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Veloso e Zarate, Halina; Triggianese, Manuela; Stoter, Jantien; Cuartero, Javier; Gilio, Renata

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Carbon Design Bottlenecks: An empirical taxonomy of the challenges integrating carbon data in the Architecture practice

HALINA VELOSO E ZARATE
Faculty of Architecture and the Built Environment,
Technische Universiteit Delft
MANUELA TRIGGIANESE
Faculty of Architecture and the Built Environment,
Technische Universiteit Delft
JANTIEN STOTER
Faculty of Architecture and the Built Environment,
Technische Universiteit Delft
JAVIER CUARTERO
BIM Manager at KAAN Architecten
RENATA GILIO
Managing Director at KAAN Architecten

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With the growing demand for sustainable accountability, the European Directive 2014/24/EU (EU 2014) pushes architects to deliver Building Information Models (BIM) as a part of procurement processes for public buildings. In the Netherlands, BIM model data is relevant to the building permitting process, which involves an environmental performance calculation (MPG). This assessment takes into consideration the embodied carbon of materials in a building. Although this analysis is performed by a qualified expert in late design phases, architects benefit from integrating carbon data in early design decision-making. Design methods supported by Life Cycle Assessment (LCA) values are needed before involving expert collaborators, and not only when applying for a building permit.

The existing carbon assessment tools require detailed data from BIM models, which are often not available at early design phases. Simplified tools have been discussed in theory, and explored in their potential applications, however, there lacks scientific literature discussing the hurdles designers face in their attempt to create such tools in practice, for their internal use throughout early design phases.

This paper focuses on the architecture professional practice and design methods supported by digital and computational technologies, regarding embodied carbon data. It investigates the challenges in integrating embodied carbon data in the design workflow, through the development of a digital tool made by designers, for designers. This paper conducts an empirical investigation within a Rotterdam-based architecture office, with a broad portfolio in BIM usage and public building projects, to identify and categorize the factors affecting carbon data integration into the design workflow. It proposes a taxonomy of challenges within the architecture office, to better communicate the designer's needs to the data providers and software developers with architects as a target user. Amongst the bottlenecks encountered are: access to data (data inclusiveness), data literacy and connecting data usage with design decision-making.

INTRODUCTION

With the growing demands for sustainable accountability, European Directive 2014/24/EU require architects to deliver Building Information Models (BIM) as part of regulatory processes. BIM is known as a tool for architects, engineers and construction managers to administrate building resources, and can enable municipalities to automate code compliance checking for building permits [1, 2]. Although there is no compulsory BIM-based building permitting process across the European Union, in The Netherlands, municipalities make use of BIM data, in the building permitting process. Data on material quantities, in the form of schedules, is used to assess the environmental performance of buildings (in Dutch known as "Milieuprestatie voor Gebouwen"- MPG)[3, 4]. To calculate the MPG, data on the "embodied carbon" of individual materials, measured in KgCO2-eq, is one of the 19 indicators assessed. This paper takes the indicator of "embodied carbon" to reflect on how architects, although not primarily responsible for Life Cycle Analysis (LCA) [5, 6] assessments (See Figure 1), integrate this type of data into their design workflow.

The design workflow can be understood in phases: 1. Project Brief and Feasibility study, 2. Concept design, 3. Developed design, 4. Procurement and execution drawings, 5. Construction and 6. Hand over and use [7]. Existing carbon assessment tools are offered commercially for BIM integration requiring building models to have been already developed till latest design phases (from 4 to 6). At this stage, if the carbon assessment of the building is too high for the regulatory standards, the design needs to accommodate challenging changes to lower the carbon impact. The paper is looking into the efficiency of the design workflow and inquires how can designers integrate carbon data in early design phases (from 1 to 3), to anticipate unexpected changes for regulatory compliance and avoid resource losses for architecture companies.

The research explores the integration of carbon data in early design phases, when making fundamental design decisions. Bridging the gap between theory and practice [8], it conducts an empirical investigation within a Rotterdam-based architecture office, with a broad portfolio in BIM usage and public building projects. It proposes 9 factors that affect the integration of

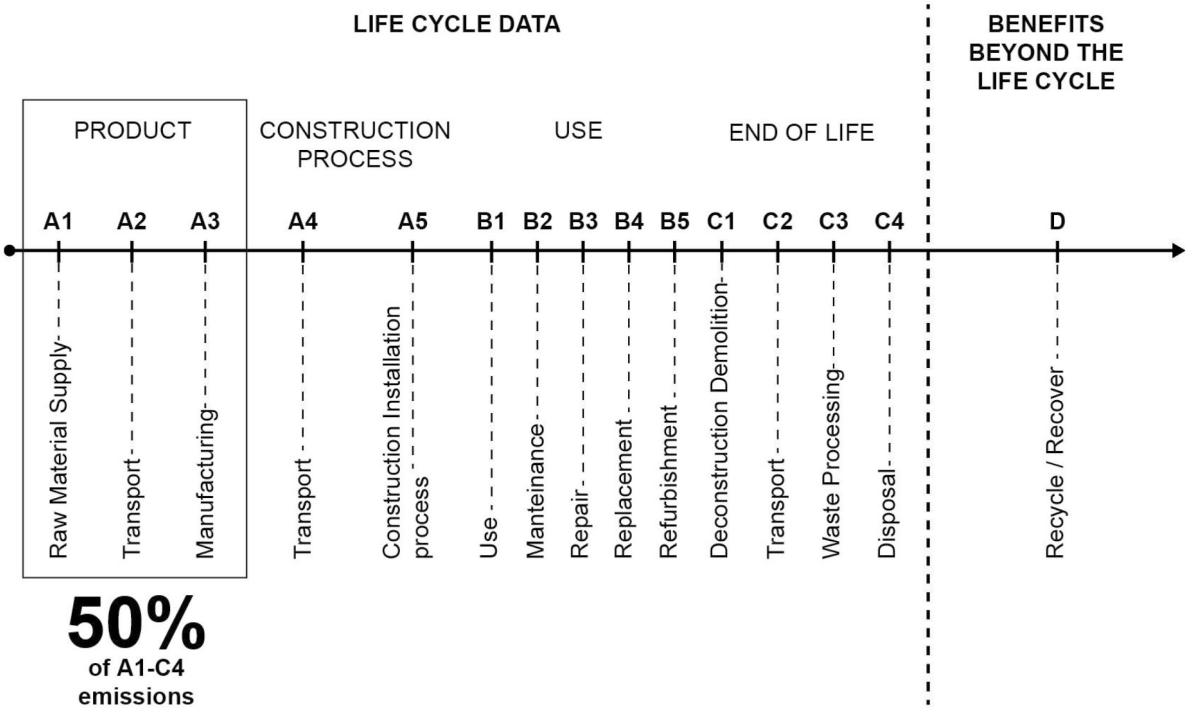


Figure 1. Life Cycle Ananlysis stages, Highlighting the A1-A3 modules, considered for the building permitting process in the Netherlands. This illustration is based on BS EN 15978, adapted from Life cycle stages in the book "How ro Calculate Embodied Carbon" (Gibbons and Orr, 2020)..

carbon data into the design workflow, by developing a digital tool to increase awareness among architects about the carbon impact of building materials. While practitioners are developing their own LCA tools to input building data (such as building dimensions and material quantities) and gain insight on the carbon impact of study design proposals, the case developed for this paper proposes a digital web-based dashboard to input material choices instead, independent of building shape or area.

Such a simplified tool responds to the early-design demand for precision in estimating carbon impact, while dealing with generalized design parameters [9]. This experiment sheds light on the practical challenges architects encounter in incorporating carbon data in early design phases, before or in parallel with volumetric studies in 3D digital modelling. It offers insights that can inform future developments in tools, databases, and data accessibility, facilitating more sustainable building design and decision-making processes. It also brings up reflections about the incorporation of data-supported design methods as part of architecture education.

METHOD

The methodology was three-fold: 1. literature review; 2. case-study within the architecture practice; 3. Qualitative methods. The literature review provided the theoretical background, including papers on the use of embodied carbon data in buildings. Amongst the scholarly papers reviewed regarding the later, 22 are compiled in the book "Embodied Carbon in Buildings: Measurement and Mitigation" (Pomponi, De Wolf, Moncaster, 2018). Additionally, 2 publications coming from architecture private practices in the Netherlands were also reviewed including "Carbon-based design" (LEVS Architects 2022), and "Carbon-based design: steps to zero", (City Foerster, 2022), the latter being relevant to introduce the regulatory framing the governmental process for building permitting and environmental check in Europe and in the Netherlands.

A gap found in literature concerned the integration of carbon data in the concept design phase, its use in the architecture practice, and in using a data representation tailored to the architectural community's visual language. Notably, the figures prevailing in these papers were predominantly tables and chart, and only 4 out of 22 scientific papers, and the 2 publications from practitioners incorporated some kind of architectural diagram to represent data about embodied carbon in buildings. None of the 24 papers utilized architectural representations to communicate carbon data, such as color-coding a building drawing to signify which elements have the worst environmental impact. Such representation, in our view, could help the designer understand the carbon weight of certain material choices and ease the integration of carbon data in design workflows. This gap in literature inspired the empirical investigation with a real life practice, following the strategy of "case study", as proposed by Yin (2002)[10].

The case study deals with "how" and "why" questions: "how designers integrate carbon data in the design workflow?", "why is the integration of carbon data in the design workflow challenging to architects?", "how can carbon data be visualized in an architectural way?". This research strategy is to investigate the design process, as shown relevant by Creswell in his book "Research Design" [11], with the focus in describing elements that are part of the tacit knowledge of the architect (Schrijver 2021) [12], bridging gap between theory and practice [8]. The criteria selection for the case study was: a. An architecture office with broad portfolio in using BIM, executing public buildings and experience with the building permitting; b. Real-life conditions for the project development, such as limited time, limited budget, limited staff dedication, demands from managers and potential clients; c. A will to develop a workflow to integrate carbon data early on the design process; d. Possibility to apply findings in a real project during concept or competition phase; e. Allow the researcher to be a part of the investigation while its developed rather than looking into historic events documented in archives. KAAN Architecten, in the Netherlands, was the architectural practice that hosted and co-developed the case-study project, entitled Karbon.

Qualitative methods involving human participants with informed consent included periodical interviews with the office's BIM manager (co-author of this paper), at the start of the case-study to frame the experiment (the development of a tool to assess carbon in early phase design, the Kabon tool); during the case-study development, to outline the expected and encountered challenges, and ponder on methodological adaptations to overcome some of the hurdles encountered, and at the end of the process, to analyse the encountered challenges. An unstructured conversation with the municipality gave overview about the building permit and MPG check process, as well as interpretation of the challenges in carbon design that are on the level of data provision and urban regulations, beyond the designer's domain. Six designers of different profiles and three project managers tested the pilot tool in two separate focus group sessions. All participants found the tool useful for consultancy during early design phases, considering its user-friendliness and ease to convey an assessment of the combination of choices across different building elements. A questionnaire with the focus-group participants helped broaden the analysis of challenges encountered in the case-study. Amongst the group's suggestions were a more robust data-base, a swifter navigation fit to non-linear thinking processes and a plug-in for software design. These, however, extrapolate the capacity of the research team, and would require computer & data scientists to achieve. These contributions were invaluable to trace the Findings and Discussion brought by this paper.

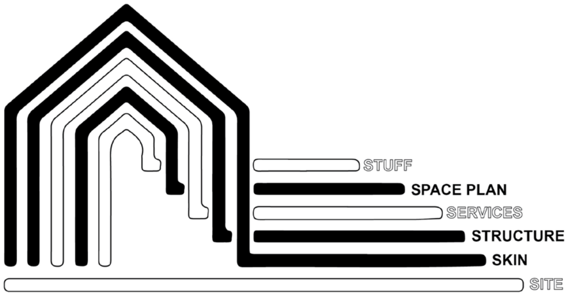


Figure 2. Simplified building model of the shearing layers, highlighting the three layers chosen for the development of the carbon based design tool. Adapted from "The Building System Carbon Framework", WBCSD 2020.

EMPIRICAL INVESTIGATION: A TOOL TO INTEGRATE CARBON DATA IN THE DESIGN PROCESS

The empirical investigation consisted in developing a simplified platform to educate architects about the carbon factor of their design decisions, creating a sense of understanding of what material choices are more or less impactful. The ambition was to visualize, in simple graphics, the carbon factor of given materials, values which were provided by open data sources. The parameters for the elaboration of this tool were:

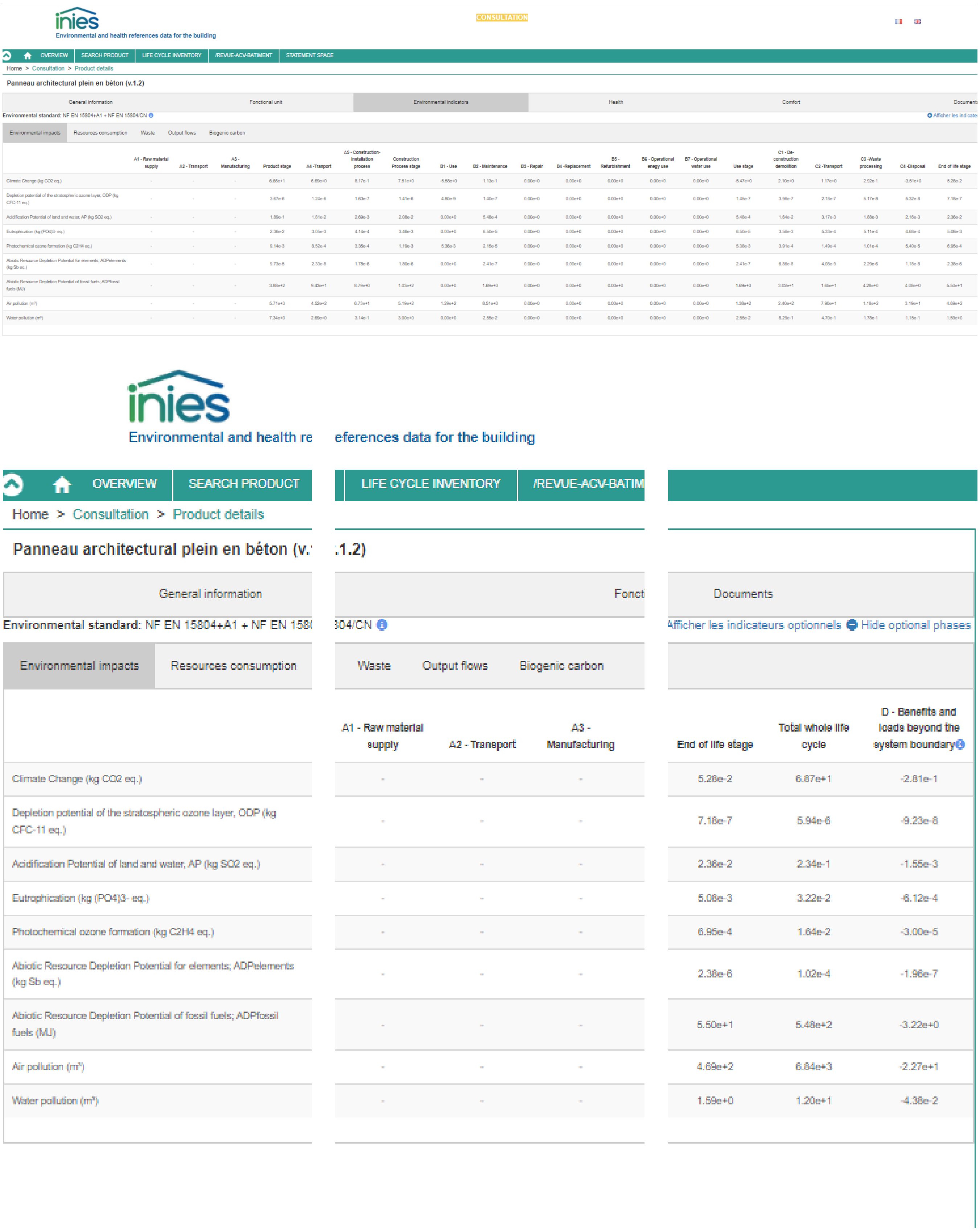
-Simple. The information about the carbon impact of a certain material choice needs to be understandable to non-experts in LCA, not only shown as raw mathematical values.

-Accessible. The data-base of reference needs to be of open access, no payment for license use required.

-Straightforward. It has to be clear if a certain material is performing better or worse than the conservative design choice (before carbon awareness).

-Visual. The tool must depict graphics that visually allude to an architecture form, for instance the schematic impression or diagrammatic geometry of a space, not only tables, bar charts and gauges.

-User-friendly. The tool must be of intuitive navigation and the designer needs to finish the navigation experience with enough knowledge for a more carbon-conscious decision-making process.



Panneau architectural plein en béton (v.1.2)

Environmental standard: NF EN 15804+A1 + NF EN 15804/CN

	A1 - Raw material supply	A2 - Transport	A3 - Manufacturing	Product stage	A4 -Tranport	A5 - Construction-Installation process	Construction Process stage	B1 - Use	B2 - Maintenance
Climate Change (kg CO2 eq.)	-	-	-	6.66e+1	6.69e+0	8.17e-1	7.51e+0	-5.58e+0	1.13e-1
Depletion potential of the stratospheric ozone layer, ODP (kg CFC-11 eq.)	-	-	-	3.67e-6	1.24e-6	1.63e-7	1.41e-6	4.80e-9	1.40e-7
Acidification Potential of land and water, AP (kg SO2 eq.)	-	-	-	1.89e-1	1.81e-2	2.69e-3	2.08e-2	0.00e+0	5.48e-4
Eutrophication (kg (PO4)3- eq.)	-	-	-	2.36e-2	3.05e-3	4.14e-4	3.46e-3	0.00e+0	6.50e-5
Photochemical ozone formation (kg C2H4 eq.)	-	-	-	9.14e-3	8.52e-4	3.35e-4	1.19e-3	5.36e-3	2.15e-5
Abiotic Resource Depletion Potential for elements; ADPelements (kg Sb eq.)	-	-	-	9.73e-5	2.33e-8	1.78e-6	1.80e-6	0.00e+0	2.41e-7
Abiotic Resource Depletion Potential of fossil fuels; ADPfossil fuels (MJ)	-	-	-	3.88e+2	9.43e+1	8.79e+0	1.03e+2	0.00e+0	1.69e+0
Air pollution (m³)	-	-	-	5.71e+3	4.52e+2	6.73e+1	5.19e+2	1.29e+2	8.51e+0
Water pollution (m³)	-	-	-	7.34e+0	2.69e+0	3.14e-1	3.00e+0	0.00e+0	2.55e-2

	B3 - Repair	B4 -Replacement	B5 - Refurbishment	B6 - Operational enegy use	B7 - Operational water use	Use stage	C1 - De-construction demolition	C2 -Transport	C3 -Waste processing	C4 -Disposal	End of life stage
Climate Change (kg CO2 eq.)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	-5.47e+0	2.10e+0	1.17e+0	2.92e-1	-3.51e+0	5.28e-2
Depletion potential of the stratospheric ozone layer, ODP (kg CFC-11 eq.)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	1.45e-7	3.96e-7	2.18e-7	5.17e-8	5.32e-8	7.18e-7
Acidification Potential of land and water, AP (kg SO2 eq.)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	5.48e-4	1.64e-2	3.17e-3	1.88e-3	2.16e-3	2.36e-2
Eutrophication (kg (PO4)3- eq.)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	6.50e-5	3.56e-3	5.33e-4	5.11e-4	4.68e-4	5.08e-3
Photochemical ozone formation (kg C2H4 eq.)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	5.38e-3	3.91e-4	1.49e-4	1.01e-4	5.40e-5	6.95e-4
Abiotic Resource Depletion Potential for elements; ADPelements (kg Sb eq.)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	2.41e-7	6.86e-8	4.08e-9	2.29e-6	1.18e-8	2.38e-6
Abiotic Resource Depletion Potential of fossil fuels; ADPfossil fuels (MJ)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	1.69e+0	3.02e+1	1.65e+1	4.28e+0	4.08e+0	5.50e+1
Air pollution (m³)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	1.38e+2	2.40e+2	7.90e+1	1.18e+2	3.19e+1	4.69e+2
Water pollution (m³)	0.00e+0	0.00e+0	0.00e+0	0.00e+0	0.00e+0	2.55e-2	8.29e-1	4.70e-1	1.78e-1	1.15e-1	1.59e+0

Panneau architectural plein en béton (v.1.2)

Environmental standard: NF EN 15804+A1 + NF EN 15804/CN

	A1 - Raw material supply	A2 - Transport	A3 - Manufacturing	End of life stage	Total whole life cycle	D - Benefits and loads beyond the system boundary
Climate Change (kg CO2 eq.)	-	-	-	5.28e-2	6.87e+1	-2.81e-1
Depletion potential of the stratospheric ozone layer, ODP (kg CFC-11 eq.)	-	-	-	7.18e-7	5.94e-6	-9.23e-8
Acidification Potential of land and water, AP (kg SO2 eq.)	-	-	-	2.36e-2	2.34e-1	-1.55e-3
Eutrophication (kg (PO4)3- eq.)	-	-	-	5.08e-3	3.22e-2	-6.12e-4
Photochemical ozone formation (kg C2H4 eq.)	-	-	-	6.95e-4	1.64e-2	-3.00e-5
Abiotic Resource Depletion Potential for elements; ADPelements (kg Sb eq.)	-	-	-	2.38e-6	1.02e-4	-1.96e-7
Abiotic Resource Depletion Potential of fossil fuels; ADPfossil fuels (MJ)	-	-	-	5.50e+1	5.48e+2	-3.22e+0
Air pollution (m³)	-	-	-	4.69e+2	6.84e+3	-2.27e+1
Water pollution (m³)	-	-	-	1.59e+0	1.20e+1	-4.38e-2

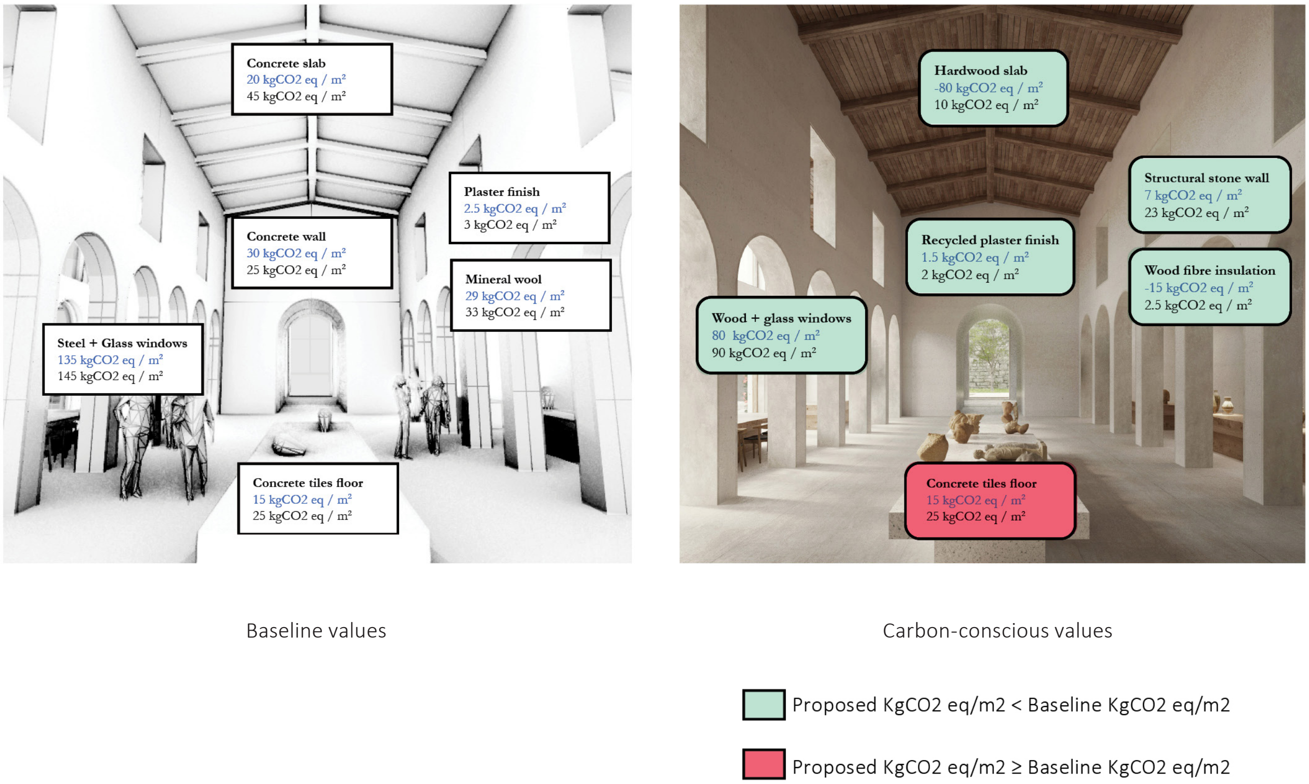
Figure 3. Screencapture and details of the INES online portal, illustrating what does a material database look like. INIES < https://www.base-inies.fr/iniesV4/dist/consultation.html?id=26912>, assessed on 09-10-2023.

With a dropdown menu of building material options, Karbon allows creating a hypothetical composition of building elements. Materials can be chosen for the shearing layers of Skin (roof, windows, exterior wall finishings), Structure (beam, column, wall, slabs) and Space Plan (ceiling, floors, doors and interior wall finishings) (See Figure 2). The composition sums the Global Warming Potential (GWP) values of each material chosen, given in KgCO2/m2 of material. A weighted distribution of those values is based on a typical (GFA) ratio breakdown, for a holistic overview of a given composition and comparison between multiple possible compositions. The output is a prototypical architectural diagram, in which the building elements are mapped in red when choosing high carbon impact material, and in green when choosing low carbon impact materials. This helps avoiding early decisions with later high GWP outcomes.

KARBON: A TOOL TO INTEGRATE CARBON DATA IN THE DESIGN WORKFLOW

Conceiving the tool made use of the concept of six shearing layers, as coined in the book "How Buildings Learn: What Happens After They're Built"[13]: Site, Structure (foundation, load-bearing elements), Skin (exterior surfaces), Services (plumbing, heating, ventilation, air conditioning, elevators), Space plan (interior walls, ceilings, floors, doors), and Stuff (furniture). The proposed tool considers skin, structure and space plan, drawn as an architecture diagram as the base for the data visualization.

The project adopted an accessible LCA database with Environmental Product Declaration (EPD). Although the Karbon project ran in the Dutch context, with a long sight to being applicable to the Dutch building permitting requirements, the national environmental database, in Dutch, Nationale Milieudatabase (NMD)[14], does not offer open access. Cost-free options were considered: INIES, Ökobaudat, Ecoinvent and the Inventory of Carbon and Energy (ICE). Initially, this research looked for a common factor between them and investigated conversion methods, benchmarks and averages of carbon factors between similar materials. Combining datasets only complicated the process beyond the capacity of the designers to handle. Choosing one single database as a reference proved to be the most logical decision for this experiment, avoiding to add uncertainty to the datasets. Choosing INIES for the free open data, relevance as an European example, with robust pool of material choices and detailed information about LCA values in each module of the Life Cycle (See Figure 3), facilitated the acquisition and processing of the information and assumptions, when needed.



Baseline values

Carbon-conscious values

🟩 Proposed KgCO2 eq/m2 < Baseline KgCO2 eq/m2

🟥 Proposed KgCO2 eq/m2 ≥ Baseline KgCO2 eq/m2

Figure 4. The visual communication of the Karbon concept, test with rendered impression overlapped with color-coded flags.

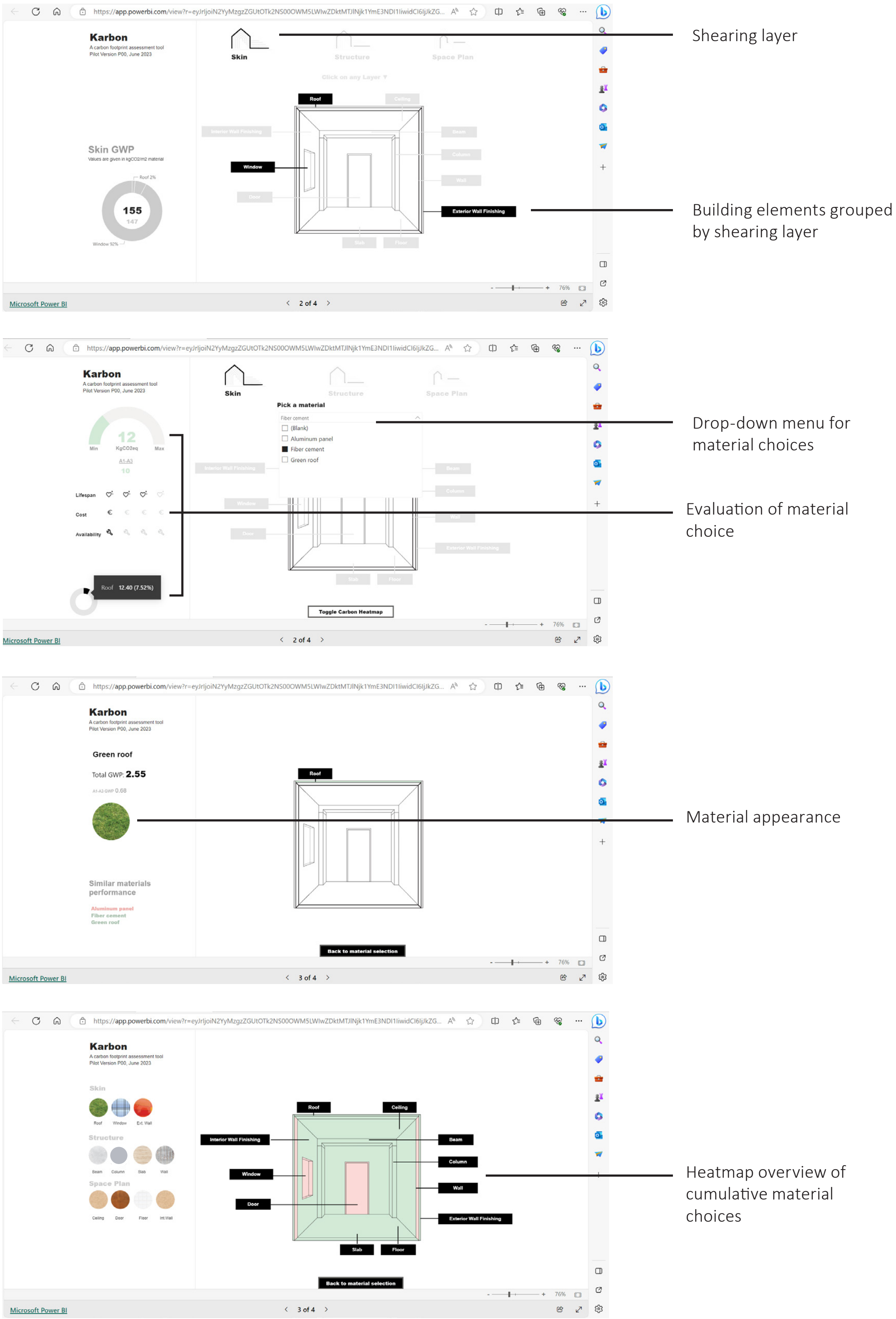


Figure 5. The Karbon tool - web based platform with clickable functionalilties and interactive navigation.

A short pool of materials was selected to test the tool's concept. For a straightforward assessment, baseline values for the carbon impact of materials were established based on materials customarily chosen on non-carbon-aware designs. For instance, concrete slabs, concrete wall, concrete tiles floor, steel and glass windows. Any material choice with values equal or greater than the baseline is represented in red. If smaller, meaning a lower carbon impact, it is represented in green. This red-green heatmap was a straightforward way to communicate to the designer if their material choice results in a better or worse alternative in comparison to conservative compositions, guiding designers to elect less impactful options. This concept was tested during a design competition of design ideas, aiming to be the winner, and gain the right to develop the project for execution. In that test of concept, the representation made use of illustrations extracted from the 3D model and rendering impressions to also provide the aesthetic result of the proposal, overlapped with colour coded flags (See figure 4).

Afterwards, the visual communication of the tool was generalized, since the project-specific representation was distracting from the purpose of the tool - to educate designers about the carbon impact of materials, no matter the shape and form of the built environment. The base drawing represented a single unit of space, represented as a sectioned cube perspective. The tool allows grouping the drawn building elements per shearing layers, and changing colours as material choices are made. Roof, exterior wall finishing, and windows represent Skin elements; Columns, Beams and Slab represent Structure elements, and Interior Wall Finishing, Door, Ceiling, and Floor represent Space Plan Elements. That concept was first sketched by hand and later on drafted digitally to build an interactive digital tool that reflected the designers choices in the diagram. The choice of software for data visualization (PowerBI) conditioned the type of graphic format needed. PNG images drafted in Adobe Illustrator were utilized in substitution of the initially ambitioned 3D model, in BIM format. This included visual samplers of material textures (See figure 5). PowerBI responded to the need for a software with the capacity of bearing interactive graphics following the architect's visual language, not only bar charts and gauges. This was important for two reasons: to visualize the impact of all material choices across different elements of a shearing layer, as a heatmap; see the sum of all choices in comparison to a pre-set baseline; and to relate the numbers seen in mathematical graphs to the architectural diagram.

The tool was hosted on a web browser with clickable functionalities to test user experience. This facilitated the communication of the carbon impact per material choice, and also aided in achieving an intuitive navigation and incorporation of carbon data in the design workflow. The tool was tested in two focus group sessions with employees, one with 6 designers, followed up by a questionnaire assessment, and another with 3 management team members. In result, 80% of the questionnaire respondents found the tool user-friendly and applicable to their own design workflow. At the end of the Karbon project, the research team had a pilot Karbon tool, that fulfilled the parameters proposed: simple, accessible, straightforward, visual, and user friendly.

FINDINGS

During the development of the Karbon tool and its validation, several challenges appeared. A taxonomy of the factors that affect significantly the incorporation of carbon data in the Karbon project are:

1. Limited access to data and tools to handle data. The NMD does not offer open access, and it is not affordable to all architecture practices. Single use licenses to access the database and the calculation instruments cost € 25,000 (entry fee) and then extra €3,054 annually, per June 2023. As a base of comparison, solely the annual cost for accessing the database is equivalent to the annual cost of a BIM design software licenses (Autodesk Revit Architecture, €3,358). Apart from the cost of data and the cost of BIM license, there are additional costs of LCA data tools. Examples of calculation instruments validated by the NMD are GPR Material, MPG Key Help, One Click LCA, Dubo Calc, MRPI MPG Tool.

2. Debatable regulatory framework. Having a paywall to access embodied carbon data (point 1) creates a paradoxical hurdle to the national regulations towards enabling and facilitating the use of data to promote sustainable development. The regulatory frameworks in the Netherlands does not support the use of alternative open databases, besides NMD, as they do not all provide the 19 indicators to perform the MPG. Additionally, the building permitting process only applies for new constructions of office buildings above 100m2 and dwellings.

3. Narrowness of available database. Because the NMD only lists items that have all 19 indicators for the MPG, the database is limited, making the adoption of this data less likely. That was also the case for the Karbon project, in which materials such as "recycled concrete" and "terrazzo" were not available in INIES, although they are known for having lower carbon impact than conservative material choices. In that case, assumptions were tested, but lowered the precision of estimations. For example, for terrazzo, the LCA module of "extraction" of the mineral stone was assumed to be removed from the total LCA carbon factor.

4. Lack of consistency and complexity of data. When consulting various open LCA datasets, their carbon factor values vary per material provider and per country. This confirmed the premise found in the literature review that the lack of consistency among datasets limits the adoption of carbon data at early stages of design, when it is the most important.

5. Lack of data literacy. Designers found difficult to make sense of the large amounts of data and highly precise figures and complex calculation methods that are used for technical specifications and code compliance. This lack of data literacy hinders adoption by companies where resources are limited, such as time, budget and liability.

6. Inappropriate data tools. The Karbon tool was conceived as a generic carbon impact visualization platform, for which purpose BIM models were too detailed and specific to be adopted. The integration with BIM in the form of a plug-in demanded model simplifications and programming hacks that were too complicated to be a part of the pilot Karbon project. PowerBI as a data visualization tool was an alternative to produce an interface with the architect's visual language, however, the more visual graphics and images, the heavier the navigation, limiting robustness and adoption of this tool.

7. Management support. The managerial factor was assessed during observations within the office experience, where the BIM Manager and Managing Director allocated time and budget for the design team to develop BIM skills though workshops and Karbon. With this, much interest was shown by employees in supporting this effort, proving management support to be an important factor to stimulate experimentation within the design practice.

8. Design education and training. Developing the Karbon tool demanded exploration with several skills that push the architect's education and training to the boundary of data-sciences and software development, for example, for compatibilizing the carbon factor values given in different units (KgCO2 equivalent to linear meter, square meter, cubic meter or weight in kilos). Another example is the use of coding and programming languages to produce interactive dashboard utilizing the software Microsoft PowerBI.

9. Design methods and workflow. PowerBI pre-set conduced a linear navigation, whereas designers operated according to non-linear, reiterative workflow [15]. In the validation of the Karbon tool, this research observed how the users experienced the navigation and functionality of the tool, and afterwards collect their feedback. While most of them stated the tool was intuitive to use, 4 out of 6 designers experienced it as inconclusive because it lacked loops in the navigation to better suit their workflow.

DISCUSSION

After analysing the finding from this research, it is possible to bring the equivalent topics for discussion:

1. Data inclusiveness. It was found that the cost factor limits access to data and tools. This paywall hinders especially medium to small size offices that would equally benefit from integrating carbon data for design-decision making.

2. Regulatory framework review. The building permitting and MPG process is debatable because it does not encompass building renovations or complementary program to dwellings (schools, health, retail). There is a forecast for population growth in the Netherlands creating a demand of 50000 new homes to be built only in Rotterdam by 2040 [16, 17]. This indicates that urban densification strategies are to create an intense burden in terms of CO2 emissions in the construction sector, although this type of intervention on the built environment does not need to comply with the MPG

3. Broadening material databases. Narrow databases set designers to make carbon assumptions for non-listed materials. Such assumption lowers the precision of the estimations of this carbon tool, but are deemed acceptable at early design phases (low-precision demand), as long as represented transparently on the documentation.

4. Simplified data. In early design phases, overly precise LCA data is not a necessary condition for understanding and representing general benefits of choosing materials by the "reduce, reuse, recycle" practice of sustainable design. The understanding that designers seek at early design stages, when most design variables are fluid [9], was of the precision of "rules of thumb". This highlights that, depending on the design limitations, the design phase and the purpose of the study, "rough is good enough".

5. Data and Design communication. Designers seem to lack the data-science expertise and training needed to simplify data with a level of certainty that can be later on validated by LCA experts. LCA experts seem to lack the design expertise to communicate carbon assessment in a simple and visual manner that non-experts can understand.

6. Simplified tools. Considering the time, budget and expertise limitations of the context of a medium-sized professional Architecture practice, it is extremely unlikely to explore the integration with BIM software such as Revit, at the extent of the creation of a plug-in or add-on. There lacks a unified platform that allows the designer to assess and graphically visualize carbon in different design phases, specifically concept design. Such platform needs to enable seamless switch between simple/rough information and detailed/precise information both about the model and the carbon values assessed. This desired platform also enables the reporting/exporting of various design iterations for scenario comparison.

7. Management push. The managerial push towards carbon design is crucial to spark interest in adopting carbon design workflow. This support is seen as a first step towards a more carbon-conscious practice.

8. Data-supported Design education and training. There needs to be a review of the curriculum of higher education institutions, to incorporate this relevant training in the formation of new architects. This also applies to updating and upgrading training offer for professionals that are have already graduated but wish to integrate data-supported methods in practice.

FACTORS AFFECTING CARBON DATA INTEGRATION IN THE DESIGN PROCESS

EXTERNAL	TECHNOLOGICAL	ORGANIZATIONAL
limited access to data and tools to handle data	**lack of consistency and complexity of data**	**management support**
debatable regulatory framework	**lack of data literacy**	**design education and training**
narrowness of available database	**inappropriate data tools**	**design methods and workflow**

Table of Conclusions, categorizing the external, technological and organizational factors affecting carbon data integration in the design process.

9. Design methods and workflow. Data-visualization tools compatible with the designers non-linear workflow.

Other topics that are also relevant to discuss, but were not explored in this paper regard the scale of projects that transcend the building scale, into more urban scale. Most scientific and practical studies about embodied carbon are done in building scale. In the urban scale, other elements also play a significant role in the embodied carbon impact of a development, such as infrastructure, distance to city centre and transportation. Such consideration at the urban scale unleashes several other topics related to using LCA data for sustainable development design. This calls for further research over, for instance, the geospatial aspects of carbon data.

CONCLUSION

This investigation encountered carbon design bottlenecks regarding : **External challenges**: 1. limited access to data and tools to handle data; 2. debatable regulatory framework; 3. narrowness of available database; **Technological challenges**: 4. lack of consistency and complexity of data; 5. lack of data literacy; and 6. inappropriate data tools; **Organizational challenges**: 7. management support for internal adoption of carbon-based decision making; 8. design education and training; 9. design methods and workflow.

By providing a taxonomy of such challenges encountered in the case of a professional architecture office, we could better discuss the needs to enhance the collaboration between designers, data providers and software developers. While this investigation has taken place by developing a digital tool for assessing embodied carbon data in architecture design, the findings can be extrapolated to the integration of other types of data in the designer's workflow. These are widely and openly available and can offer designers the context to iteratively improve their designs by evaluating their impact on numerous other aspects such as energy, noise, heat stress, day light etc. Such data is often much more complicated than the carbon data as explored in this research, highlighting the relevance in bridging the gap between data experts and designers.

This study presents a relevant reference of how practitioners can adopt design methods supported by Life Cycle Assessment (LCA) values at concept design. The insight brought up by this research, within its, are valuable to reveal challenges that need to be overcame in order to achieve the national ambitions towards sustainable development. It highlights that the permitting processes evaluating environmental performance of buildings and the use of BIM model are important, but also need to be taken as "facilitators" of sustainable design. Designing with carbon data and other environmental data should not be an exclusive skill of LCA experts, but of any architect, and in the earliest design phases.

ENDNOTES

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