Life cycle assessment for Zero Emission Buildings – A chronology of the development of a visual, dynamic and integrated approach

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Abstract. Current regulations to reduce energy consumption, and GHG emissions from buildings have focused on reducing operational impacts [1] This paper addresses the specific challenge of increasing complexity and decreasing usability when dealing with the level of detail required when modelling life cycle assessment (LCA) and integrating embodied emission calculations in the design process of a ZEB. It is well known that architectural design processes inherently have high degrees of complexity, and this paper investigates how the use of information and communication technology (ICT) in the design process can have a great impact on reducing GHG emissions and increasing sustainability in ZEBs. Visualisation is an invaluable tool to communicate complex data in an interactive way that makes it easier for non-expert users to integrate LCA thinking early and throughout the design process.

The paper presents a chronology in the development of a more visual, integrated and dynamic approach involving the use of parametric LCA models for decision-support purposes. Such an approach provides the designer with a direct link between the 3D digital model and embodied emissions data contained in the ZEB Tool to perform life cycle GHG emission calculations of buildings. Integrating LCA in a more visual and easily understood way in the holistic design process can also influence more tangible material choices in terms of, for example, architectural tectonics or cultural heritage. This allows designers the possibility to choose, for example, durable or natural materials with the lowest environmental impact or innovative materials with high or low associated emissions and consider these holistically early in the design phase when the level of design freedom is greater. The extent to which existing ICT tools and User Interfaces (UI), such as dashboards, can provide dynamic visual feedback on selected parameters, including LCA, in the design process of zero emission buildings, is discussed. The paper presents two ‘proof of concept’ dashboards to visualise LCAs at the building (ZEB) and neighbourhood (ZEN) scale. Both approaches are currently being further developed in The ZEN research centre to visualise, analyse and model the data at different scales for different ZEN Key Performance Indicators (KPIs) using visualisation and immersive technologies, such as Extended Reality (XR) technologies including Virtual Reality (VR) and Augmented Reality (AR).

1. Introduction

The environmental impact of buildings on global energy demands and on greenhouse gas (GHG) emissions released to the atmosphere has rapidly increased during recent decades. In cooperation with the EU, Norway has committed to an ambitious climate goal – a 40 percent reduction in greenhouse gas emissions by 2030 compared to 1990 levels. However, it is increasingly recognised that this needs to be accompanied by a parallel focus on reducing embodied impact [2,3]. At the European level, the revised directive on Energy Performance of Buildings (EPBD) requires that all new buildings should be nearly zero energy by 2020 [4]. This is particularly important in Norway, since Norwegian Zero Emission
Buildings (ZEB) [5] have high-energy efficiency and the share of embodied material emissions was found to be around 60 – 75% of total emissions [6]. The most efficient way of reducing a building’s environmental impact is to address it in the design stage when design freedom is the greatest, but equally uncertainty is high with an unlimited number of design options. This paper targets innovation to reduce GHG emissions in architectural design solutions and design processes for construction, renovation and transformation. The design process is where critical decisions are made.

The design process is informed by many different factors such as the architect's skills, geographical and cultural circumstances, financial aspects and technical possibilities. Architectural design processes, therefore, have a high degree of complexity, which can be difficult to sort out and communicate. The use of information and communication technology (ICT) in this phase can have a great impact on sustainability and on the performance of the building design. [7] Urban planning processes involve diverse stakeholders and there is a clear need for efficient dialogue tools to support communication in transdisciplinary environments. The Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN) [8] develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society. Researchers, municipalities, industry and governmental organisations work together in the ZEN research centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. [8, 9, 10]

The role of ICT and a more visual approach, using dynamic and integrated ICT tools, is investigated to inform early design decisions with technical scientific GHG knowledge leading to emissions reduction. Moreover, this paper investigates how the use of ICT can help communicate, involve and improve participation from those involved early and throughout the design process. The work presented here with the ZEB tool [11] and integrated parametric LCA approach [12, 13] is aligned with other ongoing international initiatives in the IEA Annex 72 [14, 15], and previously in Nordic Build Sted project [16, 17], as well as, similar initiatives such as LCA Bygg, One Click LCA, InData EPD [18, 19, 20]

The aim of this paper is to present a chronology of the early work in ZEB by Houlihan Wiberg to develop a method for the calculation of embodied carbon in buildings for use as a decision-support tool. This paper also presents a chronology of the consecutive stages by Houlihan Wiberg together with her students, to integrate the ZEB Tool to develop an integrated dynamic, parametric, dashboard and visual LCA approach, and the conclusion is presented at the end of the paper.

2. The ZEB Tool

The ZEB tool methodological development described below, is connected to the Norwegian ZEB definition and ambition levels developed by the Norwegian ZEB research centre from 2009-2016. According to the ZEB definition, a ZEB can be achieved by offsetting greenhouse gas (GHG) emissions from the entire life cycle of the building through the generation of onsite renewable energy. The system boundaries for LCA corresponding to the ZEB ambition levels are detailed in the Norwegian ZEB Definition. [21, 22]

2.1. Background to the ZEB Tool

A method for the calculation of embodied carbon for materials, later known as The ZEB tool, was created in 2010 by Houlihan Wiberg and developed by her until 2015. A key feature of this Microsoft (MS) excel based method tool was the organisation of the buildings components as separate linked sheets using 2 digit codes according to the NS 3451:2009 Table of building elements [23] These digits were ascribed a number aligned to the respective building component i.e. 21 foundation and groundworks, 22 load-bearing structure, 23 outer walls etc. (see Appendix 1) where material quantities were manually imported from REVIT building information models (BIM) or architect's drawings where
a BIM mode was not available. The embodied emissions for each material quantity were calculated using emission factors from either specific EPD (Environmental Product Declarations) data [24] or generic data from Ecoinvent v.3.1. [25]. In this early version, the system boundary included A1-3 (production) and B4 (replacement). The results are summarized in a «Summary» sheet with the buildings lifetime of 60 years together with other building information. This method builds upon an excel based method for the calculation of emissions from operational energy Houlihan Wiberg created in her Ph.D. during the period 2005 to 2010. [26]. Kristjansdottir and Houlihan Wiberg harmonised the method of calculating embodied carbon for materials for use in both the ZEB residential and office concept buildings between 2013 and 2015. [27, 28, 29, 30]. In this stage of development, operational emissions (B6) were calculated separately using the software SIMIEN [31] and compensation of emissions from local, renewable energy production from photovoltaic (PV) production using the software PV SYST. [32].

2.1.1. Further development of the ZEB Tool Further development of the ZEB Tool has subsequently been led by Houlihan Wiberg in collaboration with several of her students from the M.Sc. Sustainable Architecture course during consecutive years, and through ZEB summer internships funded by the research centre on Zero Emission Buildings. These former students are listed and credited as co-authors in this paper to acknowledge their contribution to the further development of the ZEB tool and the development of a more integrated and visual approach. The first ZEB internship supervised by Houlihan Wiberg with Kjendseth Wiik (nee Inman) in the summer of 2014. During this ZEB internship, a digital library of EPDs (primarily sourced from EPD-Norge) was created and embedded in the ZEB Tool excel master document. In addition, the system boundaries were extended to include transport and construction emissions (life cycle modules A4 and A5). Here, emission data is coupled with the factory, warehouse and site locations as well as transport modes to calculate transport emissions, whereby geographical data for the calculation of transport emissions are taken from Googlemaps. [33] The ZEB tool was also adapted to automatically calculate material replacements during a 60-year building reference study period (RSP) from material and component reference service lifetimes (RS) obtained from EPDs and Byggforskerien. During this internship, a drop-down menu feature linked with the embedded EPD library was created which improved the speed of calculating emissions. The EPD library contains a large range of building materials categorised according to building material types. Each category includes specific emission data from EPD-Norge (which can be accessed by using the EPD reference number) as well as a generic emission data from Ecoinvent v.3.1 [25]. When no EPDs were available from EPD-Norge, specific emission data was sourced from either the International EPD system Environdec [34], European EcoPlatform [35] or German EPDs registered with IBU [36].

Since 2015, the ZEB Tool has been further developed with Wiik and Schlanbusch to include other features, such as a 'construction library' sheet and an 'operation' sheet. [11]. Another sheet calculates emissions from construction activities (C), which is linked to the 'construction library' sheet where all generic and specific emission data for on-site construction activities are placed. Lastly, the 'operation' sheet (O) is structured according to energy carriers and is divided into three parts: operational energy use, delivered energy and energy produced on site, and exported energy. These emissions are calculated from energy supplier’s emission factors. These enhancements were tested against GHG emission calculations for the ZEB living laboratory and Campus Evenstad buildings. The objective of each step in the development has been to analyse how a more visual, integrated and dynamic approach to life cycle assessment (LCA) can be used in a holistic way to provide dynamic feedback on construction materials, zero emission buildings (ZEB) and zero emission neighbourhoods (ZEN) early and throughout the design process. Finally, all results are summarised in the 'Summary' sheet in terms of the functional unit [11] (see Appendix 1). Information from the ZEB tool can be used to improve processes, support policy and to provide a sound basis for informed decisions.

3. A Dynamic approach to the ZEB Tool
Two dynamic approaches have been used in developing the ZEB tool, the first explores connecting the ZEB tool to Revit and Dynamo, whilst the second explores connecting the ZEB tool to Rhino and Grasshopper.

3.1. Revit ~ Dynamo ~ ZEB Tool

In 2016, as part of the Nordic Built Sted [16] funded research, Hofmeister [38] supervised by Houlihan Wiberg, created a dynamic connection between the BIM software Revit[37] and the ZEB tool [11]. The objective was to develop an integrated tool that is built upon a dynamic connection between Revit and the ZEB tool through the medium of visual programming using the plug-in Dynamo to visualise design outcomes in terms of GHGs in the early design phase (see Figures 1 and 2 below). The ZEB single family house concept study [27, 28] is used as a base case, and the 3D BIM is scheduled inside the visual programming tool Dynamo and linked to the ZEB tool. Materials are selected inside the ZEB tool and connected to Dynamo for colour coding building parts in relation to the associated emissions for each component, which enables a better understanding of emissions and ensures ease of use. In addition, every change in the design and within Revit, updates the emission results dynamically. The scope of this dynamic connection is limited to the production phase (A1-A3) and uses emission data from the EPD library. [38]

![Figure 1. Screenshot from video showing emission factors in the ZEB Tool and corresponding colour coding in Dynamo. [38].](image1)

![Figure 2. Screenshot from video of emission factors in the ZEB Tool and corresponding colour coding in Dynamo. [38].](image2)

3.2. Rhino ~ Grasshopper~ ZEB Tool

In 2016, in parallel to the Revit – Dynamo approach, a similar approach was created by Auklend and Slåke under the supervision of Houlihan Wiberg, to integrate the 3D modelling software Rhino, parametric plugin Grasshopper and the ZEB tool [39]. A dynamic link between Rhino and the ZEB tool
was created to create a ‘live’ link that gives feedback on the environmental impact of material choices, which enables LCA to be considered holistically early in the design phase (see Figure 3 below). A third-party plugin Flux was used for better integration of the numerical values, and the resulting GHG emission calculations were then reported back to the Grasshopper interface. The scope of this dynamic connection is limited to the production phase (A1-A3) and uses emission data from the EPD library. Building data is transferred from Rhino to Grasshopper, and the material quantities are fed into Excel with the use of Flux, which reads the modelling information and transforms the data into a ‘json’ script which can be read by Excel [39].

Figure 3. Diagram showing the development of the ‘live link’ between the ZEB tool and the Rhinoceros model using Grasshopper [39].
4. A Parametric approach to the ZEB Tool
The first stage of this work was completed in Spring 2016 as a joint master’s thesis by two Erasmus students, Manni and Ceci, and focuses on combining parametric design principles with LCA to further develop the ZEB single family house concept model [12, 40]. This work presents an integrated workflow to evaluate embodied emissions of materials and the energy demand of the building in each stage of the design process. The work was developed in Rhino using plug ins such as Grasshopper, Diva for Grasshopper and Ladybug. An algorithm is created to describe the building geometry, which is then connected with the ZEB tool and sources data from the EPD library to perform LCA in Grasshopper (see Figure 5). The main advantage of this process is that it enables the integration of daylight optimisation with LCA. The optimisation of the building geometry is established by introducing an evolutionary solver which is dependent on certain parameters, such as, maximum amount of daylight factor and radiation [23, 26]. Data for radiance comes from the Lawrence Berkeley National Laboratory, and weather data is available from EnergyPlus. Dataflow is managed by Grasshopper’s visual programming interface which uses a ‘Python’ script [12, 40].

Figure 4. A flowchart of the parametric methodology used: the top part shows the plan while the bottom part shows the tools used to control the geometry (Gm) and deal with the related environmental analyses such as embodied energy (Ee) operational energy (Oe) solar radiation (Irrgl) and daylight factor (Df), conducted in each stage of the design process [12, 40]

5. A Dashboard approach to the ZEB Tool
In this work conducted by Tuncer in Spring 2017, a proof of concept ZEB Dashboard has been created by Tuncer and is used to visualise and integrate LCA early in the design process of a ZEB. This is achieved using a shared platform as a design decision support instrument that can be used collectively to ensure a broader understanding of GHG emissions for different design and material choices. A script creates a dashboard interface (shared platform) as a webpage that can be shared with multiple stakeholders [41]. The scope of this dynamic connection is limited to the production phase (A1-A3) and uses emission data from the EPD library. The Revit geometry is translated into a ‘json’ script inside the Flux interface and is linked to the ZEB tool in Excel. Calculated emissions from the ZEB tool are then fed back into the Flux interface (see Figure 5) The 3D Revit BIM model together with all the relevant material take-offs are connected to Flux. The Flux script uses visual programming, takes the building elements and dynamically exports the materials and quantities to the ZEB Tool. The formulas within the ZEB tool enables the use of both metric and volumetric units. [41].
6. Visual LCA for ZEN

In this work conducted in Spring 2017, the material inventory from the ZEB Living Lab [42] is used by the students, Auklend and Slåke, to create various neighbourhood configurations within the Rhino interface using a parametric script. [43] This process is connected to the ZEB tool using Flux. GHG emission results are fed back into Flux to create a dashboard interface which is also connected to Grasshopper to control and change the neighbourhood configurations, material choices and material quantities. This work marks the further development of the student’s earlier work described in section 3.2 involving the creation of a dynamic link between Rhino and the ZEB tool. This work is part of the ongoing work in ZEN to develop a User Interface (UI) in the form of a dashboard to visualise key performance indicators (KPIs), such as GHG emissions, amongst other parameters in an architectural and urban toolbox for use by diverse stakeholders to support decision making in the early design of ZENs. This work considers the scaling up from the building to neighbourhood scale in terms of material use and visualises associated embodied emissions for materials, as well, as transport emissions from the factory to a building site in Trondheim [29]. Data flow begins with Grasshopper, using Python coding, and is linked to Flux using ‘json’ language. Due to its interchangeable nature, the data flow can be read in excel and linked back to Flux in order to create an interactive dashboard interface [43].

7. Discussion and Further Work

The ZEB tool marks a significant advancement in terms of integrating LCA early and throughout the design process. The tool provides a robust, reliable and transparent method of embodied emission calculations using a more visual, integrated and dynamic approach. Such an approach demonstrates its versatility and ability to provide feedback on design and material choices, largely as a result of the integrated EPD database and the interoperability of the platforms described. The ZEB tool is currently limited for use at the building scale, although a ‘proof of concept’ model has been created whereby it can be scaled to neighbourhood level. Different alternative configurations and associated environmental impacts can be assessed at this scale. The detailed EPD library creates a wide range of product selections.
for different design options depending on the project requirements and provides a vast number of permutations in terms of GHG emission results. The organised layout of the building components according to the Table of Building Elements linked sheets provides more transparency and a faster approach to the calculation of the environmental impact of material choices. However, a limitation of the ZEB tool has been the lack of visualisation which can be problematic for most of the stakeholders and non-expert users, since many non-expert users may not understand the implications of the quantitative results in terms of their material and component design choices. Another limitation is that the tool lacks a work sharing aspect, which can limit the integration of the parties involved in the design process, making the tool available only for individual expert users. However, despite these limitations, the MS Excel based ZEB tool provides an advantage in terms of interoperability with different general design software thus enabling quick links through using third-party plugins. The ever expanding and more complete database can form the foundation of a more visual LCA platform that uses the computational and methodological qualities of the ZEB tool.

Future development should be directed towards architects for use in the early design phase, when the reduction of GHG emissions has the greatest potential for optimisation. Without the possibility for direct collaboration, this can result in the creation of ‘closed box’ tools only for the use of a handful of experts. Keeping the tool limited to a MS Excel format might create problems in the future, since the ever-increasing amount of available data that can be incorporate in the EPD database may be difficult to manage, thus, a more open source approach should be considered in the future, such as EPD Norge’s InData project [30] In addition, it is recommended to explore other platforms to take advantage of a more visual representation of results to ensure communication and ease of use.

The Revit-Dynamo and Rhino-Grasshopper dynamic approaches provide a good foundation for future research and further development. They provide an integrated and dynamic feedback during the early design phase and a visual representation of the environmental impact of the various material and component choices using colour coding i.e. red for high emission and green for low emissions. The excel based approach provides flexibility to include emerging ‘state of the art’ or natural, bio-based materials not normally included in generic databases or EPD platforms. A limitation for both the Dynamic LCA approach for Rhino and Revit has been the lack of access to available data for the same LCA modules in different selected EPDs which meant the LCA analyses had to be limited to the production phase (A1-A3) only. In addition, larger models require better software specifications and only work with certain volumetric units which can create problems between different Dynamo versions. Since the majority of BIM software uses various programming languages, the data and 3D model need to be translated into a common format that can be easily read.

The parametric LCA work also represents an important step in the development of a more visual, parametric and dynamic approach to enable LCA to be considered early in the design process. This optimisation approach can be applied to a larger scale i.e. ZEN neighbourhood scale, although it would require a processor with enough capacity to handle the vast amounts of data required for different shapes and embodied emission calculations. A limitation is that the parametric approach is dependent on the MS Excel environment to conduct LCA calculations, although most of the design is managed through the Grasshopper interface. The ZEB dashboard approach demonstrates the possibilities of work sharing and interoperability between different platforms. Future work will include the further development of the ZEB tool into a web-based application within which the EPD library and embodied emission calculations are embedded as currently being conducted by Skaar et al. in ZEN. Such a web-based application would enable the possibility of customisation and collaboration, and further development of the connection between the 3D Revit integrated with more materials and components, in order to provide ‘live’ feedback on the embodied emissions. Furthermore, a great improvement in performance would be achieved if all data is placed inside a cloud server. The ZEN dashboard provides a proof of concept to visualise the environmental impact of scaling up from building to neighbourhood level by defining a
series of base cases and then expanding them into multiple permutations. It is also worth mentioning that this process delivers a prefabricated approach on neighbourhoods. The ZEN dashboard demonstrates that visualisation can contribute to the design of ZENs by making LCA more understandable and intuitive for diverse stakeholders. It also proved that different layouts create various impacts on GHG emissions which can be easily communicated. In terms of ICT, different programmes use various coding languages, and to connect data flow in a seamless manner, an intermediary application or plugin is needed, hence the use of Flux which is structured on ‘json’ for its interchangeable qualities.

In the visual LCA for ZEN work, putting numbers into context is essential for all stakeholders to benefit from visualising KPIs (such as GHG emissions) early in the design process. By utilising visualisation methods which inspire and engage diverse stakeholders to explore the environment and learning by putting numbers into context, we can promote ZEN’s vision of sustainable neighbourhoods more easily and to a wider audience. The next step in the development of a more integrated and visual approaches is currently being further developed in The ZEN research centre to visualise, analyse and model different ZEN KPIs at different scales using visualisation and immersive technologies, such as Extended Reality (XR) technologies including Virtual Reality (VR) and Augmented Reality (AR), as well as, the development of a user interface such as a Dashboard.

8 Conclusion

The paper provides a chronology of the development of a more visual, integrated and dynamic approach for LCA assessment early and throughout the design process. The results demonstrate how this approach can improve stakeholder participation and effectively integrate science-based knowledge on GHG emissions and other KPIs into the future development of the user-centred architectural and urban ZEN toolbox for design and planning, operation and monitoring of ZENs.

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Figure 1. An illustration of the summary sheet from the ZEB tool, where construction, operation and material emissions are summarised. Illustration includes an overview of the calculation and library sheets included in the tool [11].