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

To cite this article: A Houlihan Wiberg *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **352** 012054

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

A Houlihan Wiberg [1], M. Kjendseth Wiik[2], H Auklend[1], M Løkland Slåke[1], Z Tuncer[1], M Manni[1], G Ceci[1], T Hofmeister[1]

[1] Department of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology, Trondheim, Norway

[2] SINTEF Community, Børrestuveien 3, 0373 Oslo, Norway

Corresponding author: aoife.houlihan.wiberg@ntnu.no

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 (RSL) obtained from EPDs and Byggforskserien. 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]

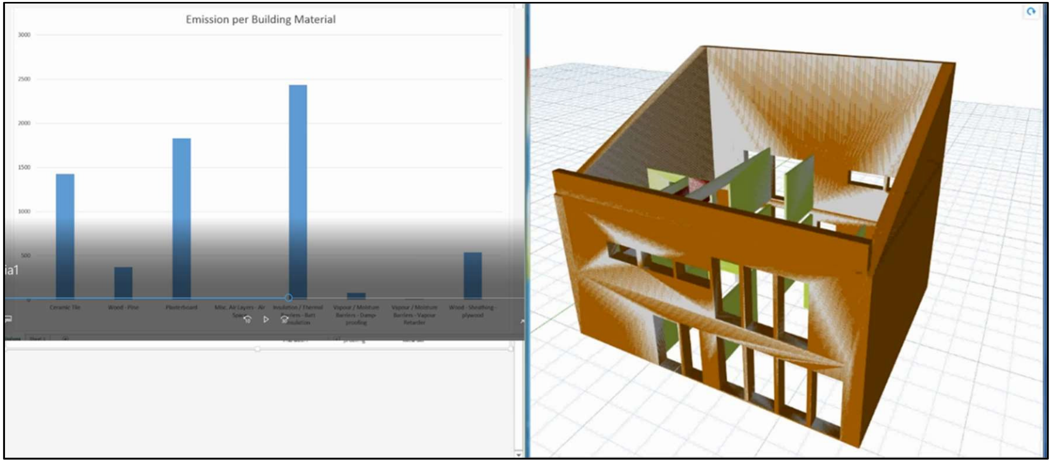


Figure 1. Screenshot from video showing emission factors in the ZEB Tool and corresponding colour coding in Dynamo. [38].

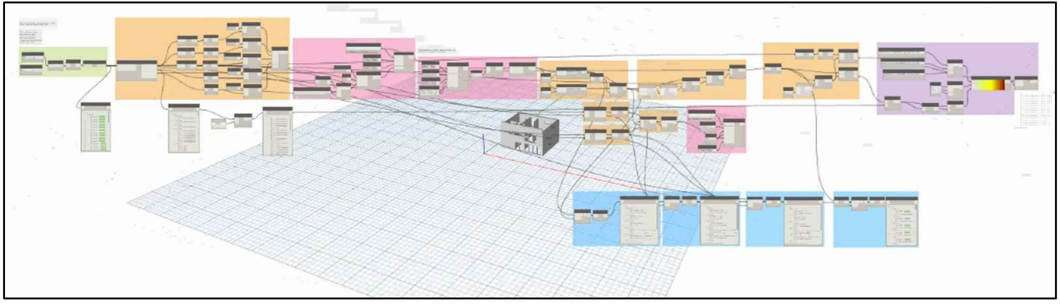
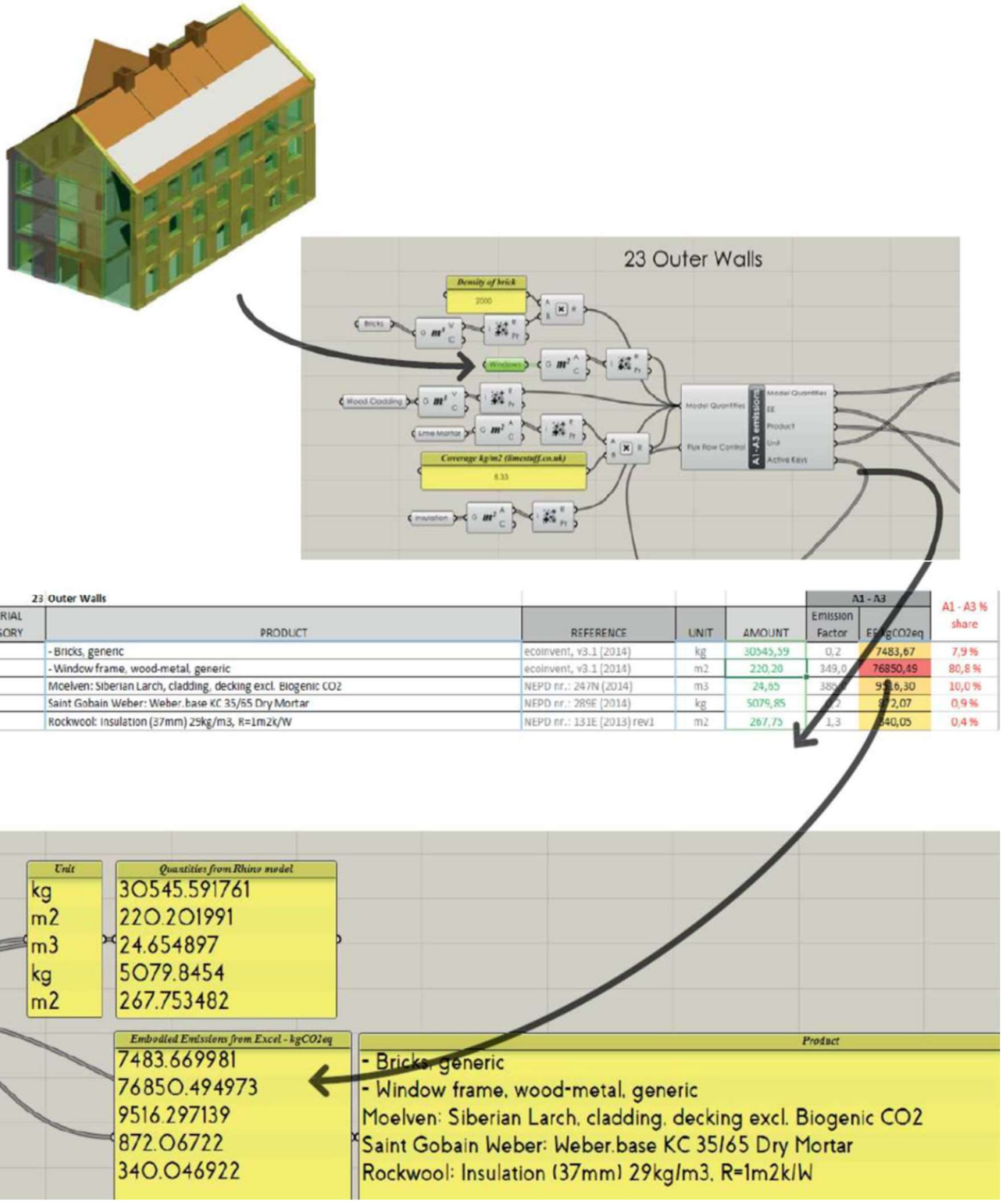


Figure 2. Screenshot from video of emission factors in the ZEB Tool and corresponding colour coding in Dynamo. [38].

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].



23 Outer Walls

MATERIAL CATEGORY	PRODUCT	REFERENCE	UNIT	AMOUNT	A1 - A3 Emission Factor	A1 - A3 EE kgCO2eq	A1 - A3 % share
Bricks	- Bricks, generic	ecoinvent, v3.1 (2014)	kg	30545,59	0,2	7483,67	7,9 %
Windows	- Window frame, wood-metal, generic	ecoinvent, v3.1 (2014)	m2	220,20	349,0	76850,49	80,8 %
Wood	Moelven: Siberian Larch, cladding, decking excl. Biogenic CO2	NEPD nr.: 247N (2014)	m3	24,65	[illegible]	9516,30	10,0 %
Binders	Saint Gobain Weber: Weber.base KC 35/65 Dry Mortar	NEPD nr.: 289E (2014)	kg	5079,85	[illegible]	872,07	0,9 %
Insulation	Rockwool: Insulation (37mm) 29kg/m3, R=1m2k/W	NEPD nr.: 131E (2013) rev1	m2	267,75	1,3	340,05	0,4 %

Unit	Quantities from Rhino model
kg	30545.591761
m2	220.201991
m3	24.654897
kg	5079.8454
m2	267.753482

Embodied Emissions from Excel - kgCO2eq	Product
7483.669981	- Bricks, generic
76850.494973	- Window frame, wood-metal, generic
9516.297139	Moelven: Siberian Larch, cladding, decking excl. Biogenic CO2
872.06722	Saint Gobain Weber: Weber.base KC 35/65 Dry Mortar
340.046922	Rockwool: Insulation (37mm) 29kg/m3, R=1m2k/W

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].

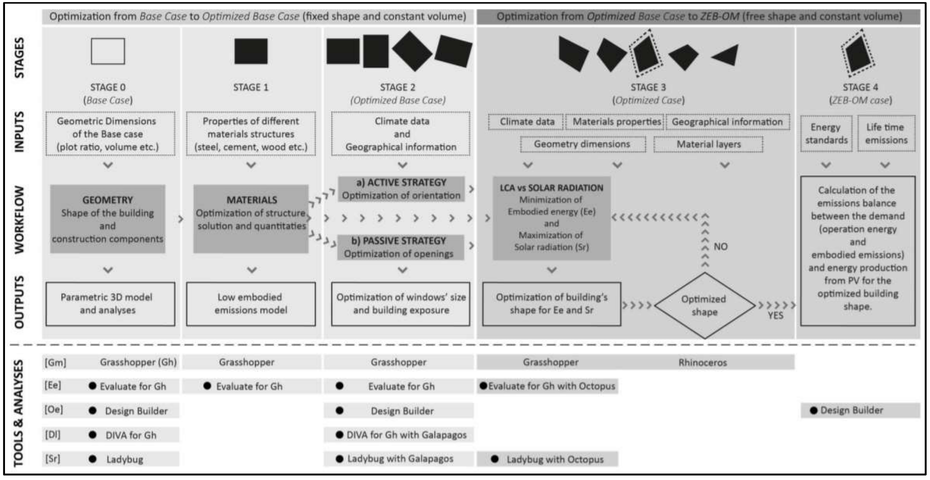
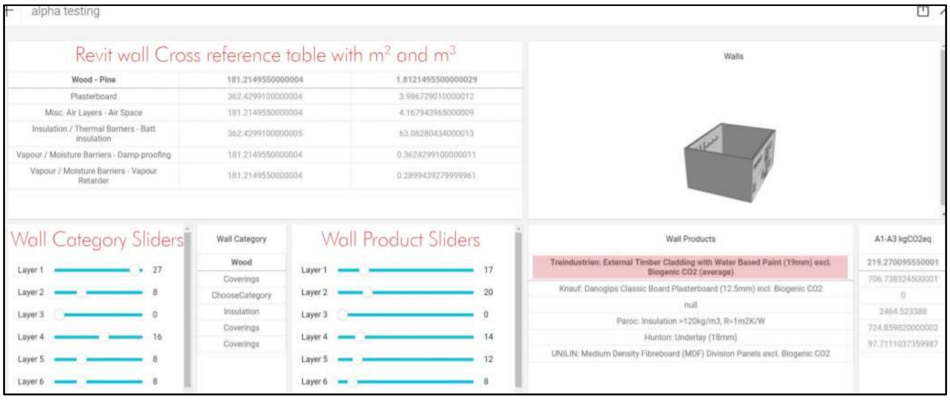


Figure 4. A flowchart of the parametric methodology used: the top part shows the plan while the bottom part shows the tools used to control the geometry (Gm) and deal with the related environmental analyses such as embodied energy (Ee) operational energy (Oe) solar radiation (Irrgl) and daylight factor (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].



alpha testing

Revit wall Cross reference table with m² and m³

Wood - Pine	181.2149550000004	1.8121495500000029
Plasterboard	362.4299100000004	3.986729010000012
Misc. Air Layers - Air Space	181.2149550000004	4.167943965000009
Insulation / Thermal Barriers - Batt insulation	362.4299100000005	63.06280434000013
Vapour / Moisture Barriers - Damp-proofing	181.2149550000004	0.3624299100000011
Vapour / Moisture Barriers - Vapour Retarder	181.2149550000004	0.2899439279999961

Walls

Wall Category Sliders

Layer 1 27
Layer 2 8
Layer 3 0
Layer 4 16
Layer 5 8
Layer 6 8

Wall Category
Wood
Coverings
ChooseCategory
Insulation
Coverings
Coverings

Wall Product Sliders

Layer 1 17
Layer 2 20
Layer 3 0
Layer 4 14
Layer 5 12
Layer 6 8

Wall Products	A1-A3 kgCO2eq
Treindustrien: External Timber Cladding with Water Based Paint (19mm) excl. Biogenic CO2 (average)	219.270095550001
Knauf: Danogips Classic Board Plasterboard (12.5mm) incl. Biogenic CO2	706.738324500001
null	0
Paroc: Insulation >120kg/m3, R=1m2K/W	2464.523388
Hunton: Underlay (18mm)	724.859820000002
UNILIN: Medium Density Fibreboard (MDF) Division Panels excl. Biogenic CO2	97.7111037359987

Figure 5. A screenshot of the ZEB dashboard approach. [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].

West Row

Nr. of Rows 6
Nr. of Stories 6
Unit Spacing 0

East Row

Nr. of Rows 6
Nr. of Stories 4
Unit Spacing 0

Figure 6. Screenshot of the ZEN dashboard tool. [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.

Acknowledgements

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN) and The Research Centre on Zero Emission Buildings (ZEB). The authors wish to thank the Norwegian University of Science and Technology (Trondheim, Norway) and the University of Perugia (Perugia, Italy) for having supported the collaboration between the two universities in this work, framed by the EU programme for education, training, youth and sport – 'ERASMUS+'. The authors wish to thank the Nordic Build Sted research project for having funded the internship for Tobias Hofmeister at NTNU.

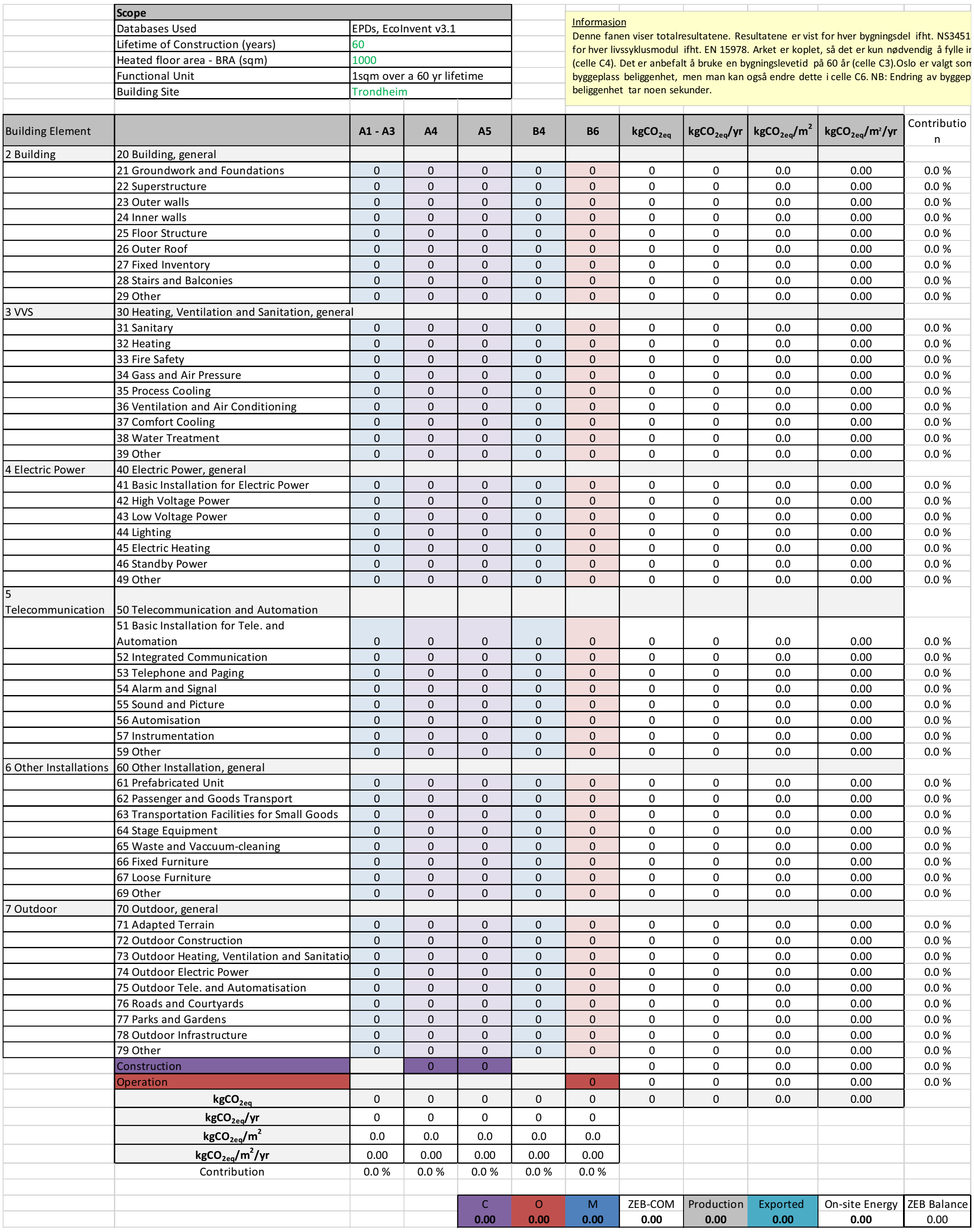
References

[1] IPCC, 2014. Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.
[2] EPBD, 2010. EPBD Directive 2010/31/ EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. European Commission, 2010.
[3] ASHRAE, 2013. ASHRAE Energy Standard for Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standards Committee 90.1,2013.
[4] Birgisdottir, H., Moncaster, A., Houlihan Wiberg, A., Chae, C., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Lutzkendorf, T., Malmqvist, T. (2017) IEA EBC Annex 57 'Evaluation of Embodied Energy and CO2eq for Building Construction'. Energy and Buildings. vol. 154.
[5] ZEB, 2017. The Research Centre on Zero Emission Buildings (ZEB). Available at: http://zeb.no/index.php/en/
[6] Kristjansdottir, T., Houlihan Wiberg, A., Andresen, I., Georges, L., Heeren, N., Good, C., Brattebø, H. (2018) Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway?. Energy and Buildings. vol. 168.
[7] Houlihan Wiberg, A., Bjerregaard Jensen, L., Beim, A. LCA in early design phases. In: Informing sustainable architecture. First Edition.(pp. 124-129) ISBN 9788750211402.

Publisher: Polyteknisk Boghandel og Forlag. København, May 2018
[8] ZEN, 2019. The Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN). Available at: https://fmezen.no/
[9] Wiik, M. K., Fufa, S. M., Baer, D., Sartori, I. & Andresen, I (2018) The ZEN definition – a guideline for the ZEN pilot areas. Version 1.0 ZEN Report 11, NTNU/SINTEF.
[10] Wiik, M. K., Fufa, S. M., Krogstie, J., Ahlers, D. Wyckmans, A., Driscoll, P., Brattebø, H., Gustavsen, A. (2018) Zero emission neighbourhoods in smart cities: Definition, key performance indicators and assessment criteria: version 1.0. Bilingual version. ZEN Report 7, NTNU/SINTEF.
[11] Wiik, M., Houlihan Wiberg, A., Schlanbusch, R., Kristjansdottir, T., 2017. ZEB Tool Manual, Technical Guide, Version 1. ZEB Project report (Internal). Norwegian University of Science & Technology, Trondheim, Norway. NTNU SINTEF.
[12] Lobaccaro, G., Houlihan Wiberg, A., Manni, M., Ceci, G., Lolli, N., Berardi, U. (2018). Parametric design to minimize the embodied GHG emissions in a ZEB. Energy and Buildings. ISSN: 0378-7788, 2018; Volume 167. p. 106-123
[13] Lolli, N., Fufa, S.M., Inman, M. (2017) A Parametric Tool for the Assessment of Operational Energy Use, Embodied Energy and Embodied Material Emissions in Building. Energy Procedia. Volume 111, (March) Available at: https://doi.org/10.1016/j.egypro.2017.03.004
[14] IEA Annex 72 (2019) - Assessing Life Cycle Related Environmental Impacts Caused by Buildings. International Energy Agency (IEA). Energy in Buildings and Communities Programme (EBC). Available at: http://annex72.iea-ebc.org/about
[15] Hollberg A., Tschetwertak J., Schneider S., Habert G. (2018) Design-Integrated LCA Using Early BIM. In: Benetto E., Gericke K., Guiton M. (eds) Designing Sustainable Technologies, Products and Policies. Springer, Cham. Available at: https://doi.org/10.1007/978-3-319-66981-6_30
[16] Nordic Build Sted (2017) Sustainable Transformation and Environmental Design. Nordic Available at: http://stednetwork.org/index.php?p=/articles
[17] Negendahl, Kristoffer. (2015). Building performance simulation in the early design stage: An introduction to integrated dynamic models. Automation in Construction. 54. 10.1016/j.autcon.2015.03.002.
[18] Birgisdottir, H., Rasmussen, F. (2019). Development of LCAbyg: A National Life Cycle Assessment Tool for Buildings in Denmark. IOP Conf. Ser.: Earth Environ. Sci. 290 012039
[19] One Click LCA (2019) Available at: https://www.oneclicklca.com/bim-based-life-cycle-assessment-guidelines/ (Accessed 05 08 18).
[20] InData project. EPD-Norge. Available: https://digi.epd-norge.no/(Accessed 05 08 18).
[21] Kristjansdottir, T., Fjeldheim, H., Selvig, E., Risholt, B., Time, B., Georges, L., Dokka, TH, Bourelle, J., Bohne, R., Cervenka, Z. A Norwegian ZEB-definition embodied emission. Sider: 41 (Illustrert) Utgivelsesår: 2014. ISBN: 978-82-536-1398-7
[22] Fufa, S.M., Dahl Schlanbusch, R., Sørnes, K., Inman, M.R., Andresen, I. A Norwegian ZEB Definition Guideline. Sider: 48 (Illustrert) Utgivelsesår: 2016 ISBN: 978-82-536-1513-4
[23] Standard Norge. (2009). NS 3451: Bygningsdelstabellen (Table of building elements).
[24] EPD Norge Environmental Product Declarations. Available : http://epd-norge.no/epder/
[25] Ecoinvent. Swiss Center for Life Cycle Inventories, EcoInvent version 3.0, available from: http://www.ecoinvent.ch/.
[26] Houlihan Wiberg, A. 2009. An Analysis Of The Performance Of Certification Schemes In The Hotel Sector In Terms Of CO2 Emissions Reduction. Ph.D. Thesis. Department of Architecture, University of Cambridge. Permanent URL http://www.dspace.cam.ac.uk/handle/1810/226841
[27] Dokka, T.H., Houlihan Wiberg, A., Georges, L., Mellegård, S., Time, Berit; Haase, M., Maltha, M., Lien, A.G., 2013. A zero emission concept analysis of a single family house. ZEB Project report 9 – 2013. ISBN 978-82-536-1324-6
[28] Houlihan Wiberg, A., Georges, L., Dokka, T.H., Haase, M., Time, B., Lien, A.G., Mellegård, S., Maltha, M. (2014) A net zero emission concept analysis of a single-family house. Energy and Buildings. vol. 74 (May).
[29] Houlihan Wiberg, A., Georges, L., Fufa, S.M., Risholt, B., Good, C., 2015. A zero emission concept analysis of a single family house: Part 2 sensitivity analysis. ZEB Project report 21–2015. ISBN 978-82-536-1449-6
[30] Georges, L., Haase, M., Houlihan Wiberg, A., Kristjansdottir, T., Risholt, B. (2015) Life cycle emissions analysis of two nZEB concepts. Building Research & Information. vol. 43 (1).
[31] ProgramByggerne. 2012. SIMIEN, SIMulation of Indoor climate and ENergy use. (Skollenborg. Retrieved

from http://www.programbyggerne.no/SIMIEN/
[32] PVsyst SA. 2013. PV-syst 5.62, Photovoltaic System Software 5.62. from http://www.pvsyst.com/en/
[33] Googlemap. Available at: https://www.google.no/maps
[34] Environdec Available at : http://www.environdec.com/
[35] Ecoplatform. Available from: http://eco-platform.org/
[36] Institutu Bau Umvelt (IBU). Available at http://ibu-epd.com/en/epdprogram/published-epds/
[37] Autodesk Revit BIM Architecture Suite.
[38] Hofmeister, T., Houlihan Wiberg, A., 2016. Emissions Visualisation ~ A dynamic, integrated approach for the ZEB Tool. (Supervisor: A. Houlihan Wiberg). Nordic Build Sted Project (unpublished). Norwegian University of Science & Technology, Trondheim, Norway.
[39] Houlihan Wiberg, A., Auklend, H. 2016. Emissions as Design Drivers. Second semester in the M.Sc. Sustainable Architecture. ISBN 9788275511308. Publisher: NTNU. Trondheim, June 2016. Available at: https://drive.google.com/file/d/0B5dx2T4jpJT5eGhPbTFxbUtaYU0/view?usp=sharing
[40] Manni, M., Ceci, G. Parametric Design Principles applied to NZEB in cold extreme climate conditions. Masters thesis submitted June 2016 (Supervisor: A. Houlihan Wiberg; G. Lobaccaro). Norwegian University of Science & Technology, Trondheim, Norway.
[41] Tuncer, Z. 2017, ZEB Tool - Transition to an Integrated and Dynamic ZEB Dashboard. Masters theory report (Supervisor: A. Houlihan Wiberg). Norwegian University of Science & Technology, Trondheim, Norway. (Online) Available: http://goo.gl/Ndgi4W(Accessed 22 02 18).
[42] Wiik, M.R, Houlihan Wiberg, A. (2017) Life Cycle Greenhouse Gas Emissions of Material Use in the Living Laboratory. Proceedings of World Sustainable Built Environment Conference 2017 Hong Kong. Transforming Our Built Environment through Innovation and Integration: Putting Ideas into Action. WSBE17.
[43] Slånke, M., Auckland, H., 2017. Visual LCA in ZENs. Interactive visualisation network for material associated GHG in preliminary neighbourhood design stages. Masters thesis submitted June 2017 (Supervisor: A. Houlihan Wiberg; Co-Supervisor: E. Reisch). Norwegian University of Science & Technology, Trondheim, Norway. (Online) Available: http://goo.gl/6sgXJB (Accessed 22 02 18).

Appendix



Scope	
Databases Used	EPDs, EcoInvent v3.1
Lifetime of Construction (years)	60
Heated floor area - BRA (sqm)	1000
Functional Unit	1sqm over a 60 yr lifetime
Building Site	Trondheim

Informasjon
Denne fanen viser totalresultatene. Resultatene er vist for hver bygningsdel ifht. NS3451
for hver livssyklusmodul ifht. EN 15978. Arket er koplet, så det er kun nødvendig å fylle i
(celle C4). Det er anbefalt å bruke en bygningslevetid på 60 år (celle C3).Oslo er valgt som
byggeplass beliggenhet, men man kan også endre dette i celle C6. NB: Endring av byggep
beliggenhet tar noen sekunder.

Building Element		A1 - A3	A4	A5	B4	B6	$kgCO_{2eq}$	$kgCO_{2eq}/yr$	$kgCO_{2eq}/m^2$	$kgCO_{2eq}/m^2/yr$	Contribution
2 Building	20 Building, general										
	21 Groundwork and Foundations	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	22 Superstructure	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	23 Outer walls	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	24 Inner walls	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	25 Floor Structure	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	26 Outer Roof	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	27 Fixed Inventory	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	28 Stairs and Balconies	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	29 Other	0	0	0	0	0	0	0	0.0	0.00	0.0 %
3 VVS	30 Heating, Ventilation and Sanitation, general										
	31 Sanitary	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	32 Heating	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	33 Fire Safety	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	34 Gass and Air Pressure	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	35 Process Cooling	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	36 Ventilation and Air Conditioning	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	37 Comfort Cooling	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	38 Water Treatment	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	39 Other	0	0	0	0	0	0	0	0.0	0.00	0.0 %
4 Electric Power	40 Electric Power, general										
	41 Basic Installation for Electric Power	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	42 High Voltage Power	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	43 Low Voltage Power	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	44 Lighting	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	45 Electric Heating	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	46 Standby Power	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	49 Other	0	0	0	0	0	0	0	0.0	0.00	0.0 %
5 Telecommunication	50 Telecommunication and Automation										
	51 Basic Installation for Tele. and Automation	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	52 Integrated Communication	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	53 Telephone and Paging	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	54 Alarm and Signal	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	55 Sound and Picture	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	56 Automisation	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	57 Instrumentation	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	59 Other	0	0	0	0	0	0	0	0.0	0.00	0.0 %
6 Other Installations	60 Other Installation, general										
	61 Prefabricated Unit	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	62 Passenger and Goods Transport	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	63 Transportation Facilities for Small Goods	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	64 Stage Equipment	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	65 Waste and Vaccuum-cleaning	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	66 Fixed Furniture	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	67 Loose Furniture	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	69 Other	0	0	0	0	0	0	0	0.0	0.00	0.0 %
7 Outdoor	70 Outdoor, general										
	71 Adapted Terrain	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	72 Outdoor Construction	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	73 Outdoor Heating, Ventilation and Sanitatio	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	74 Outdoor Electric Power	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	75 Outdoor Tele. and Automatisation	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	76 Roads and Courtyards	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	77 Parks and Gardens	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	78 Outdoor Infrastructure	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	79 Other	0	0	0	0	0	0	0	0.0	0.00	0.0 %
	Construction		0	0			0	0	0.0	0.00	0.0 %
	Operation					0	0	0	0.0	0.00	0.0 %
	$kgCO_{2eq}$	0	0	0	0	0	0	0	0.0	0.00	
	$kgCO_{2eq}/yr$	0	0	0	0	0					
	$kgCO_{2eq}/m^2$	0.0	0.0	0.0	0.0	0.0					
	$kgCO_{2eq}/m^2/yr$	0.00	0.00	0.00	0.00	0.00					
	Contribution	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %					

C	O	M	ZEB-COM	Production	Exported	On-site Energy	ZEB Balance
0.00	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.00

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].