BIM tools in external databases. Finally, the third approach promotes the information integration within the BIM model, instead of relying on BIM solely for the extraction of geometric information. This approach was briefly mentioned in the literature but has not been explored or validated so far. Therefore, the main aims of the research were the environmental and economic impact assessment of buildings, use of BIM-based tools for the improvement of LCA and LCC analyses efficiency, development of a framework and methodology to enable a BIM-based analysis, identification of the required information to be inserted in the BIM model, and creation of a tool that could assist in the performance of automatic and comprehensive analyses of buildings' sustainability.

As a result, a BIM-LCA/LCC framework was developed building on the existing models. This framework takes into consideration the information required to perform the LCA and LCC analyses within a BIM-based environment. The information to be added into the elements and materials (i.e. BIM objects) physically represented in the BIM model is also addressed. Concerning this aspect, the BIM-LCA/LCC framework is based on an environmental impact assessment method developed at the Institute of Environmental Sciences (CML) of Leiden, also known as CML 2001. This method together with the cumulative energy demand (CED) were selected as the most suitable for an LCA study because they are often used in the literature and in the environmental profile declarations (EPD) [339]. Hence, the following environmental categories are part of the proposed framework (as well as of the independent variables): acidification potential (AP); global warming potential (GWP); eutrophication potential (EP); abiotic depletion potential of materials (ADPM); abiotic depletion potential for fossil fuels (ADPE); photochemical ozone creation potential (POCP); ozone depletion potential (ODP); renewable energy (PE-Re); and non-renewable energy (PE-

NRe). The acquisition cost of the products is the only economic indicator to be included in the objects. Therefore, each BIM object contains a minimum of 10 indicators for the LCA and LCC analyses.

However, the processes required for a BIM-based LCA and LCC analysis were not mapped (i.e. indicated and structured) in the literature, yet. Hence, building on this framework, an information delivery manual (IDM) and a model view definition (MVD) that address the information exchange required for these processes were proposed. Furthermore, a BIM-based environmental and economic life cycle assessment (BIMEELCA) prototype tool was developed based on the framework and on the IDM/MVD. This tool aims to promote the use of automatic LCA and LCC analysis in BIM-based projects at early stages of the project (Streamlined analysis) and a more comprehensive analysis of the project at later stages (Complete analysis). In the end, a pilot case study located in the Netherlands was used to validate the work developed in this research. In this sense, both the tool and the pilot case study used the Autodesk Revit software, as it is the most used BIM tool in the market, particularly for sustainability simulations, according to the literature.

7.1. Research findings

This study suggests that different levels of information can be incorporated within the BIM model for different types of life cycle analyses. In this regard, for a simpler and faster analysis, a Streamlined LCA/LCC study can be performed. If the model has a low level of development (LOD), then generic data (e.g. generic LCA databases, market prices) can be used as a source for the products' environmental and economic impacts. For higher LODs (300 and above), specific data could be used whenever available (e.g. EPDs, suppliers' price indicated in the project's budget). This information is the only input required for a Streamlined analysis. Therefore, it is also argued that, if BIM objects already contained this information, an automatic LCA and LCC analysis could be performed. However, this type of analysis has two limitations. Firstly, it would only focus on the initial year (i.e. manufacturing stage). Secondly, the required time to perform this analysis depends on how much information is already contained in the model. In this regard, either the manufacturers incorporate this information in their digital objects or someone (e.g. designer, LCA/LCC specialist) has to insert this information within the objects. In contrast, for a more detailed and accurate analysis, it is argued that a Complete LCA/LCC analysis should be performed. For this purpose, site-specific information must be considered in order to cover the full life cycle of the project, such as the service life of the construction, discount rate, service life and density of each product used in the project, transportation type and distance, utilities used during the construction and operation stages, waste generated during the construction and demolition stages, and possible waste scenarios. This information can be provided by the designer or contractor of the project and differs from project to project; thus, an automatic Complete analysis is not possible.

However, there is not a single information schema that covers the domain of LCA/LCC analysis within a BIM-based environment. Therefore, an IDM/MVD was proposed based on the BIM-LCA/LCC analysis. Moreover, to support an open IDM/MVD, the industry foundation classes (IFC) schema was used as the information exchange format, similar to other research works in the field of BIM semantics and ontologies. In this regard, it was observed that 137 IFC properties are necessary in order to consider the exchange of information required for a BIM-based LCA/LCC analysis. Out of those 137 properties, 15 are already covered by the existing schema. For the Streamlined analysis, the IFC4 schema already considers nine properties at the element level (*IfcElement* entity), in which ADPE is the only category missing. In contrast, 26 compulsory properties and 111 optional properties should be considered to perform a Complete LCA/LCC analyses.

Consequently, a prototype tool was developed to support the implementation of the BIM-LCA/LCC framework and information exchange identified in the IDM/MVD 'BIM-based LCA/LCC analysis'. This tool is based on the functions accessible by the Revit application programming interface (API) platform, i.e. it reproduces the same commands that are available in the Revit itself. The tool was created using the Visual Studio Community 2017 (version 15.5.2) integrated development environment program. The programming language C# was used in its development, while the graphical user interface (GUI) was developed using windows presentation foundation (WPF), because the GUI generated by the Revit API was not flexible enough to perform such complex analyses. Unlike existing tools in the market, the BIMEELCA tool allow users to insert the required information within the BIM model for the LCA and LCC analyses (based on the BIM-LCA/LCC framework and IDM/MVD for the BIM-LCA/LCC analysis). This is done by importing the data contained in spreadsheets (XLS format) into the model and by the automatic quantity take-off generated by the BIM tool, resulting in an automatic Streamlined LCA/LCC analysis. However, as mentioned before, a more interactive approach between tool and user is required for a Complete LCA/LCC analysis (e.g. the more information is added to the tool, the more comprehensive the analysis will be).

Lastly, the framework, information schema, and prototype tool were validated in a pilot case study located in the Netherlands. A Streamlined and a Complete analysis were performed using site-specific data wherever it was possible. Furthermore, the properties required for the BIM-based LCA/LCC analysis (and that were identified in the IDM/MVD) were created and filled based on the obtained results. With these properties created, it is then possible to export the LCA and LCC information contained in the model into an IFC file. Additionally, this approach was then compared with two other traditional approaches: a BIM-based LCA analysis and an External LCA analysis. As a result, it was observed that the integration of LCA/LCC analysis with BIM is significantly influenced by the databases' flexibility and how they read the information contained within the BIM tools. In this regard, the capacity to add or edit information is fundamental to conduct an analysis representative of the actual project, i.e. the more generic data or assumptions are used, the greater the risk will be for a non-accurate LCA/LCC analysis of the project. The pertinence of geometric modelling (i.e. the accuracy of the digital representation when compared with the real object) is another aspect that can influence the results of the analyses. If some of the building assemblies (e.g. partition walls) do not have high level of detail, the obtained material's quantity might not faithfully represent the reality, thus the impacts of such solutions will not be representative as well.

Summing up, an innovative integration of sustainability-related methodologies within a BIM-based environment was successfully explored and validated in this research. The following table lists the initial expectations and the findings acquired throughout the study (Table 32).

Table 32 - Validation of the research hypothesis

Hypothesis	Validation
Which information could be incorporated in BIM objects to enable a BIM-LCA/LCC analysis?	
H1: For LCA, products with Environmental Product Declarations (EPDs) can have the LCA results and service life incorporated in the objects, while, for LCC, products can have the corresponding acquisition costs, service life, and density.	*Validated*

Hypothesis	Validation
Which processes and exchange of information are necessary for a framework that implements an LCA and LCC analysis within a BIM-based environment?	
H2: It is expected that the use of methodologies such as information delivery manual (IDM) and model view definition (MVD) would contribute to the identification of the processes and exchange of information required for a BIM-based LCA and LCC analysis.	*Validated*
***How has an automatic BIM-LCA/LCC analysis to be conducted if the necessary information is incorporated in objects*?**	
H3: Although a streamlined LCA/LCC analysis could be done automatically, considering just the production phase (A1-A3 modules), a complete LCA/LCC analysis cannot.	*Validated*

7.2. Contribution to the state-of-the-art and societal impacts

This research contributed to the state-of-the-art on sustainable construction and building information modelling. Firstly, the research findings extended the scientific knowledge on BIM semantics and ontologies through the development of an IDM and MVD for the BIM-based LCA and LCC analyses. In this regard, improvements to the IFC schema were proposed so that LCA and LCC data and studies are considered in the information exchange between stakeholders (e.g. designers, experts, clients). Moreover, the concepts and processes identified in the IDM/MVD 'BIM-LCA/LCC analysis' can be used by BIM software developers for the development of dedicated applications.

Secondly, the use of BIM models as data repositories and for information management purposes is another contribution of this research. Although this approach is currently explored in different domains of the BIM literature (e.g. safety, energy), a gap in the integration of LCA and LCC information within the model still remained. It is hoped that the findings presented in this study improve the knowledge in the domain of BIM and sustainable construction and contribute to faster and enhanced automatic simulations.

Thirdly, the results of the Streamlined and Complete LCA and LCC analyses presented in this research are expected to contribute to a better understanding of the life cycle environmental and economic impacts of the built environment in Europe, particularly in the Netherlands. The visualisation of the results (i.e. the 3D model with the colour scheme) improves the interpretation of the results of LCA and LCC studies. Additionally, the outcome of the LCA and LCC studies can later be used for the development of tailor-made BIM libraries and benchmarking at the company, national or international level.

Fourthly, the literature on sustainable construction benefited from the challenges and findings observed throughout the research. Not only an innovative LCA and LCC integration approach was proposed and validated but also how BIM tools can promote the use of LCA and LCC in the construction industry was explored.

Finally, the outcomes of this research contribute to the development of suitable semantically rich digital objects that should be stored in BIM libraries and used by a wide range of construction professionals (e.g. architectural and engineering offices, consultancy offices, contractors). It is expected that this knowledge is used by manufacturers in the digitalisation of their products and contribute to the improvement of existing data exchange templates (e.g. BIM object guides, product data templates). The use of BIM models as semantic information repositories is another aspect that was promoted in this research, contributing to the development of sustainability-related simulations that are not dependent on proprietary tools. Building on the principle that manufacturers freely share the environmental studies of their products, the same data should be used by non-proprietary tools. In this regard, if the same information is inserted in the model, it is then possible to reuse it throughout the life cycle of the project, unlike what happens with existing tools. Therefore, this research also contributes to the promotion of open data and applications, by enabling users to reuse the data regardless of the software licenses they have.

7.3. Future research paths

It is recommended that, building on the findings presented in this research, further work is done in the development of suitable BIM-based LCA/LCC tools to promote automatic simulations. The prototype BIMEELCA tool was specifically developed to support the BIM-LCA/LCC framework but additional improvements are required in order to be widely used in the construction industry. The recognition of mechanical, electrical and plumbing (MEP) elements and the improvement on the visualisation of the Streamlined and Complete analyses results are some of the aspects that should be addressed in the near future. Similarly, the IDM/MVD for the BIM-LCA/LCC analysis, based on the proposed framework, should be further improved in order to cover the MEP domain as well. This would contribute not only to a more comprehensive environmental and economic assessment of the project but also to make possible an energy analysis, which was not covered in this research.

The work developed in this research is expected to open new research paths. For instance, the principles of circular economy should be combined with the findings presented in this study. The investigation on the potential of BIM for the automatic identification of type and amount of connections is fundamental to promote the use of circular economy. A circularity index, which could be taken into consideration in more accurate LCA and LCC analyses, could be one of the outcomes of these works. Furthermore, the development of tailor-made BIM objects' libraries, specific for each company and or at (inter)national level, is another aspect that should be explored in future research. The usefulness of the BIM-LCA/LCC framework for the life cycle environmental and economic assessment of refurbishment projects is one more path that should be researched in the near future, in order to understand if data-rich models enable fast updated life cycle assessments. Moreover, the promotion of BIM models as data repositories is seen as an opportunity to develop platforms that display the impacts of the built environment at neighbourhood level (e.g. integration of BIM with geographic information system (GIS) tools for a city mapping of environmental impacts per square meter that could be used for policy making). In addition, future research should focus on the use of historical data contained within data-rich models for predictive analyses. Building on the projects' characteristics (e.g. location, type of construction) and materials used in similar projects (e.g. products/materials), a predictive LCA/LCC tool could be explored in the future. Furthermore, a predictive LCA/LCC tool could also take into consideration the most used materials and solutions in the region. The use of historical data would definitely contribute to the development of sustainability benchmarks at city and (inter)national level, as well as to the creation of smart and sustainable city models. Another future research avenue that could be further explored is the inclusion of more sustainability domains in BIM-based analyses. If other types of information were to be added to the model (e.g. that focus on energy, thermal, safety analyses), then a more comprehensive understanding of a project's impact would be possible. This would also enable the development of optimisation algorithms to improve the construction's design and improve the decision-making process at early phases of the project.

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Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2019). *Development of a BIM-based Environmental and Economic Life Cycle Analysis tool*. Under development

Santos, R., Costa, A. A., Silvestre, J. D., Vandenbergh, T., & Pyl, L. (2019). *BIM-based life cycle assessment and life cycle costing of an office building in Western Europe*. Submitted in Building and Environment

Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2019). *Informetric analysis and review of literature on the role of BIM in sustainable construction*. Automation in Construction, 103, 221-234. https://doi.org/10.1016/j.autcon.2019.02.022

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Book Chapter

Santos, R., & Costa, A. A. (2017). *Information integration and interoperability for BIM-based life-cycle assessment*. In Integrating Information in Built Environments: From Concept to Practice (pp. 91–108). CRC Press. https://doi.org/10.4324/9781315201863

Conference Papers

Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L., (2018). *A validation study of a semi-automatic BIM-LCA tool*. ptBIM - 2º congresso português de building information modelling, 17-18 May, Lisboa, Portugal

Antunes, A., Santos, R., & Costa, A. A., (2016). *Interface BIM para a Gestão de Instalações*. ptBIM - 1º congresso português de building information modelling, 24-25 November, Guimarães, Portugal

Santos, R., Neves, E., Silvestre, J. D., & Costa, A. A., (2016). *Integração de BIM com Avaliação do Ciclo de Vida: análise do estado da arte e das ferramentas disponíveis*. CINCOS'16, 3-4 November, Lisboa, Portugal

Santos, R., & Costa, A. A., (2016). *BIM-based Sustainable Design*. BIM International Conference 2016, 13-14 October, Lisboa, Portugal

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Santos, R., & Costa, A. A., (2014). *BIM research in the last decade*, BIM International Conference 2014, 9-10 October, Lisboa, Portugal

ANNEXES

Annex A.1 - Process Map for the BIM-LCA/LCC analysis and processes

A process map using the BPMN approach was developed to operationalise the proposed framework and is detailed in Figure A.1 and Figure A.2.

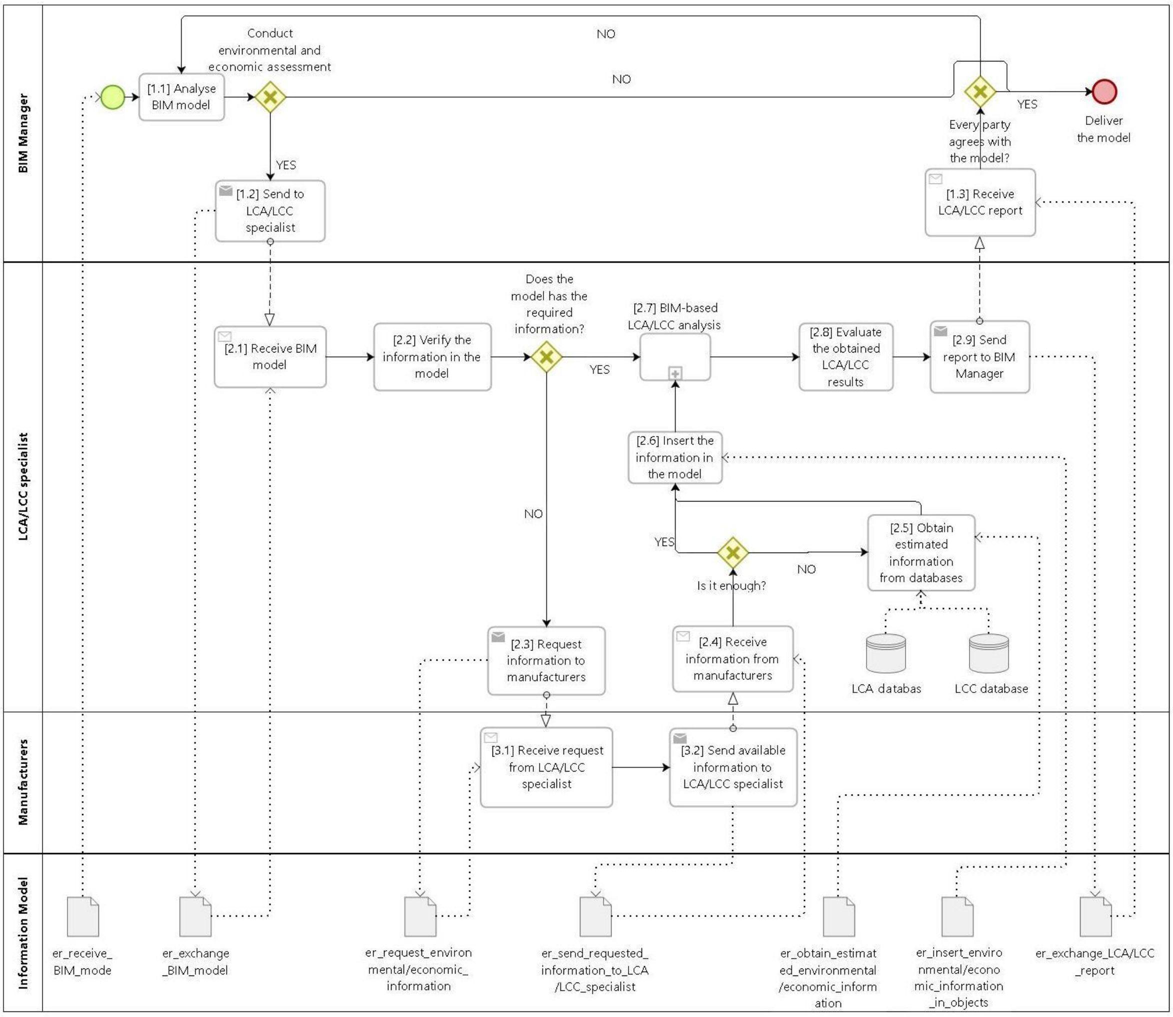


Figure A.1 - Process map of the IDM for the BIM-LCA/LCC analysis

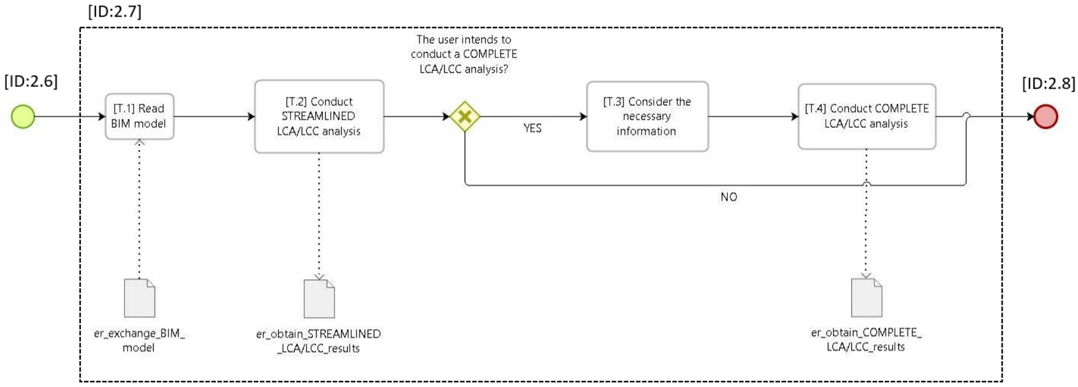


Figure A.2 - Sub-process for the [ID:2.7] BIM-based LCA/LCC analysis

A.1.1. Specification of Processes

POOL: BIM Manager

Analyse BIM Model [ID:1.1]

Type	Task	
Name	Analyse BIM Model	
Documentation	The BIM Manager's first task is to assemble and merge the BIM models of all specialties (e.g. structural, architectural, MEP) and detect possible clashes. After all the clashes are identified, the BIM Manager must contact the affected specialties (e.g. structural engineer) so that the necessary changes to the model are made. In the end, the BIM Manager should have all models without clashes.	

Send to LCA/LCC Specialist [ID:1.2]

Type	Task	
Name	Send to LCA/LCC Specialist	
Documentation	After the BIM Manager has all models free of clashes, it is now possible to conduct an environmental and/or economic analysis. If the BIM Manager believes such analyses is not needed, then the delivery of the model to the client is the next, and final, task. On the other hand, if the BIM Manager decides that these analyses are needed, then the BIM models (e.g. architectural, structural) can be sent to the LCA/LCC specialist. The BIM Manager does not need to send all the BIM models to the specialists, only the ones that are deemed as necessary (either by the client or based on the BIM Manager experience).	

	The LCA/LCC specialist can either be part of the same company or not. Along with the BIM model, further information will also be required. To conduct a precise LCA/LCC analysis, the BIM Manager must also provide the following information to the specialist: • list of materials used in the project (A1-A3 modules); • type of transportation used to transport materials from suppliers to the construction site and suppliers' location (A4 module); • construction costs and initial costs (A5 module); • estimated energy consumption for the operation phase (i.e. electricity, water, natural gas) (B modules); • lifespan of the asset. Other information will also be used in the LCA/LCC study. However, it is up to the LCA/LCC specialist to identify and justify which additional information will be used (e.g. propose waste treatment scenarios). At last, the BIM Manager and LCA/LCC specialist should also agree on the type of format in which the LCA/LCC report will be submitted. It can be in the form of a word document (.doc), portable document format (.pdf), a spreadsheet (.xls) or in Autodesk Revit (.rvt). However, if they agree, a different format can be used.

Receive LCA/LCC report [ID:1.3]

Type	Task	
Name	Receive LCA/LCC report	
Documentation	After the LCA/LCC specialist analyse the model, the BIM Manager will receive a report. This report should be in the previously agreed format and can be in the form of a word document (.doc), portable document format (.pdf), a spreadsheet (.xls) or in Autodesk Revit (.rvt). However, if they agree, a different format can be used. The information contained in the report should cover: • total environmental impacts of the project per category (LCA analysis) (**mandatory**); • total economic impact of the project (LCC analysis) (**mandatory**); • list of environmental impact of each material used in the project, as well as the corresponding functional unit and estimated durability (**mandatory**); • list of all variables used for the calculations of the LCA and LCC of the project, either given by the BIM Manager (e.g. initial costs, lifespan of the building) or estimated by the specialist (i.e. discount rate) (**mandatory**); • list of possible scenarios for waste treatment (**optional**); • set of pictures of the BIM model in which the elements (e.g. walls, windows) are grouped based on their environmental and economic impacts, by using a colour scheme (**optional**); • BIM model with environmental and economic information (**optional**).	

	Based on the expertise of the LCA/LCC specialist, the BIM Manager could also be advised regarding the impact of the project. The specialist could suggest which materials and/or elements could be replaced, as well as a list of suitable materials/elements that could be used as replacements. The information contained in the report will help the BIM Manager in the decision-making process. If the BIM Manager decides to change some of the materials/elements used in the project, the corresponding specialties should be contacted in order to verify if such option is viable (e.g. how the structural analysis is affected by that change). Based on those contacts, the BIM Manager will have to re-analyse the BIM model (e.g. perform clash detections) and send it back to the LCA/LCC specialists. Otherwise, if the BIM Manager is pleased with the report's results and with the model as it is, all BIM models can finally be submitted to the client.

POOL: LCA/LCC specialist

Receive BIM Model [ID:2.1]

Type	Task	
Name	Receive BIM Model	
Documentation	The LCA/LCC specialist's first task is when a request from the BIM Manager is received. The specialist will be asked to conduct the environmental (LCA) and economic (LCC) analysis of the lifecycle of a project. The information that the LCA/LCC specialist will require in order to conduct these two analyses are: • BIM model in Autodesk Revit format (.rvt); • lifespan of the asset; • list of materials used in the project (A1-A3 modules); • suppliers' location and type of transportation used to transport materials from suppliers to the construction site (A4 module); • construction costs and initial costs (A5 module); • estimated energy consumption for the operation phase (i.e. electricity, water, natural gas) (B modules). Other information will also be used in the LCA/LCC study. Based on the specialist expertise, a suitable discount rate that should be used for the LCC study (e.g. 4%) will have to be chosen. The specialist will also have to propose a list of possible waste treatment scenarios, for the end-of-life impacts of the project (C modules). Before the specialist begins with the LCA and LCC study, it is necessary to decide which methods will be used for the environmental and economic assessment. On this process map, which will be used in the IDM for the BIM-LCA/LCC analysis, the specialist will use the CML 2001 environmental impact assessment method, a method developed by the Institute of Environmental Sciences (CML) of Leiden University. The selected method for the economic analysis is the Net Present Value (NPV).	

Verify the information in the model [ID:2.2]

Type	Task	
Name	Verify the information in the model	
Documentation	The second task of the LCA/LCC specialist is to verify which information is already included in the model. The specialist will need to read the elements contained in the model (i.e. elements and materials) and read the information (i.e. parameters and shared parameters) contained in each element/material. The information that the specialist must look for, either within the elements (BIM objects) or materials, is detailed below: • the **type** of the element (e.g. Wall, Floor); • the **name** of the element (e.g. ExteriorWall#1); • the **thickness** of the element (if a Wall, Floor or Roof); • the **area** of the element (if a Wall, Floor or Roof); • the **volume** of the element (if a Wall, Floor, Roof, Foundation, Column or Beam); • the **density** of the element (in kg/m^3); • the **lifespan** of the element (in years); • the **quantity** of the element (if Window or Door); • the abiotic depletion potential for fossil resources (**ADPE**) of the element (in MJ); • the abiotic depletion potential for non-fossil resources (**ADPM**) of the element (in kg Sb-eq); • the acidification potential (**AP**) of the element (in kg SO_2-eq); • the eutrophication potential (**EP**) of the element (in kg PO_4^{3-}eq); • the global warming potential (**GWP**) of the element (in kg CO_2-eq); • the ozone depletion potential (**ODP**) of the element (in kg R-11-eq); • the photochemical ozone creation potential (**POCP**) of the element (in kg ethene-eq); • the use of non-renewable primary energy (**PE-NRe**) of the element (in MJ); • the use of renewable primary energy (**PE-Re**) of the element (in MJ); • the **acquisition cost** of the element (in euros). It is advisable that the specialist contributes to the development of a tool that is able to automatically read if the BIM model already contains the required information for the LCA and LCC study.	

Request information to manufacturers [ID:2.3]

Type	Task	
Name	Request information to manufacturers	
Documentation	If the BIM model or the documentation provided by the BIM Manager does not contain enough environmental and/or economic information, then the LCA/LCC specialist should contact the manufacturers of the products used in the project (based on the list provided by the BIM Manager). The specialist should ask the manufacturer all or just some of the information listed below: • the results of the LCA study of the product (i.e. material/element), in the format of an **Environmental Product Declaration** (EPD). The EPD, standardised in the EN 15804:2012, contains the LCA analysis of a product based on the CML 2001 environmental impact assessment method; • the market price of the product; • estimated maintenance costs and/or periodic maintenance of the product; • density of the product; • durability of the product.	

Receive information from manufacturers [ID:2.4]

Type	Task	
Name	Receive information from manufacturers	
Documentation	In a previous task, the LCA/LCC specialist contacted a manufacturer to obtain further environmental and/or economic information of a product. On this task, the specialist will receive the reply of that manufacturer. Depending on the available information that the manufacturer had, the specialist should receive some or all the information listed below: • the results of the LCA study of the product (i.e. material/element), in the format of an **Environmental Product Declaration** (EPD). The EPD, standardised in the EN 15804:2012, contains the LCA analysis of a product based on the CML 2001 environmental impact assessment method; • the market price of the product; • estimated maintenance costs and/or periodic maintenance of the product; • density of the product; • durability of the product.	

Obtain estimated information from databases [ID:2.5]

Type	Task	
Name	Obtain estimated information from databases	
Documentation	If the information obtained from the manufacturer of a product is not enough, the LCA/LCC specialist could resort to existing LCA and LCC databases to fill that gap. The LCA/LCC databases offer estimated values for similar products. If the manufacturer did not provide environmental information on a product, the LCA database can give estimated values for the environmental impact categories: • ADPE; • ADPM; • AP; • EP; • GWP; • ODP; • POCP; • PE-NRe; • PE-Re. If the manufacturer did not provide economic information on a product, the LCC database can give estimated values for the: • maintenance costs of the product; • maintenance period of the product; • durability of the product; • life cycle costs of a product. With this information, the specialist can then proceed for the next task.	

Insert the information in the model [ID:2.6]

Type	Task	
Name	Insert the information in the model	
Documentation	After checking if all the necessary environmental and economic information of the products used in the project are available, the LCA/LCC specialist should now insert it in the BIM model. Then the specialist must verify if the information contained in the model is enough. If not, then the specialist needs to add the necessary environmental and economic information. For that purpose, the specialist should directly add the information in the model, either in the elements or in the	

	materials used in each element. It is of **extreme importance** that the specialist inserts the environmental and economic information in each element/material using the same functional unit: • for **walls/roofs/floors**, the functional unit of the element or materials used in these elements should be per **m²**; • for **windows/doors**, the functional unit of the element or materials used in these elements should be per **unit**; • for the **remaining elements**, the functional unit of the element or materials used in these elements should be, preferably, per **m³**. It is expected that, for the first time this process is used, the specialist needs to insert all the required information in the model. However, if the specialist works within the same company as the BIM Manager, it is possible to draw guidelines on how the involved parties (e.g. structural engineer, architect) could create the BIM model. Usually, the companies use a specific range of materials and building assemblies. These could be represented as families (i.e. products) or part of the materials' library. Therefore, every time these parties develop a new family or add a new material to the project, they can also upload it in a 'green BIM library', which, in an initial phase, could be in the format of a traditional Revit project (in .rvt format). If they use families from a 'green BIM library', which contains all the elements and products that already have environmental and economic information, then they just need to import these families to the BIM projects that they are developing, thus enabling an automatic STREAMLINED LCA/LCC analysis. The above-mentioned guidelines could be part of the company's **BIM Execution Plan** (BEP). After the specialist adds the required information, he/she now should proceed to the next step, i.e. conduct a STREAMLINED and/ or COMPLETE LCA/LCC analysis.

BIM-based LCA/LCC analysis [ID:2.7]

Type	Task	
Name	BIM-based LCA/LCC analysis	
Documentation	After checking if all the necessary environmental and economic information of the products used in the project is available, the LCA/LCC specialist can now perform two types of LCA and LCC analysis: STREAMLINED and COMPLETE. The specialist should follow the sub-process detailed in Figure A.2. All the tasks identified in this sub-process are briefly detailed in this section and further detailed below. The first step is to, based on the environmental/economic information and products' quantities, perform the STREAMLINED LCA and LCC analysis. The STREAMLINED analysis consists of the assessment of the environmental and economic impacts of the A1-A3 modules, i.e. the impacts from the products' manufacturing process alone. This first analysis can potentially be automatic if the model already contains the necessary information and if a tool that was able to read and handle	

	that information already exists (e.g. BIMEELCA). The specialist can then perform a COMPLETE LCA/LCC analysis or not. If a COMPLETE analysis is desired, then the specialist will need to consider a set of project-specific information (e.g. type of transportation used to transport products from suppliers to construction site, discount rate). The more accurate the specialist wants the study to be, the more information he/she will need to consider. The COMPLETE analysis consists of the assessment of the environmental and economic impacts of the A + B + C +D modules, i.e. the impacts from the products' manufacturing process (A1-A3), transportation (A4), construction (A5), maintenance (B2-B4) and operational consumption (B6-B7), end-of-life (C2-C4), and beyond the system boundary (D). In the end, after the specialist performed the total environmental and economic impact of the project's lifecycle, it will be possible to evaluate the sustainability of the project in the next task.

Evaluate the obtained LCA/LCC results [ID:2.8]

Type	Task	
Name	Evaluate the obtained LCA/LCC results	
Documentation	After the LCA/LCC specialist obtained the environmental (LCA) and economic (LCC) analyses of the project, it is possible to evaluate the results and generate a report. The specialist could highlight which elements and materials used in the project have the highest and lowest environmental and economic impacts. Furthermore, the specialist could propose a list of environmentally friendly products or more economic products. That information could be used by the BIM Manager to suggest modifications to the existing model by replacing high impact products with lower impact products, depending on the client's goal. Based on the specialist's expertise, it is also possible to evaluate the sustainability of the project when compared with similar projects in the same country.	

Send report to BIM Manager [ID:2.9]

Type	Task	
Name	Send report to BIM Manager	
Documentation	The last task of the LCA/LCC specialist, after conducting the LCA and LCC analyses of the project and evaluating the results, is to generate a report. This report should be in the previously agreed format and can be in the form of a word document (.doc), portable document format (.pdf), a spreadsheet (.xls) or in Autodesk Revit (.rvt). However, if they agree, a different format can be used. The information contained in the report should cover: • total environmental impacts of the project per category (LCA analysis) (**mandatory**); • total economic impact of the project (LCC analysis) (**mandatory**);	

	• list of environmental impact of each material used in the project, as well as the corresponding functional unit and estimated durability (**mandatory**); • list of all variables used for the calculations of the LCA and LCC of the project, either given by the BIM Manager (e.g. initial costs, lifespan of the building) or estimated by the specialist (i.e. discount rate) (**mandatory**); • list of possible scenarios for waste treatment (**optional**); • set of pictures of the BIM model in which the elements (e.g. walls, windows) are grouped based on their environmental and economic impacts, by using a colour scheme (**optional**); • BIM model with environmental and economic information (**optional**). After completion, the report should be forwarded to the BIM Manager to be used as a support for the decision-making process.

Read BIM model [ID: T.1]

Type	Task	
Name	Read BIM model	
Documentation	The first task that the LCA/LCC specialist will do is to read the model. The specialist must read all the elements (BIM objects) and materials represented in the project, the information contained in it and the corresponding quantities. For the **elements**, the specialist must identify: • the **type** of the element (e.g. Wall, Floor); • the **name** of the element (e.g. ExteriorWall#1); • the **thickness** of the element (if a Wall, Floor or Roof); • the **area** of the element (if a Wall, Floor or Roof); • the **volume** of the element (if a Wall, Floor, Roof, Foundation, Column or Beam); • the **density** of the element (in kg/m^3); • the **lifespan** of the element (in years); • the **quantity** of the element (if Window or Door); • the abiotic depletion potential for fossil resources (**ADPE**) of the element (in MJ); • the abiotic depletion potential for non-fossil resources (**ADPM**) of the element (in kg Sb-eq); • the acidification potential (**AP**) of the element (in kg SO_2-eq); • the eutrophication potential (**EP**) of the element (in kg PO_4^{3-}eq); • the global warming potential (**GWP**) of the element (in kg CO_2-eq); • the ozone depletion potential (**ODP**) of the element (in kg R-11-eq); • the photochemical ozone creation potential (**POCP**) of the element (in kg ethene-eq); • the use of non-renewable primary energy (**PE-NRe**) of the element (in MJ); • the use of renewable primary energy (**PE-Re**) of the element (in MJ); • the **acquisition cost** of the element (in euros).	

	For the **materials**, the specialist must identify: • the **name** of the material (e.g. Concrete_C25/30); • the **volume** of the material per length of the hosting element (e.g. per 1 m2 of wall, there is 0.5m3 of brick); • the **density** of the material (in kg/m_3); • the **lifespan** of the material (in years); • the abiotic depletion potential for fossil resources (**ADPE**) of the material (in MJ); • the abiotic depletion potential for non-fossil resources (**ADPM**) of the material (in kg Sb-eq); • the acidification potential (**AP**) of the material (in kg SO_2-eq); • the eutrophication potential (**EP**) of the material (in kg PO_4^{3}-eq); • the global warming potential (**GWP**) of the material (in kg CO_2-eq); • the ozone depletion potential (**ODP**) of the material (in kg R-11-eq); • the photochemical ozone creation potential (**POCP**) of the material (in kg ethene-eq); • the use of non-renewable primary energy (**PE-NRe**) of the material (in MJ); • the use of renewable primary energy (**PE-Re**) of the material (in MJ); • the **acquisition cost** of the material (in euros).

Conduct STREAMLINED LCA/LCC analysis [ID: T.2]

Type	Task	
Name	Conduct STREAMLINED LCA/LCC analysis	
Documentation	In this task, the specialist can conduct a STREAMLINED LCA and LCC analysis of the project based on the information contained in the elements of the BIM model. The STREAMLINED analysis consists of the assessment of the environmental and economic impacts of the A1-A3 modules, i.e. the impacts from the products manufacturing process alone. To obtain the results for a STREAMLINED analysis, the indicators (i.e. environmental impact category or acquisition cost) should be multiplied by the elements' quantity: • for walls/roofs/floors the tool will multiply their area by each indicator (i.e. environmental impact category or acquisition cost); • for windows/doors, the tool will multiply their quantity (i.e. number of instances) by each indicator; • for the remaining elements (as the columns, frames, foundations), the tool will multiply their volume by each indicator. After this STREAMLINED LCA/LCC analysis, the specialist can proceed to the next task. It is **important to highlight that this first analysis can be automatic** if the model already contains the necessary information and if a tool that was able to read and handle that information already exists.	

Consider the necessary information [ID: T.3]

Type	Task	
Name	Consider the necessary information	
Documentation	If the LCA/LCC specialist desires to conduct a COMPLETE LCA/LCC analysis, in which the modules A4-A5, B2-B4, B6-B7, C2-C4, and D are also considered, then it is necessary to consider site specific information. For that purpose, a tool should be developed to handle all the necessary information within a BIM-based environment. For the A4 module, which covers the impacts from the transportation of products from suppliers to construction site, the specialist can either consider a predefined transportation distance or consider a transportation for each material, as well as the corresponding distance. For the A5 module, which covers the impacts during the construction phase, the specialist can consider an estimated value for the energy, water, and natural gas consumption. Furthermore, the option to define a predefined waste generated during construction (e.g. 2% of total environmental impacts from the elements) or to specify it for each material should also be possible. If the specialist decides to include the utilities consumption in the study, then it should be possible to include the environmental impacts and costs for each utility based on the country where the project is going to be built (or was built). Moreover, the specialist can also consider the construction activities costs (e.g. apply mortar or paint a square meter of a wall). For the operation impacts (B2-B4 + B6-B7) it is necessary that the specialist defines the lifespan of the asset, the discount rate, and the initial costs of the project, if desired. The first two variables are used for the quantification of the number of replacements the materials require and for the LCC calculations, using the NPV method. Another variable that can be considered is the estimated replacement period for the asset (B2-B4). This will be, at maximum, the same as its lifespan of. If lower, it means that replacements on the asset will only be done until that period. For instance, if it is 55 years and the lifespan is 60, it means that the replacements will only be done until the asset has 55 years, thus influencing the number of replacements. The last information to be analysed in these modules are the estimated utilities consumption (i.e. electricity, water, natural gas), also using the same information as A5 module, based on the country where the project is going to be built (B6-B7). For the C modules, the specialist can define the type of transportation to be used for the disposal phase and the distance between the construction site and the waste treatment facilities (C2), similar to the A4 module. It can either be based on a predefined scenario or a specific type of transportation and distance can be defined for each material. Furthermore, the specialist has to define the type of waste processing and disposal for each material used in the project (C3-C4). The environmental impacts and costs of each waste treatment **are based on the weight of the material**, thus, the consideration of the materials' density is very important. At last, the benefits beyond the system boundary (module D) are obtained based on the avoided impacts due to the recycled/recovered/reused materials. Therefore, the specialist must provide the estimated percentage of materials (i.e. materials resulting from demolition waste) that are going to be treated and their estimated price (e.g. the price of a recycled material). After all the	

	above-mentioned information is filled, or just some of it, the specialist can now perform the COMPLETE LCA and LCC analysis of the project.

Conduct COMPLETE LCA/LCC analysis [ID: T.4]

Type	Task	
Name	Conduct COMPLETE LCA/LCC analysis	
Documentation	After all the site-specific information is added by the LCA/LCC specialist, it is now possible to conduct the COMPLETE LCA/LCC analysis. The COMPLETE analysis consists of the assessment of the environmental and economic impacts of the A + B + C + D modules, i.e. the impacts from the products' manufacturing process (A1-A3), transportation (A4), construction (A5), maintenance (B2-B4) and operational consumption (B6-B7), end-of-life (C2-C4), and beyond the system boundary (D). With a cradle to cradle analysis (COMPLETE) analysis, some elements that seemed to be environmentally friendly when considering just the A1-A3 modules, might not appear to be so 'green'. If the elements have materials with low durability, that means they will have to be replaced more often throughout the life cycle of the asset.	

POOL: Manufacturers

Receive request from LCA/LCC specialist [ID:3.1]

Type	Task	
Name	Receive request from LCA/LCC specialist	
Documentation	Due to the limited information that an LCA/LCC specialist has, further information will be requested to the manufacturer of a product (either a material or an element). The manufacturers must then look in their database if they have all or some of the information listed below: • the results of the LCA study of the product (i.e. material/element), in the format of an **Environmental Product Declaration** (EPD). The EPD, standardised in the EN 15804:2012, contains the LCA analysis of a product based on the CML 2001 environmental impact assessment method; • the market price of the product; • estimated maintenance costs and/or maintenance period of the product; • density of the product; • durability of the product.	

	If the manufacturer does not have the EPD of the product, it is possible to request that service to an external organisation, in order to have environmental information of their product for future requests.

Send available information to LCA/LCC specialist [ID:3.2]

Type	Task	
Name	Send available information to LCA/LCC specialist	
Documentation	After the manufacturer collects all the requested information, listed below, they should send it to the LCA/LCC specialist: • the results of the LCA study of the product (i.e. material/element), in the format of an **Environmental Product Declaration** (EPD). The EPD, standardised in the EN 15804:2012, contains the LCA analysis of a product based on the CML 2001 environmental impact assessment method; • the market price of the product; • estimated maintenance costs and/or periodic maintenance of the product; • density of the product; • durability of the product.	

A.1.2. Specification of Data Objects

LCA database

Type	Data Object
Name	LCA database
Documentation	The LCA/LCC specialist have to, in case there is not enough environmental information on the product(s) to be included in the project, resort to LCA databases. There are several LCA databases, each with specific purposes. For the construction industry, GaBi, SimaPro, and Ecoinvent are the most used ones. The specialist can either obtain the estimated environmental impacts for a product (e.g. a brick) or model its production.

LCC database

Type	Data Object
Name	LCC database
Documentation	The LCA/LCC specialist have to, in case there is not enough economic information on the product(s) to be included in the project, resort to LCC databases. When compared with LCA

	databases, the LCC tools are mostly excel-based, without including specific databases, i.e. users must introduce in the spreadsheets all the cost information related to the product to be analysed. Some known LCC databases are the BKI-Baukosten (GE) and RSMeans (US).

A.1.3. Specification of Exchange Requirements

er_receive_BIM_models

Type	Data Object
Name	er_receive_BIM_models
Documentation	The scope of this exchange requirement is the exchange of information, particularly BIM models, to enable the clash detection of the different specialties' models. Therefore, each BIM model to be exchanged should represent the project to be submitted by the end of the design stage as much as possible. The BIM models provided by each specialty (e.g. architecture, structural, MEP, energy) should be analysed by the BIM Manager. It is the role of the BIM Manager to detect incompatibilities between the models (clash detection) and solve, or help to solve, them as fast as possible. Only after the clash detection is performed the BIM Manager can submit the models, and project documentation, to the client and gain full financial approval for the project (i.e. at the end of the design stage). These models can also be used for other types of life cycle analysis (e.g. environmental and economic) if the client or BIM Manager desires. Information provided through this exchange requirement includes: • BIM model – architectural design; • BIM model – structural design; • BIM model – MEP design; • BIM model – energy design; • All BIM models developed during the design stage.

er_exchange_BIM_model

Type	Data Object
Name	er_exchange_BIM_model
Documentation	The aim of this exchange requirement is the exchange of information, particularly BIM models, to allow the performance of environmental (LCA) and economic (LCC) analysis of a project. The information exchanged on this exchange requirement should contribute to the work to be developed by the LCA/LCC specialist and should be provided by the BIM Manager. The BIM Manager must first select the models to be analysed and then, based on these models, also provide a full list of all materials and elements (e.g. windows, doors) to be used in the project. This can also be done for already existing buildings, if the purpose is solely an environmental and/or economic assessment.

	Furthermore, the BIM Manager should indicate the lifespan of the asset or the period of analysis (it can be lower than the lifespan of the asset). Information provided through this exchange requirement includes:
	• all the BIM models, in Revit format (.rvt), that will be analysed;
	• Word (.doc) and/or Excel (.xls) document that contains:
	  • list of materials used in the project;
	  • type of transportation used to transport materials from suppliers to the construction site and suppliers' location;
	  • construction costs and initial costs;
	  • estimated energy consumption for the operation phase (i.e. electricity, water, natural gas);
	  • lifespan of the asset.

er_request_environmental/economic_information

Type	Data Object
Name	er_request_environmental/economic_information
Documentation	This purpose of this exchange requirement is to exchange environmental and economic information between the LCA/LCC specialist and the manufacturer of a specific product (material or element). If the BIM models do not contain environmental and/or economic information in the objects, and if the information provided by the BIM Manager is not enough, then the LCA/LCC specialist should contact the manufacturer of the products that are lacking such information. Information provided through this exchange requirement includes: • the results of the LCA study of the product (i.e. material/element), in the format of an **Environmental Product Declaration** (EPD). The EPD, standardised in the EN 15804:2012, contains the LCA analysis of a product based on the CML 2001 environmental impact assessment method; • the market price of the product; • estimated maintenance costs and/or periodic maintenance of the product; • density of the product; • durability of the product.

er_send_requested_information_to_LCA/LCC_specialist

Type	Data Object
Name	er_send_requested_information_to_LCA/LCC_specialist
Documentation	This purpose of this exchange requirement is to exchange environmental and economic information between the LCA/LCC specialist and the manufacturer of a specific product (material or element). Although similar to the 'er_request_environmental/economic_information', this exchange requirement will likely have less information than the requested. This is because most manufacturers do not have EPDs of their products, thus the information they send to the LCA/LCC specialist is often less than the requested. Furthermore, the format in which the information is sent to the specialist might not be the same as the format of how the information was requested. Information provided through this exchange requirement includes: • the results of the LCA study of the product (i.e. material/element), in the format of an **Environmental Product Declaration** (EPD); • the market price of the product; • estimated maintenance costs and/or periodic maintenance of the product; • density of the product; • durability of the product.

er_obtain_estimated_environmental/economic_information

Type	Data Object
Name	er_obtain_estimated_environmental/economic_information
Documentation	The aim of this exchange requirement is to identify and obtain estimated values for the environmental and/or economic impacts of products that do not have enough information. If the manufacturer of a specific product did not provided enough information, the LCA/LCC specialist can use LCA and/or LCC databases to fill that gap. The LCA and LCC databases contain estimated values for similar products. The LCA databases can contain specific (e.g. EPD), average (e.g. average of EPDs or average national), and generic data on several products. The specialist can either obtain the estimated environmental impacts for a product (e.g. a brick) or model its production. The LCC databases usually contain estimated life cycle cost data on different type of buildings, construction works and elements. Information provided through this exchange requirement includes: • ADPE of the product; • ADPM of the product; • AP of the product; • EP of the product;

	• GWP of the product; • ODP of the product; • POCP of the product; • PE-NRe of the product; • PE-Re of the product; • density of the product; • maintenance costs of the product; • maintenance period of the product; • durability of the product; • life cycle costs of a product.

er_insert_environmental/economic_information_in_objects

Type	Data Object
Name	er_insert_environmental/economic_information_in_objects
Documentation	The scope of this exchange requirement is the exchange of information between the documentation that the LCA/LCC specialist have with the BIM model. After the specialist collects all the required environmental and economic information to perform the LCA and LCC analysis of the study, it is necessary to insert it in the BIM model(s). The specialist can insert the information directly in the objects (i.e. elements) and/or in the materials. Each indicator represents an environmental impact category (e.g. GWP, AP), acquisition cost, or a mechanical property (i.e. durability and density) of the product. These indicators must be inserted as parameters in the objects/materials. Information provided through this exchange requirement includes: • ADPE of the product; • ADPM of the product; • AP of the product; • EP of the product; • GWP of the product; • ODP of the product; • POCP of the product; • PE-NRe of the product; • PE-Re of the product; • density of the product; • durability of the product; • acquisition cost of the product.

er_obtain_STREAMLINED_LCA/LCC_results

Type	Data Object
Name	er_obtain_STREAMLINED _LCA/LCC_results
Documentation	This exchange requirement covers the information exchanged between the BIM model and the LCA/LCC specialist, in which the specialist obtains the LCA and LCC results of a STREAMLINED analysis. The STREAMLINED analysis consist in the assessment of the environmental and economic impacts of the A1-A3 modules, i.e. the impacts from the products manufacturing process alone. After the specialist introduces all the information to be analysed, it is now possible to obtain an initial analysis based on the information contained in the model alone. If the information was already contained in the model, then this type of analysis can be done in an automatic fashion. Afterwards, the specialist can extract the LCA/LCC results of a STREAMLINED analysis. Information provided through this exchange requirement includes (for A1-A3 modules): • total ADPE of the project; • total ADPM of the project; • total AP of the project; • total EP of the project; • total GWP of the project; • total ODP of the project; • total POCP of the project; • total PE-NRe of the project; • total PE-Re of the project; • total costs of the project.

er_obtain_COMPLETE_LCA/LCC_results

Type	Data Object
Name	er_obtain_COMPLETE_LCA/LCC_results
Documentation	This exchange requirement covers the information exchanged between the BIM model and the LCA/LCC specialist, in which the specialist obtains the LCA and LCC results of a COMPLETE analysis. The COMPLETE analysis consist in the assessment of the environmental and economic impacts of the A + B + C + D modules, i.e. the impacts from the products' manufacturing process (A1-A3), transportation (A4), construction (A5), maintenance (B2-B4) and operational consumption (B6-B7), end-of-life (C2-C4), and beyond the system boundary (D). If the specialist decided to conduct a COMPLETE LCA and LCC analysis, several site-specific information that will have an impact on the results must be considered. The more information is considered, the more accurate the result is.

	Information provided through this exchange requirement includes (for A-D modules): • total ADPE of the project; • total ADPM of the project; • total AP of the project; • total EP of the project; • total GWP of the project; • total ODP of the project; • total POCP of the project; • total PE-NRe of the project; • total PE-Re of the project; • total costs of the project.

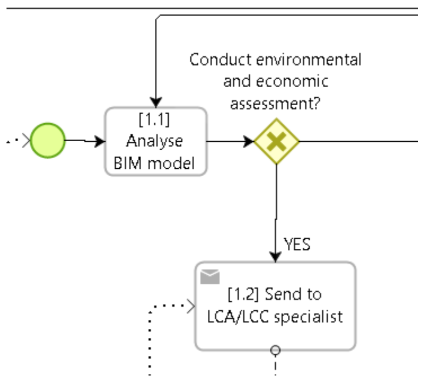
er_exchange_LCA/LCC_report

Type	Data Object
Name	er_exchange_LCA/LCC_report
Documentation	This exchange requirement represents the main goal of the 'BIM-LCA/LCC analysis' process map. It covers the information exchanged between the LCA/LCC specialist and the BIM Manager, in which the specialist delivers a report on the environmental and economic impacts of the project. Based on the expertise of the LCA/LCC specialist, the BIM Manager will have access to more information (e.g. national or international benchmarks and highest contributions of materials) that will help in the decision-making process. If necessary, the BIM Manager can suggest modifications to the project (e.g. select more environmentally friendly products or products that have lower life cycle costs). Information provided through this exchange requirement includes: • total ADPE of the project (**mandatory**); • total ADPM of the project (**mandatory**); • total AP of the project (**mandatory**); • total EP of the project (**mandatory**); • total GWP of the project (**mandatory**); • total ODP of the project (**mandatory**); • total POCP of the project (**mandatory**); • total PE-NRe of the project (**mandatory**); • total PE-Re of the project (**mandatory**); • total costs of the project (**mandatory**); • list of environmental impact of each material used in the project, as well as the corresponding functional unit and estimated durability (**mandatory**);

	• lifespan of the asset (**mandatory**); • discount rate (**mandatory**); • list of possible scenarios for waste treatment (**optional**); • list of the amount of recycled materials (**optional**); • set of pictures of the BIM model in which the elements (e.g. walls, windows) are grouped based on their environmental and economic impacts, by using a colour scheme (**optional**); • BIM model with environmental and economic information (**optional**).

A.1.4. Specification of Coordination Point Gateways

Conduct environmental and economic assessment?

Type	Exclusive Gateway
Name	Conduct environmental and economic assessment?
Documentation	The first gateway's purpose is to outline the BIM Manager decision on whether an environmental and economic analysis should be conducted (Figure A.3).  Figure A.3 - Conduct environmental and economic assessment? If 'Yes', the next process is Task [1.2], which is send the information to the LCA/LCC specialist, if 'No', then the BIM model will be proposed to the client as it is.

Every party agrees with the model?

Type	Exclusive Gateway
Name	Every party agrees with the model?
Documentation	This gateway represents the last decision of the BIM-LCA/LCC process map (Figure A.4). It represents the decision that the BIM Manager must make regarding the project's design (i.e. type of elements and materials used).

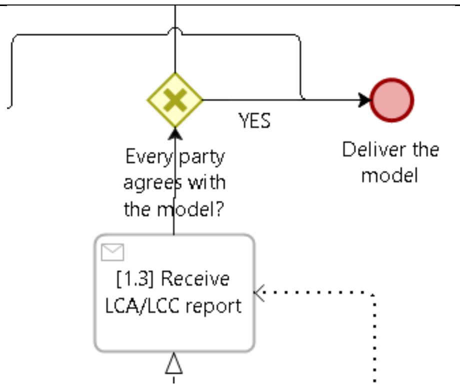


Figure A.4 - Every party agrees with the model?

If the BIM Manager, as well as other parties involved in the decision-making process, agree with the project's design and BIM model, then all the relevant documentation shall be delivered to the client. If the decision is negative, taking into consideration the LCA/LCC specialist's report, then the BIM Manager should contact all the parties that need to make changes to their model (e.g. structural engineer) and re-analyse the BIM models again. It is up to the BIM Manager to send the updated BIM model to the specialist again.

Does the model has the required information?

Type	Exclusive Gateway
Name	Does the model have the required information?
Documentation	This gateway represents the results of an initial verification of the BIM model performed by the LCA/LCC specialist (Figure A.5).

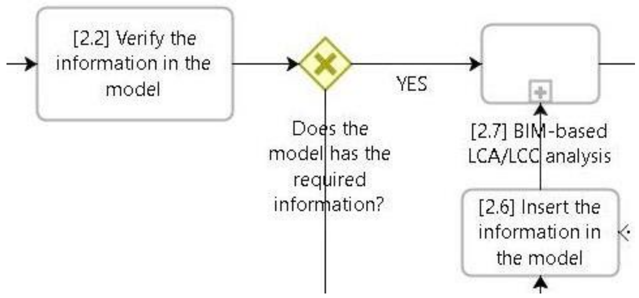
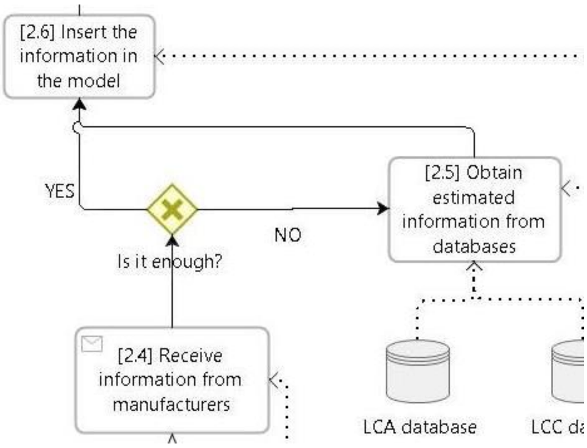


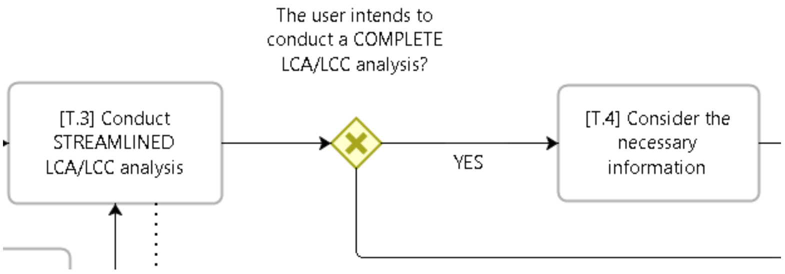
Figure A.5 - Does the model have the required information?

The LCA/LCC specialist will, as soon as the model is obtained, verify if there is environmental and economic information contained in its elements and materials. If not, then the specialist will contact the manufacturers of the materials/elements that do not have information in order to obtain the necessary information. If the BIM model already contains the necessary environmental and economic information, then it is already possible to conduct the LCA and LCC analysis.

Is it enough?

Type	Exclusive Gateway
Name	Is it enough?
Documentation	The feedback of the manufacturers will be the cornerstone of this gateway (Figure A.6).  Figure A.6 - Is it enough? If the information provided by the manufacturers is enough for the LCA/LCC specialist (i.e. environmental and/or economic data was provided), then it can be inserted in the model. If not, then the specialist must resort, if desired, to LCA/LCC databases to obtain estimated values for the product(s) that are lacking that information.

The user intends to conduct a COMPLETE LCA/LCC analysis?

Type	Exclusive Gateway
Name	The user intends to conduct a COMPLETE LCA/LCC analysis?
Documentation	This gateway represents the decision of the LCA/LCC specialist to conduct a COMPLETE LCA and LCC analysis (Figure A.*7*).  Figure A.7 - The user intends to conduct a COMPLETE LCA/LCC analysis?

	If the specialist decides to conduct the COMPLETE analysis (or if the BIM Manager asked for it), then site-specific information must be considered. That information will enable the environmental and economic assessment of the project's life cycle, from cradle to cradle. If the specialist decides to not conduct the COMPLETE analysis, then a report can be elaborated and delivered to the BIM Manager.

Annex A.2 – Table that lists the IFC properties required for the BIM-LCA/LCC analysis

Table A.1 - List of properties required for the information exchange within the BIM-LCA/LCC analysis

Information required	Description	IFC PropertySet
Project level	*Required information that is site-specific and should be provided by the user*	*Pset_BuildingCommon contains the properties common to the definition of all instances of IfcBuilding*
Lifespan of the building	Represents the expected estimated service life of the asset.	*Pset_BuildingCommon.**Pset_ProjectLifeSpan** → IfcTimeMeasure*
Discount rate	Represents the expected discount rate that the project will be subject to during its life cycle	*Pset_BuildingCommon.**Pset_ProjectDiscountRate** → IfcReal*
Utilities consumption (A5)	Represents the expected utilities consumption during the construction phase of the project	*Pset_BuildingCommon.**Pset_ProjectConstructionElectricity** → IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectConstructionWater** → IfcReal* *Pset_BuildingCommon.**Pset_ProjectConstructionNaturalGas** → IfcReal*
Utilities consumption (B)	Represents the expected utilities consumption during the operation phase of the project	*Pset_BuildingCommon.**Pset_ProjectOperationElectricity** → IfcReal* *Pset_BuildingCommon.**Pset_ProjectOperationWater** → IfcReal* *Pset_BuildingCommon.**Pset_ProjectOperationNaturalGas** → IfcReal*
ADPE (utilities)	Represents the consumption of natural resources (fossil fuels)	*Pset_BuildingCommon.**Pset_ProjectElectricityADPE** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterADPE** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasADPE** → IfcMassMeasure*
ADPM (utilities)	Represents the consumption of natural resources (materials)	*Pset_BuildingCommon.**Pset_ProjectElectricityADPM** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterADPM** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasADPM** → IfcMassMeasure*
AP (utilities)	Represents the contribution of anthropogenic emissions for the decrease of water's pH, i.e. acidification of the water and soil.	*Pset_BuildingCommon.**Pset_ProjectElectricityAP** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterAP** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasAP** → IfcMassMeasure*
EP (utilities)	Represents the impacts of the oversupply of nutrients (e.g. Nitrogen and Phosphorous) in the ecosystems which, in turn, will change the quality of water, soil and species composition.	*Pset_BuildingCommon.**Pset_ProjectElectricityEP** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterEP** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasEP** → IfcMassMeasure*
GWP (utilities)	Represents the global warming effect caused by greenhouse gas emissions.	*Pset_BuildingCommon.**Pset_ProjectElectricityGWP** → IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterGWP** →*

Information required	Description	IFC PropertySet
		IfcMassMeasure *Pset_BuildingCommon.**Pset_ProjectNaturalGasGWP*** → *IfcMassMeasure*
ODP (utilities)	Represents the amount of ozone destroyed by a gas over its lifetime.	*Pset_BuildingCommon.**Pset_ProjectElectricityODP*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterODP*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasODP*** → *IfcMassMeasure*
POCP (utilities)	It is caused mainly by road traffic, solar radiation, and poor geographical conditions for air flow, contributing to the ozone creation.	*Pset_BuildingCommon.**Pset_ProjectElectricityPOCP*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterPOCP*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasPOCP*** → *IfcMassMeasure*
PE-NRe (utilities)	Represents the amount of energy consumed using non-renewable sources.	*Pset_BuildingCommon.**Pset_ProjectElectricityPE-NRe*** → *IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterPE-NRe*** → *IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasPE-NRe*** → *IfcEnergyMeasure*
PE-Re (utilities)	Represents the amount of energy consumed using renewable sources.	*Pset_BuildingCommon.**Pset_ProjectElectricityPE-Re*** → *IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterPE-Re*** → *IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasPE-Re*** → *IfcEnergyMeasure*
Cost (utilities)	Represents the cost one must pay to acquire a specific product.	*Pset_BuildingCommon.**Pset_ProjectElectricityCost*** → *IfcMonetaryMeasure* *Pset_BuildingCommon.**Pset_ProjectWaterCost*** → *IfcMonetaryMeasure* *Pset_BuildingCommon.**Pset_ProjectNaturalGasCost*** → *IfcMonetaryMeasure*
ADPE (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDADPE*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEADPE*** → *IfcMassMeasure*
ADPM (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDADPM*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEADPM*** → *IfcMassMeasure*
AP (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDAP*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEAP*** → *IfcMassMeasure*
EP (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDEP*** → *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEEP*** → *IfcMassMeasure*
GWP (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDGWP*** →

Information required	Description	IFC PropertySet
		IfcMassMeasure *Pset_BuildingCommon.**Pset_ProjectCOMPLETEGWP** →* *IfcMassMeasure*
ODP (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDODP** →* *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEODP** →* *IfcMassMeasure*
POCP (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDPOCP** →* *IfcMassMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEPOCP** →* *IfcMassMeasure*
PE-NRe (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDPE-NRe** →* *IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEPE-NRe** →* *IfcEnergyMeasure*
PE-Re (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDPE-Re** →* *IfcEnergyMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETEPE-Re** →* *IfcEnergyMeasure*
Cost (LCA/LCC results)	*(description above)*	*Pset_BuildingCommon.**Pset_ProjectSTREAMLINEDCost** →* *IfcMonetaryMeasure* *Pset_BuildingCommon.**Pset_ProjectCOMPLETECost** →* *IfcMonetaryMeasure*
Object level (i.e. element)	*Required information that is element-specific and should be included in BIM objects*	*Elements already contain most of the specific properties within the PropertySet Pset_EnvironmentalImpactIndicators*
Durability	The lifespan of an element (i.e. its durability)	*IfcElement.ExpectedServiceLife → IfcTimeMeasure*
Density	The density of an element	***IfcPhysicalQuantity.Pset_Density*** *→ IfcMassDensityMeasure*
Quantity	*Representation of the element's quantities*	*IfcPhysicalSimpleQuantity.IfcQuantityArea → IfcAreaMeasure* *IfcPhysicalSimpleQuantity.IfcQuantityVolume →* *IfcVolumeMeasure* *IfcPhysicalSimpleQuantity.IfcQuantityCount → IfcCountMeasure* *IfcPhysicalSimpleQuantity.**Pset_QuantityThickness** →* *IfcLengthMeasure*
ADPE	*(description above)*	*Pset_EnvironmentalImpactIndicators.* ***Pset_ResourceDeplitionFossilPerUnit*** *→ IfcMassMeasure*
ADPM	*(description above)*	*Pset_EnvironmentalImpactIndicators.ResourceDepletionPerUnit →* *IfcMassMeasure*
AP	*(description above)*	*Pset_EnvironmentalImpactIndicators.* *AtmosphericAcidificationPerUnit → IfcMassMeasure*
EP	*(description above)*	*Pset_EnvironmentalImpactIndicators.EutrophicationPerUnit →* *IfcMassMeasure*
GWP	*(description above)*	*Pset_EnvironmentalImpactIndicators.ClimateChangePerUnit →* *IfcMassMeasure*
ODP	*(description above)*	*Pset_EnvironmentalImpactIndicators.* *StratosphericOzoneLayerDestructionPerUnit → IfcMassMeasure*
POCP	*(description above)*	*Pset_EnvironmentalImpactIndicators.* *PhotochemicalOzoneFormationPerUnit → IfcMassMeasure*
PE-NRe	*(description above)*	*Pset_EnvironmentalImpactIndicators.*

Information required	Description	IFC PropertySet
PE-Re	*(description above)*	*NonRenewableEnergyConsumptionPerUnit → IfcEnergyMeasure* *Pset_EnvironmentalImpactIndicators.* *RenewableEnergyConsumptionPerUnit → IfcEnergyMeasure*
Cost	*(description above)*	*IfcCostValue.AppliedValue → IfcMonetaryMeasure*
Construction Activities costs	*The costs of all activities required to assemble a specific element*	*IfcCostValue.**Pset_AssemblyCost** → IfcMonetaryMeasure*
Material level	*Required information that is material-specific and should be included in BIM objects*	*As materials do not contain specific properties for the LCA and LCC analysis, the PropertySet **Pset_MaterialEnvironmentalImpacts** was created in the IfcProperty entity. However, the existing PropertySet Pset_MaterialCommon contains some of the required information*
Durability	The lifespan of a material (i.e. its durability)	*Pset_MaterialCommon.**Pset_Material_Lifespan** → IfcTimeMeasure*
Density	The density of a material	*Pset_MaterialCommon.MassDensity → IfcMassDensityMeasure*
Quantity	*Representation of the material's quantities*	*IfcMaterialLayerSet.TotalThickness → IfcLengthMeasure* *IfcMaterialLayerSet.**Pset_MaterialVolume** → IfcVolumeMeasure*
ADPE	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ResourceDeplitionFossilPerUnit**→ IfcMassMeasure*
ADPM	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ResourceDepletionPerUnit** → IfcMassMeasure*
AP	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_AtmosphericAcidificationPerUnit** → IfcMassMeasure*
EP	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_EutrophicationPerUnit** → IfcMassMeasure*
GWP	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ClimateChangePerUnit** → IfcMassMeasure*
ODP	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_StratosphericOzoneLayerDestructionPerUnit** →* *IfcMassMeasure*
POCP	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_PhotochemicalOzoneFormationPerUnit** → IfcMassMeasure*
PE-NRe	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_NonRenewableEnergyConsumptionPerUnit** →* *IfcEnergyMeasure*
PE-Re	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_RenewableEnergyConsumptionPerUnit** → IfcEnergyMeasure*
Cost	*(description above)*	*Pset_MaterialEnvironmentalImpacts.**Pset_AppliedValue** →* *IfcMonetaryMeasure*
ADPE (A4)	The ADPE impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ResourceDepletionFossilPerUnitA4**→ IfcMassMeasure*
ADPM (A4)	The ADPM impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ResourceDepletionPerUnitA4** → IfcMassMeasure*
AP (A4)	The AP impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_AtmosphericAcidificationPerUnitA4** → IfcMassMeasure*
EP (A4)	The EP impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_EutrophicationPerUnitA4** → IfcMassMeasure*
GWP (A4)	The GWP impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ClimateChangePerUnitA4** → IfcMassMeasure*
ODP (A4)	The ODP impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_StratosphericOzoneLayerDestructionPerUnitA4** →* *IfcMassMeasure*

Information required	Description	IFC PropertySet
POCP (A4)	The POCP impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_PhotochemicalOzoneFormationPerUnitA4*** → *IfcMassMeasure*
PE-NRe (A4)	The PE-NRe impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_NonRenewableEnergyConsumptionPerUnitA4*** → *IfcEnergyMeasure*
PE-Re (A4)	The PE-Re impact due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_RenewableEnergyConsumptionPerUnitA4*** → *IfcEnergyMeasure*
Cost (A4)	The costs due to the transportation of the material	*Pset_MaterialEnvironmentalImpacts.****Pset_AppliedValueA4*** → *IfcMonetaryMeasure*
Transportation (A4)	*The distance between supplier of a material and the construction site*	*Pset_MaterialEnvironmentalImpacts.****Pset_DistanceA4*** → *IfcReal*
ADPE (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ResourceDeplitionFossilPerUnitC2*** → *IfcMassMeasure*
ADPM (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ResourceDepletionPerUnitC2*** → *IfcMassMeasure*
AP (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_AtmosphericAcidificationPerUnitC2*** → *IfcMassMeasure*
EP (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_EutrophicationPerUnitC2*** → *IfcMassMeasure*
GWP (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_ClimateChangePerUnitC2*** → *IfcMassMeasure*
ODP (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_StratosphericOzoneLayerDestructionPerUnitC2*** → *IfcMassMeasure*
POCP (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_PhotochemicalOzoneFormationPerUnitC2*** → *IfcMassMeasure*
PE-NRe (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_NonRenewableEnergyConsumptionPerUnitC2*** → *IfcEnergyMeasure*
PE-Re (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_RenewableEnergyConsumptionPerUnitC2*** → *IfcEnergyMeasure*
Cost (C2)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.****Pset_AppliedValueC2*** → *IfcMonetaryMeasure*
Transportation (C2)	*The distance between demolition site and the waste treatment for a material*	*Pset_MaterialEnvironmentalImpacts.****Pset_DistanceC2*** → *IfcReal*
Percentage of Waste (A5)	The percentage of waste generated during construction activities of a specific material	*Pset_MaterialEnvironmentalImpacts.****Pset_WastePercentageA5*** → *IfcReal*
Name of Waste Processing	Name of the waste processing that is expected for a specific material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_MaterialWasteProcessingName*** → *IfcText*
Percentage of Waste Processing	Percentage of a material that is expected to be processed (e.g. recycled).	*Pset_MaterialEnvironmentalImpacts.* ***Pset_MaterialWasteProcessingPercentage*** → *IfcReal*
Name of Waste Disposal	Name of the waste disposal that is expected for a specific material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_MaterialWasteDisposalName*** → *IfcText*
Percentage of Waste Disposal	Percentage of a material that is expected to be disposed (e.g. landfill).	*Pset_MaterialEnvironmentalImpacts.* ***Pset_MaterialWasteDisposalPercentage*** → *IfcReal*

Information required	Description	IFC PropertySet
ADPE (WP)	The ADPE impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_ADPE*** → *IfcMassMeasure*
ADPM (WP)	The ADPM impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_ADPM*** → *IfcMassMeasure*
AP (WP)	The AP impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_AP*** → *IfcMassMeasure*
EP (WP)	The EP impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_EP*** → *IfcMassMeasure*
GWP (WP)	The GWP impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_GWP*** → *IfcMassMeasure*
ODP (WP)	The ODP impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_ODP*** → *IfcMassMeasure*
POCP (WP)	The POCP impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_POCP*** → *IfcMassMeasure*
PE-NRe (WP)	The PE-NRe impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_PE-NRe*** → *IfcEnergyMeasure*
PE-Re (WP)	The PE-Re impact caused by the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_PE-Re*** → *IfcEnergyMeasure*
Cost (WP)	The cost or profit due to the Waste Processing of a material	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WP_Cost*** → *IfcMonetaryMeasure*
ADPE (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_ADPE*** → *IfcMassMeasure*
ADPM (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_ADPM*** → *IfcMassMeasure*
AP (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_AP*** → *IfcMassMeasure*
EP (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_EP*** → *IfcMassMeasure*
GWP (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_GWP*** → *IfcMassMeasure*
ODP (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_ODP*** → *IfcMassMeasure*
POCP (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_POCP*** → *IfcMassMeasure*
PE-NRe (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_PE-NRe*** → *IfcEnergyMeasure*
PE-Re (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_PE-Re*** → *IfcEnergyMeasure*
Cost (WD)	*(description above)*	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_WD_Cost*** → *IfcMonetaryMeasure*
Percentage of Waste (SM)	Percentage of secondary material to be used in the manufacturing process (i.e. percentage of material recovered from other systems to replace primary materials)	*Pset_MaterialEnvironmentalImpacts.* ***Pset_Material_SM_Percentage*** → *IfcReal*

Annex A.3 – Tables for the elements and materials used in the Pilot Case Study

Table A.2 - List of elements in the pilot case study

No.	Type of element	Name of element	Thickness (mm)	Area (m^2)	Volume (m^3)	Quantity (Unit)
1	Ceilings	Ceiling #1	0	386.41	7.73	0
2		Ceiling #2	0	64.64	0.97	0
3		Ceiling #3	0	215.80	8.63	0
4	Doors	Hardwood door 1130x2315	0	2.94	0.04	2
5		Hardwood door 680x2315	0	1.94	0.04	2
6		Hardwood door 880x2315	0	2.42	0.04	26
7		Hardwood door 880x2315 (glazed)	0	3.22	0.08	5
8		Hardwood door 930x2315	0	2.53	0.04	4
9		Hardwood door 930x2315 (glazed)	0	2.53	0.04	2
10		Hardwood double door 2x880x2315	0	4.51	0.05	6
11		Revolving Door	0	7.33	0.59	1
12		Exterior Door	0	0.00	0.11	6
13	Floors	Concrete slab 200mm	200	116.32	23.26	0
14		EPS 140mm	140	355.32	49.75	0
15		Exterior Stairs #1	0	3.42	0.41	0
16		Exterior Stairs #2	0	3.34	0.41	0
17		Floor #1	200	27.75	5.55	0
18		Floor #2	325	920.37	299.12	0
19		Floor #3	380	976.26	370.98	0
20		Floor #4	0	17.26	3.03	0
21		Floor #5	0	14.53	2.54	0
22		Flooring #1	80	1731.20	138.50	0
23		Ground Floor Slab	390	721.77	281.49	0
24		Main Stair steps	66	35.41	2.34	0
25		Perforated Plasterboard Ceiling	30	43.53	1.31	0
26	Roofs	Roofing #1	217.9	1030.26	224.10	0
27		Steel Canopy #1	0	27.58	18.45	0

No.	Type of element	Name of element	Thickness (mm)	Area (m^2)	Volume (m^3)	Quantity (Unit)
28		Steel Canopy #2	0	27.58	18.45	0
29		Steel Canopy #3	0	27.76	18.64	0
30		Steel Canopy #4	0	83.96	56.66	0
31		Steel Canopy #5	0	82.95	55.49	0
32		Steel Canopy #6	0	83.92	56.49	0
33		Steel Canopy #7	0	63.74	0.42	0
34		Steel Deck Roof	0.8	53.99	0.04	0
35	Stairs	Stairs #1	0	0.00	7.17	0
36		Stairs #2	0	0.00	4.17	0
37	Columns	Concrete Column 250x250	0	0.00	0.42	0
38		SHS250x10	0	0.00	0.61	0
39		SHS250x12.5	0	0.00	0.81	0
40		SHS250x16	0	0.00	0.15	0
41		SHS250x8	0	0.00	0.49	0
42		SHS300x10	0	0.00	0.46	0
43		SHS300x12.5	0	0.00	0.23	0
44		SHS300x16	0	0.00	0.14	0
45	Foundations	Concrete Pile 320x320	0	0.00	129.40	0
46		Concrete Pile Heads 2100x1875x850	0	0.00	10.14	0
47		Concrete Pile Heads 2200x700x850	0	0.00	5.20	0
48		Concrete Pile Heads 2200x800x850	0	0.00	4.46	0
49		Concrete Pile Heads 2300x12300x850	0	0.00	8.95	0
50		Concrete Pile Heads 700x800x850	0	0.00	1.43	0
51		Foundation Wall 450x400	0	0.00	1.13	0
52		Foundation Wall 500x600	0	0.00	26.76	0
53		Foundation Wall 600x600	0	0.00	36.98	0
54	Framing	25x260mm	0	0.00	0.03	0
55		25x330mm	0	0.00	0.01	0
56		25x360mm	0	0.00	0.01	0
57		70x25mm	0	0.00	0.00	0
58		70x30mm	0	0.00	0.00	0

No.	Type of element	Name of element	Thickness (mm)	Area (m^2)	Volume (m^3)	Quantity (Unit)
59		HEA240	0	0.00	0.08	0
60		HEB240	0	0.00	0.10	0
61		IFB300x20+300x25&560x35mm	0	0.00	2.58	0
62		IFB300x20+300x40&560x35mm	0	0.00	0.84	0
63		IFB300x30+300x40&560x35mm	0	0.00	0.82	0
64		IFB360x20+300x25&560x35mm	0	0.00	2.24	0
65		IFB360x20+300x40&560x35mm	0	0.00	1.13	0
66		IFB360x30+300x40&560x35mm	0	0.00	1.13	0
67		L150x15	0	0.00	0.02	0
68		L200x150x15 for 265mm HC	0	0.00	0.02	0
69		L200x150x15 for 320mm HC	0	0.00	0.02	0
70		L50x5	0	0.00	0.01	0
71		L60x5	0	0.00	0.16	0
72		RHS120x60x8	0	0.00	0.03	0
73		SHS100x6.3	0	0.00	0.20	0
74		SHS120x5	0	0.00	0.05	0
75		SHS120x8	0	0.00	0.25	0
76		SHS50x3	0	0.00	0.00	0
77		SHS50x3.2	0	0.00	0.02	0
78		SHS60x4	0	0.00	0.03	0
79		SHS80x4	0	0.00	0.02	0
80		SHS80x6.3	0	0.00	0.00	0
81		Steel Beam 300-15x466x3	0	0.00	0.03	0
82		Steel Beam 400-15x330x5	0	0.00	0.08	0
83		Steel Beam 400-15x470x5	0	0.00	0.05	0
84		Steel Beam 400x300x3+2x 15x3	0	0.00	0.05	0
85	**Walls**	Concrete Foundation Wall #1	150	174.98	26.25	0
86		Concrete Foundation Wall #2	50	72.75	3.64	0
87		Concrete Foundation Wall #3	200	95.32	19.03	0
88		Concrete Wall #1	202	331.38	66.75	0
89		Concrete Wall #2	252	10.54	2.59	0

No.	Type of element	Name of element	Thickness (mm)	Area (m^2)	Volume (m^3)	Quantity (Unit)
90		EPS Wall 140mm	140	229.13	32.08	0
91		EPS Wall 160mm	160	10.20	1.63	0
92		Glazed Curtain Walls	25	742.34	0.00	0
93		Glazed Partition Walls	25	672.03	0.00	0
94		Main Stair Railway	200	42.11	8.36	0
95		Partition Wall #1	103	1013.40	104.35	0
96		Partition Wall #2	203	143.84	28.95	0
97		Partition Wall #3	303	6.90	2.09	0
98		Partition Wall #4	403	13.24	5.33	0
99		Partition Wall #5	73	99.95	7.29	0
100	**Windows**	Rooflight Window	0	1.44	0.27	1
101		Façade Window	0	0.00	0.05	25
102		Longlight Window	0	24.00	1.37	4

Table A.3 - List of materials in the pilot case study

No.	Name of material	Volume (m^3)
1	Aluminium 30mm	1.31
2	Aluminium - Rooflight Window (dummy)	0.00
3	Aluminum - Revolving Door (dummy)	0.22
4	Aluminium – Exterior Door (dummy)	0.33
5	Aluminium - Facade Window (dummy)	0.44
6	Aluminium - Longlight Window (dummy)	0.30
7	Bamboo 20mm	0.71
8	Bamboo Main Stair	8.36
9	Bitumen layer 6.9mm	7.07
10	EPS Insulation 130mm	93.83
11	EPS Insulation 140mm	81.82
12	EPS Insulation 160mm	1.63
13	EPS Insulation 20mm	34.62
14	EPS Insulation 210mm	216.01
15	Glass (Glazed Partition Wall)	7.06

No.	Name of material	Volume (m^3)
16	Glass Wool 15mm	0.97
17	Glass Wool 20mm	7.73
18	Glass Wool 40mm	8.63
19	Glass Wool 45mm	4.50
20	Glass Wool 50mm	50.66
21	Glass Wool 75mm	12.21
22	Gypsum Wall Board 12.5mm	57.22
23	Hardwood doors - 1130x2315 (dummy)	0.09
24	Hardwood doors - 680x2315 (dummy)	0.08
25	Hardwood doors - 880x2315 (dummy)	1.12
26	Hardwood doors - 880x2315 (glazed) (dummy)	0.36
27	Hardwood doors - 930x2315 (dummy)	0.17
28	Hardwood doors - 930x2315 (glazed) (dummy)	0.09
29	Hardwood double door - 2x880x2315 (dummy)	0.30
30	Metal – Steel	224.63
31	Paint	3.23
32	Partition Wall framework #1	1.01
33	Partition Wall framework #2	0.16
34	Partition Wall framework #3	0.10
35	Precast Concrete 200mm	89.35
36	Precast Concrete 250mm	2.57
37	Precast Hollow Core 150mm	4.16
38	Precast Hollow Core 200mm	144.35
39	Precast Hollow Core 265mm	243.90
40	Precast Hollow Core 320mm	312.40
41	Reinforced Concrete	276.60
42	Screed 46mm	1.63
43	Screed 50mm	1.39
44	Screed 60mm	260.98
45	Structural Steel	9.61
46	Structural Steel - Hollow Sections	3.42
47	Triple Glass (Glazed Curtain Wall)	58.86
48	Vapor Barrier PE 0.2mm	1.02

Table A.4 - Composition of each construction element used in the pilot case study

No.	Composition of each element
1	Glass Wool 20mm
2	Glass Wool 15mm
3	Glass Wool 40mm
4	Hardwood door 1130x2315 (dummy)
5	Hardwood door 680x2315 (dummy)
6	Hardwood door 880x2315 (dummy)
7	Hardwood door 880x2315 (glazed) (dummy)
8	Hardwood door 930x2315 (dummy)
9	Hardwood door 930x2315 (glazed) (dummy)
10	Hardwood double door 2x880x2315 (dummy)
11	Glass; Wood; Metal – Panel; Rubber; Aluminum - Revolving Door (dummy)
12	Glass doors; Aluminum - Exterior Door (dummy)
13	Precast Concrete 200mm
14	EPS Insulation 140mm
15-16	Reinforced Concrete
17	Screed 50mm; Precast Hollow Core 150mm
18	Screed 60mm; Precast Hollow Core 265mm
19	Screed 60mm; Precast Hollow Core 320mm
20-21	Reinforced Concrete
22	Screed 60mm; EPS Insulation 20mm
23	Screed 60mm; Precast Hollow Core 200mm; EPS Insulation 130mm
24	Bamboo 20mm; Screed 46mm
25	Aluminium 30mm
26	Bitumen layer 6.9mm; Vapor Barrier PE 0.2mm; EPS Insulation 210mm
27-34	Metal – Steel
35-37	Reinforced Concrete
38-44	Structural Steel - Hollow Sections
45-53	Reinforced Concrete
54-71	Structural Steel
72-80	Structural Steel - Hollow Sections
81-84	Structural Steel
85-87	Reinforced Concrete

No.	Composition of each element
88	Paint; Precast Concrete 200mm; Paint
89	Paint; Precast Concrete 250mm; Paint
90	EPS Insulation 140mm
91	EPS Insulation 160mm
92	Triple Glass (Glazed Curtain Wall)
93	Glass (Glazed Partition Wall)
94	Bamboo Main Stair
95	Paint; Gypsum Wall Board 12.5mm; Gypsum Wall Board 12.5mm; Partition Wall framework #1; Glass Wool 50mm; Gypsum Wall Board 12.5mm; Gypsum Wall Board 12.5mm; Paint
96	Paint; Gypsum Wall Board 12.5mm; Air Barrier - Air Infiltration Barrier; Partition Wall framework #2; Glass Wool 75mm; Air Barrier - Air Infiltration Barrier; Gypsum Wall Board 12.5mm; Paint
97	Paint; Gypsum Wall Board 12.5mm; Air Barrier - Air Infiltration Barrier; Partition Wall framework #2; Glass Wool 75mm; Air Barrier - Air Infiltration Barrier; Gypsum Wall Board 12.5mm; Paint
98	Paint; Gypsum Wall Board 12.5mm; Air Barrier - Air Infiltration Barrier; Partition Wall framework #2; Glass Wool 75mm; Air Barrier - Air Infiltration Barrier; Gypsum Wall Board 12.5mm; Paint
99	Paint; Gypsum Wall Board 12.5mm; Partition Wall framework #3; Glass Wool 45mm; Gypsum Wall Board 12.5mm; Paint
100	ISR_Kozijn; Aluminium; Gorter_Material 1; Aluminum - Rooflight Window (dummy)
101	RR_31_glas; Aluminum – Facade Window (dummy)
102	Triple Glass; VELUX Aluminium; Skylight Aluminium; Skylight Glassfibre Insulation; RR_aluminium_RAL 9010; Aluminium Roof Longlight; Aluminum - Longlight Window (dummy)

Table A.5 - Environmental and economic impacts per functional unit of the construction elements (A1-A3 modules)

Element no.	Functional Unit	Density (kg/m^3)	Lifespan (years)	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
1	m^2	78.0	50	5.4E+1	5.3E-7	1.7E-2	2.5E-3	3.0E+0	3.9E-7	1.0E-3	7.4E+1	3.0E+1	23.9
2	m^2	54.0	50	4.1E+1	3.8E-7	1.3E-2	1.6E-3	2.2E+0	3.3E-7	8.1E-4	5.1E+1	2.4E+1	28.3
3	m^2	71.0	50	7.1E+1	6.4E-7	2.3E-2	3.2E-3	4.0E+0	5.0E-7	1.3E-3	9.6E+1	3.4E+1	27.4
4	pc	715.0	30	1.7E+3	2.9E-3	2.8E-1	5.4E-2	-1.4E+1	1.1E-5	5.4E-2	1.8E+3	2.0E+3	280.0
5	Pc	715.0	30	9.9E+2	1.7E-3	1.6E-1	3.2E-2	-8.2E+0	6.5E-6	3.2E-2	1.1E+3	1.2E+3	230.0
6	Pc	715.0	30	1.3E+3	2.3E-3	2.1E-1	4.1E-2	-1.1E+1	8.5E-6	4.2E-2	1.4E+3	1.5E+3	245.0
7	Pc	715.0	30	1.3E+3	2.3E-3	2.2E-1	4.2E-2	-1.1E+1	8.7E-6	4.3E-2	1.4E+3	1.6E+3	290.0
8	Pc	715.0	30	1.4E+3	2.4E-3	2.3E-1	4.4E-2	-1.1E+1	8.9E-6	4.4E-2	1.5E+3	1.6E+3	260.0
9	Pc	715.0	30	1.4E+3	2.4E-3	2.3E-1	4.4E-2	-1.1E+1	9.0E-6	4.4E-2	1.5E+3	1.6E+3	305.0
10	Pc	715.0	30	2.5E+3	4.4E-3	4.1E-1	8.0E-2	-2.1E+1	1.6E-5	8.1E-2	2.7E+3	2.9E+3	820.0
11	Pc	35.0	20	3.5E+4	5.0E-2	1.3E+1	1.1E+0	2.9E+3	7.8E-7	8.7E-1	4.1E+4	9.8E+3	32000.0
12	Pc	433.1	50	4.5E+3	2.3E-3	1.3E+0	1.5E-1	3.7E+2	8.8E-6	1.3E-1	5.2E+3	8.7E+2	1113.8
13	m^2	2352.2	100	9.0E+2	3.3E-4	4.0E-1	1.6E-1	9.4E+1	5.0E-6	5.1E-2	1.1E+3	5.4E+1	53.7

Element no.	Functional Unit	Density (kg/m^3)	Lifespan (years)	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
14	m^2	25.0	100	3.2E+2	2.1E-6	2.7E-2	2.5E-3	1.1E+1	3.9E-7	5.9E-2	3.3E+2	2.0E+0	314.3
15	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
16	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
17	m^2	1950.0	50	4.0E+2	8.9E-5	1.5E-1	4.3E-2	6.4E+1	2.1E-6	7.9E-3	4.0E+2	7.5E+1	43.2
18	m^2	1990.8	50	6.4E+2	1.6E-4	2.5E-1	7.4E-2	1.1E+2	3.8E-6	1.3E-2	6.6E+2	1.2E+2	48.2
19	m^2	1992.1	50	7.5E+2	1.9E-4	3.0E-1	8.9E-2	1.3E+2	4.6E-6	1.6E-2	7.8E+2	1.4E+2	51.2
20	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
21	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
22	m^2	1468.8	50	1.8E+2	4.7E-6	2.4E-2	3.3E-3	1.5E+1	5.7E-8	9.8E-3	1.5E+2	2.0E+1	14.1
23	m^2	1334.0	50	8.2E+2	1.2E-4	2.2E-1	5.9E-2	9.4E+1	3.2E-6	6.5E-2	8.4E+2	1.0E+2	367.5
24	m^2	1686.4	35	3.7E+2	2.4E-5	2.1E-1	2.3E-2	2.7E+1	1.0E-6	1.5E-2	3.4E+2	2.2E+1	18.4
25	m^2	680.0	50	3.0E+1	1.4E-4	3.3E-3	7.5E-4	1.9E+0	2.2E-10	3.5E-4	3.0E+1	2.4E+0	29.4
26	m^2	65.2	30	4.9E+2	1.7E+1	4.7E-2	4.2E-3	1.7E+1	6.1E-7	8.9E-2	5.2E+2	4.9E+0	118.9
27	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
28	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
29	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
30	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
31	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
32	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
33	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
34	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
35	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
36	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
37	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
38	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
39	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
40	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
41	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
42	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
43	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
44	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
45	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
46	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
47	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
48	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
49	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
50	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
51	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
52	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
53	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
54	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1

Element no.	Functional Unit	Density (kg/m^3)	Lifespan (years)	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
55	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
56	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
57	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
58	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
59	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
60	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
61	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
62	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
63	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
64	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
65	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
66	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
67	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
68	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
69	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
70	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
71	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
72	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
73	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
74	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
75	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
76	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
77	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
78	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
79	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
80	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
81	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
82	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
83	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
84	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
85	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
86	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
87	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
88	m^2	2342.8	100	1.1E+3	3.8E-4	4.3E-1	1.7E-1	1.0E+2	5.0E-6	5.5E-2	1.2E+3	7.2E+1	88.7
89	m^2	2344.6	100	1.3E+3	4.7E-4	5.3E-1	2.1E-1	1.3E+2	6.2E-6	6.7E-2	1.5E+3	8.6E+1	102.1
90	m^2	25.0	100	3.2E+2	2.1E-6	2.7E-2	2.5E-3	1.1E+1	3.9E-7	5.9E-2	3.3E+2	2.0E+0	314.3
91	m^2	25.0	100	3.7E+2	2.4E-6	3.0E-2	2.9E-3	1.3E+1	4.5E-7	6.7E-2	3.8E+2	2.3E+0	314.3
92	m^2	7715.6	50	1.4E+3	6.3E-4	3.9E-1	5.9E-2	1.1E+2	2.3E-6	4.8E-2	1.6E+3	2.5E+2	375.0
93	m^2	1661.9	60	5.5E+3	9.1E-4	2.5E+0	2.6E-1	4.1E+2	4.0E-5	1.3E-1	6.2E+3	5.5E+2	160.0
94	m^3	1080.0	35	1.3E+4	1.0E-3	9.9E+0	1.0E+0	8.7E+2	5.1E-5	6.8E-1	1.3E+4	3.8E+2	228.2
95	m^2	382.4	50	3.4E+2	5.3E-5	6.9E-2	8.1E-3	2.1E+1	3.0E-7	8.0E-3	3.9E+2	2.5E+1	83.6

Element no.	Functional Unit	Density (kg/m^3)	Lifespan (years)	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
96	m^2	118.4	50	3.6E+2	5.4E-5	8.7E-2	1.0E-2	2.1E+1	3.3E-7	7.9E-3	3.9E+2	2.7E+1	87.8
97	m^2	118.4	50	3.6E+2	5.4E-5	8.7E-2	1.0E-2	2.1E+1	3.3E-7	7.9E-3	3.9E+2	2.7E+1	87.8
98	m^2	118.4	50	3.6E+2	5.4E-5	8.7E-2	1.0E-2	2.1E+1	3.3E-7	7.9E-3	3.9E+2	2.7E+1	87.8
99	m^2	311.7	50	3.2E+2	5.3E-5	7.2E-2	8.2E-3	1.9E+1	2.5E-7	7.2E-3	3.5E+2	2.4E+1	83.6
100	m^2	263.0	50	4.6E+3	4.1E-3	6.6E-1	7.0E-2	1.2E+2	1.5E-6	1.2E-1	4.6E+3	1.4E+3	1189.7
101	pc	355.9	50	2.0E+3	2.8E-3	5.2E-1	6.6E-2	1.5E+2	3.4E-6	5.4E-2	2.3E+3	3.7E+2	412.9
102	m^2	400.0	40	4.9E+3	5.1E-3	2.1E+0	2.2E-1	3.9E+2	3.0E-5	1.0E-1	6.0E+3	7.2E+2	1638.3

Table A.6 - Environmental and economic impacts of the materials per functional unit (A1-A3 modules)

Material no.	Functional Unit	Density (kg/m^3)	Lifespan (years)	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-}eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
1	m^2	680.0	50	3.0E+1	1.4E-4	3.3E-3	7.5E-4	1.9E+0	2.2E-10	3.5E-4	3.0E+1	2.4E+0	29.4
2	m^2	263.0	50	4.6E+3	4.1E-3	6.6E-1	7.0E-2	1.2E+2	1.5E-6	1.2E-1	4.6E+3	1.4E+3	1189.7
3	pc	35.0	20	3.5E+4	5.0E-2	1.3E+1	1.1E+0	2.9E+3	7.8E-7	8.7E-1	4.1E+4	9.8E+3	32000.0
4	pc	433.1	50	4.5E+3	2.3E-3	1.3E+0	1.5E-1	3.7E+2	8.8E-6	1.3E-1	5.2E+3	8.7E+2	1113.8
5	pc	355.9	50	2.0E+3	2.8E-3	5.2E-1	6.6E-2	1.5E+2	3.4E-6	5.4E-2	2.3E+3	3.7E+2	412.9
6	m^2	400.0	40	4.9E+3	5.1E-3	2.1E+0	2.2E-1	3.9E+2	3.0E-5	1.0E-1	6.0E+3	7.2E+2	1638.3
7	m^2	1080.0	35	2.7E+2	2.0E-5	2.0E-1	2.0E-2	1.7E+1	1.0E-6	1.4E-2	2.6E+2	7.6E+0	8.4
8	m^3	1080.0	35	1.3E+4	1.0E-3	9.9E+0	1.0E+0	8.7E+2	5.1E-5	6.8E-1	1.3E+4	3.8E+2	228.2
9	m^2	1260.9	30	3.1E+0	7.9E-9	1.9E-4	2.8E-5	5.0E-2	1.8E-8	5.2E-5	3.4E+0	1.3E-1	70.3
10	m^2	25.0	100	3.0E+2	2.0E-6	2.5E-2	2.3E-3	1.0E+1	3.6E-7	5.5E-2	3.1E+2	1.9E+0	314.3
11	m^2	25.0	100	3.2E+2	2.1E-6	2.7E-2	2.5E-3	1.1E+1	3.9E-7	5.9E-2	3.3E+2	2.0E+0	314.3
12	m^2	25.0	100	3.7E+2	2.4E-6	3.0E-2	2.9E-3	1.3E+1	4.5E-7	6.7E-2	3.8E+2	2.3E+0	314.3
13	m^2	25.0	100	4.6E+1	3.0E-7	3.8E-3	3.6E-4	1.6E+0	5.6E-8	8.4E-3	4.8E+1	2.9E-1	4.1
14	m^2	25.0	100	4.8E+2	3.2E-6	4.0E-2	3.8E-3	1.7E+1	5.9E-7	8.8E-2	5.0E+2	3.0E+0	43.2
15	m^2	1661.9	60	5.5E+3	9.1E-4	2.5E+0	2.6E-1	4.1E+2	4.0E-5	1.3E-1	6.2E+3	5.5E+2	160.0
16	m^2	54.0	50	4.1E+1	3.8E-7	1.3E-2	1.6E-3	2.2E+0	3.3E-7	8.1E-4	5.1E+1	2.4E+1	14.2
17	m^2	78.0	50	5.4E+1	5.3E-7	1.7E-2	2.5E-3	3.0E+0	3.9E-7	1.0E-3	7.4E+1	3.0E+1	23.9
18	m^2	71.0	50	7.1E+1	6.4E-7	2.3E-2	3.2E-3	4.0E+0	5.0E-7	1.3E-3	9.6E+1	3.4E+1	27.4
19	m^2	40.0	50	6.0E+1	1.0E-6	2.1E-2	3.2E-3	3.5E+0	1.2E-7	1.1E-3	6.4E+1	3.8E+0	16.8
20	m^2	40.0	50	2.2E+1	3.8E-7	8.3E-3	1.3E-3	1.4E+0	4.7E-8	4.4E-4	2.3E+1	1.7E+0	16.8
21	m^2	40.0	50	1.0E+2	1.7E-6	3.6E-2	5.4E-3	5.8E+0	1.9E-7	1.8E-3	1.1E+2	6.3E+0	16.8
22	m^2	712.0	50	3.1E+1	4.6E-7	4.9E-3	9.4E-4	2.2E+0	5.9E-8	6.8E-4	4.0E+1	1.2E+0	3.3
23	pc	715.0	30	1.7E+3	2.9E-3	2.8E-1	5.4E-2	-1.4E+1	1.1E-5	5.4E-2	1.8E+3	2.0E+3	280.0
24	pc	715.0	30	9.9E+2	1.7E-3	1.6E-1	3.2E-2	-8.2E+0	6.5E-6	3.2E-2	1.1E+3	1.2E+3	230.0

Material no.	Functional Unit	Density (kg/m^3)	Lifespan (years)	ADPE (MJ)	ADPM (kg Sb eq)	AP (kg SO_2 eq)	EP (Kg PO_4^{3-} eq)	GWP (kg CO_2 eq)	ODP (kg R-11 eq)	POCP (kg C_2H_4)	PE-NRe (MJ)	PE-Re (MJ)	Cost (euros)
25	pc	715.0	30	1.3E+3	2.3E-3	2.1E-1	4.1E-2	-1.1E+1	8.5E-6	4.2E-2	1.4E+3	1.5E+3	245.0
26	pc	715.0	30	1.3E+3	2.3E-3	2.2E-1	4.2E-2	-1.1E+1	8.7E-6	4.3E-2	1.4E+3	1.6E+3	290.0
27	pc	715.0	30	1.4E+3	2.4E-3	2.3E-1	4.4E-2	-1.1E+1	8.9E-6	4.4E-2	1.5E+3	1.6E+3	260.0
28	pc	715.0	30	1.4E+3	2.4E-3	2.3E-1	4.4E-2	-1.1E+1	9.0E-6	4.4E-2	1.5E+3	1.6E+3	305.0
29	pc	715.0	30	2.5E+3	4.4E-3	4.1E-1	8.0E-2	-2.1E+1	1.6E-5	8.1E-2	2.7E+3	2.9E+3	820.0
30	m^3	7850.0	100	1.6E+5	1.7E-1	7.2E+1	4.9E+1	1.6E+4	9.1E-4	8.2E+0	1.9E+5	1.5E+4	534.9
31	m^2	1400.0	10	8.0E+1	2.6E-5	1.5E-2	1.2E-3	4.0E+0	1.7E-11	1.7E-3	8.5E+1	8.9E+0	17.5
32	m^2	7750.0	60	3.6E+1	4.2E-8	1.2E-2	6.6E-4	3.1E+0	1.4E-8	1.5E-3	3.6E+1	5.3E-1	18.8
33	m^2	7750.0	60	3.6E+1	4.2E-8	1.2E-2	6.6E-4	3.1E+0	1.4E-8	1.5E-3	3.6E+1	5.3E-1	29.5
34	m^2	7750.0	60	3.6E+1	4.2E-8	1.2E-2	6.6E-4	3.1E+0	1.4E-8	1.5E-3	3.6E+1	5.3E-1	25.3
35	m^2	2352.2	100	9.0E+2	3.3E-4	4.0E-1	1.6E-1	9.4E+1	5.0E-6	5.1E-2	1.1E+3	5.4E+1	53.7
36	m^2	2352.2	100	1.1E+3	4.2E-4	5.0E-1	2.1E-1	1.2E+2	6.2E-6	6.4E-2	1.3E+3	6.8E+1	67.1
37	m^2	2000.0	60	2.9E+2	8.6E-5	1.3E-1	4.1E-2	5.3E+1	2.1E-6	6.8E-3	3.2E+2	5.9E+1	33.2
38	m^2	2000.0	60	3.8E+2	1.1E-4	1.7E-1	5.4E-2	7.1E+1	2.9E-6	9.0E-3	4.2E+2	7.8E+1	43.2
39	m^2	2000.0	60	5.0E+2	1.5E-4	2.3E-1	7.2E-2	9.4E+1	3.8E-6	1.2E-2	5.6E+2	1.0E+2	38.2
40	m^2	2000.0	60	6.1E+2	1.8E-4	2.8E-1	8.6E-2	1.1E+2	4.6E-6	1.4E-2	6.7E+2	1.3E+2	41.2
41	m^3	2352.2	100	4.5E+3	1.7E-3	2.0E+0	8.2E-1	4.7E+2	2.5E-5	2.6E-1	5.3E+3	2.7E+2	268.4
42	m^2	1950.0	50	1.1E+2	3.4E-6	1.6E-2	2.3E-3	1.0E+1	6.4E-10	1.1E-3	8.2E+1	1.5E+1	10.0
43	m^2	1950.0	50	1.2E+2	3.7E-6	1.7E-2	2.5E-3	1.1E+1	6.9E-10	1.2E-3	8.9E+1	1.6E+1	10.0
44	m^2	1950.0	50	1.4E+2	4.4E-6	2.0E-2	2.9E-3	1.3E+1	8.3E-10	1.4E-3	1.1E+2	1.9E+1	10.0
45	m^3	7850.0	100	1.3E+5	2.3E-3	2.8E+1	2.9E+0	1.4E+4	2.0E-6	5.5E+0	1.4E+5	6.6E+3	17670.1
46	m^3	7850.0	100	2.0E+5	2.1E-3	4.4E+1	4.2E+0	2.0E+4	8.9E-7	6.8E+0	2.0E+5	4.3E+3	17670.1
47	m^2	7715.6	50	1.4E+3	6.3E-4	3.9E-1	5.9E-2	1.1E+2	2.3E-6	4.8E-2	1.6E+3	2.5E+2	375.0
48	m^2	1250.0	30	1.7E-6	1.7E+1	6.6E-3	4.3E-4	7.5E-1	8.2E-10	6.9E-4	1.8E+1	1.7E+0	5.4