A Comparative Analysis of LCA Tools: Studying the Façade of a Campus Lab Building

Laleh Amany

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Thesis Committee:
Kate Simonen, Chair
Alex Anderson

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Abstract

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Chair of Thesis Committee:
Kate Simonen, Associate Professor
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Through the advancement of sustainable design methods, life cycle assessment (LCA) is becoming a significant part of sustainable practices. To have reliable assessment results, however, the strengths and weaknesses of the assessment tools should be explored. This thesis studies life cycle assessment as a method to evaluate the environmental impacts of the buildings. The purpose of this study is to compare the analyses results of two LCA tools: the Revit-based Tally plugin and the Athena Impact Estimator (IE). The study explores a building façade system as the case study at three different scales: the primary materials, façade components, and the whole-building façade. Athena IE and Tally are applied to the case study to compare the user input framework, bill of materials, and outputs. While the development of BIM-based LCA tools helps designers, engineers, and contractors, this study finds that the tools are highly dependent on the data input methods to generate reliable LCA outcomes. It also suggests that in order to improve software interfaces, a wider consideration of LCA input methods is necessary.

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DEDICATION

This thesis is lovingly dedicated to my mother, Zar, who is the constant source of inspiration, encouragement, and stamina to undertake my difficulties and to face the eventualities of life with strength and courage.

1. Introduction

This chapter presents an introduction to this Master of Science research study. It describes different aspects of sustainability and the relationship between sustainability and the building industry. It also explores the necessity of this research, describing different features of environmental impacts in the building industry as they relate to sustainability assessments.

1.1 Building industry and environmental impacts

1.1.1. Sustainability and Building Industry

Construction is the major consumer of raw materials in the United States. Figure 1 shows that by the end of the 20th century the US construction sector used more than 70% of all available materials in the world. The fact that the U.S. consumes approximately one-third of the whole world's building materials and consequently produces a huge amount of environmental pollution, shows the importance of exploring how to control the environmental effects of buildings. Another reason to emphasize the importance of this issue is that only 8% of 2.1 billion metric tons of construction materials could be renewed (Matos & Wagner, 1998).

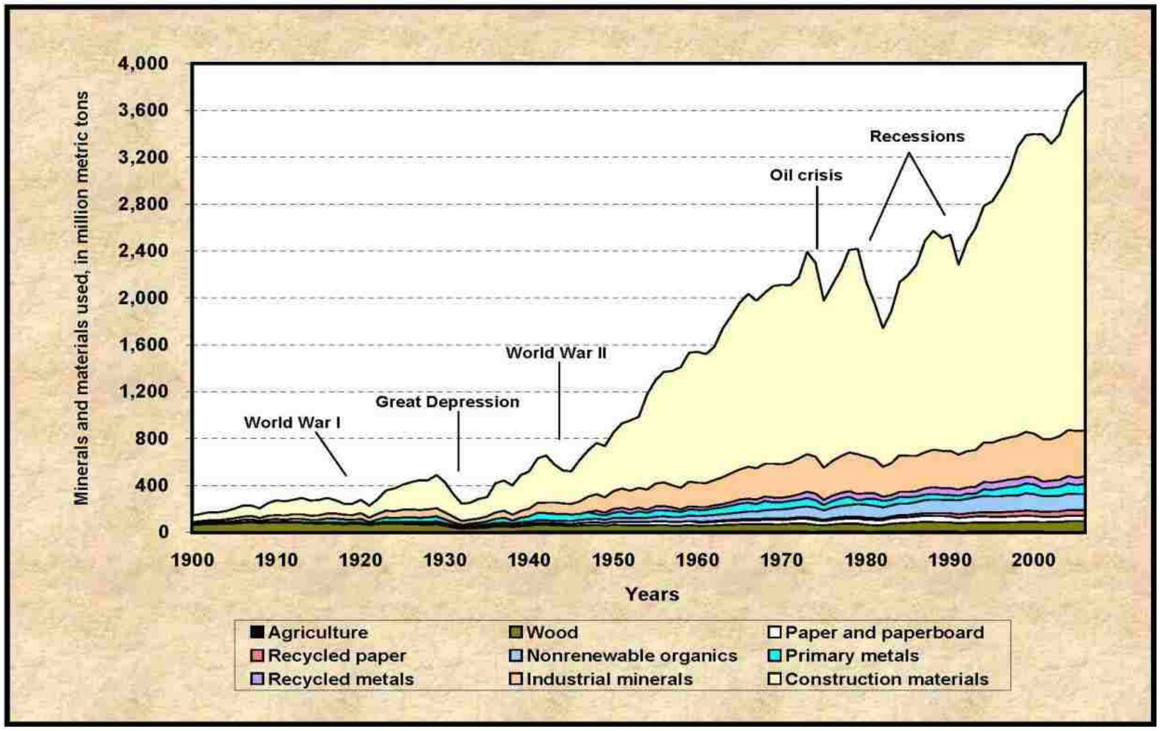

Figure 1: Material and mineral consumption in the United States, 1900-2006. Source: Matos 2009

One of the main sources of climate change is greenhouse gas emission, produced in the extraction, refinement, transportation, use, and disposal of these materials (IPCC, 2007). The US Environmental Information Agency (EIA) indicates that the building construction sector contributes 39% of the carbon dioxide emissions and consumes 72% of the electricity in the US (EIA CBECS 2003). Reducing Greenhouse Gas (GHG) emissions is the concern of many experts in the building construction industry, such as architects, engineers, government, and clients (Hsu, 2011).

An evaluation system can encourage experts to control and analyze the environmental impacts of a project. Participants in the building industry have found that these kinds of evaluating systems, can bring more value for their projects. As part of this effort, several environmental rating systems have been generated in recent years. The US Green Building Council (USGBC) has defined Leadership in Energy and Environmental Design (LEED) as the most common rating system for building sustainability. Another well-known effort to reduce GHG emissions of buildings is the Architecture 2030 Challenge, which encourages designers to use solutions to reduce operating GHG emissions of buildings by the year 2030.

The United Nations defines sustainability as responding to the present demands without negatively affecting future generations' needs (United Nations 1987). It cannot be overlooked, however, that building owners and contractors are often concerned mostly with short-term economic issues. In other words, they are looking for a building with the lowest construction budget, and the highest level of efficiency in operation, goals that are often not easy to reach. On the other hand, architects and designers are concerned about aesthetics, which sometimes are compatible with sustainability issues and sometimes conflict with them (Hsu, 2011). Another definition for sustainability that is known as the "triple bottom line" illustrates it as a process that must consider social, financial, and environmental effects. It means that suitability is not defined just by environmental effects, but that social issues, such as interaction with users, and economic concerns are also important (Hacking and Guthrie 2008). This concept emphasizes that environmental impacts must not be overshadowed by economic and social interests. Nearly all the experts concerned with sustainability issues complain, however, about the lack of interest in environmental impacts among building owners and contractors (Cristiane Buenoa M. F., 2018). This lack of attention comes from considering short-term interests instead of the long-term impacts of buildings that are the concern of sustainability.

1.1.2. Environmental Impacts

A current challenge for construction industry professionals is designing buildings that incorporate sustainable factors and requirements (WBDG Sustainable Committee, 2011). Energy scarcity and environmental concerns encourage solutions to increase efficiency and reduce environmental impacts (IEA, 2018). These have become some of the main concerns of the building design industry (Ahmad Faiz Abd Rashid, 2015). A crucial aspect of these concerns is that the environmental impacts of a product or a project are not limited to the period of building construction and operation. The environmental impacts of the materials should be considered for their full lifecycle, which generally includes material harvesting, processing, transportation, construction, use, and disposal or recycling. Life Cycle Assessment (LCA) is a methodology used to assess the different environmental impacts of building materials during the whole period of their life. In addition to environmental impacts, financial issues, business-related points, amenity needs, and efficiency are the factors that should be considered throughout the life cycle of a project or a building (United States Environmental Protection Agency, 2010). Business-related issues such as the accountability of the design process, budget management, quality control, and the completion times are all the responsibilities of the project managers. On the other hand, the evaluation of the amenity needs is explored by the planners and those who prepare the master plan of the projects. Because this study concerns the environmental impacts of a project, it is not limited to the design, construction, or operation section of a building. It is a multi-disciplinary area of concern to architectural designers, engineers, contractors, and other participants in the building industry. The multi-disciplinary aspect of the environmental impacts makes it critical to understand the methods used for LCA calculation and investigation in the design process of a project.

In an environmental aware design process, appropriate decisions should be made as early as possible. Considering the life cycle environmental impacts tends to be more important in the early stages of the design process than the middle and late stages, because cost and energy factors can be applied most easily and with fewer alterations at the beginning of a project (Cristiane Buenoa M. F., 2018). This is why it is necessary to integrate LCA tools with BIM-based design tools, which will be discussed in the next chapters. In the early design stages the specifications for items such as the combination of materials, the building's physical properties, and the MEP-related issues of each building could be easily revised based on the designers' detection. Contemporary design tools are emerging to help designers to develop the final design based on the minimizing the environmental impacts of each project. Building Information Modeling (BIM) using sustainability-based tools has made it possible to incorporate environmental analysis in the early stages of design (J.K.W. Wong, 2015) . Early environmental analysis could be run if the designers know the very first specifications of a project such as the size of the walls, openings and materials, that all are available in each step of the project in a BIM-based design tool.

Life Cycle Assessment (LCA) facilitates systematic evaluation of environmental effects of a project during the different stages of a project life cycle (Hsu, 2011). The emissions are reported by estimating the different environmental impacts categories. To protect the environment from the negative effects of the emissions, exploring and analyzing the environmental impacts and their long-term effects are significant in a project. The integration of LCA and BIM (as the current industry standard design and representation platform) would contribute significantly to meeting the building sector demands for efficiency in environmental aware design processes. (Cristiane Buenoa, Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in (90), 2018)

2. Background

2.1. LCA (Life Cycle Assessment)

A method is needed to record the full environmental impact of a building or product. Life Cycle Assessment (LCA) is an approach established in the mid-1980s to assess a building or product from the perspective of its emissions and pollutions during its full life cycle (Simonen, 2014). LCA has become a wide-spread methodology in environmental analysis issues because of its capabilities in:

-Including various factors of environmental topics,
-Defining a framework for environmental assessments,
-The possibility of measuring each impact in the different stages of the project separately.
(G. Finnveden, 2009) (Klöpffer, 2006)

LCA addresses a building's total environmental impact over a wide range of stages from material extraction, manufacturing, construction, and use (operations, maintenance, and refurbishment) through eventual demolition and disposal (Simonen, 2014). The LCA data reports are often classified into three different classes:

"-Cradle-to-gate
-Cradle to grave
-Cradle-to-cradle"

The classification of the LCA reports is shown in Fig 2 (Simonen, 2014).

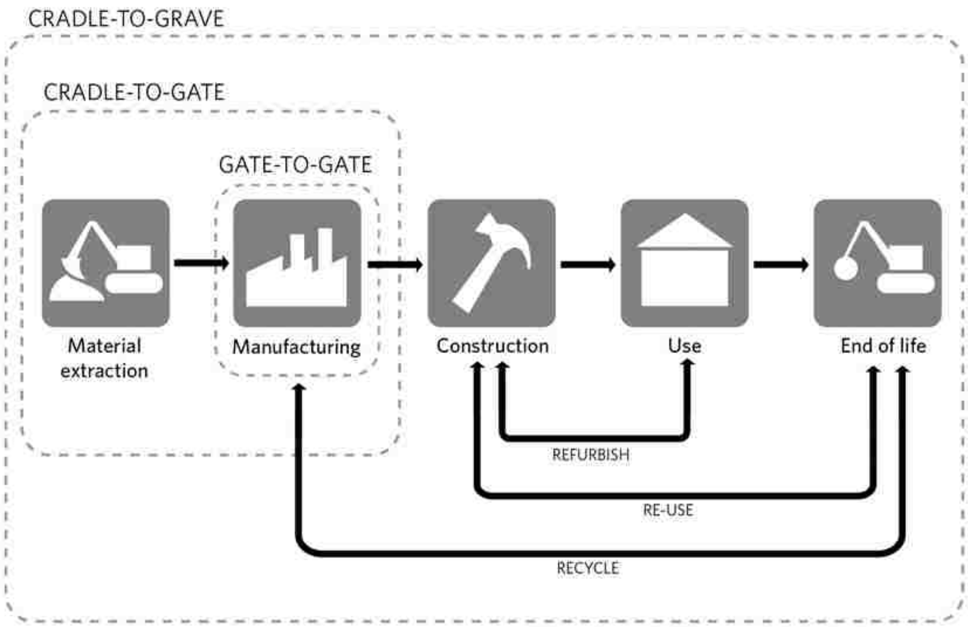

Figure 2. The classification of LCA

table 1 shows a comprehensive definition of different LCA stages developed by German EPD system, Institut Bauen and Umwelt e.V (IBU).

Product Stage			**Construction Process Stage**		**Use Stage**							**End of Life**				**Beyond the system boundaries**
Raw Material Supply	Transport	Manufacturing	Transport	Construction-Installation Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Demolition	Transport	Waste Processing	Disposal	Re-use Recycle
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**

Table 1, Life Cycle Assessment stages

By using the ISO 14040/44 standard, LCA considers the cradle-to-grave environmental impacts of all components or services. "ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements" (International Organization for Standardization (ISO), 2007). LCA helps designers and professionals to assess how buildings will perform in the defined environmental metrics, and to consider more applicable alternatives where the proposed building does not meet the LCA standards. The defined metrics of LCA are:

- global warming ("carbon footprint"),
- acidification ("acid rain"),
- eutrophication ("algal bloom"),
- photochemical oxidant creation ("summer smog"),
- ozone depletion ("the ozone hole") (http://www.gbci.org, 2017).

Generally, the main problem of working with LCA is that it is a relatively new practice and therefore is rarely applied on the projects. As a result, the professional resources related to it are very limited. Because AEC (Architecture, Engineering and Construction) professionals have difficulty integrating new methods that are not widely understood, in most cases, they would need extra training to have a better knowledge of using LCA tools properly. The minimum requirements to conduct an LCA are available as ISO standards. But in some cases, they are not detailed enough for AEC professionals to use in developing and applying an accurate LCA study (Kaethner, 2011). Most of the software programs that are available in this field act like a "black box" that operates the computations and calculations, while the main step for designers is gathering data and information to provide as inputs for the LCA tools. In order to encourage experts to be involved in LCA, the U.S. Green Building Council (USGBC) has assigned a section in the LEED rating system for LCA analysis. But it needs more time to make it commonly used among architects and designers (Hsu, 2011).

A notable problem in the field of LCA studies is the comparability of different LCA studies. The flexibility of goals and scopes and the different units of the impacts and materials make it hard to compare the different LCA studies. For example, to compare different studies 'carbon' emission

as one the main impact categories in an LCA study is reported as carbon dioxide equivalents (CO2e), which weights greenhouse gas emissions based on their global warming potential (GWP); it considers the effects of different gases and reports them using one comparable unit. While other environmental impacts should not be forgotten, to make it possible to make better comparisons among LCA studies, the GWP has become a mandatory factor in recent studies (Hsu, 2011).
The area unit is another important factor in this field. Some reports are based on the square footage while some others are based on the gross area of the building. To make it possible to have consistent studies, normalizing the results per unit area is an issue that must be resolved.

2.1.1 LCA and LEED

The US Green Building Council (USGBC) developed an environmental rating system in 2000 known as Leadership in Energy and Environmental Design (LEED). It focuses on the recognition of green buildings based on benchmarks that establish standards for different levels of certification using a rating credit system. The rating system can work as a framework for measuring the factors of promoting environmental effects of a project (Hsu, 2011). The LEED rating system can be applied on almost any kind of building, including existing ones or new buildings. The main purpose of LEED is encouraging clients and experts to develop more sustainable buildings.
The US Green Building Council (USGBC) as the responsible organization of LEED certificate identified that LCA and its multi-functional benchmarks can be used to drive building performance. LCA enables a multi-aspect environmental evaluation through the comparison of each related parameter of a proposed building design to those of a baseline building (http://www.gbci.org, 2017).
A new credit was introduced recently for LEED v4 Building Design and Construction (BD+C) regarding the building Life-cycle Impacts. The option 4 for this credit is LCA with a maximum of three points. This credit focuses on the early design stages of a project to encourage making decisions aimed at reducing environmental impacts. Building professionals use LCA as a tool to estimate the material manufacturing energy use and environmental impacts in all life cycle phases of a project such as material preparation, production, construction, operation, and demolition.

The LCA-related credit of LEED v4 requires a 10 percent reduction of a project's environmental impacts in comparison with a baseline building defined by the user by using Athena IE as a life cycle assessment software tool.

To be qualified for getting the LEED points for the LCA section some other issues should be considered:

-The comparability of the baseline and proposed building in size, type, direction, and location.

-The improvement of at least 5% in energy efficiency for the proposed building in comparison with the baseline building.

- Considering the same service life of the proposed building and the baseline one for at least 60 years for maintenance and replacement.

-All six parameters of environmental impacts listed below should be assessed in the LCA report:

- global warming potential (greenhouse gases), in kg CO_2e;
- depletion of the stratospheric ozone layer, in kg CFC-11;
- acidification of land and water sources, in moles H+ or kg SO_2;
- eutrophication, in kg nitrogen or kg phosphate;
- formation of tropospheric ozone, in kg NOx, kg O_3 eq, or kg ethene;
- and depletion of nonrenewable energy resources, in MJ)

To get LCA points the global warming potential (GWP) results of a building LCA, along with any other two reduced impact categories, should have at least 10 percent reduction in comparison with a defined baseline building. Impacts in the remaining categories should not have increased more than 5 percent in comparison with the baseline. The LCA should consider the material production, construction process, operation stage and end-of-life stage, which is called cradle-to-grave assessment. In other words, the LCA report assessment is related to the scopes A1–A4, B1–B7 and C1–C4 according to ISO 21930 and is limited to the building structure and enclosure.

In the LEED v4, an extra point is awarded to those projects with a reduction of 10 percent in all six impact classifications, instead of only three of them.

2.2. Building Information Modeling (BIM)

During recent decades, the benefits of Building Information Modeling (BIM) and its resource savings during design, planning, and construction of new buildings has caused a great increasing interest in the construction sector (M. Nepal, 2008) (D. Bryde, 2013). In the 1970s, 3D modeling started to develop based on the Computer-Aided Design (CAD) in different industries. The basic concept of BIM was increasingly used in many industries, while the construction industry was restricted in using traditional 2D design (Teicholz Eastman, 2011). In the early 2000s the construction sector started to use BIM in pilot projects by architects and engineers (H. Penttilä, 2007). Preplanned design, conflict detection, visualization, cost and data management became the main purposes of the studies. (Teicholz Eastman, 2011) (Z. Wassouf, 2006). At first BIM focused on preplanning, design, construction and infrastructure, but after a while it started considering earlier stages of life cycles to maintenance, refurbishment, deconstruction and end of life phases (Teicholz Eastman, 2011)

International standards defines BIM as "shared digital representation of physical and functional characteristics of any built object which forms a reliable basis for decisions" (ISO Standard, 2010.)

BIM works as a tool that shares digital representation of physical and functional characteristics of any built object which forms a reliable basis for decisions. (T. Cerovsek, 2011) (G. Lee, 2006). Objects in BIM are classified as functional, semantic or topologic information (Teicholz Eastman, 2011). For instance, expenses are considered as functional information. Affinity, Compression are instances of functional information. Finally, the data related to object locations, adjacency, density and intersections are considered as topologic information.

Figure 3 shows that BIM can be explored from different perspectives. BIM in a limited scope is considered just as a digital model of a building and only involves in the modeling geometric creation issues (A. Watson, 2011). Commercial BIM works beyond just modeling a building. It works with integrated data management, component collection and general purposes (Teicholz Eastman, 2011).

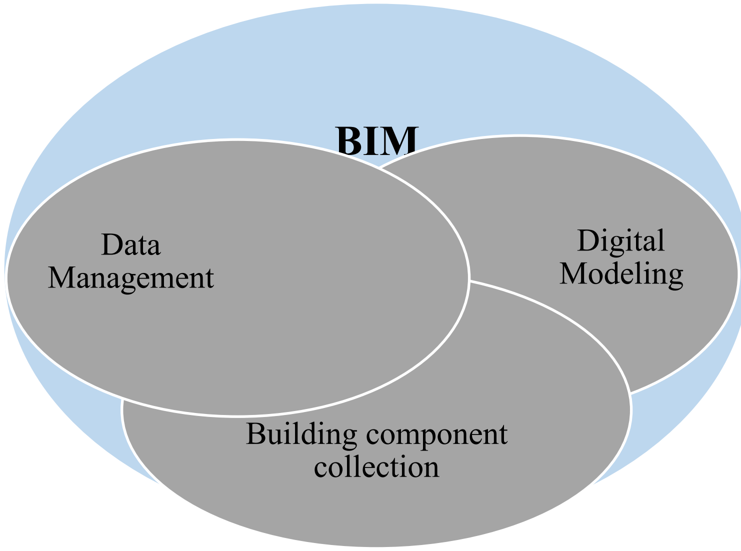

Figure 3, BIM application areas

2.3. LCA and BIM

The process of dealing with building information in different steps of creation, saving, controlling, transferring, and contribution of the information through the use of a shared digital model is known as Building Information Modeling (BIM) (R.Valande, 2008)

The opportunity to use different kinds of information related to a project in a single platform has made BIM the appropriate tool for the different steps of the design and construction process (T. Hartmann, 2008). The particular aspect of BIM that is discussed in this study is the capability for sustainability evaluation and the opportunity it offers of applying relevant decisions during the different steps of the project (J. Schade, 2013) (K. Wong, 2013). Regarding the multi functionality of the BIM-based design tools, sustainability analyses are more accurate and detailed by using BIM-based methods in comparison with traditional mechanisms (Azhar, 2010). On the other hand, regardless of the benefits of BIM-based analyzing methods, the lack of interoperability with Life Cycle Assessment (LCA) tools is the main problem in the assessment of the embodied energy (A. Schlueter, 2009) (A. Jrade, 2013). In this study, we are looking for the solutions to reduce the time and effort in using BIM-based data extraction as the inputs of LCA tools (S. Shrivastava, 2012)

2.3.1. LCA and BIM-based sustainable design

To have an efficient application of LCA analysis in the process of design, the early stages of the design should be considered for the LCA-affected decisions. The main point is that in the early stages of the design, key decisions could be applied less costly and more efficient, applicable and reliable ways. On the other hand, there are some challenges in applying LCA analysis during the early stages of the design in BIM-based design tools. That is; most of the variables and data sources are not available at that stage, and the calculations should be based on the quantitative predictions and available inventories (B. Ilhan, 2016).

Despite many improvements in the integration of BIM and LCA, there are still many weaknesses; these force experts to spend substantial cost and energy in gathering and using the other sources of information for the BIM-based design process (B. Ilhan, 2016). To address these challenges, Ilhan and Yaman have established a framework for green building certification. They propose that environmental analysis in the BIM-based design process could be performed through an interdisciplinary collaboration of design, construction and maintenance professionals (B. Ilhan, 2016). Their work results in an improved green building assessment tool (GBAT), which helps the designers in the process of documenting green building certification.

Some experts assert that the integration of sustainability issues into BIM is not as straightforward as it seems. Oti et al. explain that the limitations, in this case, can be divided into two main groups. First: The complexity of the factors that define sustainability makes it difficult to apply in the early design stages, Second: The defined sustainability variables for BIM-based design tools are not adequate yet (A.H. Oti, 2016). To overcome these limitations, LCA as a framework that emphasizes a combination of sustainability requirements and design system implementations have been developed. The main point of this modeling framework is to keep sustainability factors and design issues beside each other (A.H. Oti, 2016). The framework considers preparation, construction, operation, and end-of-life of materials. Its implementation focuses on the environmental aspects of sustainability, particularly the effects of carbon emission and ecological impacts on sustainability-based decisions related to structural solutions and sustainability assessments (A.H. Oti, 2016).

It should be mentioned that Oritz et al. have classified the application of LCA for "building materials and components combinations (BMCC) and for the whole process of construction (WPC)" (O. Ortiz, 2009).

To develop the BIM-based LCA analysis, three approaches have been considered by Wang et al. (E. Wang, 2011): intelligent advanced technologies, performance evaluation methodologies, and finance assessment analysis. The first approach focuses on the simulations and calculations by using the available inventories in the first step and improving these using machine learning systems in the next step. The second approach investigates the LCA analysis by evaluating the environmental effects of components during the different stages of their life. The last approach is specified to the economic aspects of the projects (E. Wang, 2011). The BIM-LCA integration process has considered all these three aspects and comprised all the mentioned areas in supporting the environmental analysis during the different steps of the design (Ajayi, 2015) (E. Wang, 2011).

The existing BIM-based assessing tools would make it possible to have a quick LCA analysis in comparison with traditional methods, but some discrepancies could be found due to the modeling process issues. An ideal tool for design and assessment makes it possible to do the analysis in the early design stages to have the benefit of an environmentally-aware design process and to manage the multiple design alternatives (Negendahl, 2015).

Among different CAD software tools, Rhino, Revit, and SketchUp, by supporting different BPS tools as plugins or services, have made themselves more than just CAD software (Negendahl, 2015). This study examines integration of LCA software with Revit, the main BIM-based tool in the design industry.

BIM is a crucial assessment tool for green building design in the areas of construction facilities, integrated data exchange, operations management, and performance analyses. Green BIM could be considered as a platform to ease the Green Building Assessment (GBA) process by calculating the GBA scores and managing the design process based on these scores (Y. Lu, 2017). The GBA examines the environmental impacts of the project in each step and notifies the practitioners to revise the design if it is not following the GBA minimum scores and qualifications.

The major problems of BIM application in green building design section include: the feeble interoperability of green BIM applications, lack of applicable standards of green BIM assessment tools and debatable accuracy of BIM-based prediction reports (Cristiane Buenoa M. F., 2018).

2.4. LCA Tools

The aim of this study is to identify the gaps between LCA tools and BIM and specifically, evaluate two selected LCA tools, Tally and Athena.

This evaluation is based on a comparison between the LCA results of Athena and Tally on three different scaled case studies. First, a specific amount of the raw materials, second, a limited piece of a curtain wall as a part of the University of Washington's Population Health Building façade, and third, getting the whole building LCA of this building.

2.4.1. Athena Impact Estimator (Athena IE)

Athena Impact Estimator for building (IE4B) has been the pioneer of whole-building life cycle assessment (LCA) in North America, and it is the only free software that has made a progress in the quantification of sustainability in the built environment. Using Athena Impact Estimator, experts can analyze and compare the environmental impacts of industrial, institutional, commercial and residential buildings. Athena IE works as a text-based (The input data are introduced by text, entering by the user) LCA tool, while Tally is a BIM-based one(The input data are derived from the BIM model).

This study is mainly focused on comparing the results of the three LCA studies and exploring the differentials and uncertainties between these assessment tools.

Athena considers the environmental impacts of:

- Material manufacturing, including resource extraction and recycled content
- Related transportation
- On-site construction

- Regional variation in energy use, transportation and other factors
- Building type and assumed lifespan
- Maintenance and replacement effects
- Demolition and disposal

In Athena the first step in getting the LCA analysis of a building is entering the following information about the building:

- geographic location (the most representative North American city),
- the square footage,
- the building's expected life.

Athena provides cradle-to-grave implications in the following categories:

- Global Warming Potential
- Acidification Potential
- Human Health Respiratory Effects Potential
- Ozone Depletion Potential
- Photochemical Smog Potential
- Eutrophication Potential
- Fossil Fuel Consumption

2.4.2. Tally

Tally was chosen from among all BIM-based LCA tools because of its ability to work as a plug-in directly in the most well-known BIM software (Autodesk Revit), and consequently its ease of use. Tally allows architects and engineers to assess the environmental impacts of the projects by working within the Revit software. The assessment is based on the relationships between BIM modeling elements and construction material from the Tally database. Tally methodology is based on LCA standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011 that are brought in appendix 2.2. Tally works with a custom designed LCA database that quantifies the environmental impacts by using the architectural specifications and material characteristics in Tally's database obtained from Gabi Thinkpad (Innovations, 2018). Figure 5 is a schematic diagram of the Tally process for getting the LCA analyses of the projects.

Tally considers the environmental impacts of:

- Material manufacturing, including resource extraction and recycled content
- Related transportation
- On-site construction
- Regional variation in energy use, transportation and other factors
- Building type and assumed lifespan
- Maintenance and replacement effects
- Demolition and disposal

In Tally the first step in getting the LCA analysis is making the 3D model of the building. After defining the material information for each element by determining the building's expected life and the square footage, the LCA report can be derived.

Tally provides cradle-to-grave implications in the below categories:

- Global Warming Potential
- Acidification Potential
- Ozone Depletion Potential
- Smog Formation Potential
- Eutrophication Potential
- Primary Energy Demand
- Non-Renewable Energy Demand
- Renewable Energy Demand

2.4.4. A summary of differences in Tally and Athena

Tally works with a cloud based LCI with the capability of updating constantly based on industry standards, and Tally has a further option to download the latest versions of LCI by contacting Kieran Timberlake and applying it on the Revit Model. Athena's LCI is not cloud-based, and it cannot be updated in real time.

In both, sometimes it happens that a project material is not available in the database, and the user is required to address this absence by redefining or replacing a similar one-making an approximation based on professional judgement.

The LCI data in Tally is built from databases and models created in the Gabi software, Gabi 6 (Joshua Schultz, 2017). The values in Athena IE are assessed based on the relevancy of different emissions (land, water, air and resources) and LCI dataset (Joshua Schultz, 2017) which is created by the Athena SMI team based on LCA studies and databases

Athena and Tally a are brought together in table 2 with their limitations and features as identified during this study.

BIM-LCA Tool	Features	Limitations
Athena Athena Impact Estimator (North America)	• User-friendly interface • Possibility of defining new material	• Not able to work with 3D geometry • Importing the data manually • Calculating the area or the volume by the user • The assessment methods and inventory datasets cannot be updated by the user.
Tally™ Kieran Timberlake Innovations in partnership with Autodesk and PE International (USA)	• As a Revit plug-in, it allows the user to perform LCA in BIM environment, with no special modelling practices, • Available information and tutorials, • Available non-commercial licenses, • user-friendly interface.	• Only works with Autodesk Revit software, • The assessment methods and inventory datasets cannot be updated by the user. Requires a rigorously created Revit model-often more rigorous than required in practice.

Table 2, Athena / Tally Comparison

3. Methodology

This study analyzes and compares the process and results of the two most commonly available LCA tools, Tally as a BIM-based LCA tool and Athena Impact Estimator (IE), as a text-based one. The exterior enclosure of a building under construction at the University of Washington is considered as the case study to analyze. A summary of the accomplished analyses is depicted in Figure 6. The three different LCA studies and analyses undertaken in this thesis are as follows:

- Evaluate the primary materials in the façade independently with both tools
- Evaluate a portion of the façade with both tools
- Evaluate the full exterior enclosure with Athena

The first section is the analysis of four material units of a typical curtain-wall façade. The second section is the application of both LCA tools on a section of a curtain wall of a building that is described later and analyzing why Tally does not work properly on the whole façade of this building. And the last section is the LCA results of the full enclosure of the mentioned building derived from Athena IE. The focus is on how the results from Athena and Tally for the four raw components of a curtainwall are different from each other, how the tools assess different LCA stages, normalization of the data based on the US normalization factors for TRACI 2.1., how the available tools respond to the needs of the experts in the industry, and on their availability among designers.

An outline of this study's analyses is depicted in figure 4.

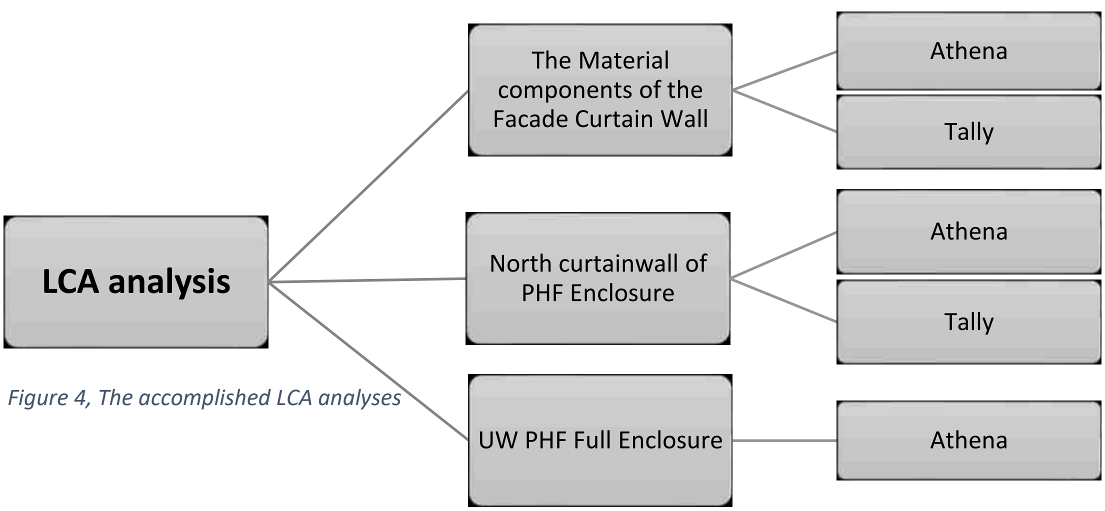

Figure 4, The accomplished LCA analyses

3.1. The analysis of four material units

In the first step, the analysis is applied to four material units of a typical curtain-wall façade shown in figure 5 (1′x1′x1′ equal to 1 cubic foot). They are simulated in both Athena and Tally to compare their LCA results.

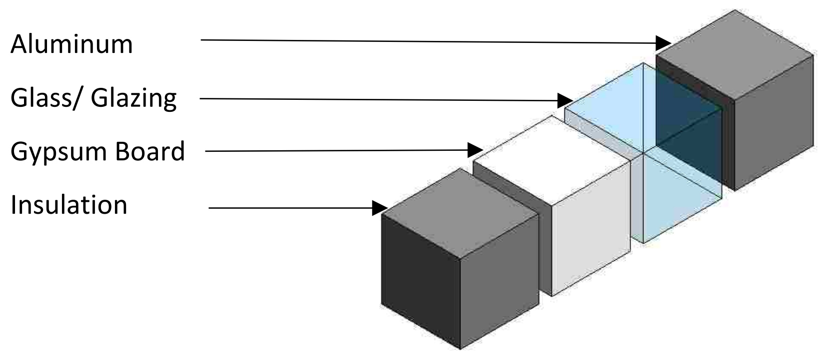

Figure 5, The Material components of the Facade Curtain Wall

3.1.1. Comparison of the Tally and Athena inputs

The quantity take-offs in Tally are derived from the geometric 3D model, while they should be manually entered in Athena. In order to have a comparison that minimizes errors and conflicts, due to the different metrics and definition of the materials in Tally and Athena, each material and its amount is defined as brought in table 3. On the other hand, the units in Athena are predefined, while in Tally they are based on the model and defining the density of the material. In order to understand the LCA impacts per unit of material, in Tally each material is modeled as a 1′x1′x1′ cube and in Athena each amount is entered manually based on the existing material density in Athena's LCI, because as mentioned, Athena does not work based on the 3D geometry. For instance, the Aluminum cast is defined by density of 275 kg/m^3 in Tally, but 2.7 tons/m^3 in Athena. So, the amount in Athena should be 0.076 Tons short to be equal to 1 cubic foot in Tally. All material entries and outputs are brought below and summarized in table 3.

Aluminum by 2.7 tons/m³ density

1 f³ = 0.028 m³

*0.028m³ * 2.7 tons/m³ = 0.076 Short Tons Aluminum*

Glass with 1/2" thickness… 6.5 pound/ sf

24 sf = 1 f³

*24 * 6.5=156 pound =0.078 Short Tons Glass*

Gypsum Wall Board with 1/2" thickness

24 sf = 1 f³

Insulation Cellulose with 1" thickness

12 sf = 1 f³

Tally					
Type	Density	Amount	Finish	Service Life	
Aluminum, Cast	2750 kg/m3	1 f³	None	60 years	
Glazing, monolithic sheet	100% by Vol.	1 f³	_	60 years	
Gypsum Wall Board, Natural	100% by Vol.	1 f³	None	60 years	
Insulation, Cellulose	100% by Vol.	1 f³	_	60 years	
Athena					
Type	Density	Amount	Unit	Equal Amount	Service Life
Aluminum Casting	2.7 Tons/m3	0.076	Tones (short)	1 f³	60 years
Glazing Panel	6.5 pound/sf	0.078	Tones (short)	1 f³	60 years
1/2" Regular Gypsum Board	1/2" thickness	24	Sf	1 f³	60 years
Blown Cellulose	1" thickness	12	Sf	1 f³	60 years

Table 3, The Material entries and quantities in Athena and Tally

The life cycle in Athena IE is defined for each material over 60 years (as a manually entered data). While, in Tally for each material there is an adjustable default set that have been changed all to 60 years to have an equal span for the comparison of both tools.

3.2. Case Study

3.2.1. Introduction

The UW Health Population Facility building is used here as the case study to perform the LCA analyses at different scales, with the goal of comparing two common LCA analysis tools: Tally and Athena. One purpose of the study is to show how LCA analyses of a building can be different depending on the assessment tool. The results section, explains and analyzes the differences between the outputs. The building is considered in a limited part of its façade for both Athena and Tally, and Athena is used to get the LCA results for the whole façade.
The Population Health Facility (PHF) at the University of Washington (UW) is a nine-story, 390,000 gross square foot building currently under construction. The UW Department of Architecture is assisting with project's pursuit of obtaining LEED certification, specifically with the whole building life-cycle assessment (WBLCA) option of the building life-cycle impact reduction credit. The project team consists of:

- Architect: The Miller Hull Partnership
- Structural engineer: KPFF Consulting Engineers
- Life cycle assessment (LCA): UW Department of Architecture

As the LEED LCA credit section considers the enclosure and the structure of the buildings, this study focuses on the enclosure LCA result. Throughout the study, the LCA analysis are applied on the enclosure of the building using two common analyzing tools: Tally and Athena. The purpose of the study is to show how an LCA analyses of a building can be different depending on the assessment tool. This section documents the methodology and results of the WBLCA by Athena and Tally, which each performs the analysis differently.

As it is mentioned in Section 2.1.1, in order to meet the requirements of the LEED WBLCA credit, the designed building must have a 10% reduction in three of six environmental impact categories, one of them must be global warming potential, compared to a baseline or "benchmark" building. The six impact categories are:

- global warming potential (greenhouse gases), in kg CO2e;
- depletion of the stratospheric ozone layer, in kg CFC-11;
- acidification of land and water sources, in moles H+ or kg SO2;
- eutrophication, in kg nitrogen or kg phosphate;
- formation of tropospheric ozone, in kg NOx, kg O3 eq, or kg ethene; and
- depletion of nonrenewable energy resources, in MJ.

Both the test building and the benchmark building are similar in that they are same size (same floor area, same height and dimensions), but their structural and enclosure design differ. The benchmark building and the as-built building can be broadly described as follows:

- Benchmark building: Mildly reinforced concrete slabs at all levels. With the typical UW building's façade, Brick- mortar cladding.
- As-built building (UW Population Health Building): Mildly reinforced concrete slabs at basement levels, post-tensioned (PT) concrete slabs at upper levels. Cladding is a mix of curtain wall and precast concrete panels.

Material quantity estimates were described for both buildings by the structural engineer. See the attachment Appendix A for an original copy of the estimating description. These estimates were used to determine the material quantities for both buildings.

3.2.2. Goal and scope

The goal of this study is to get the LCA results of the UW PHF project to be compared with the baseline project results in order to get the LEED building life-cycle impact reduction credit. If the requirements of this credit are met, then the project can collect 3 LEED points in pursuit of its LEED certification.

The scope of this study encompasses the full life cycle of the building, life cycle stages A – D (cradle-to-cradle).

4. Results

Table 4 summaries the impact assessment results in all LCA categories and the bar charts show the % difference for each material as assessed by different tools. Despite having the equal data input into Tally and Athena, the total LCA results in different LCA stages have substantial discrepancies. Direct comparisons of the results are difficult to comprehend, so the differences are calculated as the percentage difference for each material and life cycle stage. There are discrepancies in these values for almost all the categories and materials even though the material amounts used for the analysis by each tool are identical. The percentage differences are therefore attributable to the different LCI for each assessment tool. The bar charts show that in almost all categories and impacts, Athena presents a higher amount in comparison with Tally.

To have a well-founded comparison, among all LCA impact categories, five LEED-Important factors are selected in the next comparisons and analysis because LEED focuses on these categories more than the others. They are:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EuP)
- Ozon Depletion Potential (ODP)
- Smog Potential (SP)

Tables 5-8 and the figures 6, 8, 10, and 12 show the LCA calculations and their discrepancies for each material separately. The value of the Global warming Potential is much higher than the others, so, in order to show all the impacts in a single bar chart, the numbers axis is considered as a logarithmic scale with a base of 10.

	Global Warming Potential		
	Tally	Athena	% Difference
Aluminum	193.07	243	21
Glazing	84.62	257.1	67
Gypsum Wall Board	6.74	7.42	9
Insulation	2.54	2.63	3

	Acidification Potential		
	Tally	Athena	% Difference
Aluminum	0.079	1.16	93
Glazing	0.071	2.3	97
Gypsum Wall Board	0.02	0.06	67
Insulation	0.01	0.03	67

	Smog Potential		
	Tally	Athena	% Difference
Aluminum	7.45	12.3	39
Glazing	8.77	36.2	76
Gypsum Wall Board	0.49	1.09	55
Insulation	0.07	1.19	94

	Total Primary Energy		
	Tally	Athena	% Difference
Aluminum	3,158.78	3210	2
Glazing	1,139.78	1310	13
Gypsum Wall Board	219.76	117	-88
Insulation	40.85	38.9	-5

	Non-Renewable Energy		
	Tally	Athena	% Difference
Aluminum	2,601.61	3170	18
Glazing	1,078.41	761	-42
Gypsum Wall Board	211.51	112	-89
Insulation	6.44	38.8	83

Table 4, LCA Results, Tally and Athena

4.1. Section 1

Aluminum

ALUMINUM		PRODUCT	PROCESS	USE	END OF LIFE	Module D	Total (A to D)
Global Warming Potential	GWP Tally	127.71	2.82	0	0.17	62.37	193.07
	GWP Athena	189.7623	5.4602	0.0000	82.7567	-34.6424	243.3369
Acidification Potential	AP Tally	0.36	0.01	0	0	0.41	0.79
	AP Athena	0.9299	0.0626	0.0000	0.3929	-0.2292	1.1562
Eutrophication Potential	EuP Tally	0.01	0.00	0	0	0.01	0.02
	EuP Athena	0.0186	0.0033	0.0000	0.0099	-0.0038	0.0280
Ozone Depletion Potential	ODP Tally	8.18E-09	9.65E-14	0	3.15E-14	2.81E-09	1.10E-08
	ODP Athena	1.05E-08	2.96E-10	0.00E+00	7.91E-09	-1.54E-09	1.72E-08
Smog Potential	SP Tally	3.83	0.43	0	0.02	3.17	7.45
	SP Athena	8.1250	1.7589	0.0000	4.2053	-1.7830	12.3064

Table 5, Tally vs. Athena IE LCA results for Aluminum.

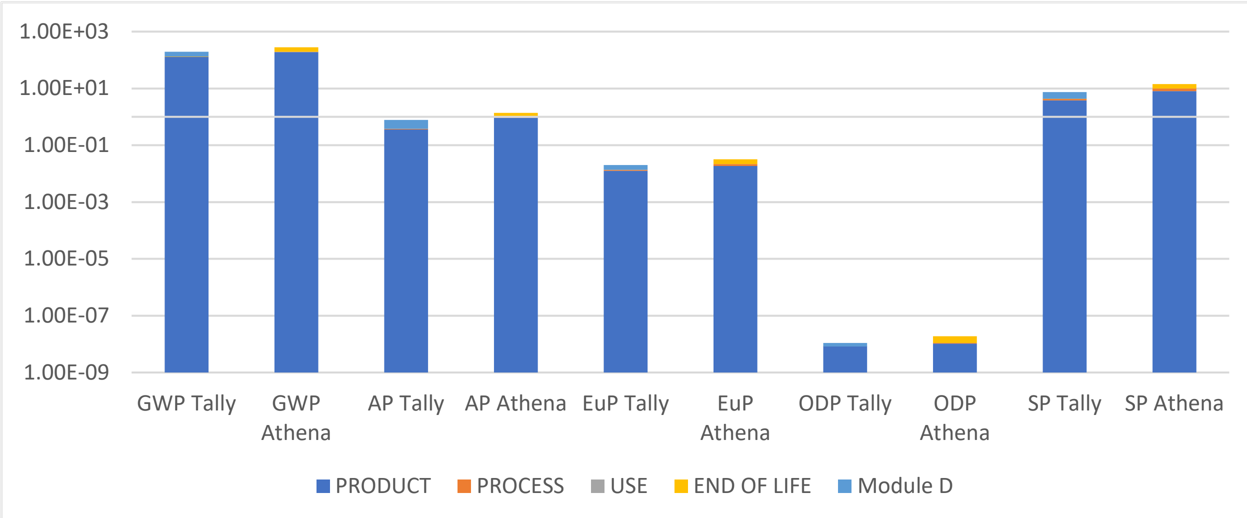

Figure 6, Tally vs. Athena IE LCA results for Aluminum

The aluminum LCA analyses show that Athena predicts a greater impact in almost all LCA impact categories, in comparison with the Tally results. In each category thehighest impact and the largest difference occurs in the "product" stage, while impacts in the "use" stage LCA results are all zero in both the Athena IE and Tally results. In other words, Aluminum does not have any LCA impacts during its usage life.

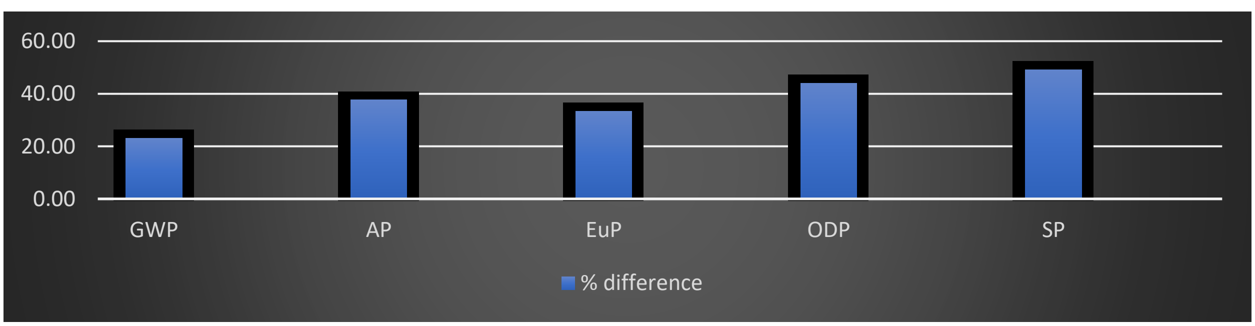

Figure 7, The percentage difference of the LCA results for Aluminum

Figure 7 illustrates the difference percentage of each LCA category result for Athena IE and Tally. The difference is calculated using the average amount of results based on the formula below:

$$\% \, Difference = \frac{Difference \; of \; Athena \; and \; Tally \; Result}{Average \; of \; Athena \; and \; Tally \; Result} * 100$$

As is obvious in the bar chart the largest difference belongs to Smog potential and the smallest one is for Global warming potential

Glazing

Another component that is considered in the study is glazing. It has been examined as a scope of Glass with 1/2″ thickness and by the weight of 6.5 pound per square footage.

GLAZING		PRODUCT	PROCESS	USE	END OF LIFE	Module D	Total (A to D)
Global Warming Potential	GWP Tally	77.87	3.63	0	3.11	0.00	84.61951584
	GWP Athena	139.36	1.48	115.70	0.57	0.00	257.12
Acidification Potential	AP Tally	0.68	0.02	0	0.01	0.00	0.710102978
	AP Athena	1.24	0.02	1.03	0.01	0.00	2.30
Eutrophication Potential	EuP Tally	0	0.03	0	0	0	2.99E-02
	EuP Athena	0.04	1.01E-03	3.67E-02	3.42E-04	0.00	0.08
Ozone Depletion Potential	ODP Tally	3.33E-11	1.24E-13	0	5.73E-13	0	3.40E-11
	ODP Athena	1.40E-07	5.88E-11	1.15E-07	2.00E-11	0.00	2.55E-07
Smog Potential	SP Tally	7.93	0.56	0	0.29	0.00	8.77E+00
	SP Athena	19.19	0.52	16.27	0.17	0.00	36.15

Table 6, Tally vs. Athena IE LCA results for Glazing

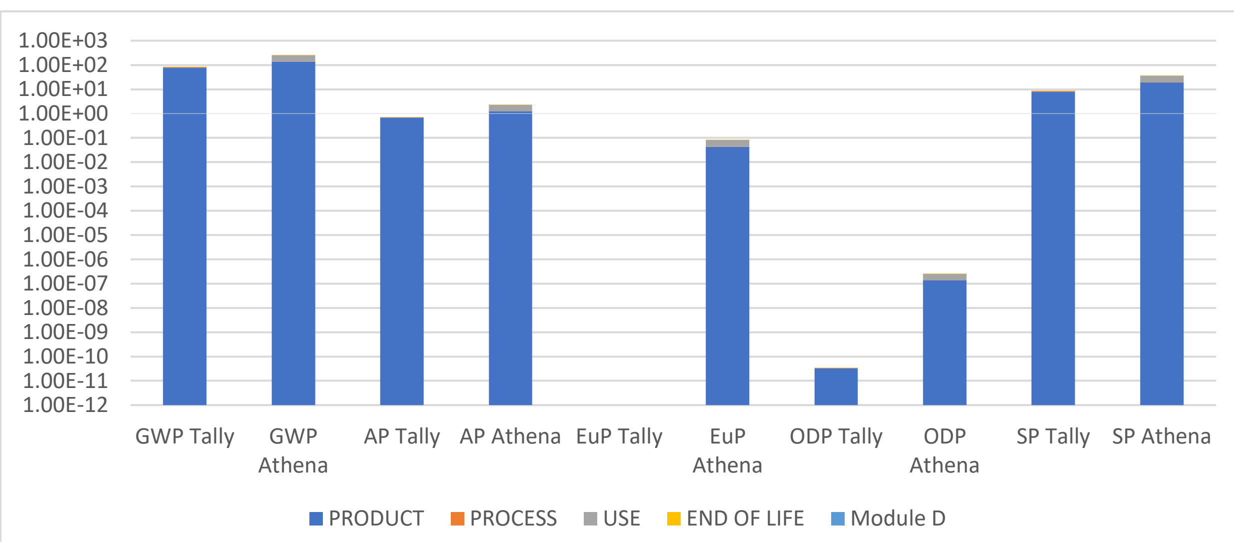

Figure 8, Tally vs. Athena IE LCA results for Glazing

Glazing LCA analyses show that Athena predicts a greater impact in almost all LCA impact categories, in comparison with Tally results. As with aluminum in each category the highest impact and largest percentage difference occurs in the "product" stage while the "Module D" stage LCA results for glass are all zero in both Athena IE and Tally results.

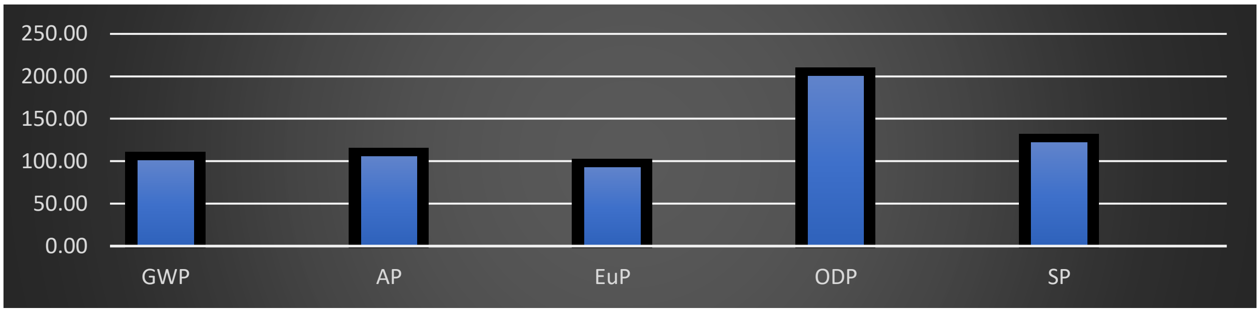

Figure 9, The percentage difference of the LCA results for Glazing

The differences have a high amount of percentage for glazing when comparing the Athena and Tally results. It is obvious that the LCI for each tool has notable differences at least for this defined kind of glazing.

Insulation

The third component of the study is insulation. The Insulation considered is a cellulose type with 1″ thickness.

Insulation		PRODUCT	PROCESS	USE	END OF LIFE	Module D	Total (A to D)
Global Warming Potential	GWP Tally	-1.87	0.06	-1.25	0.55	-0.03	2.54
	GWP Athena	0.15	2.48	0.00	5.76E-03	0.00	2.64
Acidification Potential	AP Tally	0.00	0.00	0.01	0.00	0.00	0.01
	AP Athena	1.28E-03	3.54E-02	0.00	5.54E-05	0.00	3.67E-02
Eutrophication Potential	EuP Tally	0	0	0	0	0	0.00
	EuP Athena	3.64E-05	2.20E-03	0.00	3.45E-06	0.00	2.24E-03
Ozone Depletion Potential	ODP Tally	5.57E-13	2.16E-15	5.69E-13	9.16E-15	-3.56E-14	1.10E-12
	ODP Athena	1.44E-09	1.80E-10	0.00	2.01E-13	0.00	1.62E-09
Smog Potential	SP Tally	0.02	0.01	0.04	0.01	0.00	0.07
	SP Athena	0.02	1.17	0.00	1.75E-03	0.00	1.19

Table 7, Tally vs. Athena IE LCA results for Insulation

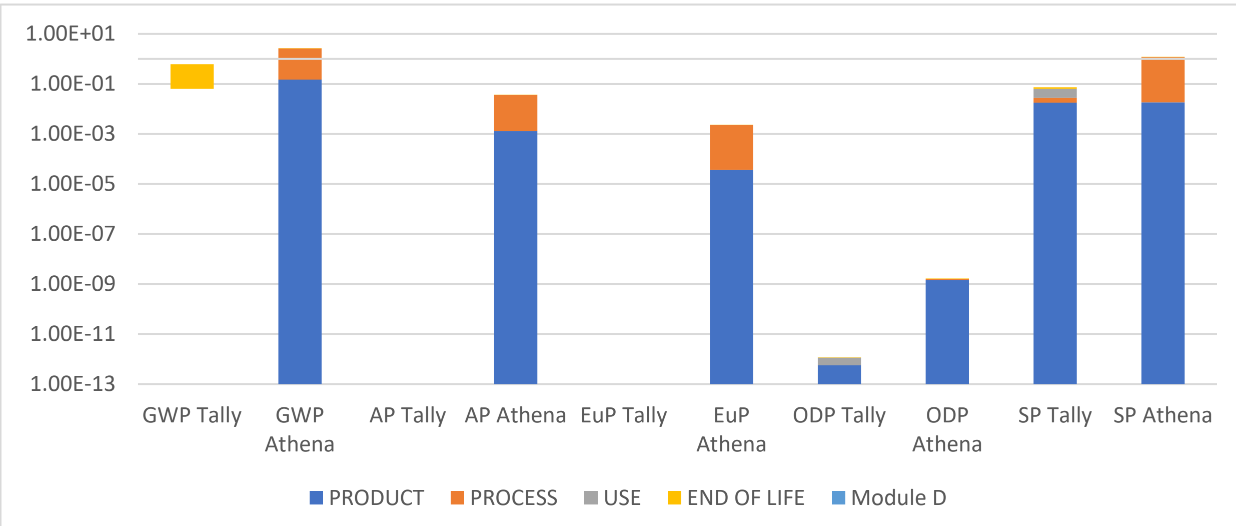

Figure 10, Tally vs. Athena IE LCA results for Insulation

Insulation LCA analyses show that Athena predicts greater impacts in almost all LCA impact categories, in comparison with Tally results. The distinct result for Insulation in comparison with other components is the zero amount of GWP, Ap, and Eup calculated by Tally. This may be because, generally, since one cubic footage of the Insulation is a very small amount of material in comparison with the total amount needed in a building, all results, even the GWP amounts, are very small in comparison with other materials.

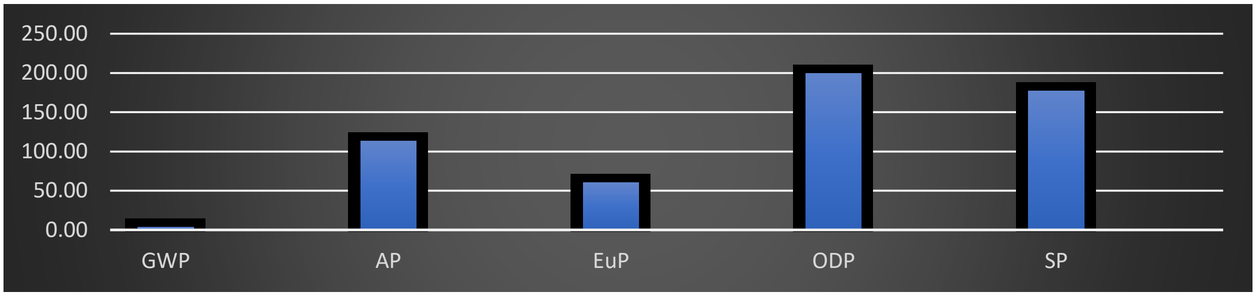

Figure 11, The percentage difference of the LCA results for Insulation

The differences cover a wide range of percentage for insulation when comparing the Athena and Tally results. It has a very small amount for GWP but a huge number for ODP and SP.

Gypsum Wall Board (GWB)

The fourth component of the study is Gypsum Wall Board.

Gypsum Wall Board		PRODUCT	PROCESS	USE	END OF LIFE	Module D	Total (A to D)
Global Warming Potential	GWP Tally	5.53	0.21	6.74	1.00	0.00	13.47
	GWP Athena	5.29	1.99	0.00	0.15	0.00	7.42
Acidification Potential	AP Tally	0.00	0.00	0.01	0.00	0.00	0.02
	AP Athena	0.04	0.03	0.00	1.40E-03	0.00	0.07
Eutrophication Potential	EuP Tally	0.00	0.00	0.00	0.00	0.00	0.00
	EuP Athena	3.51E-03	1.69E-03	0.00	8.69E-05	0.00	5.29E-03
Ozone Depletion Potential	ODP Tally	5.98E-13	7.29E-15	7.89E-13	1.83E-13	0.00	1.58E-12
	ODP Athena	1.18E-08	1.23E-09	0.00	5.07E-12	0.00	1.30E-08
Smog Potential	SP Tally	0.12	0.03	0.25	0.09	0.00	0.49
	SP Athena	0.31	0.74	0.00	0.04	0.00	1.09

Table 8, Tally vs. Athena IE LCA results for GWB

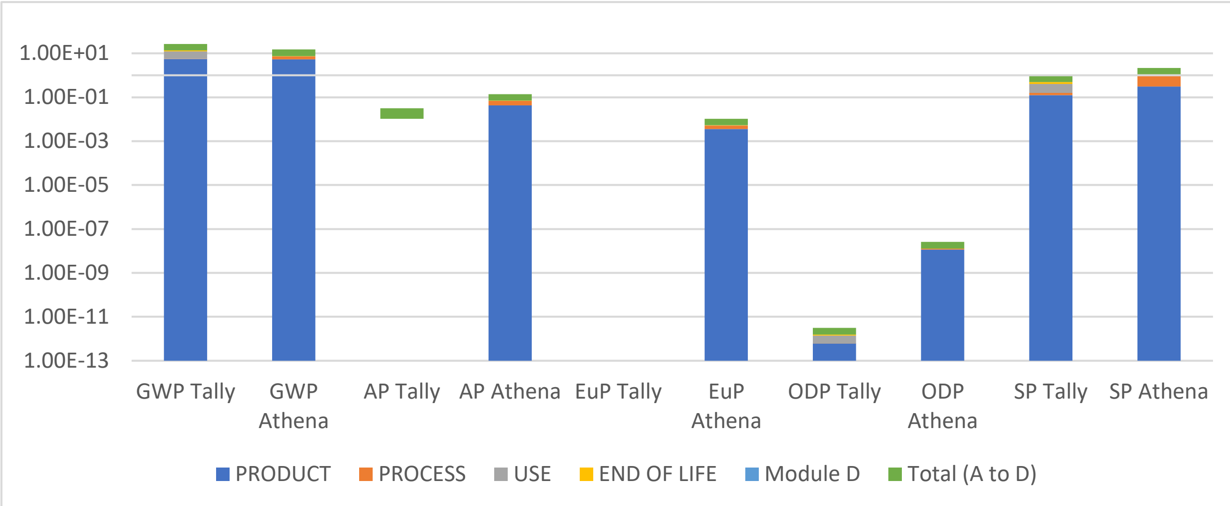

Figure 12, Tally vs. Athena IE LCA results for GWB

Gypsum Wall Board LCA analyses show that Athena predicts a greater impact in all LCA impact categories except GWP, in comparison with Tally results. The distinct result for GWB in comparison with other components is the zero amount of GWP and Ap calculated by Tally in Product and Produce stages, while the "Module D" stage LCA results are all zero in both Athena IE and Tally results.

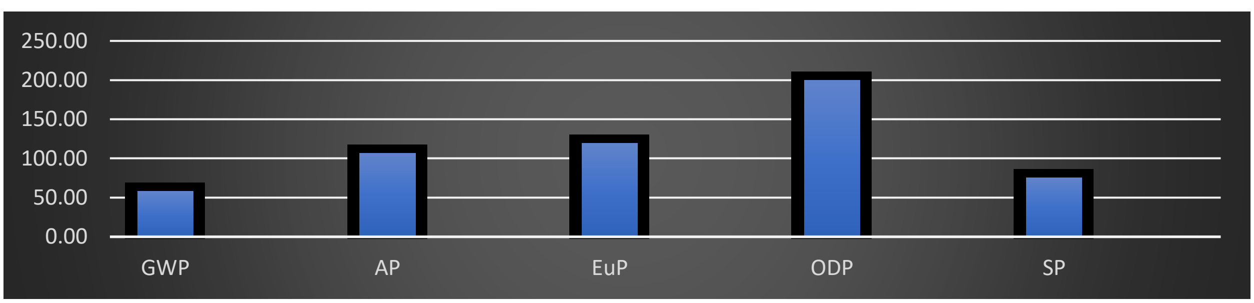

Figure 13, The percentage difference of the LCA results for GWB

4.2. Section 2

The application of LCA tools on a section of a curtain wall in the UW PHF Building

At the second step of the analyses, a limited part of the Population Health Facility (PHF) Building's façade is simulated in Athena and Tally. The curtainwall of the north side façade is considered. The comparative results are brought in figure 15 The difference is calculated by the below formula:

$$\% \, Difference = \frac{Difference \; of \; Athena \; and \; Tally \; Result}{Athena \; Result} * 100$$

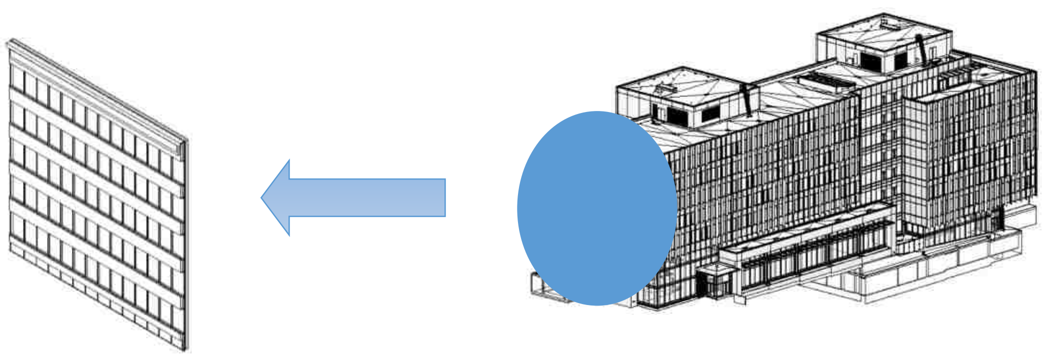

Figure 14, North Elevation Curtain Wall

	Acidification Potential (kgSO2eq)	Eutrophication Potential (kgNeq)	Global Warming Potential (kgCO2eq)	Ozone Depletion Potential (CFC-11eq)	Smog Formation Potential (kgO3eq)	Primary Energy Demand (MJ)	Non-renewable Energy Demand (MJ)
Tally	515.98	17.22	96,120.62	8.00E-06	5,868.12	1,528,743.95	1,304,111.26
Athena	746.61	22.97	92,328.12	0	9,409.22	844,498.79	832,539.46
Difference	230.63	5.75	3,792.50	0	3,541.10	684,245.15	471,571.80
Difference, Athena compared to Tally (%)	30.89	25.04	4.11	-85.23	-37.63	81.02	56.64

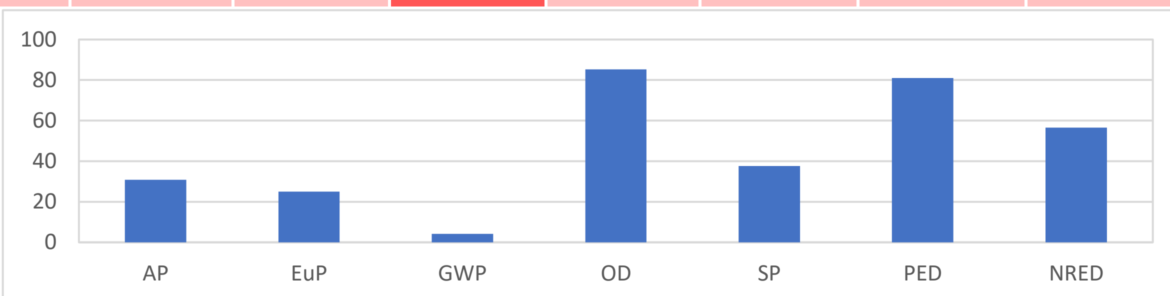

Figure 15, Comparison of the Tally and Athena Results for North curtainwall of PHF

The Global "Warming Potential" is the factor that indicates the amount of the carbon emission of a project; it is the most important factor in environmental impacts throughout the different LCA stages. The results and their orders of carbon emission for each step are shown in table 9. While there is a small discrepancy in its total amount, the amounts related to each LCA stage have notable differences. The differences in the different stages come primarily from the differences in the way each tool defines the stage divisions. For instance, Athena considered more carbon emissions during the "use" and "End of life" stage, while, Tally has calculated the carbon emissions more in "Module D" and "Product" stage.

	Global Warming Potential (Kg Co^2 eq)		
	Tally	Athena	% Difference
End of Life	501.11	7,222.37	93.06
Maintenance and Replacement	15,902.52	30,943.43	48.61
Module D	52,141.06	22,927.96	127.41
Product	130,583.36	75,575.54	72.79
Transportation	1,274.69	7,222.37	82.35
Grand Total	96,120.62	92,328.11	4.11

The order of Difference Percentage
End of Life
Transportation
Product
Maintenance
Module D

Table 9, Comparison of GWP in Tally and Athena Results base on Stage Division

Figure16 shows the difference percentage of each LCA stage in pie chart to show that the "Module D" has the largest difference while, the "Maintenance and Replacement" (or "Use") ihas the smallest.

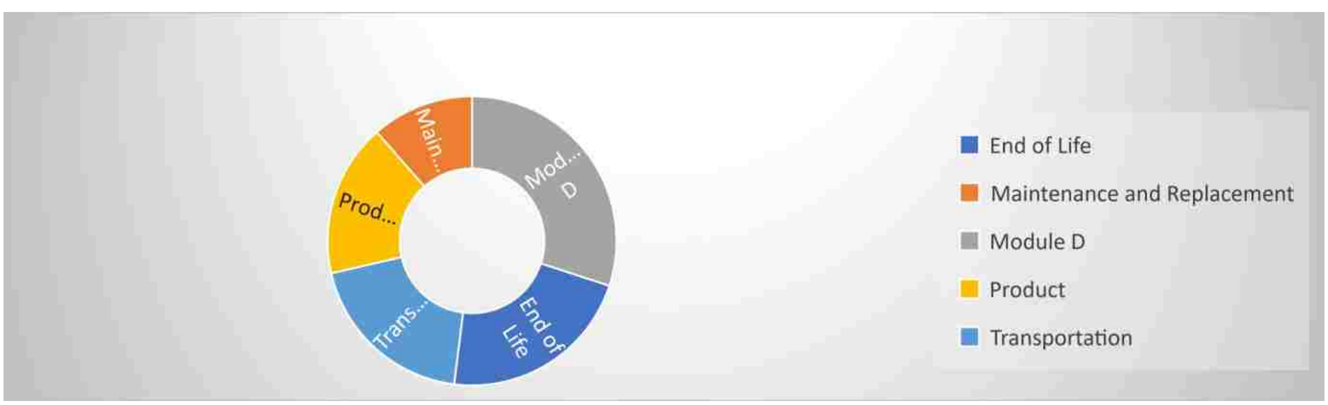

Figure 16, difference percentage of each LCA stage pie chart

In addition to the critical differences in the LCI and calculations methods, the mechanisms for generating the quantity take-offs in the two platforms is a major factor in producing the discrepancies of the total LCA impacts analysis. The whole materials units are Kg, so the total amounts can be compared in the grand total of material. The Bill of Materials Report from Athena and Tally for the north façade curtainwall of the Population Health Facility (PHF) Building is shown in tables of figure 17.

Bill of Materials Report (Athena)

Project: NCW

Material	Unit	Total Quantity		Unit (kg)	
Aluminum Extrusion	Tons (short)	6.5619		kg	5952.843
EPDM membrane (black, 60 mil)	lbs	543.5212		kg	0.122292
Glazing Panel	Tons (short)	28.3212		kg	25692.5
Screws Nuts & Bolts	Tons (short)	0.2304		Kg	208.992
Spandrel Panel	Tons (short)	1.4993		kg	1360.125
Grand Total					

Bill of Materials Report (Tally)

Row Labels	Sum of Mass Total (kg)
Curtain Panels	20,484.82
System Panel: PHF Shadow Box Glazing (UCW-1C)	8,275.56
System Panel: PHF Vision Glazing (UCW-1A)	12,209.26
Curtain Wall Mullions	20,914.53
Rectangular Mullion: ELICC Coping w/o Frame (MM-2)	3,567.07
Rectangular Mullion: UCW STACK JOINT TOWER	6,058.95
Rectangular Mullion: Unitized_ 2 1/2"x 6 1/2" - SSG Horizontal TOWER	2,838.34
Rectangular Mullion: Unitized_ 3"x 6 1/2" - SSG Vertical TOWER	8,450.16
Grand Total	

Figure 17, Bill of Materials of the north façade curtainwall of the PHF Building

Tally/ Athena consumed material (Difference Percentage) = 19%

4.3. Section 3

The full enclosure of PHF Building LCA analysis by Athena

Tally is dependent on the Revit 3D model of a project to develop LCA analysis. All the Tally results would be derived based on the model specifications. The Revit Model of the PHF building enclosure was not created using the proper material specifications, so Tally's LCA analysis could not be reliable for further investigations. Because in Athena IE all data is imported manually, it can produce LCA results without ta Revit 3D model. The whole LCA results for the full PHF enclosure are shown in table 10.

LCA Measures	Unit	Walls	Roofs	Total
Global Warming Potential	kg CO2 eq	2.41E+06	1.97E+06	**4.38E+06**
Acidification Potential	kg SO2 eq	1.36E+04	1.76E+04	**3.12E+04**
HH Particulate	kg PM2.5 eq	1.87E+04	4.04E+04	**5.90E+04**
Eutrophication Potential	kg N eq	4.99E+02	6.25E+02	**1.12E+03**
Ozone Depletion Potential	kg CFC-11 eq	4.18E-03	2.03E-03	**6.21E-03**
Smog Potential	kg O3 eq	1.92E+05	2.77E+05	**4.69E+05**
Total Primary Energy	MJ	2.56E+07	1.03E+07	**3.59E+07**
Non-Renewable Energy	MJ	2.38E+07	6.09E+06	**2.99E+07**
Fossil Fuel Consumption	MJ	1.96E+07	6.03E+06	**2.57E+07**

Table 10, for the full PHF enclosure LCA results

The detailed LCA analysis of the PHF building's enclosure is shown in table 11. The LCA values are divided by their LCA stages to show which stage has the most environmental effect and which one has the least.

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)		
LCA Measures	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**
Global Warming Potential	kg CO2 eq	2.88E+06	2.18E+04	**2.91E+06**	5.25E+04	3.37E+04	**8.62E+04**
Acidification Potential	kg SO2 eq	1.99E+04	2.44E+02	**2.01E+04**	2.74E+02	3.82E+02	**6.55E+02**
HH Particulate	kg PM2.5 eq	3.40E+04	1.16E+01	**3.40E+04**	1.08E+02	1.79E+01	**1.26E+02**
Eutrophication Potential	kg N eq	6.42E+02	1.51E+01	**6.57E+02**	1.06E+01	2.36E+01	**3.42E+01**
Ozone Depletion Potential	kg CFC-11 eq	4.68E-03	8.29E-07	**4.68E-03**	3.33E-04	1.28E-06	**3.35E-04**
Smog Potential	kg O3 eq	2.65E+05	7.81E+03	**2.73E+05**	4.79E+03	1.22E+04	**1.70E+04**
Total Primary Energy	MJ	2.74E+07	3.16E+05	**2.77E+07**	5.07E+05	4.84E+05	**9.91E+05**
Non-Renewable Energy	MJ	2.40E+07	3.16E+05	**2.44E+07**	4.86E+05	4.84E+05	**9.70E+05**
Fossil Fuel Consumption	MJ	1.84E+07	3.16E+05	**1.87E+07**	4.22E+05	4.83E+05	**9.05E+05**

	USE (B2, B4 & B6)				END OF LIFE (C1 to C4)		
LCA Measures	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**	De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**
Global Warming Potential	1.20E+06	3.07E+04	0.00E+00	**1.23E+06**	1.22E+05	1.33E+04	**1.36E+05**
Acidification Potential	1.06E+04	3.41E+02	0.00E+00	**1.09E+04**	7.03E+02	1.27E+02	**8.31E+02**
HH Particulate	2.46E+04	1.68E+01	0.00E+00	**2.46E+04**	9.71E+01	7.06E+00	**1.04E+02**
Eutrophication Potential	3.73E+02	2.11E+01	0.00E+00	**3.94E+02**	2.61E+01	7.92E+00	**3.40E+01**
Ozone Depletion Potential	1.20E-03	1.19E-06	0.00E+00	**1.20E-03**	1.01E-05	4.62E-07	**1.06E-05**
Smog Potential	1.60E+05	1.09E+04	0.00E+00	**1.71E+05**	1.25E+04	4.02E+03	**1.65E+04**
Total Primary Energy	6.33E+06	4.45E+05	0.00E+00	**6.78E+06**	1.66E+06	1.93E+05	**1.86E+06**
Non-Renewable Energy	3.77E+06	4.45E+05	0.00E+00	**4.21E+06**	1.58E+06	1.93E+05	**1.78E+06**
Fossil Fuel Consumption	3.71E+06	4.44E+05	0.00E+00	**4.16E+06**	1.52E+06	1.93E+05	**1.71E+06**

	BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
LCA Measures	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
Global Warming Potential	2.17E+04	0.00E+00	**2.17E+04**	**4.36E+06**	**4.38E+06**
Acidification Potential	-1.29E+03	0.00E+00	**-1.29E+03**	**3.25E+04**	**3.12E+04**
HH Particulate	1.39E+02	0.00E+00	**1.39E+02**	**5.89E+04**	**5.90E+04**
Eutrophication Potential	5.22E+00	0.00E+00	**5.22E+00**	**1.12E+03**	**1.12E+03**
Ozone Depletion Potential	-1.38E-05	0.00E+00	**-1.38E-05**	**6.22E-03**	**6.21E-03**
Smog Potential	-8.30E+03	0.00E+00	**-8.30E+03**	**4.77E+05**	**4.69E+05**
Total Primary Energy	-1.42E+06	0.00E+00	**-1.42E+06**	**3.73E+07**	**3.59E+07**
Non-Renewable Energy	-1.40E+06	0.00E+00	**-1.40E+06**	**3.13E+07**	**2.99E+07**
Fossil Fuel Consumption	2.09E+05	0.00E+00	**2.09E+05**	**2.54E+07**	**2.57E+07**

Table 11, Detailed Life Cycle Assessment of UW PHF Enclosure by Life Cycle Stages by Athena

To have a graphical comparison, the LCA results for the enclosure are depicted in figure 18 based on their different LCA stages.

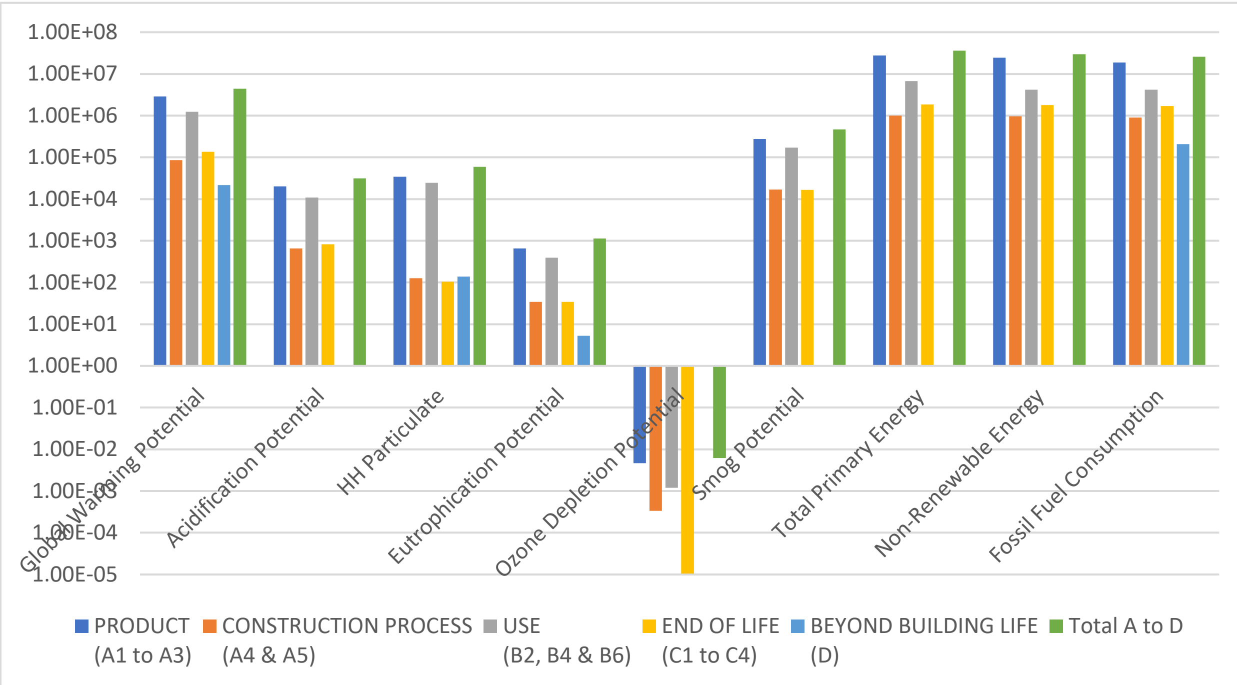

Figure 18, Detailed Life Cycle Assessment of UW PHF Enclosure by Life Cycle Stages by Athena

Normalization

To have a reasonable interpretation of the LCA results, a reference is necessary. In other words, the LCA results are not enough to judge a project for its environmental impacts. Hence normalization helps practitioners to interpret results based on a common reference. There are two different methods of normalization that are categorized in the figure 19. The first method is considered in this section of this study to normalize the LCA results.

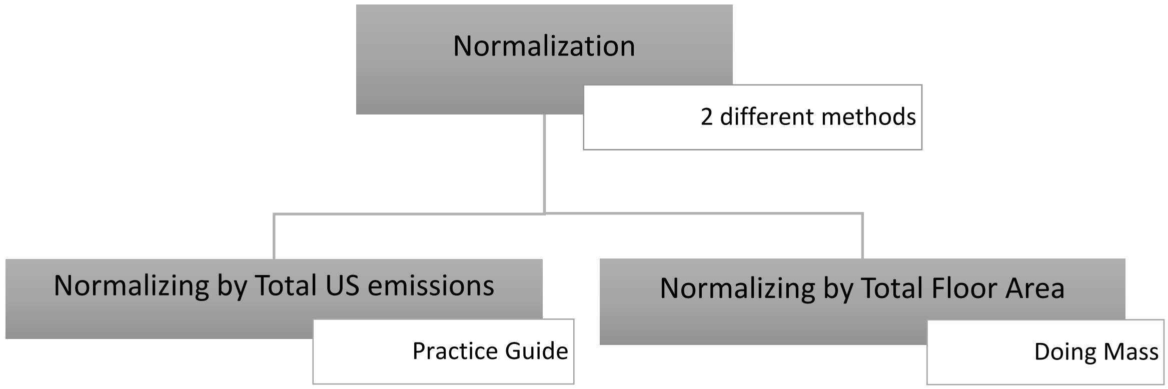

Figure 19, Normalization Methods

Normalization works as a tool to distinguish the importance of LCA factors and enables the practitioners to understand how each factor reflects the impacts on the environment (Morten Ryberg, 2014). In this study the normalization factors are from TRACI 2.1 LCIA model.

As a general definition the normalization factors (NFs) are estimated by the total amount of each category divided by the number of residents of a considered area within a defined period of time as shown in below Eq (Morten Ryberg, 2014).

$$NFi = \frac{\sum CFi, s \ \times Es}{P}$$

NF_i is the normalization factor per capita per year for i impact category.

$CF_{i,s}$ is the characterization factor that is defined as the impact per kg emitted of substance s for impact category i.

Es is emissions of materials for the considered area (kg per year) (US for this study)

P is the number of residents of the reference area or in other words, capita.

Table 13 shows the calculated NFs. The Nfs are brought in for all the LCA impact categories used in TRACI 2.1 in two different geographical areas. The US area and the five LEED-important factors are considered for this study, as they are highlighted in table 12.

Impact category	Normalization factors and reference year				
	US 2008		US–CA 2005/2008*		Ratio: US/US–CA
	Impact per year	Impact per person year	Impact per year	Impact per person year	
Ecotoxicity-non-metals (CTUe)	2.3×10^{10}	7.6×10^{1}	2.5×10^{10}	7.4×10^{1}	1.02
Ecotoxicity-metals (CTUe)	3.3×10^{12}	1.1×10^{4}	3.7×10^{12}	1.1×10^{4}	1.00
Carcinogens-non-metals (CTUcanc.)	1.7×10^{3}	5.5×10^{-6}	1.7×10^{3}	5.1×10^{-6}	1.08
Carcinogens-metals (CTUcanc.)	1.4×10^{4}	4.5×10^{-5}	1.5×10^{4}	4.3×10^{-5}	1.05
Non-carcinogens-non-metals (CTUnon-canc.)	1.1×10^{4}	3.7×0^{-5}	1.1×10^{4}	3.4×10^{-5}	1.09
Non-carcinogens-metals (CTUcanc.)	3.1×10^{5}	1.0×10^{-3}	3.4×10^{5}	1.0×10^{-3}	1.01
Global warming (kg CO_2 eq)	7.4×10^{12}		8.0×10^{12}	2.4×10^{4}	1.01
Ozone depletion (kg CFC-11 eq)	4.9×10^{7}		4.9×10^{7}	1.5×10^{-1}	1.10
Acidification (kg SO_2 eq)	2.8×10^{10}		3.2×10^{10}	9.5×10^{1}	0.96
Eutrophication (kg N eq)	6.6×10^{9}		7.00×10^{9}	2.1×10^{1}	1.04
Photochemical ozone formation (kg O_3 eq)	4.2×10^{11}		4.9×10^{11}	1.5×10^{3}	0.96
Respiratory effects (kg $PM_{2.5}$ eq)	7.4×10^{9}		1.0×10^{10}	3.0×10^{1}	0.82
Fossil fuel depletion (MJ surplus)	5.3×10^{12}		6.6×10^{12}	1.9×10^{4}	0.89

* The study used a combined inventory with US and Canada, the reference years are 2008 and 2005 respectively

Table 12, The TRACI 2.1 Normalization Factors

LCA Measures	Unit	Roofs	Walls	Total	Façade Impact/ Sf of the Facade	Normalization Factor/ Impact per Year (From Practice Guide)	Normalized Impacts Results
Global Warming Potential	kg CO2 eq	3.34E+06	2.41E+06	**5.74E+06**	5.95E+01	2.40E+04	2.39E+02
Acidification Potential	kg SO2 eq	4.00E+04	1.36E+04	**5.36E+04**	5.56E-01	9.10E+01	5.89E+02
Eutrophication Potential	kg N eq	1.97E+03	4.99E+02	**2.47E+03**	2.56E-02	2.20E+01	1.12E+02
Ozone Depletion Potential	kg CFC-11 eq	2.10E-03	4.18E-03	**6.28E-03**	6.51E-08	1.60E-01	3.93E-02
Smog Potential	kg O3 eq	9.96E+05	1.92E+05	**1.19E+06**	1.23E+01	1.40E+03	8.48E+02
Total Primary Energy	MJ	3.15E+07	2.56E+07	**5.71E+07**	5.92E+02		
Non-Renewable Energy	MJ	2.72E+07	2.38E+07	**5.10E+07**	5.29E+02		
Fossil Fuel Consumption	MJ	2.69E+07	1.96E+07	**4.65E+07**	4.82E+02	1.70E+04	2.74E+03
HH Particulate	kg PM2.5 eq	4.10E+04	1.87E+04	**5.97E+04**	6.19E-01		

Table 13, The PHF Enclosure Normalized LCA Results

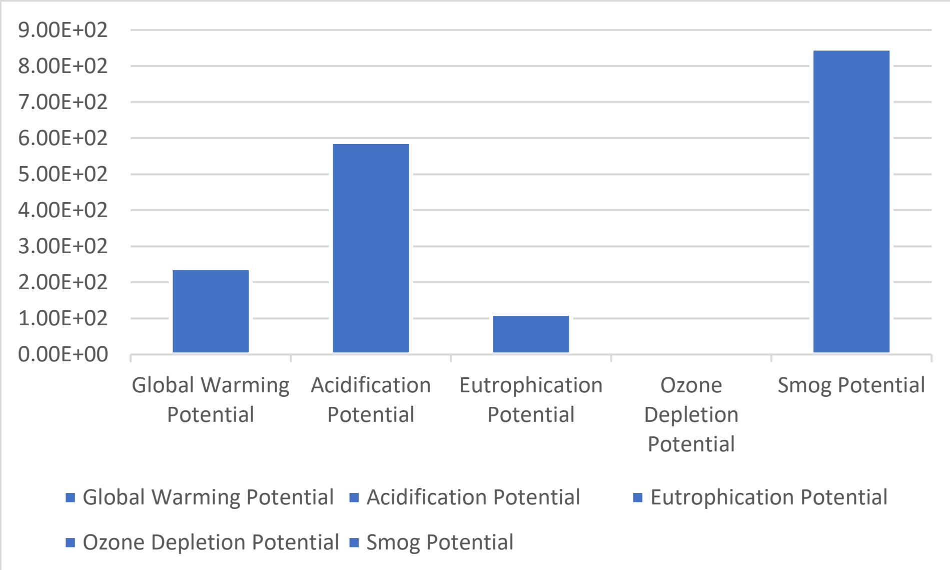

Figure 20, The normalized Impact of PHF Enclosure LCA results

LCA Tools Evaluation

Each LCA tool has different characteristics that indicate its level of applicability. There are two main factors that indicate the appropriateness of an LCA tool to make it widespread among design experts and professionals (Hsu, 2011):

1) Simplicity
2) Effectiveness

Simplicity allows easy adoption by designers, clients, and stakeholders who can then apply LCA analyses on their projects and find solutions to control their environmental impacts. Simplicity comes in two different areas; the simplicity of use, and the clarity of the results. Effectiveness improves the ability of the tools to overcome limitations by defining more common metrics and more reliable results. Figure 21 shows the Applicability of an LCA tool as a diagram and the table 14 shows the evaluation of Tally and Athena based on these factors.

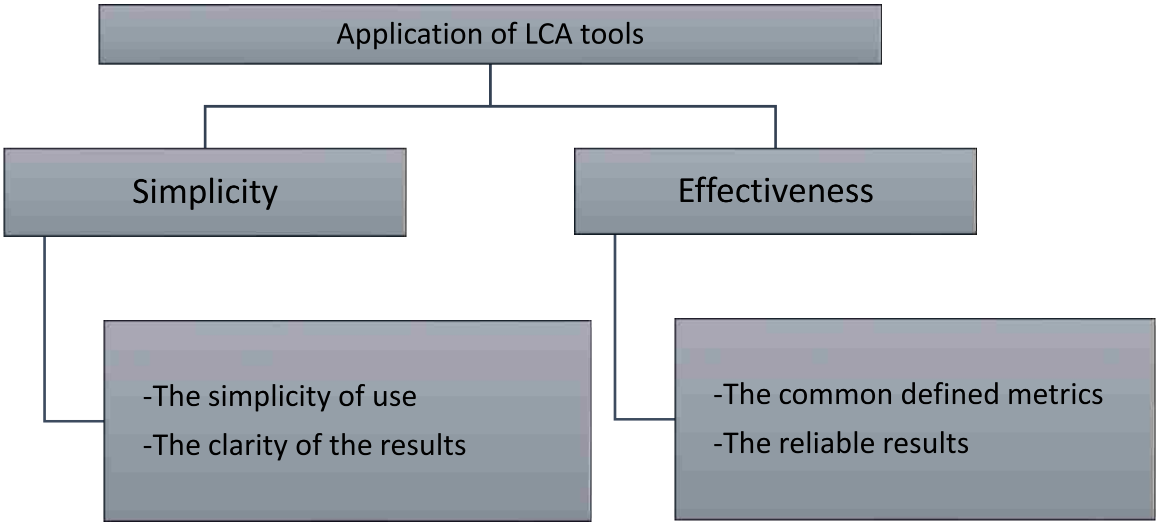

Figure 21, Applicability of an LCA tool

	Simplicity		Effectiveness	
	simplicity of use	clarity of the results	common defined metrics	reliable results
Tally	●●●○○	●●●●●	✓	Depends on the Model
Athena	●●●●●	●●●●●	✓	Depends on the inputs

Table 15, Tally/ Athena Evaluation

5. Discussion and Conclusion

In this research I have done a study on how an LCA analyzing tools might affect the results of an LCA analysis and how a tool could be efficient in the process of assessment. I found some different issues that should be mentioned in this section:

- The right time for applying LCA on a project has sparked a heated debate among the experts. Environmental consultants believe that these kinds of assessments are better to apply at the earliest stages of the design. In this regard, it should not be forgotten that the budget and available resources are determinative factors to make it possible (Joshua Schultz, 2017). However, the LCA analyses are typically applied on the later stages of the design. In fact, commonly the experts leave it aside and work on the other aspects of a project until the project is developed by the details. The absence of LCA analysis in the first stages of the design, causes excessive energy and cost for the later stages' modifications. So, based on this discussion it would be useful for an LCA tool to be applicable in different stages of the design with different requirements for inputs. This would allow the simple application of LCA analysis tools and would encourage experts to use them in early stages of the design.

- Another issue is the applicability of analyses in different industry areas. Applicability is defined by its marketable potential. While Athena is just applicable in the building and construction industry, Tally because of the different methods it usest could be applied in different areas of the industry because of the possibility of having their 3D models.

- One the most important factors in determining the reliability of both Athena and Tally is the material information databases that are derived from industry. In both tools there are limitations, and they need extension in available materials data especially manufacturer specific data such as is included in environmental product declarations (EPDs). Both tools can be updated as better data is available.

- It is a concern to consider different weights for the different LCA categories. It will be important when for example, a design may have a reduction in GWP but an increase in another category. How should the impacts be prioritized or weighted? It could be relevant to location, project type or a local guideline.

- Another issue is related to the LEED certificate. As the WBLCA credit of LEED is based on comparison of the as-built building with the benchmark building, defining the benchmark building is critical and could be the source of serious doubts and uncertainties.

5.1. Conclusion

In this research the discrepancies of the LCA results produced by two different tools – Athena and Tally– have been studied with the aim of exploring the reasons for these differences. The findings showed that even though working with a BIM-based analyzing tool is more efficient, it has some other conflicts and problems. For example, the complexity of the modeling in BIM-based tools can affect the reliability of the final LCA results. This should be considered by software developers, architects, and designers. Software developers should be aware that how the tools' interfaces are effective in encouraging LCA practitioners to apply LCA analyses on the projects. It should be mentioned that definitely the architects and designers need to have software skills to use analyzing tools efficiently and ideally.

It is hoped that this research works as a guideline for applying whole-building LCA analyses with the approach of using different tools and exploring the discrepancies of the results.

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