

Design Strategies for Timber Construction in the Netherlands: A ‘Transparent Guide’ to Maximise Carbon Storage and Minimise Embodied Energy.

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ABSTRACT

This research examines the complexities of assessing environmental performance in the context of building design, focusing on the balance between CO₂ sequestration and embodied energy. Central to this study is the development of a model designed to maximize carbon uptake and minimize the embodied energy of buildings. Key results include the identification of critical parameters, such as the extension of a building's lifespan and its relationship with environmental impact, as well as the crucial balance between CO₂ and embodied energy. The model emphasizes the importance of these parameters, with particular attention to the lack of data on life cycle energy and its impact on carbon accounting. The methodology involves the identification and critical evaluation of these parameters, and Dutch databases, such as the Nationale Milieu Database (NMD) and calculation methods like the MPG, transforming them into a model for practical application within the design process. This study concludes that extending a building's lifespan plays a significant role in reducing its carbon footprint over time, and that transparent, standardized methodologies and comprehensive data collection are essential to optimize the environmental impact of building designs.

Keywords: Carbon Storage, Embodied Energy, Environmental Impact, Guide, Model, Timber.

Preface

This thesis represents the culmination of a challenging and rewarding academic journey. My interest in sustainable building practices began during my undergraduate studies, where I became deeply inspired by materials. Natural materials captured my interest due to their texture and tactile qualities. A natural material conveys a sense of time and experience, whereas a plain white wall offers little in terms of engagement or temporal expression. Following a brief study of materials, I sought to further develop my understanding and delve deeper into designing with ecologically responsible materials. However, it quickly became apparent that the knowledge and data regarding ecological materials were fragmented and lacked coherence. Through an extensive research effort in collaboration with Wouter Brugman, we aimed to establish an accurate assessment of ecological materials. During this process, all available environmentally responsible materials were compiled and treated as puzzle pieces in the design of an ecological floating home. This research was awarded the Jury Prize in the 2021 Bouw&Infra Awards.

This research has led me to question whether the existing assessment methodologies are accurate and transparent. My doubts arose particularly from observing near-perfect scores for buildings where significant improvements were still possible. Additionally, a separate study on climate challenges and flooding provided insight into the clear increase in weather-related impacts, further supported by an understanding of planetary boundaries.

I am deeply grateful to my supervisors, Ir. G. (Gilbert) Koskamp and Ir. L. (Loes) Thijssen, for their invaluable guidance and constructive feedback. Special thanks also to Jeroen Verberne, Gert-Jan Nabuurs, Arjan van Timmeren, Sacha Brons and Willem van Genugten for their time and many of their insights.

Overall, with this research, I aim to provide clarity for myself and for designers in the assessment of buildings. Furthermore, I hope to inspire a mindset, focused on designing buildings that achieve optimal carbon sequestration and minimal embodied energy, with the ultimate purpose of reducing environmental impact and combating climate change.

Stan van Etten

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1. Introduction

In the contemporary era, there seems to be a growing awareness of the importance of treating nature and energy in an appropriate manner. This line of thinking also extends to the Dutch construction sector, where the primary focus is on carbon uptake and embodied energy. A report by the 'Global Alliance for Buildings and Construction' indicates that the construction sector is responsible for approximately 37% of global emissions, with 11% of this figure attributable to material use (Construction, 2023). Of the 9.020 million tonnes of building materials required in Europe, 3.4% are supplied to the Dutch market (Haisma, 2023). Consequently, wood construction can occupy a crucial position within this sector due to its ability to absorb carbon.

Nevertheless, as a consequence of this awareness, an increasing number of newly developed construction methodologies, models and measurement data are becoming available, which should facilitate the industry's ability to make informed decisions regarding the selection of materials and designs. In practice, the vast quantity of new information, among other factors, frequently demonstrates that the construction industry is not being guided in the optimal direction (Brugman and Van Etten, 2021). The comprehensive models, including the EPD, LCA, MKI, MPG when considered alongside databases such as the NMD and Ecoinvent, certifications such as BREEAM and BENG, in addition to the NEN standards and selected manuals, do not facilitate the understanding of design choices, despite their stated intentment to do so.

1.1 Problem statement

In the Netherlands, there is a growing interest in timber construction and CO₂-negative building. However, architects, contractors and other building professionals are experiencing difficulties in comprehending and implementing the numerous and complex rules and systems, which frequently results in the suboptimal capture of CO₂ and the insufficient minimisation of embodied energy. This is, at least in part, attributable to a lack of knowledge and experience. Despite the growing availability of information on sustainable timber construction, many architects and contractors lack the practical experience necessary to fully utilise the specific techniques and design strategies that can minimise CO₂ emissions and embodied energy. Conventional construction techniques, such as those involving concrete and steel, are frequently deeply rooted in the industry, and therefore the transition to building with wood requires a reassessment of familiar design processes and techniques (Brugman and Van Etten, 2021).

Furthermore, there is a lack of familiarity with the tools and calculation methods involved. Specific

calculation tools, such as LCA (Life Cycle Assessment) and MKI (Environmental Cost Indicator), require a certain degree of specialised knowledge. As a result, some architects and contractors struggle to make informed choices to reduce the environmental impact of their projects. In order to attain certification such as BREEAM, it is necessary to have a comprehensive understanding of sustainability and the selection of appropriate materials. For smaller companies, the complexities and costs involved may appear discouraging, particularly regarding integrating timber construction into their projects.

In the course of this transition, certain testing methods and certifications have been the subject of criticism. The models that are made available are frequently incomplete or require modification to provide an accurate assessment of the sustainable nature of wood (Heuvel, 2024). In this way, the lack of clarity and incomplete calculation methodologies do not always facilitate optimal design choices for the construction industry.

The Minervahaven in Amsterdam provides an illustrative example of the aforementioned issues. A considerable number of these building structures have been completed within the last five years. However, many of these structures are composed of concrete and steel. It is plausible that if architects and contractors were better supported in the application of timber construction techniques and the use of clarified sustainability calculations, there would have been a higher proportion of timber buildings than have been constructed to date.

1.2 Objective of this study

The aim of the research will mainly focus on funnelling and simplifying key metrics (LCA, MKI, MPG) and strategies, to better understand the outcomes of CO₂ uptake and minimum embodied energy prior to a construction project. *"Early engagement between the architect and the timber panel fabricator is crucial to streamline and optimise the design process and to secure the fabrication time window to meet the project construction schedule"* (Lehmann, 2023). The systematic collection and examination of hybrid data may serve as an effective approach to the adoption of optimal design strategies, aligned with established norms governing test models, databases, and certifications. This process can facilitate enhanced CO₂ capture, ensuring a transparent and structured methodology.

Main question

"How can design decisions for timber construction in the Netherlands be optimised into a guide for maximum carbon uptake and minimum embodied energy?"

Sub questions

1. Which existing data models and design strategies for timber construction contribute to CO₂ uptake and embodied energy reduction?
 2. How can these data models and design strategies be filtered and ordered to understandable parameters for a timber project?
 3. How can these parameters for optimal CO₂-uptake and minimum embodied energy in timber construction be integrated into a clear and transparent manual?
-

This study will focus on filtering appropriate construction strategies and measurement methods to clarify design strategies for timber construction in the Netherlands. The aim is to produce a transparent and understandable guide using specific parameters, which will enable professionals to understand how to optimise CO₂ uptake while reducing the embodied energy of projects in advance.

1.3 Relevance and Contribution

In the year 2024, a wide range of studies have been conducted on the environmental impact of timber construction in comparison to traditional building materials such as concrete and steel. The majority of these studies indicate that the construction of buildings with wood has a significant positive impact on the uptake of CO₂. Indeed, research conducted in 2020 estimated that substituting conventional construction materials with wood in half of new urban construction could achieve 9% of the global emissions reduction necessary to meet the 2030 targets to limit global warming to below 1.5 degrees Celsius (Himes, 2020). However, the majority of these studies focus on merely naming comparative results, showcasing life-cycle assessment calculations. Consequently, these studies do not provide adequate guidance to designers, thereby lacking a solution for how to achieve optimal results. Nevertheless, a synthesis formed by combining these studies may serve as the basis for a comprehensive sustainable design manual.

This overview allows for quicker and better decision-making, allowing professionals to be engaged at an early stage to comprehend, in advance, factors such as construction costs and construction methods. In light of the current housing deficit in the Netherlands, estimated at 401,000 homes, and the planned construction of additional housing units, the optimisation, widening of knowledge and clarification of systems and materials will facilitate the attainment of the Paris climate targets (Ordering, 2024). An optimisation of timber housing, as an

alternative to traditional building materials such as concrete and steel used at the Minervahaven buildings in Amsterdam, would facilitate the Netherlands' progress towards achieving the global warming limit to a maximum of 1.5 degrees Celsius.

1.4 Approach and limitation

The research methodology focuses on narrowing down and pinpointing the vast array of design parameters. By critically engaging with datasets, calculation methods, and the development of design strategies in collaboration with experts, the design process in P3 can be effectively guided. The research method involves identifying parameters, critically evaluating them, converting them into a model, and testing them within the design process.

Although the model is developed based on numerous parameters explored with experts, it cannot incorporate all available information. Including too much data would render the model overly complex, diminishing its usability, as seen in other methodologies. Not all ancillary information that impacts the final outcome was included during the research period. Furthermore, each designer has their own approach and uses different methods, leading to varied experiences with the model. Nonetheless, the model serves as a supportive tool that highlights the key aspects, offering a clear framework for design.

1.5 Short recap

The Dutch construction sector is increasingly focused on reducing CO₂ emissions and embodied energy, with wood construction seen as a key strategy for carbon uptake. However, despite a growing body of information, architects and contractors face challenges in navigating complex guidelines, certifications, and environmental calculations (such as LCA, MKI, MPG). This can hinder optimal material and design choices for sustainable building. The goal of this research is to simplify these metrics and create a clear guide to support informed decisions in timber construction. Ultimately, this resource aims to boost carbon building practices and contribute to climate goals by enabling better understanding of CO₂ uptake and embodied energy impacts in construction projects.

2. Methods

This research encompasses a broad range of housing types and seeks a general approach to CO₂ efficiency in relation to embodied energy. The topics and research methods outlined below required an in-depth exploration of existing material assessment methodologies, approached primarily through expert knowledge and scientific literature. A comprehensive theoretical source analysis and expert discussions have led to a critical examination of current material assessment methodologies. Given the wide array of emerging methodologies, ongoing data improvements, and continuous subjective developments, the research is positioned at a sensitive juncture.

Subsequently, the parameters associated with the building type in question will be examined, with a view to identifying those that potentially exert the greatest influence. In accordance with the municipal vision of a high-density housing development, this building type will comprise apartments.

2.1 Identifying parameters

This study aimed to identify parameters that, when combined through a model, could provide insights into an improved design process with higher carbon sequestration and lower embodied energy. Initial steps involved investigating how CO₂ is stored and how the atmosphere interacts with carbon emissions. This phase examined the impact on biomass, such as tree removal. Insights into tree growth cycles and sustainable forest management were gained through discussions with Gert-Jan Nabuurs, an expert in sustainable forest ecosystems.

Additionally, collaboration with experts like Sacha Brons and Jeroen Verberne focused on accurately defining carbon and the role of other gases in timber construction. Following this clarification of carbon dynamics in the atmosphere, the relationship between CO₂ and embodied energy was explored. This connection allows for the integration of disparate figures, enabling a more comprehensive evaluation of their significance.

Subsequently, a critical examination of current Dutch assessment methodologies, such as EPDs, LCAs, and their calculation methods, was conducted. By broadly analyzing their functionality and underlying data, numerous critiques were identified concerning the Nationale Milieu Database (NMD). The research delved into the functional use, transparency, accuracy of calculations, and the validity of provided data. Emerging initiatives, such as "Het Nieuwe Normaal," were also investigated, linking previous research on the ecological value of buildings. These new transparent insights contribute to a clearer understanding of material assessment compared to standardized methods.

2.2 Controversial discussion

By engaging in discussions with multiple experts who possess knowledge in various facets, the comprehensiveness of the parameters was expanded and largely covered within the scope of the research. This approach allowed for a multifaceted examination of the subject, identifying what aspects are, or are not, worthy of further investigation. A significant portion of these discussions led to critiques, which are ultimately presented in the chapter [discussion](#). These critiques impact both the methodologies examined and address the sensitivity and complexity of the research itself.

2.3 Putting parameters into use (model)

Then, together with experts, the parameters were filtered and completed into only the most important parameters that influence environmental impact and together form a coherent and accessible manual. During the design phase, the manual will be subjected to a case study analysis. Ultimately, it is essential that architects, contractors and other professionals involved in the construction industry are able to gain an overview of the impact of specific choices made for a given project in terms of CO₂ uptake and embodied energy. Through a process of human review, these choices are converted into project-specific parameters. To illustrate, by making design choices at an early stage as an architect, the stakeholders involved can be engaged in advance to facilitate the transfer of information or design options within a project and optimise them.

The design of phase P3 will be initiated by utilising the manual developed in P2 as a reference point. A trial phase in P3 will facilitate the gathering of data regarding the manual's usability, thereby enabling the identification of potential areas for enhancement.

2.4 Extension of materials and building systems

Due to the relatively short duration of the research, the investigation into materials and construction systems will continue in phase P3. By focusing on materials and construction systems that align with the design strategy of the model, information can be gathered within a defined scope. This approach enables a structured assessment of the environmental impacts of materials and construction systems, minimizing time loss. This inventory process runs concurrently with a design project in Amsterdam's Minervahaven, where office buildings are being extended with timber construction.

2.5 Status Quote

This research aims to identify the shortcomings of current datasets and design methodologies. These datasets are currently incomplete and lack clarity,

hindering designers from making informed decisions. By emphasizing missing and non-transparent data, such as carbon storage and emissions, as well as the embodied energy of materials, the research seeks to enhance design insights over time. Additionally, it is crucial that this study provides a critical analysis of the LCA, NMD, and MPG, helping designers understand how to navigate design parameters independently of an opaque and unmanageable system focused solely on achieving the highest scores.

The goal of this research is to simplify these metrics and create a clear guide to support informed decisions in timber construction. Ultimately, this resource aims to boost carbon building practices and contribute to climate goals by enabling better understanding of CO₂ uptake and embodied energy impacts in construction projects.

3. Parameters of environmental impact

3.1 The basic functioning of stored carbon

Current calculation methods discuss different types of carbon terminologies. A key term in this research is 'stored carbon', which refers to carbon absorbed by plants and trees through photosynthesis and stored in the biomass of the plant or tree. This stored carbon is not permanently sequestered; it can be released back into the atmosphere through combustion (a significant part of the current end-of-life stage), decay by bacteria or fungi, or consumption by insects (Buchanan and Levine, 1999). Stored carbon is therefore a temporary solution that can be prolonged by extending the life of a building. The urgency of storing carbon for an extended period of time is therefore significant.

3.2 Negative CO₂-balance

A key concept for understanding the CO₂-cycle is the distinction between biogenic carbon¹ and fossil carbon². The current industry, which relies on burning fossil-stored carbon, is adding an excess of carbon to the biosphere-atmosphere that exceeds the processing capacity of existing biomass (Fig.1). Balancing atmospheric carbon can only be achieved through replanting and regeneration at a rate equal to or greater than the removal of biomass (Buchanan and Levine, 1999).

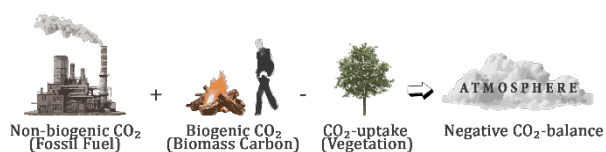


Fig. 1. Process resulting in negative CO₂-balance.

¹ Organic carbon produced by living organisms, such as humans or animals, through respiration or the combustion of biomass.

3.3 The impact of biomass removal in forests

The removal of trees results in a temporary reduction in carbon uptake, known as Carbon Debt. However, according to an FSC representative, CO₂-storage in an FSC-certified forest remains neutral over a 25–30-year period due to sufficient replanting. Although tree harvesting reduces carbon uptake initially, the long-term balance is maintained through adequate reforestation. According to SGS Search (2024), there is a negative Carbon Debt at the micro level at the time of harvesting, but not at the macro or forest level due to replanting (Kanselaar et al., 2022). A forest can only sell FSC-certified wood if it meets these carbon requirements, ensuring that sustainable forest management provides reliable guarantees of carbon sequestration.

3.4 The Concept of CO₂-Equivalent in Timber Construction

CO₂-equivalents are frequently discussed. While the carbon uptake of a building is often measured in kilograms, CO₂e or CO₂eq is sometimes used. This metric includes not only greenhouse gas emissions like carbon dioxide (~76%), but also nitrous oxide (N₂O, ~6%), methane (CH₄, ~16%), and fluorinated gases (F-gases, ~2%), the dominant air pollutants from construction stage fossil fuel combustion (Sandanayake, et al., 2018; Environmental Protection Agency, 2014). CO₂-eq, the unit for measuring the warming effect of greenhouse gases, is expressed in the Global Warming Potential (GWP) by converting other gases to their CO₂-equivalent (CO₂-equivalent, 2024). CO₂ has a GWP of 1 over a 100-year reference period, meaning 1 kg of CO₂ equals 1 kg of CO₂eq. Other greenhouse gases have higher GWP values, meaning smaller amounts contribute more to eq. For example:

- Methane (CH₄): GWP of about 25, so 1 kg CH₄ equals 25 kg CO₂eq (CO₂-equivalent, 2024).
- Nitrous oxide (N₂O): GWP of about 298, so 1 kg N₂O equals 298 kg CO₂eq (CO₂-equivalent, 2024).

In a dialogue with Sacha Brons (2024) of ClimateCleanup, it was noted that calculating additional greenhouse gases using the GWP metric provides greater accuracy, especially given the significant impact of certain gases (Brons, 2024). Sustainable building standards like BREEAM and MPG in the Netherlands use CO₂eq, as it aligns with methodologies such as Life Cycle Assessment (LCA). However, in timber construction, emissions of methane and nitrous oxide are minimal compared to

² Fossil fuels contain stored carbon that was sequestered underground millions of years ago.

concrete or steel (Sandanyake, et al., 2018). Sustainable forest management aims to reduce these emissions, which primarily occur during biomass combustion or under anaerobic conditions. Proper waste management of wood by-products is therefore essential to prevent such emissions (Sanna, 2018).

3.5 Correlation of Life Cycle Energy and Whole Life Carbon with LCA.

The energy required for extracting, producing, transporting, and processing building materials contributes to the CO₂-emissions of a project. For instance, the use of fossil fuels for material production increases embodied energy (EE) and associated greenhouse gas emissions. Therefore, selecting materials and construction systems that maximise carbon storage while minimising energy demand is crucial (Azari and Abbasabadi, 2018).

EE is closely linked to carbon emissions. Higher EE typically results in greater carbon emissions, depending on the energy source used during the pre-use phase. The accompanying diagram compares this with the LCA discussed in (Fig 2). The construction phase (initial EE), maintenance phase (recurrent EE), and demolition phase (demolition EE) together form the total embodied energy. The CO₂-emissions from these phases are called Embodied Carbon, corresponding to phases A, B1-B5, C, and D of the LCA. Material choices at these stages have a significant

impact on both EE and carbon emissions, as well as influencing a building's operational energy.

Operational Energy (OE) refers to the energy used for heating, cooling, lighting, and operating a building (Azari and Abbasabadi, 2018). This energy can be reduced through design strategies such as natural ventilation and advanced insulation. Modern systems can also contribute to a negative OE, potentially making Operational Carbon negligible in contemporary buildings. However, reducing the use of technical systems remains important for lowering Embodied Energy (EE).

Table 1 shows that initial embodied energy (EE) is various from operational energy (OE) in 50 years. It illustrates that wooden window frames have a lower EE but higher OE over a 50-year period compared to PVC frames. Table 2 demonstrates that in buildings with a long lifespan, operational energy typically has a much greater impact than the embodied energy of materials. It is noticeable that standard (st) housing in all categories - apartment (A), semi-detached (SD) and detached (D) - has a higher operational energy than new (new) or advanced new (anew) housing. This is due to the improved insulation values of new buildings. It is also evident that embodied energy is only a small part of the total energy use in MJ/(m²*a), with this EE being higher in new buildings (Koezjakov et al., 2018). This is related to the 'modern' choice of

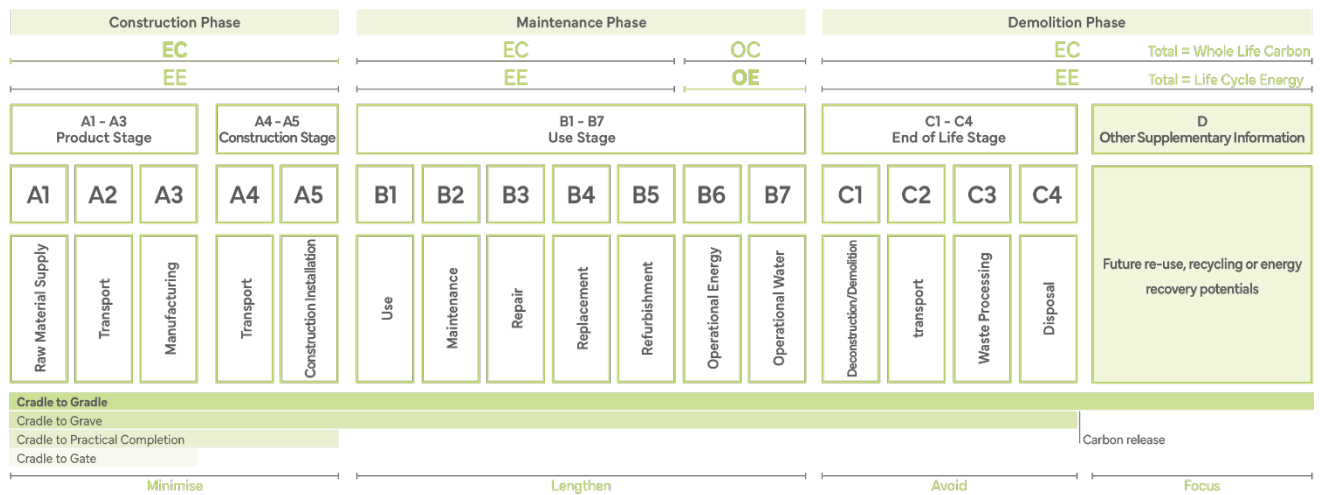


Fig. 2. The LCA in relation to Life Cycle Energy and Whole Life Carbon.

Table 1

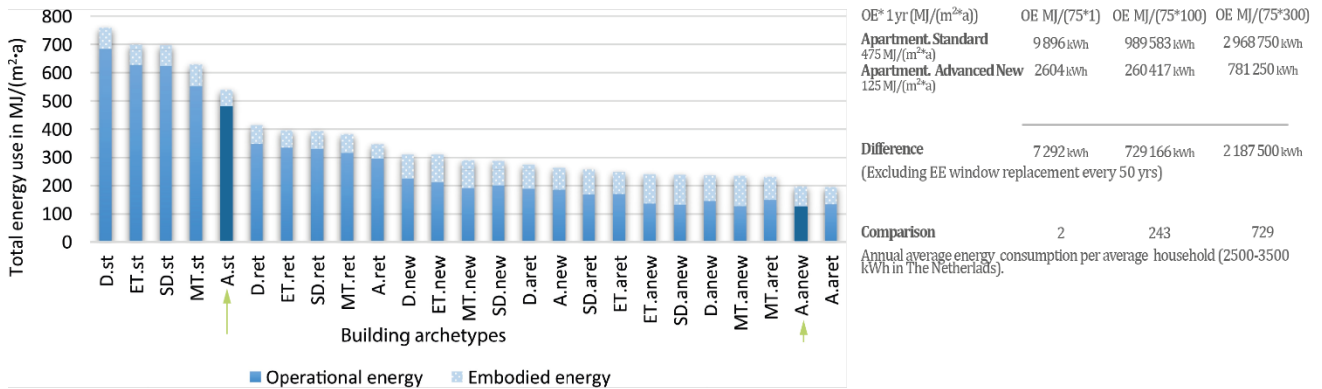
Cradle-to-grave embodied energy and 50-yr operational energy performance of different window systems (Azari and Abbasabadi, 2018).

| Frame Material | Glazing Recycled content | Conductivity of window (W/m2/ °C) | EE of window (kWh) | OE* 50 yrs (kWh) |
|--------------------------------|--------------------------|-----------------------------------|--------------------|------------------|
| PVC | 0 | double 0.65 | 352.6 | 1427.4 |
| PVC | 30% | double 0.65 | 312.6 | 1427.4 |
| Aluminum without thermal break | 0 | double 0.89 | 2218.5 | 2194.5 |
| Aluminum without thermal break | 30% | double 0.89 | 1643.5 | 2194.5 |
| Aluminum with thermal break | 0 | double 0.77 | 2219 | 1600 |
| Aluminum with thermal break | 30% | double 0.77 | 1644 | 1600 |
| wood | - | double 0.68 | 138.2 | 1906.8 |
| wood | - | single 1.14 | 84.1 | 2548.9 |

*Assumes zero heat transfer through building envelope (wall, etc.).

Table 2

Specific annual total energy use in MJ/(m²·a) in the residential building archetypes in the Netherlands divided in operational and embodied energy use. (MT: midterrace, SD: semi-detached, ET: end-of-terrace, D: detached, st: standard, ret: retrofit, anew: advance new, aret: advance retrofit) (Koezjakov et al., 2018).



materials compared to standard (st) houses. Standard houses are not insulated and use wooden window frames instead of aluminium, which reduces the embodied energy. However, over a longer period of time it is not beneficial to the total life cycle energy.

The building envelope (floors, walls, roof, and finishes) contributes 48-50% of the embodied energy in a standard house, due to key components such as thermal insulation and window systems. Using high-quality insulation significantly reduces operational energy. While increasing glazing can improve thermal resistance, it also increases embodied energy. Over time, OE will outweigh EE and yield benefits. Azari and Abbasabadi (2018) conclude that, while operational energy is more important in the long term, the embodied energy of key materials should not be overlooked, as it is likely to constitute a larger share of total carbon in a low-carbon building.

A key conclusion is that, with accurate data on the EE of a material or product and OE over 50 reference years, the environmental impact of design choices can be assessed. However, both older, newer and existing studies on EE reveal inconsistent and poorly reported methodologies, problems with data generalisability, geographical variability and limited reproducibility, still resulting in insufficient clarity in measurement (Dixit et al., 2012; Wolf, et al., 2017). Standardising and making this data universally available for different climates would aid in optimising buildings and their energy consumption. This could provide insights into the optimal balance between CO₂-storage, required energy and insulation values (or thickness).

Nonetheless, existing studies outline a clear trend showing the increasing importance of EE relative to OE in the energy use of buildings throughout their lifecycle (Fig. 3) (Azari & Abbasabadi, 2018).

4. Understanding the assessment of the Dutch MPG of buildings.

The Milieu Prestatie Gebouwen (MPG) evaluates a building's environmental performance throughout its lifecycle, using data from Life Cycle Assessments (LCA) and Environmental Product Declarations (EPD) to quantify the impact of materials and products. This assessment method requires extensive expertise and necessitates clarity regarding the relationship between LCA, EPD, and MKI. Forthcoming, the components of the MPG calculation method are outlined, followed by an analysis of their interconnections and key critiques.

4.1 Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) (Fig. 2) primarily evaluates environmental impacts related to energy, air, water, land, health, and ecology, covering the entire lifecycle of a material or building, from raw material extraction to production, transport, use, and end-of-life stage (recycling or waste disposal). However, design choices must consider additional factors.

The complexity of LCA calculations requires substantial data and expertise, but data gaps often lead to assumptions or generic data, reducing accuracy (Verberne, 2024). From January 2025, the A1 set of 11 indicators expanded to 19, incorporating the new European standard (EN15804+A2). A key change is the division of climate change into four sub-indicators: total, fossil, biogenic, and land use change. This requires clear separation of biogenic and fossil carbon emissions and storage, preventing double-counting but complicating interpretation.

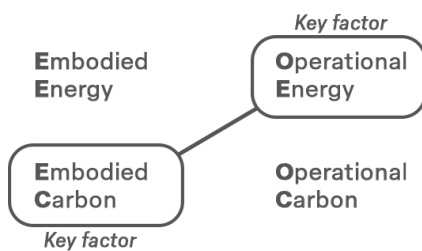


Fig. 3. Greater connection between OE and EC as key factor than EE and OC.

In a conversation with Jeroen Verberne (2024), it became evident that LCAs often fail to address long-term environmental impacts in a comprehensive way. Uncertainties in future scenarios, the complexity of material lifetimes and the low priority given to Category D impacts hinder a full assessment (Verberne, 2024). Arjan van Timmeren (2024) noted that materials such as concrete and steel can be favourably presented by including scenarios in category D for potential future reuse, despite their high CO₂-eq emissions. However, without the implementation of an official recycling or reuse policy, these scenarios should not be included in the LCA. As stated by NMD: “Processing scenarios must align with practice and be well-supported, as outlined in the Calculation Method” (Nationale Milieu Database, 2021). Promoting category D remains challenging due to limited practical examples.

While LCA remains a valuable tool, it is essential to avoid double counting and to use transparent data. It currently provides the most comprehensive material assessment, with Phase D playing a crucial role in improving environmental performance.

4.2 Environmental Product Declaration (EPD)

An Environmental Product Declaration (EPD) is a standardized document quantifying a product's environmental performance across its lifecycle, including data on greenhouse gas emissions, energy use, and water consumption. Based on a Life Cycle Assessment (LCA), EPDs allow comparisons to be made between similar materials in terms of environmental impacts, such as carbon footprint or global warming potential (GWP), and are used by certification schemes such as BREEAM and LEED, although access to these is not free. The EN 15804 standard outlines the collection, reporting and verification of EPD data. The A2 update requires the reporting of environmental impacts for modules C1-C4 (cradle to grave) and module D, including end-of-life scenarios, ensuring a comprehensive life cycle assessment (Circular Ecology, 2025).

Product Category Rules (PCR) guide the creation of EPDs by specifying the methodologies and data requirements for LCAs, ensuring consistency in environmental impact calculations.

4.3 Nationale Milieu Database (NMD)

After independent verification, data are submitted to the National Environmental Database (NMD). There are three categories in the database:

Cat. 1: Verified, product-specific data, owned by manufacturer (score 0.10)

Cat. 2: Verified industry/sector data, owned by industry (score 0.15).

Cat. 3: Unverified, generic data compiled by LCA experts (score 0.30).

Designers achieve better scores by selecting materials from Category 1, as opposed to Categories 2 or 3. This system encourages the use of cat. 1 materials but offers limited clarity on the overall MKI score. Although substantial data is provided, verifying it is challenging. Companies like Madaster MPG Tool, GPR Gebouw, and MPG Calc offer paid services to calculate MPG scores. This while understanding and independently working with this data can be complex, necessitating external expertise.

The NMD's methodology is transparent in terms of calculation but lacks clarity on the reasoning behind the data. This flexibility in interpretation, such as varying assumptions about building lifespan, can lead to discrepancies in scores (Fig. 5). Additionally, the calculation software is proprietary, requiring a license and payment to access MPG results, which limits accessibility and transparency for non-experts. Consequently, the NMD's approach raises concerns about the openness and comprehensibility of material data (Fig. 4).

There is still a significant lack of information. According to Willem van Genugten (2025) of Carbon Lap, the NMD database is significantly incomplete compared to European databases such as One Click LCA. This is due to the NMD's reluctance to integrate environmental data from external sources. For example, German data sources are significantly more accurate but are not permitted for use in the Netherlands. Even for the same manufacturer there are discrepancies between the LCA results of the NMD and the One Click LCA (Genugten, 2025). For instance, a KERTO Rippa wooden hollow-core floor is not yet included in Category 1, although a generic wooden hollow-core floor is listed in Category 3. As a result, constructing a building with comprehensive, brand-specific data remains challenging. It is assumed that preparing an LCA and EPD is time-consuming and costly, which can be a barrier for start-up companies.

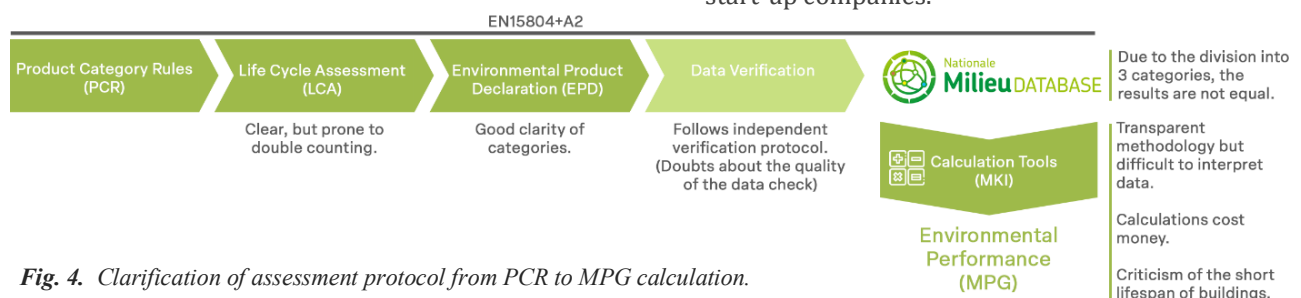


Fig. 4. Clarification of assessment protocol from PCR to MPG calculation.

Module A1-3: Productie

$$M_{A1-3,bw} = \sum_{p,i} Q_{pr} \times M_{A1-3,pr}$$

Waarbij:

$M_{A1-3,bw}$ = milieu-impactscore module A1-3 op bouwwerkniveau (gelijk aan milieu-impactscore Productiefase op bouwwerkniveau)
 l = aantal producten in het bouwwerk (l)
 Q_{pr} = aantal eenheden product in het bouwwerk
 $M_{A1-3,pr}$ = milieu-impactscore module A1-3 per eenheid product

$$MKI_{A1-3,bw} = \sum_{m,k} M_{A1-3,bw} \times W_m$$

Waarbij:

$MKI_{A1-3,bw}$ = MKI module A1-3 op bouwwerkniveau (gelijk aan MKI Productiefase op bouwwerkniveau)
 k = aantal milieu-impactcategorieën (mi)
 $M_{A1-3,bw}$ = milieu-impactscore module A1-3 op bouwwerkniveau
 W_m = weegfactor milieu-impactcategorie

$$MPG_{A1-3} = MKI_{A1-3,bw} / (A_{bvo} \times L_{bw})$$

Waarbij:

MPG_{A1-3} = Milieuprestatie Gebouw Productiefase
 $MKI_{A1-3,bw}$ = MKI Productiefase op bouwwerkniveau
 A_{bvo} = bruto vloeroppervlakte
 L_{bw} = levensduur bouwwerk

Fig. 5. Example of MKI construction per module and phase of EN15804 (3.2.2 Module A1-3: Production) .

4.4 Clash between BENG and MPG

BENG prioritises energy efficiency through high-performance materials, which can increase embodied carbon, negatively impacting MPG scores. Buildings excelling in BENG (low operational energy) may score poorly on MPG due to material impacts, while those with low MPG may underperform in BENG. Smaller buildings are also penalised due to lower floor area ratios, a system some experts justify, though it seems counterintuitive (Korbee, 2022).

In conclusion, the National Environmental Database, with the updated EN15804 + A2 standard, provides the sole foundation for environmental performance assessment. However, significant adjustments are still needed, making the framework increasingly complex. The data remains difficult to interpret within a disorganised information network. Moreover, the MPG fails to genuinely encourage carbon sequestration, as it does little to drive CO₂ reduction.

5. Parameters from a new methodology

5.1 Het Nieuwe Normaal (HNN)

A methodology addressing various definitions of circular construction is *Het Nieuwe Normaal* (HNN). HNN aims to accelerate the transition to a circular economy by operationalising a set of clear indicators. Unlike the MPG, which uses a single total score, HNN evaluates performance based on individual indicators, as "they represent different aspects with different units" (Het Nieuwe Normaal, 2025). This implies separate indicators with individual weightings for a design guide, as outlined in Appendix A.

HNN uses nine indicators that define design standards, indicators, and concepts in clear and manageable 'parameters.' These methodologies align with a previous study on ecological material criteria, compiled with experts such as Willem Böttger, Hajo Schilperoort, Fred van de Burgh, and Jasper Sluis (Brugman and Van Etten, 2021). Therefore, the indicators can be considered as validated.

HNN also uses the Paris Proof Material-Related Emissions protocol, calculating CO₂-eq / m² GFA. This approach is logical, as it incorporates floor area into carbon sequestration or emissions calculations, ensuring smaller homes are not disadvantaged by a less favourable floor-to-wall ratio. Also, reducing living space per person significantly lowers climate impact (Het Nieuwe Normaal, 2025). HNN states that calculating sequestration in buildings is a relatively new field, with methods still under development. For instance, emissions from the harvesting and processing of wood, such as root decay and bark burning, are not always fully accounted for.

In summary, HNN provides clear and valuable insights without overly complex calculations. It relies on the NMD, which Jeroen Verberne (2024) (HNN co-founder) acknowledges as the "only" validated method, though not necessarily the correct one.

6. Results

Various models, such as LCA, EPD, NMD, MPG, and HNN, have been examined for their assessment methodologies. These methodologies were evaluated in relation to the carbon- and embodied energy behaviours of materials. Subsequently, connections were made between the parameters identified in this research, which, in a clear and structured manner, form the foundation for a universal design strategy. (A review of the model will take place on December 17th. In the design phase, P3, the model will be used to implement further improvements.)

6.1 Parameters into one model

The model (Fig. 6) serves as a guide to maximize carbon uptake and minimize the (embodied) energy of a building during the initial design phase. The key parameters are outlined in the model and should each be assessed for their impact on *environmental impact categories*. This model focuses on individual performances of the environmental impact and does not combine these into a single, unified figure.

The current model consists of a selection of design aspects. It is intended merely to provide an early indication of potential environmental impacts during the design phase and to provide an overview of design strategies. The model directs attention to the correct project-specific parameters, allowing the appropriate experts to be engaged early in the process.



Fig. 6. Guide to maximize CO₂-uptake and minimize Embodied Energy

6.2 Usage

The model (Fig. 6) consists of *environmental impact*, *core strategy*, *material & construction system*, and *carbon balance recovery*. The environmental impact focuses on the key parameters around which the whole model revolves. The other categories influence this environmental impact, with some parameters having a greater impact than others. For example, extending the life of a building can have a significant negative impact on embodied energy due to additional protective overhangs and additional material use. However, this may be beneficial in terms of carbon storage, particularly if the overhang contributes to a longer lifespan of the building, and so on. It is up to the user to reason this relationship based on knowledge and expertise. By continually reflecting on each "design decision," or parameter, the user can understand its impact on each environmental performance. Please refer to [Appendix B](#) for the strategy and guidelines for each parameter.

7. Discussion

7.1 Measurement of reuse/recycling processes and carbon sequestration

The carbon storage in buildings is widely recognised as a temporary measure in climate mitigation. "In the short term, CO₂-storage compensates for remaining emissions; in the long term, it helps to remove net CO₂ from the atmosphere" (Het Nieuwe Normaal, 2025). Although the infinite disassembly and reuse of materials is theoretically appealing, it remains largely a vision with limited large-scale practical application in the current construction industry. End-of-life scenarios in life cycle analyses (LCA), under module D, can only be accounted for if it is convincingly demonstrated that the return process or recycling system is operational (Kanselaar, Ewijk, & Casper, 2022). To maximise temporary carbon storage, it is strategically important to retain materials in buildings for long durations. This requires an

integrated approach, where biomass growth is carefully regulated and monitored. Only with such control can it be ensured that enough trees grow over the lifespan of a building to offset the net carbon debt. According to Gert-Jan Nabuurs (2024) from Wageningen University, trees such as poplars and spruces take about 80 years to mature, while oaks may require up to 150 years.

This implies that for every timber construction project, it is crucial to calculate beforehand how many trees are needed to replace the wood used within a predefined lifespan. For example, with a minimum building lifespan of 80 years and the use of poplar wood, the total number of trees cut for construction must be replanted. Therefore, it is essential to quantitatively determine the timber stock in a building to accurately assess how much reforestation is needed to close the loop sustainably. As a matter of fact, building with wood only makes sense if more is replanted than is removed. Figure 7 shows that CO₂ emissions increase if there is no replanting. It is also noticeable that after 60 years, without reuse or recycling (category D), emissions are back to where they started and count for extra embodied carbon (Hawkins et al., 2021). This shows the importance of planting additional biomass.

7.2 Calculation with sawing losses

It is crucial to differentiate between the number of trees used and the actual carbon stored in a building. When conducting LCA of a wooden beam, the sawdust produced in the sawmill is excluded to avoid double counting. However, sawmill losses are often significant and are usually only partially included in the LCA due to the lack of specific and hardly manageable data. A wood waste management study found that '110 million tons of harvested wood biomass are converted into energy every year. This constitutes nearly 69% of already processed wood, with burned wood treated as zero-emission' (Zbiec et al., 2022).

The correct calculation of carbon storage begins once the wooden beam is actually placed in the building, including emissions from transport (modules A2, A4) and production and construction (modules A3, A5). A complicating factor is that when residual wood is processed, much of it is converted into chipboard, insulation and the like. However,

much of the residual wood is burned or converted into wood pellets, releasing biogenic carbon during the combustion of this product. According to a recent study 'The current world trade in wood pellets is estimated at over 30 million tonnes and is increasing at a rate of more than 10% per year' (Lee et al., 2024).

7.3 Short building life span in the LCA

It is important to note that in a significant number of LCA calculations, the lifespan of materials is predefined. For instance, the Nationale Milieu Database estimates the lifespan of a free-span wooden channel floor at 75 years, which is extremely short for such a product. Many old buildings still have beam layers that have been in place for several centuries with lesser quality of construction detailing. Similarly, environmental performance estimates for project examples often assume a 'minimum' building lifespan of 75 years. This timeframe is such that the trees have not yet reached maturity, thereby implying that the design of such buildings may not support long-term CO₂-storage. The relatively short lifetime of 75 years ensures comparability of results within the calculations, but does not encourage the improvement of long term data. Also, while the MPG score accounts for multiple aspects, this overall score does not necessarily optimise long-term CO₂-storage, and the final MPG figure offers little insight into CO₂-storage impact, instead providing a general summary.

7.4 Timber availability through market forces

A key point of discussion is the expansion of the wood construction industry. While there is a slight increase in processing capacity across Europe, a significant proportion of the available wood is still allocated to other uses such as firewood, paper, cardboard, pallets, crates and construction timber (Nabuurs, 2024). In addition, some forests have been affected by disease, making them unsuitable for sustainable timber production (Patacca et al., 2022).

This raises the question of whether the current forestry sector can meet the growing demand for timber construction. The debate on scaling up is directly linked to the need to increase carbon storage in buildings to ensure that timber construction contributes to a more sustainable use of this valuable resource.

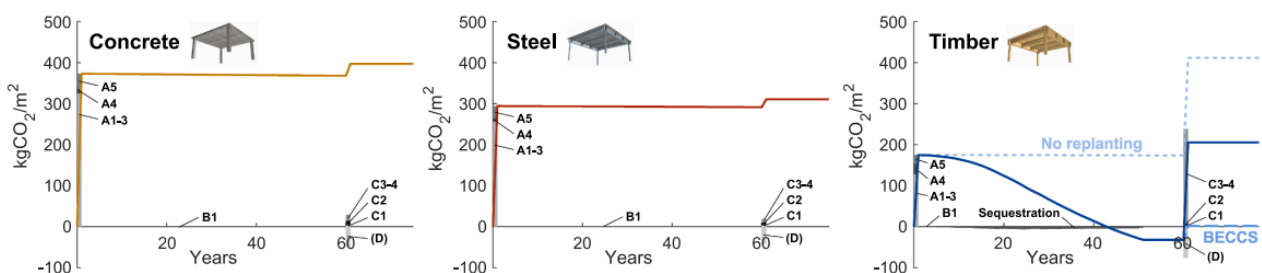


Fig. 7. Cumulative cradle-to-grave CO₂ emissions for equivalent concrete, steel and timber buildings based on designs from a previous study carried out by Buro Happold (Hawkins et al., 2021).

7.5 Credit system to drive the longevity of a building

The use of timber construction offers significant CO₂ reduction benefits by avoiding the emissions associated with concrete and steel. To encourage the long-term use of wood, it is suggested that the long-term benefits of biogenic carbon sequestration in bio-based building materials, which is currently under-utilised, should be taken into account (Oever and Gursel, 2024).

During a presentation by Carbon Story's in Rotterdam, Climate Cleanup highlighted the potential for investing in removing carbon from the atmosphere and stabilising the market through government investment. The current European Emissions Trading System (ETS) already incentivises CO₂ reduction, with upcoming tightening of regulations for industries such as cement and steel expected by 2030, making carbon emissions more costly. In addition, forestry carbon credits can be sold for positive environmental performance (Carbon Stories, 2024).

By sequestering carbon for longer periods, investment in carbon sequestration may increase. Therefore, accurate carbon accounting and proposals to demonstrate and track the long-term carbon storage benefits of buildings need to be developed.

7.6 Limitations of the study

The gap between research and practical implementation often results in a lack of realism. Manufacturers typically specify a lifespan based on warranties, although the actual lifespan could be longer. Similarly, the Nationale Milieu Database (NMD) establishes rules regarding legislation and third-party collaboration. Additionally, clients are often constrained by costs, making the optimization of design principles that benefit environmental impact impractical in most cases. This may contribute to the slow emergence of practical examples. Furthermore, innovation carries inherent risks, and financing a building with an extended lifespan of 300 to 400 years requires a collective effort. This principle is rarely applied as few are willing to bear these costs. Further research is needed to explore how such a collective can be structured to cover these expenses.

The scope of this research examines the existing parameters from current models. Although methodologies and interest in environmentally focused parameters are relatively new, a wealth of information is available for each parameter. However, it is challenging to thoroughly analyse and evaluate this vast amount of knowledge and methodologies within a limited time frame. Consequently, the model incorporates the 'most critical' components to provide insights into CO₂-balanced design. Further research could enhance the

model and eliminate inaccuracies. Additionally, there is still a lack of data, such as embodied energy and operational energy of materials, which currently prevents the full optimization of buildings from being accurately calculated. The assumption that a design achieves the 'optimal balance between CO₂ and EE' will remain relatively subjective.

Conclusion

In conclusion, the assessment of environmental performance in the Dutch context, particularly through tools like the MPG, is complex and often opaque, making it difficult for designers to fully understand and optimize carbon impact. The increasing awareness of the environmental costs of buildings calls for more clarity in the methodology, especially in relation to CO₂ storage and embedded energy. The use of wood as a building material offers significant benefits in terms of CO₂ sequestration, but current assessment systems do not always encourage a long-term perspective on CO₂ reduction.

One clear solution to these challenges is the extension of a building's lifespan, which directly impacts its carbon storage potential. A longer lifespan allows for more time to offset carbon emissions through sequestration, mitigating the carbon created during the construction phase. Tree planting initiatives and the responsible management of biomass are critical in this approach, ensuring that carbon storage can be maximized over the long term.

Incorporating the principle of extending the lifespan into design strategies will not only reduce the immediate carbon footprint but also contribute significantly to sustainable construction. This extended lifespan should be incentivized through mechanisms like carbon credits for timber and material reuse, which would align the industry with long-term environmental goals. Ensuring that these systems are transparent and comprehensible is vital for making informed, impactful design decisions that prioritize both environmental performance and longevity.

Furthermore, the model developed in this research aims to provide deeper insights into design strategies that optimize CO₂ sequestration and minimize embodied energy. However, the lack of accurate and comprehensive data limits the model's ability to deliver its optimal results. It is therefore crucial that the necessary data be systematically and correctly gathered to refine these strategies. The full integration of such a model, alongside transparent methodologies, will significantly enhance the effectiveness of data-driven decision-making and sustainable design practices.

Ultimately, the future of sustainable building design lies in the careful balance between material choice, carbon accounting, and design decisions that prioritize durability and long-term impact. It is

essential that designers, policymakers, and stakeholders focus on the long term and recognize the importance of extending building lifespans. By implementing transparent and standardized methodologies, combined with a focus on data collection and lifespan extension, the construction sector can make a substantial contribution to CO₂ reduction and the transition to a circular economy.




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Appendix A

Methodology HNN: nine separate indicators with individual weightings for a design guide.

Translated from Dutch (Het Nieuwe Normaal, 2025)

| Theme | Clarification | Circular principle |
|---|---|--|
|  <p>Environmental impact Taking care of the environment</p> | <p>The Milieuprestatie Gebouw (MPG) provides insight into the total environmental impact over the entire life cycle of the structure. The MPG is also part of the Besluit Bouwwerken Leefomgeving (Bbl).</p> | Design and build with the lowest possible Milieuprestatie Gebouw (MPG). |
| | <p>Material-related CO₂-emissions provide an insight into the CO₂ impact of the production of building materials and components, including the construction process. This is in line with the DGBC's Paris Proof Protocol.</p> | Design and build with the lowest possible material-related CO₂ emissions . |
| | <p>Material-related CO₂-storage is the amount of CO₂ stored in biobased building materials, which is that is extracted from the atmosphere.</p> | Design and build with the highest possible material-related CO₂-storage . |
|  <p>Material Use Protect material stocks and prevent depletion</p> | <p>The proportion of responsibly sourced materials refers to the total amount of circular material: bio-based, reused or recycled.</p> | Design and build with the highest possible proportion of responsibly sourced materials : bio-based, reused or recycled. |
| | <p>The share of healthy materials addresses the number of materials and building products used in a building that are demonstrably non-toxic.</p> | Design and build with as high a proportion of healthy materials as possible. |
| | <p>Construction waste management provides insight into the extent to which construction waste is avoided and how any waste is reused.</p> | Design and build with as little residual material released during construction as possible. |
|  <p>Value Preservation Protecting existing value towards the future</p> | <p>Adaptive capacity is the degree to which a building can be modified during its lifetime, for example to accommodate new layouts or functions.</p> | Designed and built for maximum adaptive capacity . |
| | <p>Detachability provides insight into the extent to which products, components and materials are mutually detachable.</p> | Design and build with the highest possible detachability . |
| | <p>The re-use potential provides an insight into the extent to which products, components or materials can be expected to be re-used at the end of their useful life.</p> | Design and build with maximum re-use potential . |

Appendix B

Strategy & Guidelines

CAT. 1: ENVIRONMENTAL IMPACT

The first category includes all parameters that assess the carbon, energy and environmental performance of a building. The MPG (Environmental Performance of Buildings) is also included as this calculation is required by Dutch legislation.

CO₂-eq / m² GFA

This unit should ideally be kept as high as possible (higher negative or positive number). It gives an indication of greenhouse gas emissions per square metre of gross floor area and helps to offset excessive material use.

Carbon Storage (Construction Stored Carbon)

This is the total carbon stored in the building, excluding sawing losses. For buildings with an extremely long lifespan (200 years or more), storage is very beneficial. *Core strategies* can be played with that use additional material, but at the same time extend the lifespan.

Whole Life Carbon

This parameter reflects the total carbon used during the building's construction, use and demolition phase. The lower the figure, the better.

Life Cycle Energy

This parameter reflects the total energy (MJ) consumed during the construction, use and demolition phase of the building. The lower the number the better.

Note that operational energy (OE) often has a greater impact than embodied energy (EE).

MPG (Milieu Prestatie Gebouw)

This parameter is mandatory for new office buildings (larger than 100 m²) and new residential buildings. The MPG focuses on the environmental impact of materials.

CAT. 2: Core strategy

This category drives design decisions before, during or after the sketch phase. It is important to think back to the environmental impact at each design decision.

Extend lifespan

Extending the life of a building is one of the key principles. Long-term carbon storage can restore the carbon balance in the atmosphere. The longer the life of a building, the more trees can grow in relative terms.

Some basic principles that need good attention are; fire protection, moisture protection and UV-protection.

For example, consider overhanging or oversizing the structure. These 'add-ons' are only useful in cases of genuine longevity, as they consume extra material. Slight over-dimensioning can be beneficial for unforeseen future situations such as wind forces, earthquakes or re-use potential. It is reasonable to assume that oversizing does not begin until a service life of at least 160 years has been achieved.

The ability to add columns can also increase adaptability, extending the life of the building and equipment.

Insulation +

A high insulation value has a positive effect on the operating energy of a building. This is because it consumes more energy than the initial embodied energy. This also reduces the load on technical installations. Windows can have four or even five panes. Finally, ventilation is also possible through parts of the building that can be opened if the windows become too heavy.

Minimum of building services

Technical installations are already a major factor in the embodied carbon and embodied energy of a building. Installations also require maintenance and replacement. Over an extremely long lifetime, it is more efficient to design with simple design solutions that work with natural influences to also keep OC and OE low.

Some basic principles that apply are; minimal use of mechanical services, natural ventilation, adaptable shading for heating or cooling and water-positive projects. In water-positive projects, buildings (and infrastructure) collect, treat and reuse more water than they use. The aim is to have a positive impact on the local water balance and the environment.

Low m² per occupant

A lower number of square metres per person improves the CO₂-eq/m²GFA. Material and energy are allocated more efficiently to the usable area.

CAT. 3: Material & Building System

This category goes one step further in the design process, but is important to consider beforehand. Choosing a building system or material in advance can say a lot about the design. Early involvement of experts can therefore reduce EE or promote carbon storage.

Material Choice

A very important parameter is the choice of materials or the combination of materials. These have an impact on durability, insulation value, vapour permeability, carbon storage and so on. But also soil depletion, material stocks, recycling, etc. In combination with the *Core Strategy*, the choice of

materials can have an even more efficient effect on environmental impact.

A small-scale materials study will follow in P3.

Ensure that minimal materials are used to avoid unnecessary soil depletion.

HNN clarifies material use (Het Nieuwe Normaal, 2025);

- Design and build with the highest possible proportion of responsibly sourced materials: bio-based, reused or recycled.
- Design and build using as many healthy, non-toxic materials as possible.
- Design and build with as little residual material released during construction as possible.

Building System

The building system, together with the *Core Strategy*, is also more efficient in terms of environmental impact. The choice of building system creates value for the future in terms of possible redevelopment. In addition, the building system obviously affects the quantity and choice of materials. Consider spans and joints.

A small-scale study of building systems will follow in P3.

HNN comments on value retention (Het Nieuwe Normaal, 2025);

- Design and build with maximum adaptability to new layouts or functions.
- Design and build with the highest possible degree of detachability. This applies to large components, but also, for example, to waterproof, vapour-permeable films that can be removed instead of water-repellent wood fibre boards filled with bitumen emulsion.
- Design and build with maximum reuse potential.

CAT. 4: Carbon Balance Recovery

This category shows the insight and reflection on why the previous steps were taken and provides the final contribution to closing and optimising the circle.

Writing Plan D

One of the most important parameters is the writing of Phase D of the LCA. This gives the designer a perspective on the future and ensures that changes are made early in the design phase, for example in the construction system or additional protection. A good starting point is to double the harvesting period of the tree species used. This doubling of time ensures that enough trees can regrow to better restore the atmospheric CO₂-balance. A 75-year life span with an 80-year harvesting period is neither logical nor regenerative. In addition, monitoring and writing a maintenance plan helps to better anticipate future scenarios.

Replanting

One of the main reasons we build circular is to reduce CO₂-emissions. But there is little point in reducing carbon emissions if no trees are planted. Too much fossil carbon is being burned and released into the atmosphere. A big benefit to the CO₂ balance is to offset the carbon debt created by doubling the biomass.

Guide to maximize Carbon Uptake and minimize Embodied Energy

