

DEVELOPING A DECISION SUPPORT TOOL FOR MINIMIZING EMBODIED CARBON IN EARLY DESIGN STAGE FAÇADE MATERIAL SELECTION

N.MISTRY,

University of New South Wales, Sydney, Australia

nimat.mistry@gmail.com

z5260592@ad.unsw.edu.au

Abstract. Carbon emissions are a major contributor to global warming. The Architecture, Engineering and Construction (AEC) industry is responsible for 39% of total global embodied carbon (WGBC 2019). This is compounded by the fact that it is estimated by 2050 68% of the global population will reside in urban areas (Budig. et al, 2020). This will inevitably result in more buildings which in turn will result in more carbon emissions. During the early stages of building design more than 50% of the embodied carbon is 'locked away'. Given this, it is estimated that 70%-80% of a building's environmental impact is determined in the early stages of design but only 20% - 25% of the design fees are spent in this stage (Ferries & Salgueiro 2015). Exacerbating this problem, is that AEC industry tools to assess embodied carbon quantities related to material selection are typically applied in latter design stages where they function to assess rather than impact design decisions. The range of tools that are applicable to early design stages tend to be focused on structural analysis and are predictive in nature, making the tool only as good as the data set. To address the lack of early stage design decision support tools to address embodied carbon assessment, the research outlined here adopts an action research approach to iteratively investigate and develop a decision support tool that provides embodied carbon estimates without the need for a detailed design in collaboration with the industry partner Bates Smart Architects. More specifically, the research focuses on façades and its material selection using the visual scripting environment of Grasshopper in conjunction with Revit. This research contributes to scholarship that explores the development of computational design decision support tools. Developing an integrated decision support tool capable of predicting façade embodied carbon values for preliminary design concepts aims to raise awareness of, and mitigate the prevalence of early design decisions that lock-in high embodied carbon levels in building projects.

Keywords. Embodied carbon; Decision Support; Facade; Concept design; Sustainability.

1. Introduction: (Research context and motivations)

Carbon emissions are a key contributing factor to global warming which effects each and every one of us and our futures. We as a whole are currently in a position to make a positive change for the betterment of all humans. Especially as computational designers, we have the capability of extracting valuable information from data and optimally visualizing it so it can be used to make connections and correction in the AEC industry. According to the World Green Building Council the “building and construction are responsible for 39% of all carbon emissions in the world”. This issue is compounded by a growing population which will need to be housed. With 68% of the population expected to be living in urban areas by 2050 (Budig. et al, 2020) reducing carbon emissions is increasingly becoming an urgent issue. The motivation for this research project is to help with the reduction of embodied carbon in the built environment. With a focus on material selection as the type of material has a significant impact on the amount of embodied carbon depending on how its sourced, manufactured. and transported. The Footprint company / the Greenbook notes that “It is generally within the first few days of the schematic design musings that over 50% of the embodied carbon footprint gets “locked away”. Current tools tend to focus on late stage designs as they require a high level of detail to assess the amount of embodied carbon in a building. The few tools that can be employed at an early stage are generally focused on the whole building or only structure. They are also predictive meaning they are only as good as their source data set. The other issue is that predictive tools are generally typologically limited meaning you cannot assess a residential building if the data set the tools’ source is office buildings the outputs produced will be inaccurate.

This research reasons that if architects and designers were made aware of how material selection at concept design stage impacts embodied carbon values this might generate design outcomes with overall lower embodied carbon. To respond to this, the project aims to create an early stage decision support tool that enables the designer / architect to make an informed decision, in terms of embodied carbon, when making material selections for the early stages specifically relating to façade material without the need for a detailed model.

This research explores developing such a decision support tool by creating a script that can be applied to building masses using the programs Revit, Rhino inside Revit, and Grasshopper. Revit will contain the building mass as that is the preferred program by the industry partner and the industry at large and will also contain the façade types that materials can be applied to. Tally is a plugin for Revit from Autodesk that will enable is to get the

carbon data for each façade swatch. Then the use of Rhino inside Revit will allow for grasshopper to process the data and to output embodied carbon for each face of the mass and create an interface for the tool using the plugins Human UI, Lunchbox, and Wombat.

Applying the Action Research method, the process is an iterative one that allows for a continuous feedback loop from the industry partner allowing the tool to be amended and refined throughout the research process. The tool is also tested against an existing building that has a highly detailed model to see if the tool is producing outcomes in an acceptable range of variance.

The following sections of this thesis describe the research aims, research question and iterative investigation and development of a decision support tool to assist designer's in understanding embodied carbon in relation to material specification and geometry. Lastly, a collection of further explorations and steps that can be taken to improve and apply the tool to other areas of the building are noted as future research that can be explored in relation to this tool.

2. Research Aims

This research aims to create a decision support tool that allows designers and decision makers to factor in embodied carbon at an early stage of design through façade material selection, hopefully reducing the amount of embodied carbon produced by the AEC industry.

To create tool that is not based on predictive methods and is therefore open to new materials and façade assemblies that will occur in the future.

3. Research Question(s)

Based on the issues outlined in the introduction and the derived aims, the question the research this project investigates is:

How can a decision support tool be developed to connect embodied carbon prediction to early stage façade material selection?

4. Methodology

This research adopts the overarching methodology of action research. This is a proactive approach to research that seeks to problem solve as well as contribute to the theoretical aspect of the field (Ahmad et al. 2010). Action research is a participatory approach that engages industry stakeholders in the research process and aims to addresses a current problem and solve it by affecting the processes and practices of the field as well as contributing theoretically to the field by exploring new avenues through testing and recording the results. In this research project, the industry partner Bates Smart Architects has contributed to defining the problem and providing feedback throughout the development of a decision support tool for evaluating embodied carbon quantities in early stage façade material selection.

In action research the researcher collaboratively works with the practice to enhance the “competencies of both researchers and practitioners” (Ahmad et al. 2010) and in doing so “links theory and practice to generate a solution” (Ahmad et al. 2010). This cyclical nature of our weekly meeting is also a part of action research. As “diagnosing, action planning, taking action, evaluating, and specifying learning” (Ahmad et al. 2010) are all looped steps in action research. The tool is developed using the visual scripting program Grasshopper which is run in Revit using the tool Rhino.Inside.Revit. The plugins Human UI (User interface), Lunchbox (Read and write excel), and Wombat (read and write text files) are also used. The project has gone through many iterative cycles.

As part of the research we are taking previous explorations in the field in to account and using them in shaping the path of the current research through information that highlights the methods and successes or failures of previous attempts in this field to identify the gap and where more research can be conducted to add to existing knowledge. This has led to the understanding that predictive methods are not the most suitable when dealing with multiple typologies and newer materials. It has also led to understanding that most tools that are currently available, require a high level of detail, focus on the whole building or only the structure. This signifying the need for a tool that can overcome these challenges.

5. Background Research/Literature review

Carbon emission are a major factor propelling global warming. Construction activities and buildings are key contributors to global warming producing 39% of the whole worlds carbon emissions (WGBC 2019). Currently 55% of the global population resides in urban areas and it is estimated that by 2050 68% of the global population will reside in urban areas this is a significant increase. Considering that the Architecture, Engineering and Construction (AEC) industry is currently responsible for 39% of the worlds carbon emissions, (Budig. et al, 2020) this makes global warming an issue that needs to be addressed by the AEC industry. Addressing the issue of global warming through the reduction of carbon emissions is a large and complex problem in the AEC industry and requires changes to many aspects of how the industry operates.

In the AEC industry, the main method for evaluating carbon emissions and environmental impact in building projects is known as the Life Cycle Assessment (LCA). The LCA method was originally developed in the 1970s to assess consumer products such as packaging and beverages. Over the years the assessment has been applied to many products, materials and services to ascertain their environmental impact. During the last decade it has also been widely used in the AEC industry to measure a building's environmental impact (Hollberg et al 2018). However, it is important to note that the simple evaluation of a building's environmental impact is not productive. To affect outcomes, the reduction of carbon emission should be considered far earlier in the design process to allow architects and other stakeholders in the AEC industry to make informed decisions. So, while the LCA is a robust method for evaluating a building's environmental impact, it does not necessarily influence design decision making towards carbon emission reduction as it is difficult to integrate in the design process. The two main reasons for this are:

- 1) expertise in LCA, meaning the understanding required to interpret the outputs of the LCA that is not typically the scope of an architect/designer (Meex Et al 2018), and
- 2) the LCA is usually conducted in latter design stages where significant building massing and detailing has been resolved leaving little or no room for change without incurring large costs (Coenders et al 2009).

Equally, the complexity of the LCA necessitates detailed information of building materials, which is often not available as it is usually not decided

upon at such an early stage, making the task “time and labor intensive” (Meex et al 2018). The LCA also requires a need for expertise not only for the input of data to gain an accurate assessment but expertise is also required in understanding the produced report, which generally consists of complex data both numerical and indicative. This makes it difficult for a non-expert, such as an architect, to decipher, comprehend, and to communicate the information to their team and other stake holders (Meex et al 2018).

The other main obstacle relating to the LCA being effective is the assessment is usually conducted at a late design stage where the design is adequately resolved for the LCA. This is because of the level of detail that is required to conduct the assessment (Budig et al 2020; Meex et al 2018; Hollberg et al 2018). The problem with conducting the LCA at such a late stage of design is the assessment has no avenue to make a meaningful impact on the design as at this late stage it is too costly to implement large scale design adjustments (Coenders et al 2009).

The most effective solution to this is to find a way to assess the carbon emission at an early stage of design such as the concept or schematic design stage (Budig et al 2020, Meex et al 2018). The reason to implement this evaluation at an early stage is so it can be used to affect meaningful design changes that can aid in the reduction of carbon emission with the cost of these changes being viable in terms of time, money and labor. “Early stage of the architectural conception process, the schematic stage, where only 20–25% of the design fees are spent, but about 70–80% of environmental impact and operating costs are determined”(Ferries & Salgueiro 2015)

A predictive tool is one possible way to address the implementation of a carbon reduction tool in early stages of design as demonstrated by Budig et al (2020). Budig et al (2020) have designed a tool that takes the massing of a building as an input and outputs a approximate prediction of the embodied carbon from that mass. Utilizing machine learning (ML) the tool is trained on a set of data collected from existing buildings and accordingly makes its prediction about the given mass. The ML method allows for multiple iterations to be run through the tool at the concept stage without the need for a highly resolved design as would be needed in the traditional LCA method allowing it to affect meaningful change to the design. There are a few issues with the predictive ML method. It can only provide prediction within a large range. If the building type is non-typical a prediction becomes very difficult. The major concern is the predictions of the tool are only as good as the data set that it has been trained on (Belem et al 2019). Typology is also an issue with the predictive method limiting it based on the data set. Meaning if the

tool is trained on office building it can only make predictions for future office building you cannot input a residential building and get a reliable output as the elements and quantities of elements differ. One other key issue with a predictive tool is that it can only work on what has previously been done (data sets) it would be impossible to predict the carbon contained in a building that uses newer materials or assemblies as there is no data set to draw upon to make a prediction.

The other possible route is creating an early stage decision support tool. There are limited examples of early stage material selection decision support tools making it a viable area for explorations as early stage design decision in regards to material selection is an area of architectural design practice where over 50% of the buildings embodied carbon is ‘locked away’ (Footprintgreenbook 2019). “It is estimated that most decisions determining the sustainability of a project are made in the first 1 percent of a project’s program” (Coenders 2009). While there are a few programs such as Bombyx and Tally that evaluate and aid in material selection they require a much more detailed design than what is available at an early design stage (Budig et al. 2020). Enough information is available to create a material decision support tool “at the concept stage of any project the design team already have a significant amount of information regarding the building such as location, number of floors, occupancy, preferred glazed areas, insulation standards, thermal mass and required internal environmental conditions.” (Alastair & Bennadji 2004). Decision support tools enable the best of both worlds’ scenario “where human designer and the computer form a complementary partnership” (Chapman et al. 2000) The human is intuitive, creative, can balance the aesthetics, client demands, and budget of a project in its selection of materials, a computer has unlimited memory to hold all the information about materials, embodied carbon, and is able to calculate numbers accurately and with speed. Creating a tool that does not limit the architect nor does it prescribe a solution rather aids in the decision of selecting the most appropriate material taking into account its embodied carbon. This paper aims to research such a tool with a focus on building facades.

6. Case Study

6.1 Scope

The original scope for the research project was to create a tool that could estimate the embodied carbon of a building at an early design stage. This tool would take in to account the structure, floor and ceiling combination, and the façade. Through the initial meetings the scope was narrowed to focus on the façade as this would better suit the 10-week parameter of the research project and would allow for investigation in to part of the building that has not had not been widely explored in this respect.

6.2 Logic

Discussion in the first few meetings revolved around what method should be pursued to get the required outcome. The method that was settled upon was to create swatches of façade types in Revit where the material could be changed and to multiply that by the face of a given mass using grasshopper [Fig.1]. The reasons for choosing this method was that it was simple and would over load the computer while running the tool. This method was also desirable as the end number regarding the amount of embodied carbon did not need to be precise but only needed to be estimate with an acceptable variance.

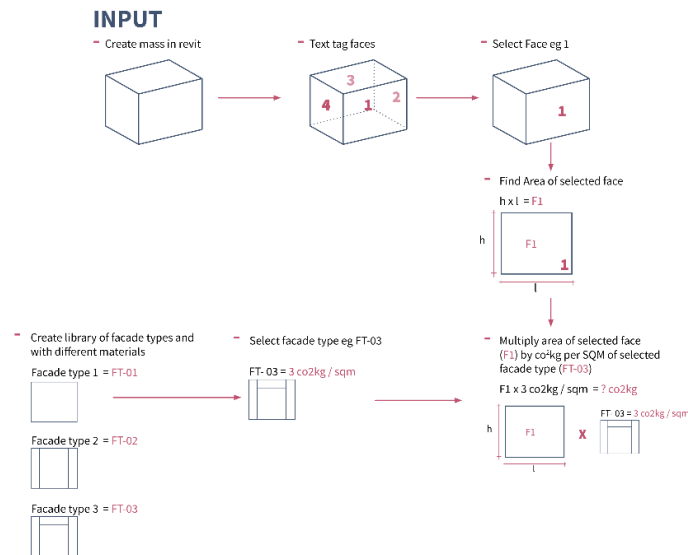


Figure 1. Logic

6.3 Rhino.Inside.Revit + Grasshopper

The next step in the research was to figure out how to bring massing from Revit into Rhino in order to use Grasshopper to extract data from the mass such as the areas of its faces. The reason for keeping the original massing in Revit was that that is the BIM program that the industry partner uses to create massing and the same can be said for the industry at large. The solution to this was to use Rhino.Inside.Revit a software plugin for Revit that allows the user to run Rhino inside Revit space meaning you can bring in elements from Revit into Rhino and vice versa as well as manipulate and extract data from the elements using either program. The first step was to bring in the mass from Revit into Rhino so Grasshopper could be used to extract the area of the mass's faces. [Fig.2]

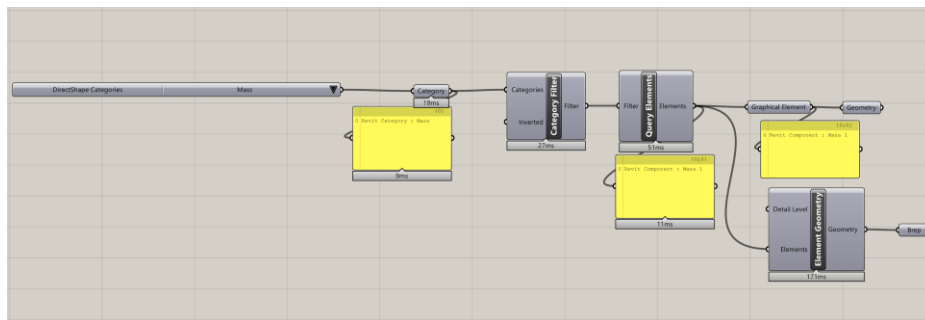


Figure 2. Mass Revit to Rhino Script

The next step was to tag the faces so there was a visual aid to discern which face the user was choosing. Initially all the faces were tagged using numbers starting at 1. The first issue that became evident was that the top and bottom faces were being tagged as well this was incorrect as there would be no façade on these faces. The solution was to cull the top and bottom face and only tag the remaining faces [Fig.3] [Fig.4].

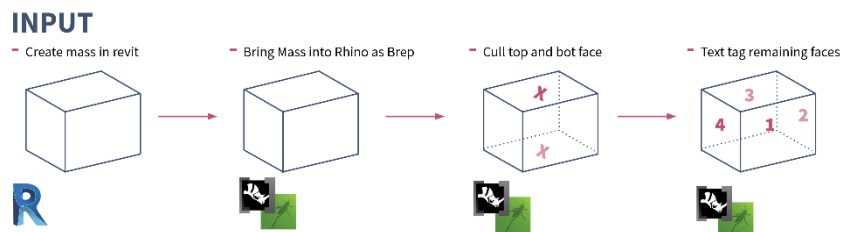


Figure 3. Cull top and bottom face

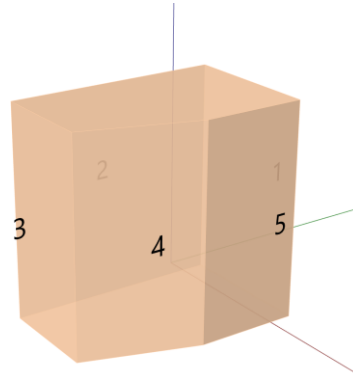


Figure 4. Tagged mass in Rhino

Once the faces were tagged it was easier to understand which face the area was being extracted from and made it easier to check if the output information was correct.

6.4 Façade Types

The next step was to create typical façade types in Revit as families to which materials could be assigned [Fig.5]. These façade types are used as swatches to get the embodied carbon per square meter data. Façade types need to be created because only one material cannot be applied to the face of the mass as facades are usually made up of multiple materials e.g. aluminum for the mullions and glass for the panel etc. For this reason, different typical facade types need to be created. This system is also beneficial because new façade types and materials can be added in the future as and when required.



Figure 5. Façade types with different materials

6.5 Tally

The next step was to get the embodied carbon data for each façade type swatch. This was done using Tally, a plug in for Revit. Tally is plugin from Autodesk that allows for the quantification of a buildings environmental impact, but required data that is usually not available at early design stages of a project, but since the facade type swatches based on typical façade types this information is available to us so we can estimate required information for Tally. Once all the façade types are made, each faced type is attached to an Option in Revit the facades types as options are then run through Tally to get an output of how much embodied carbon each swatch contains. This information is output by Tally in an Excel [Fig.6].

Row Labels	Values Sum of Acidification Potential Total (kgSO2eq)	Sum of Eutrophication Potential Total (kgNreq)	Sum of Global Warming Potential Total (kgCO2eq)	Sum of Ozone Depletion Potential Total (CFC-11eq)	Sum of Smog Formation Potential Total (kgO3eq)	Sum of Primary Energy Demand Total (MJ)	Sum of Non- renewable Energy Demand Total (MJ)	Sum of Renewable Energy Demand Total (MJ)	Sum of Mass Total (kg)
FT-01	39.35	1.65	5,773.65	2.26E-05	519.88	86,384.21	80,591.82	5,559.34	3,168.18
FT-02	38.31	1.67	5,836.45	1.78E-05	510.15	87,649.28	81,812.11	5,687.74	4,482.33
FT-03	38.28	1.71	5,728.12	1.93E-05	505.60	87,566.42	81,529.94	5,690.78	3,625.73
FT-04	40.25	1.62	6,353.93	3.04E-05	568.69	97,591.08	89,140.51	8,028.10	3,075.65
FT-05	31.28	1.55	5,881.51	1.48E-05	440.78	90,969.83	84,122.14	6,687.95	7,888.23
FT-06	31.19	1.68	5,448.17	2.09E-05	422.60	89,838.39	82,993.08	6,700.11	4,461.83
FT-07	39.35	1.65	5,773.65	2.26E-05	519.88	86,384.21	80,591.82	5,559.34	3,168.18
FT-08	38.31	1.67	5,836.45	1.78E-05	510.15	87,649.28	81,812.11	5,687.74	4,482.33
FT-09	38.28	1.71	5,728.12	1.93E-05	505.60	87,566.42	81,529.94	5,690.78	3,625.73
FT-10	42.66	1.78	6,441.08	3.04E-05	568.52	97,071.60	90,181.13	6,518.32	3,342.06
FT-11	41.62	1.80	6,503.88	2.55E-05	558.79	98,336.66	91,401.42	6,646.73	4,656.21
FT-12	41.60	1.83	6,395.54	2.70E-05	554.24	98,053.80	91,119.15	6,649.77	3,799.61
FT-13	40.25	1.62	6,353.93	3.04E-05	568.69	97,591.08	89,140.51	8,028.10	3,075.65
FT-14	31.28	1.55	5,881.51	1.48E-05	440.78	90,969.83	84,122.14	6,687.95	7,888.23
FT-15	31.19	1.68	5,448.17	2.09E-05	422.60	89,838.39	82,993.08	6,700.11	4,461.83
FT-16	43.67	1.81	6,644.20	3.27E-05	583.32	100,324.28	93,099.62	6,810.19	3,394.98
FT-17	42.63	1.84	6,707.00	2.78E-05	573.59	101,589.34	94,319.91	6,938.59	4,709.13
FT-18	42.61	1.87	6,598.67	2.94E-05	569.05	101,306.48	94,037.64	6,941.63	3,852.53
FT-19	41.58	1.67	6,568.43	3.28E-05	583.47	100,776.00	92,194.73	8,123.04	3,163.32
FT-20	32.46	1.58	5,928.62	1.58E-05	453.69	91,385.24	84,582.18	6,633.63	7,457.79
FT-21	32.37	1.69	5,537.67	2.14E-05	437.29	90,364.48	83,563.57	6,644.60	4,366.58
FT-22	43.67	1.81	6,644.20	3.27E-05	583.32	100,324.28	93,099.62	6,810.19	3,394.98
FT-23	42.63	1.84	6,707.00	2.78E-05	573.59	101,589.34	94,319.91	6,938.59	4,709.13
FT-24	42.61	1.87	6,598.67	2.94E-05	569.05	101,306.48	94,037.64	6,941.63	3,852.53
FT-25	41.58	1.67	6,568.43	3.28E-05	583.47	100,776.00	92,194.73	8,123.04	3,163.32
FT-26	32.46	1.58	5,928.62	1.58E-05	453.69	91,385.24	84,582.18	6,633.63	7,457.79
FT-27	32.37	1.69	5,537.67	2.14E-05	437.29	90,364.48	83,563.57	6,644.60	4,366.58
FT-28	43.67	1.81	6,644.20	3.27E-05	583.32	100,324.28	93,099.62	6,810.19	3,394.98
FT-29	42.63	1.84	6,707.00	2.78E-05	573.59	101,589.34	94,319.91	6,938.59	4,709.13
FT-30	42.61	1.87	6,598.67	2.94E-05	569.05	101,306.48	94,037.64	6,941.63	3,852.53
FT-46	41.58	1.67	6,568.43	3.28E-05	583.47	100,776.00	92,194.73	8,123.04	3,163.32
FT-47	32.46	1.58	5,928.62	1.58E-05	453.69	91,385.24	84,582.18	6,633.63	7,457.79
FT-48	32.37	1.69	5,537.67	2.14E-05	437.29	90,364.48	83,563.57	6,644.60	4,366.58
FT-49	43.67	1.81	6,644.20	3.27E-05	583.32	100,324.28	93,099.62	6,810.19	3,394.98
FT-50	42.63	1.84	6,707.00	2.78E-05	573.59	101,589.34	94,319.91	6,938.59	4,709.13
FT-51	42.61	1.87	6,598.67	2.94E-05	569.05	101,306.48	94,037.64	6,941.63	3,852.53
FT-52	44.03	1.77	7,061.74	3.85E-05	619.43	108,675.37	99,282.48	8,831.85	3,291.84
FT-53	34.91	1.67	6,421.93	2.15E-05	489.65	99,284.61	91,669.93	7,342.45	7,586.31
FT-54	34.83	1.79	6,030.98	2.71E-05	473.24	98,263.85	90,651.32	7,353.41	4,495.10
FT-55	48.00	1.98	7,514.75	4.28E-05	646.77	114,264.34	105,607.42	8,061.04	3,621.78
FT-56	46.96	2.00	7,577.55	3.79E-05	637.04	115,529.41	106,827.70	8,189.44	4,935.93
FT-57	46.94	2.03	7,469.22	3.95E-05	632.49	115,246.55	106,545.44	8,192.48	4,079.33
FT-58	44.16	1.72	7,375.83	4.29E-05	647.05	115,092.50	103,948.45	10,467.93	3,197.06
FT-59	31.91	1.66	6,875.98	2.42E-05	470.09	108,438.60	99,398.37	8,672.72	10,164.14
FT-60	31.78	1.85	6,249.51	3.31E-05	443.81	106,802.93	97,766.14	8,690.29	5,210.76
FT-61	44.16	1.72	7,375.83	4.29E-05	647.05	115,092.50	103,948.45	10,467.93	3,197.06
FT-62	31.91	1.66	6,875.98	2.42E-05	470.09	108,438.60	99,398.37	8,672.72	10,164.14
FT-63	31.78	1.85	6,249.51	3.31E-05	443.81	106,802.93	97,766.14	8,690.29	5,210.76
FT-64	48.00	1.98	7,514.75	4.28E-05	646.77	114,264.34	105,607.42	8,061.04	3,621.78
FT-65	46.96	2.00	7,577.55	3.79E-05	637.04	115,529.41	106,827.70	8,189.44	4,935.93
FT-66	46.94	2.03	7,469.22	3.95E-05	632.49	115,246.55	106,545.44	8,192.48	4,079.33
FT-67	43.81	1.70	7,363.20	4.29E-05	647.07	115,167.78	103,797.64	10,686.73	3,158.45
FT-68	26.61	1.48	6,020.79	1.38E-05	397.24	95,121.20	87,352.25	7,579.52	10,433.25
FT-69	26.47	1.68	5,347.22	2.34E-05	368.98	93,362.54	85,597.30	7,598.41	5,107.43
FT-70	45.90	1.84	7,438.98	4.28E-05	646.92	114,716.06	104,702.53	9,373.89	3,390.12
FT-71	36.79	1.74	6,799.17	2.58E-05	517.14	105,325.30	97,089.98	7,884.48	7,684.59
FT-72	36.70	1.86	6,408.22	3.14E-05	500.74	104,304.54	96,071.37	7,895.45	4,593.38
FT-73	49.33	2.43	13,063.79	-2.67E-06	744.47	149,381.45	134,309.33	14,879.91	31,987.63
FT-74	17.54	1.23	6,910.72	-1.80E-07	398.14	62,180.13	57,263.23	4,745.05	35,734.80
FT-75	7.36	0.45	3,422.80	6.89E-10	148.30	48,914.67	45,867.53	3,006.26	12,217.11

Figure 6. Tally output as Excel

The column name Sum of Global warming potential is the column that provides the information of how much embodied carbon each façade swatch contains

6.6 Grasshopper + Lunchbox

The next step in the research was to find a way to import the embodied carbon data that Tally had output as an Excel file. For this I initially tried to use the Bumble Bee plugin for grasshopper but Bumble Bee required the source excel file to be open in order to access the data. The next plugin I tried was Lunchbox, this worked with a closed Excel file and only required a path to the file [Fig.7].

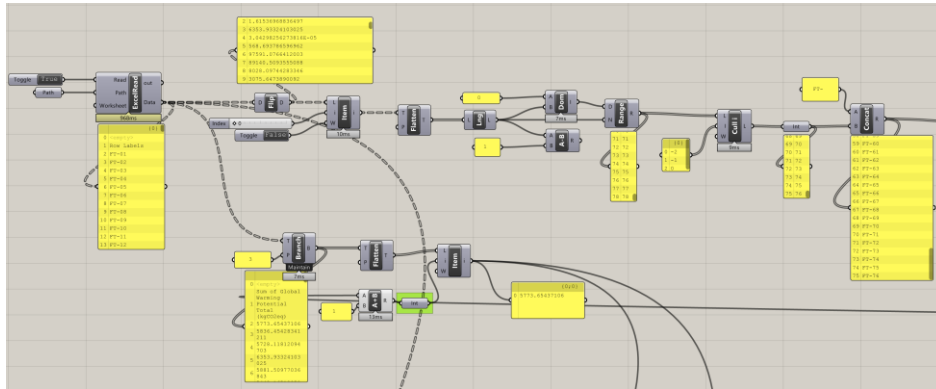


Figure 7. Grasshopper + Lunchbox. Read Excel

The next step was to find embodied carbon per square meter for each type swatch [Fig.8] and multiply it by the areas of the selected mass face which would give an estimate of how much embodied carbon the face would contain if it was to use that particular façade type with those particular materials [Fig.9]

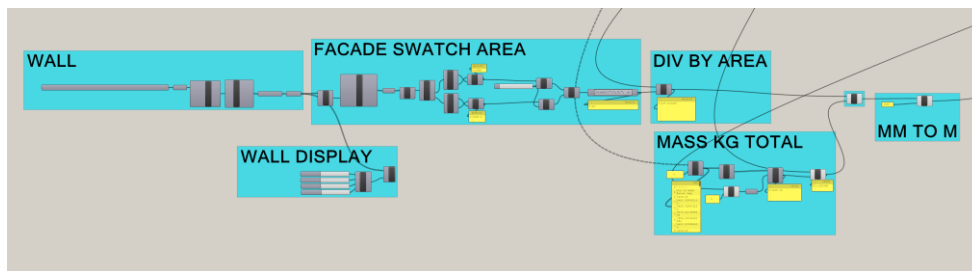


Figure 8. Embodied carbon per square meter

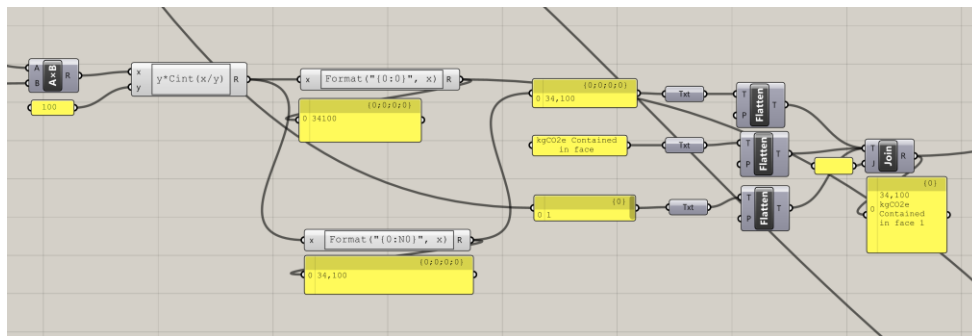


Figure 9. Embodied carbon contained in face

The subsequent issue to navigate was, how to export to an Excel file from Grasshopper. This was easy enough to solve as the plugin Lunchbox has a component that enables writing to an Excel file. The issue came in the form of not being able to append to an Excel file, meaning you could only write to the file once but it would not allow you to add information to it again later. This was a problem as each mass face's embodied carbon needed to be appended to the output excel file. The answer to this was to cache the data in a .txt file that could be appended using the plugin Wombat and once all the data had been attained it could be written to an Excel file all at once [Fig.10].

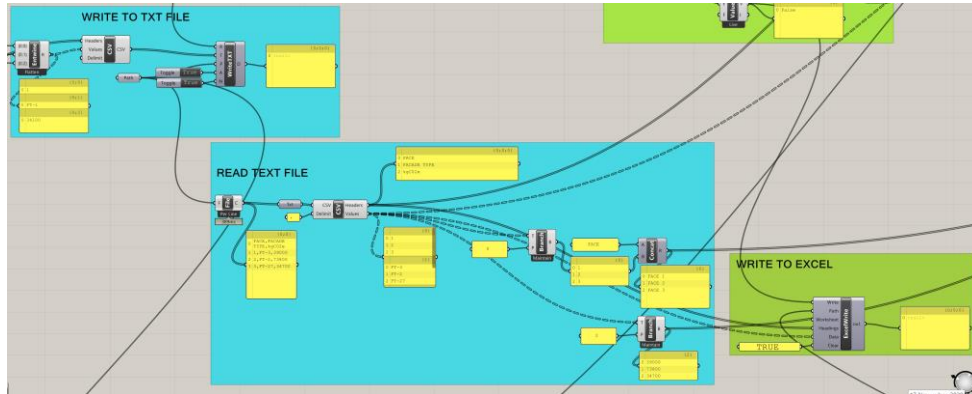


Figure 10. Text file to Excel

6.9 User Interface – Human UI

The subsequent part of the tool that now needed to be worked on was the user interface. The user interface was set up utilizing a Grasshopper plugin called Human UI. The plugin enables the creation of a window in which many elements can be added, ranging from text and drop-down menus to graphs and tables. This plugin proved to be incredible useful in creating the interface. The user interface needed to contain the following:

- A drop down for the user to select a face of the mass
- A drop down for the user to select the façade and material type
- An image of the façade and material type that had been selected above
- Text indicating the amount of embodied carbon
- A save button to save the face and face type combination (Face 1 x FT-3)
- A table showing all the combinations that had been saved so far
- A graph displaying the information from the table above as a visual aid
- An input box to specify the path where the final Excel is to be saved
- Save button to save the Excel file at the specified location

Later a clear button was added to the interface because there needed to be a way to erase data from when the tool had been used previously.

When the main interface was complete as [Fig.11], to make it more aesthetically pleasing and succinct I made another window that shows the mass and number for the text tagged mass faces instead of the user having to view them in Rhino [Fig.12].

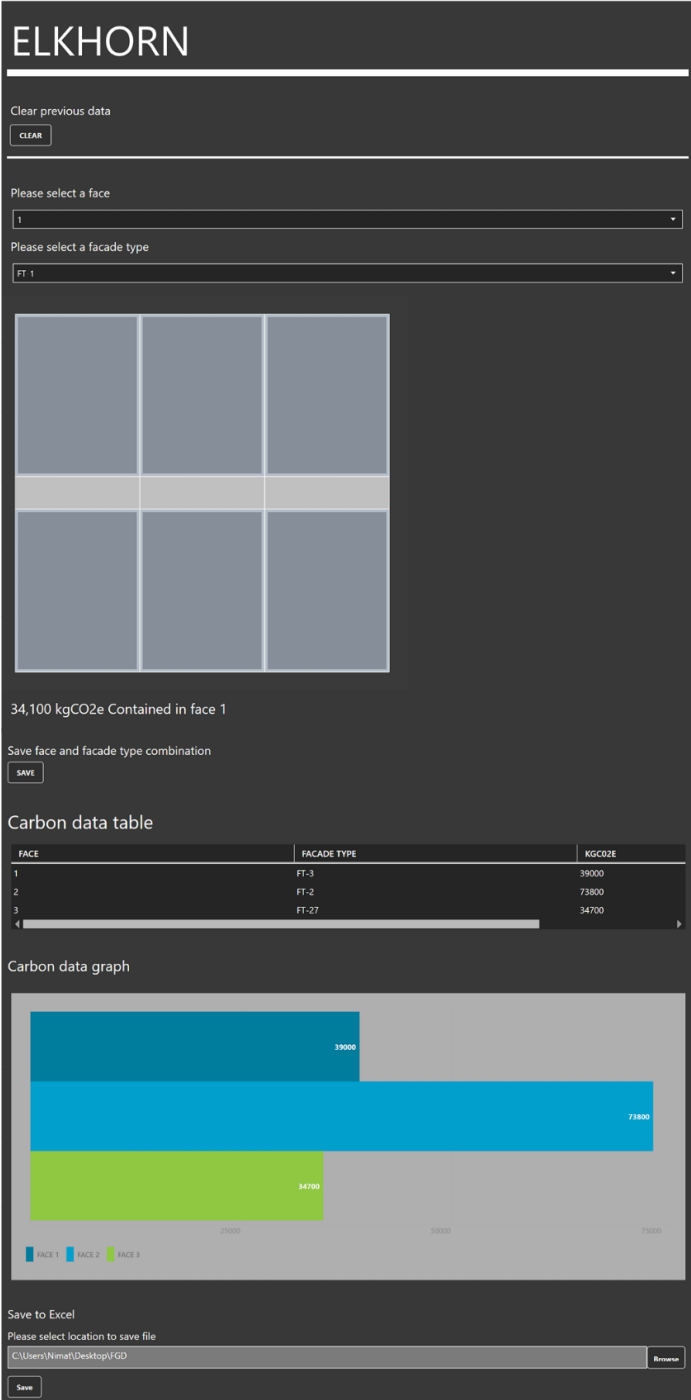
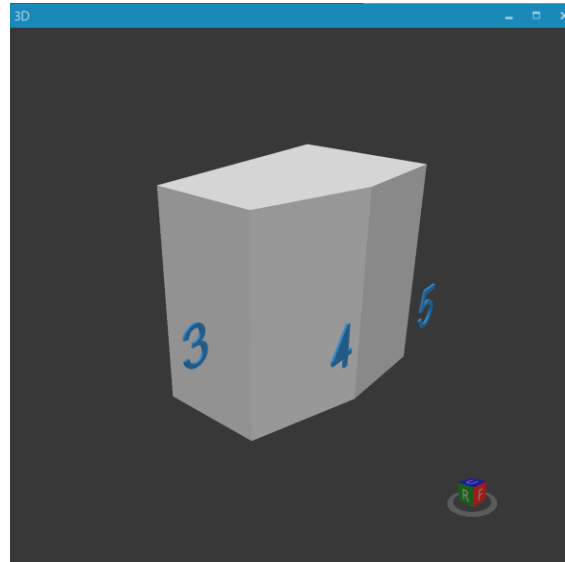


Figure 11. Main user interface*Figure 12. 3D user interface*

6.10 Final Output

The final output of this research is the user interface through which the tool runs as shown in Fig.11 and Fig.12 as well as an Excel file [Fig.13] containing the same data as shown in the interface so that it can be used to make other types of visual aids.

	A	B	C
1	FACE	FACADE TYPE	kgCO2e
2	1	FT-3	39000
3	2	FT-2	73800
4	3	FT-27	34700
5	4	FT-11	42300
6	5	FT-32	59500
7			

Figure 13. Exported Excel

6.11 Overview + Script

The tool entailed a lot of steps and a lot of trial and error, below is a diagrammatic over view of the logic and steps taken [Fig.14] and a full depiction of the Grasshopper script [Fig.15].

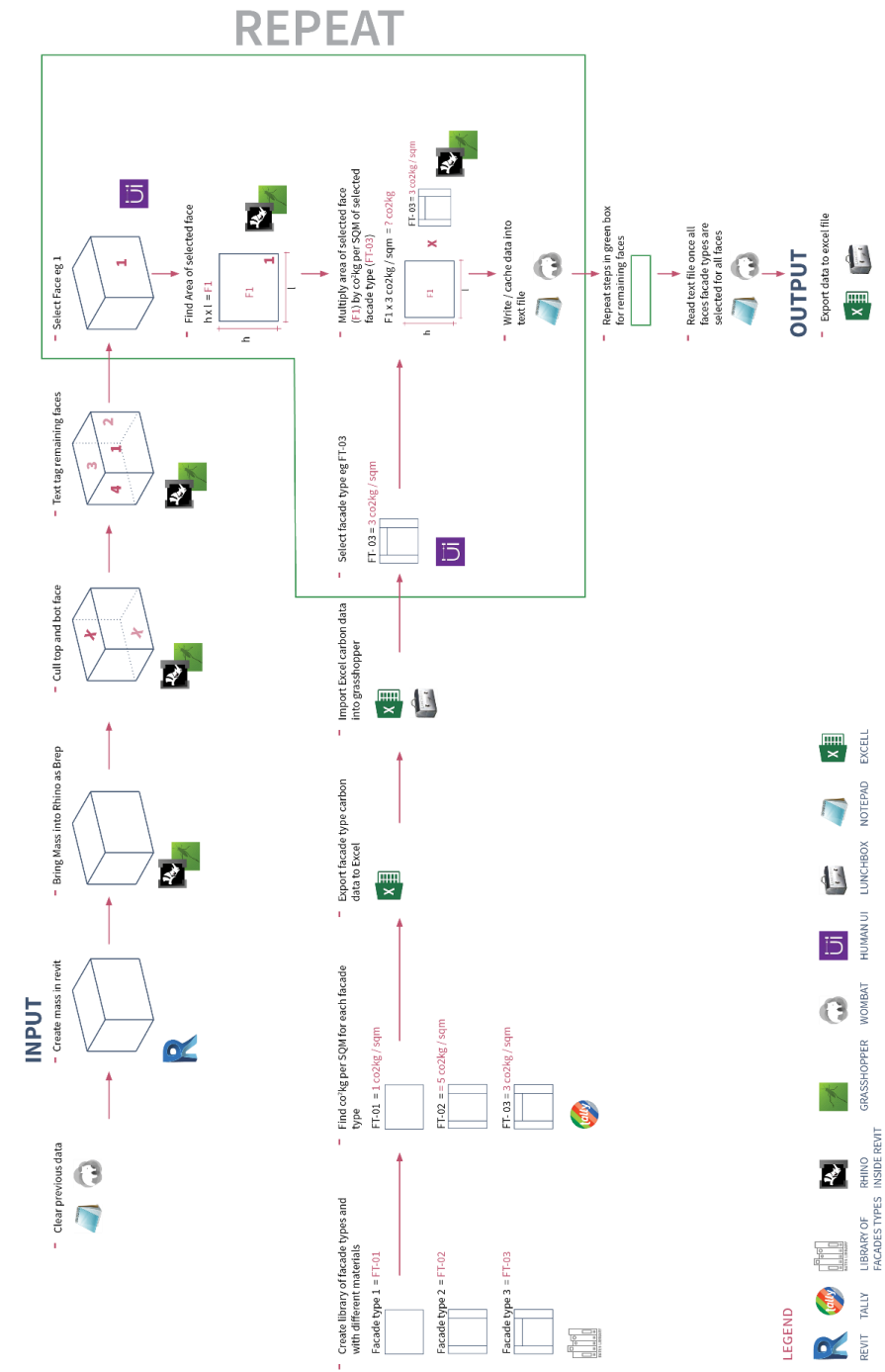


Figure 13. Exported Excel

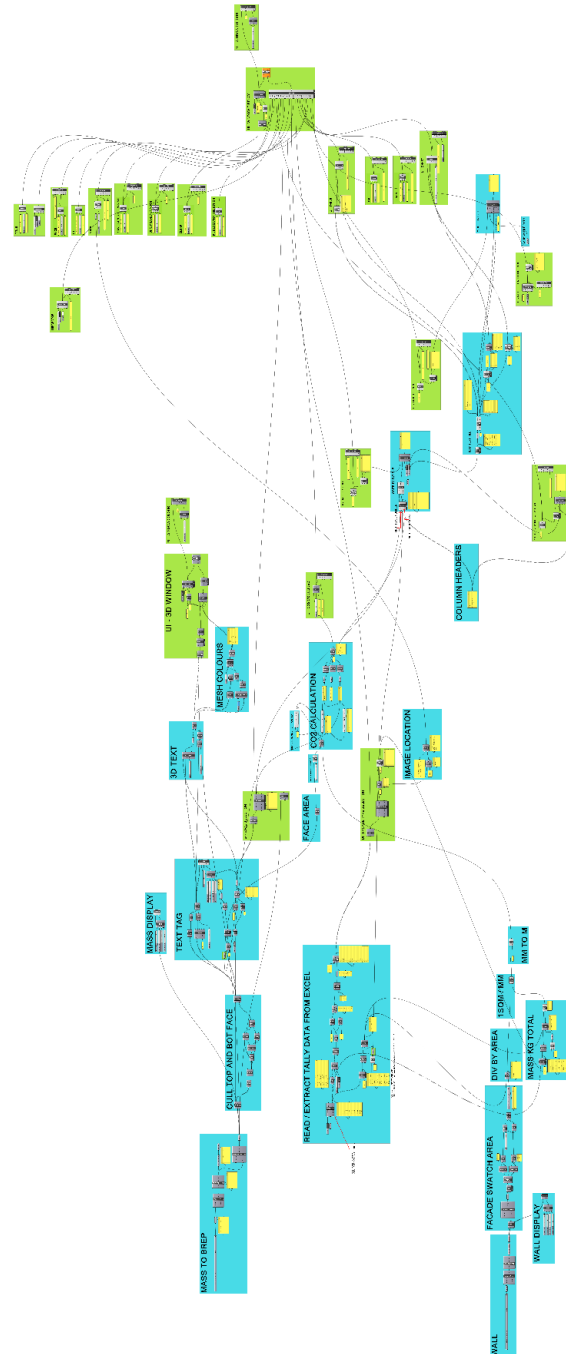


Figure 15. Grasshopper. Full Script. Green = Human UI

7. Discussion (evaluation and significance)

The outcome of this research is a tool that connects embodied carbon with early stage façade material selection decision making. The tool does show a correlation between material choice and the amount of embodied carbon that the façade contains, clearly changing the amount of embodied carbon when the material in a façade is changed. However, it is uncertain if this tool will influence design decisions. This is because the tool was not able to be tested in a design workflow due to the set 10-week time frame of this project.

The tool was tested against a detailed model of an already built building to assess the legitimacy of the developed tools carbon results. One face of the existing model was selected to be tested. The selected face was ran through Tally, an industry recognized tool for LCA calculations. The result from Tally was the face contained 171625 kgco2eq of embodied carbon. The same face was then run through the developed tool and the closest façade type from the library was selected. Some key differences between the actual façade and the closest select façade were, floor to floor height and bay length. The result that the decision support tool produced was that the selected face contained 145200 kgco2eq of embodied carbon. This is a difference of approximately 15%. Due to the key differences noted above this is an acceptable variance in outcome.

The tool has the potential to become a stand-alone tool but it has a few limitations. The most significant of which is that it relies heavily on the plugin Tally for its carbon data, if the carbon data could be internalized by the tool it would be a huge step in it becoming a stand-alone tool.

The tool is also expandable meaning more and newer materials and assemblies can be added as they are made available in the future. This shows the tool breaks the pigeonhole of predictive tools that beholden to their data sets.

The developed tool can be reconfigured and applied in many different aspects of the AEC industry. It could so be applied to structure, to a whole building package. In the future it could be that a swatch would contain the structure, floor and ceiling assembly, façade, and furniture and could work from floor area. The possible applications of the logic behind the tool are vast. This tool shows that in early design stage when most things are in flux an educated estimate can be a valuable factor to take in to account.

8. Conclusions

Current tools in the AEC industry that address embodied carbon are not employable at the early stages of design. Many of the tools need highly detail models to give an accurate assessment making them only applicable to the later design stages. The tools that are applicable to early design stages are predictive and limited typologically and precedentially due to their reliance on data sets.

The developed decision support tool indicates that its possible to make a tool that can estimate the amount of embodied carbon in facades at early design stages without the need for a highly detailed model. It also shows that there is a relationship between material selection and the amount of embodied carbon contained in the façade. Furthermore, it demonstrates that a tool can be developed that can take on future materials and assemblies when they become available making it flexible and adaptable for the future.

It is optimistic to think that once the AEC industry has this carbon knowledge that they will make the most environmentally sustainable decisions. Being cautiously optimistic it is acceptable to think the industry might make slightly better decisions if armed with the carbon knowledge.

Acknowledgements

My deepest and sincere thanks to Dr. Nicole Gardner, Professor Matthias Hank Haeusler, and Daniel Yu for guiding me through this project.

Thank you to Bates Smart for being my industry partner. Specifically, a big thanks to Aaron Coats, Stephen Green, Peter Pittas, Kingsley Castillo, and Marius Hatleveit.

References

- Ahmad, I., Azhar, S. & Sein, M.K. 2010, Action Research as a Proactive Research Method for Construction Engineering and Management, *Journal of Construction Engineering and Management*, vol. 136, no. 1, pp. 87–98.
- Bennadji, A. & H. Ahriz, P.A. 2004, Computer Aided Sustainable Design, 1st ASCAAD International Conference, e-Design in Architecture KFUPM, pp. 125–35.
- Budig, M., Heckmann, O., Hudert, M., Ng, A.Q.B., Xuereb Conti, Z. & Lork, C.J.H. 2020, Computational screening-LCA tools for early design stages, *International journal of architectural computing*, p. 147807712094799.
- Catarina, B., António, L. & Luís, S. 2019, On the Impact of Machine Learning Architecture without Architects?, pp. 274–93.

- Chapman, A., Pohl, J. & Pohl, K.J. 2000, Computer-aided design systems for the 21st century: some design guidelines, Timmermans, Harry (Ed.), Fifth Design and Decision Support Systems in Architecture and Urban Planning - Part one: Architecture Proceedings (Nijkerk, the Netherlands), pp. 307–24.
- Coenders, J., Kimpian, J., Mason, J., Jestico, D. & Watts, S. 2009, Sustainably Tall: Investment, Energy, Life Cycle, Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Chicago (Illinois), pp. 130–43.
- Company, Footprint . n.d., Net Zero Carbon Design – Just Got Easier, <https://footprintgreenbook.com>, viewed 2020, <<https://footprintgreenbook.com/uncategorized/net-zero-carbon-design-just-got-easier/>>.
- Council, W.G.B. n.d., New report: the building and construction sector can reach net zero carbon emissions by 2050, <https://www.worldgbc.org>, viewed 2020, <<https://www.worldgbc.org/news-media/WorldGBC-embodied-carbon-report-published>>.
- Hearn, G. & Foth, M. 2005, Action Research in the Design of New Media and ICT Systems, Topical Issues in Communications and Media Research, Nova Science Publishers, pp. 79–94.
- Hollberg, A., Hildebrand, L. & Habert, G. 2018, Environmental design - Lessons learned from teaching LCA, Sustainable Computational Workflows [6th eCAADe Regional International Workshop Proceedings, pp. 65–74.
- Lynette, B., Michael, Heckmann, Oliver, Ng Qi Boon, Amanda, Hudert, Markus, Lork, Clement and Cheah, 2020, Data-driven Embodied Carbon Evaluation of Early Building Design Iterations, Anthropocene, Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference, pp. 303–12.
- Meex, E., Hollberg, A., Knapen, E., Hildebrand, L. & Verbeeck, G. 2018, Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design, Building and environment, vol. 133, pp. 228–36.
- Salgueiro, I.B. & Ferries, B. 2015, An ‘Environmental BIM’ Approach for the Architectural Schematic Design Stage, International Journal of Architectural Computing, vol. 13, no. 3–4, pp. 299–312.