Faculty of Engineering Technology

Whole Life Carbon Thinking

Data and market analysis of whole life carbon in Dutch thermal insulation renovation projects

MSc. Sustainable Energy Technology Thesis

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Abstract

The building and construction sector has become notorious for its high amount of greenhouse gas emissions. The transition from being emission-heavy to a net-zero built environment is acknowledged as an important step in fighting climate change as a whole. Nonetheless, the choices that market players and other relevant stakeholders continuously make in this context are mainly focused on the so-called operational carbon emissions: the emissions resulting from the use of a building. Emissions resulting from certain materials, processes and technologies used for the construction, renovation and demolition of a building, called embodied carbon emissions, are often overlooked. Meanwhile, embodied carbon can is accounting for an increasing share of a buildings environmental impact over its entire lifetime. Because of this imbalance in focus on operational and embodied carbon, well-intended sustainability measures applied to a building can have negative environmental impacts as compared to leaving the building in its current state, especially when looking at renovations. By finding the economic and strategic value in reducing embodied and operational carbon simultaneously, key stakeholders can be prompted to enhance decision-making in this context, making the built environment truly more sustainable.

With the intend to motivate key stakeholders to reduce embodied as well as operational carbon in their renovation projects, this research sets out to find the market and strategic value of doing so. Specifically, the drivers and barriers for parties in this socio-technical system to acknowledge embodied carbon as a key aspect to sustainable construction are searched for. For this, relevant literature, stakeholders, and (inter)national policies are analyzed. It was found that thermal insulation renovation of dwellings, specifically terraced houses in between two other houses, was a proper starting point to focus on based on the found emission mitigation potential. The most important actors in this field are identified to be investors and developers. Main barriers and drivers for these stakeholders were identified in the context of policies and the market. The indicated barriers include vagueness in policy context and Environmental, Social and Governance (ESG) considerations, higher initial investment costs and the rewarding of reducing operational as opposed to embodied carbon. Drivers are found in future tightening of policies, such as the European Trading System and its overarching European Green Deal, and the increase of monetary value for the real estate, as well as less tangible benefits such as enhanced corporate reputation.

In order to put the findings of this research into practice and make embodied carbon a more accessible matter, an Excel-based tool was developed that provides insights into the actual outcomes of renovations for terraced houses. Interviews were held with investor stakeholders to both shape the results of this research and the design of the tool. First, a regression model was built that is able to predict the annual gas consumption of a dwelling after its renovation. The tool is able to predict both the financial and environmental return on investment on the basis of data widely acknowledged in the Dutch renovation market. A tool validation in the form of two scenario studies was conducted, the results of which prove the necessity of such tools to be available to a wider audience. It is concluded that a shift in focus from operational carbon to both embodied and operational carbon is necessary to guarantee sustainable decision making in renovation projects. Key focus points of further research include concrete policy improvements, acquiring more up-to-date data for the tool, and implementing other sustainability measures in a similar fashion.

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List of Acronyms

BCI	Building Circularity Index
BENG	Bijna Energie Neutrale Gebouwen / Nearly Zero Energy Buildings
BREEAM	Building Research Establishment Environmental Assessment Method
CBS	Centraal Bureau voor de Statistiek / Statistics Netherlands
COSIS	Cost Optimal Sustainable Investment Tool
DGNB	Deutsche Gütesiegel Nachhaltiges Bauen / German Sustainable Building Council
EIB	Economisch Instituut voor de Bouw / Dutch Economic Institute for Construction
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
ETS	Emissions Trading System
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MAE	Mean Average Error
MPG	MilieuPrestatie Gebouwen / Environmental Performance Buildings
MRPI	Milieu Relevante Product Informatie / Environmentally Relevant Product Information
NMD	Nationale Milieu Database / National Environmental Database
PBL	Planbureau voor de Leefomgeving / Netherlands Environmental Assessment Agency
RIVM	Rijksinstituut voor Volksgezondheid en Milieu / National Institute for Public Health and the Environment
RVO	Rijksdienst voor Ondernemend Nederland / Netherlands Enterprise Agency
RQ	Research question
RMSE	Root Mean Squared Error
SGEI	Service of General Economic Interest
SQ	Sub-question
SSM	Stakeholder Salience Model
SVR	Support Vector Regression
WGBC	World Green Building Council

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I Introduction

A. Context

Ever since the Industrial Revolution, unparalleled economic and technological growth was observed globally. While this arguably had a lot of positive influences on society, large amounts of carbon dioxide (CO_2) emissions as a result of this development have triggered the enhanced greenhouse effect. Due to this, climate change has become one of the most urgent global challenges today. A higher average global temperature, crop failure, and a rising sea level are but a mere grasp of effects that have been observed by scientists as a result of climate change [1, 2]. Consequently, to diminish these effects, efforts are being made for limiting the amount of greenhouse gas emissions. An example of this is the Paris Climate Agreement, adopted by a majority of national and international leaders in 2015 with the intent to keep global warming well below 2°C compared to pre-industrial times through numerous emissions mitigation strategies [3].

Emission mitigation strategies play a key role in limiting the negative effects of climate change. To effectively make a difference, they are a necessity in all sectors emitting large amounts of greenhouse gas emissions. Of these sectors, buildings and constructions are said to account for 39% of the global energy-related share of carbon dioxide emissions [4]. Being one of the most emission-heavy sectors of this era, significant improvements can be made in this field in terms of emission mitigation. Within the built environment specifically, Life Cycle Assessments (LCAs) are increasingly being used to assess potential environmental impacts of energy use and materials of a building over its entire life cycle [5]. Within these assessments, two points of focus exist: on the one hand, there is the so-called "operational carbon": the CO_2 equivalents of greenhouse gases released during the use of a building. Current decision makers have been focusing on this part of emissions extensively in the past. On the other hand, there is the "embodied carbon" part, the greenhouse gases released when certain materials, technologies or processes are used for the construction and renovation of a building. This part has been proven to often be overlooked in making the built environment more sustainable and is said to potentially pose a dangerous issue [6]. Due to the imbalance in focus on these two phenomena, informed decisions about making changes to a building as compared to leaving the building untouched cannot be made with regard to environmental impact [7]. Moreover, knowing that embodied carbon accounts for 11% of total emissions worldwide [4], meaningful impact can be achieved when focusing on both embodied and operational carbon in a balanced manner.

To highlight the relevance of embodied carbon in the built environment, multiple efforts have been made to make it more measurable through the use of LCAs in national and international policy. In multiple countries of the European Union, for instance, building renovation passports are being worked on, that require the initiator of a renovation to report on, amongst other environmental issues, equivalent CO_2 emissions [8]. In the Netherlands, the MilieuPrestatie Gebouwen (MPG) indicates the environmental impact of the materials used in a building through applying LCAs, which has been enforced since 2018. It is a mandatory benchmark for every application of an environmental permit for new office buildings bigger than 100 m^2 and newly built houses [9].

B. Problem statement

Embodied carbon in the built environment is such a significant part of total emissions worldwide, that it becomes paramount for the battle against climate change to find a proper balance in reducing both embodied and operational carbon. By means of LCAs and data analyses, the carbon footprint of a building can be determined, and thus the embodied as well as the operational carbon can be quantified, such that the parties building, renovating, and using the building can take it into account and reduce the total environmental costs through its whole life cycle.

That being said, actively reducing this embodied part of greenhouse gas emissions is seen to have quite some obstacles. High capital costs and long payback times, if any, are mentioned to be the cause of this, along with parties having trouble with defining good measurable reduction methods within projects [6, 10]. Additionally, the fear of higher initial costs alone is reported to be the main barrier toward the realization of "greener" buildings [6, 10, 11].

Emissions worldwide need to be cut down to limit accelerated climate change and serious abatement of emissions is possible in the built environment. Therefore, the need for parties to actively keep track of their embodied carbon and reduce it where possible becomes imperatively clear. Currently, only a limited amount of organizations are doing this while the techniques for quantifying and reducing it are already available. Hence, a contradictory situation arises in which organizations are able to quantify and thus reduce embodied carbon in building projects but are choosing not to participate in this endeavour as explained by the aforementioned reasons. One of the possible explanations for this, is that those organizations see too little value in reducing embodied carbon to actually do it. Like Hahn et al. explain on the topic of paradoxical corporate sustainability, *"...contributions to sustainable development will be limited to those sustainability aspects that promise to result in positive effects on the economic performance or the market position of the firm within a comprehensible timeframe."* [12, p. 239]. Accordingly, economic and strategic value in reducing embodied and operational carbon simultaneously needs to be found for the market regime and its fellow participants to make it a more acknowledged and dealt with issue.

1) Research objectives

As mentioned above, a balanced reduction of embodied and operational carbon in the built environment is expected to significantly help in mitigating climate change worldwide. In order to achieve this, aside from developing technologies that help with gaining insight into this, market players are to be prompted to use these technologies and consequently reduce their own carbon footprint. With a focus on both the technical and social aspects of emissions in the built environment, this study seeks to meet two key research objectives:

- To identify what could drive market players to reduce embodied carbon in their renovation projects;
- To develop a tool that stimulates said market players to reduce embodied carbon in their renovation projects.

In order to effectively meet these objectives, research boundaries should be defined. Tackling emissions from renovations is hypothesized to be an effective first step in reducing overall emissions in the built environment. That is why the focus of this research will be specifically on renovation projects. To ensure the availability of applicable data to the researcher, the used data will specifically

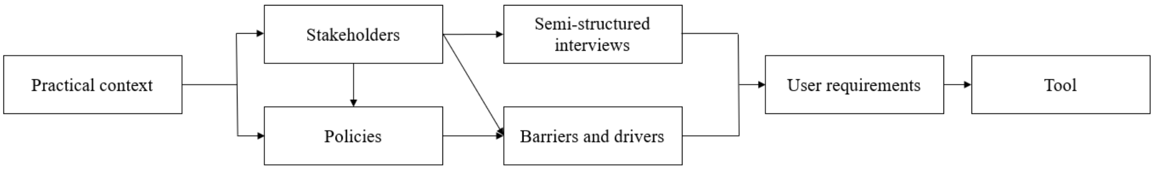


Fig. 1: Design approach to develop the tool of this research.

cover renovation projects in the Netherlands. Additionally, for this research it is expected that gathering data for renovation projects in the Netherlands is doable in an acceptable time frame. To add a supplementary boundary, which is anticipated to lead to more accurate results, A certain kind of renovation projects conducted on a specific type of building will be chosen. The specific type of building will be determined based on the urgency of making that type more sustainable. This way, a demarcated practical context is found for both the remainder of this research and the to be developed tool. After that, the relevant stakeholders and policies can be analyzed to find the main barriers and drivers in this context. Together with the results of semi-structured interviews, the barriers and drivers facilitate the possibilities to formulate substantiated user requirements for the tool resulting from this research, successfully finalizing the methodological part of this thesis. An illustration of the approach to come to user requirements and ultimately the tool is shown in Figure 1.

The essential outcomes of this research will be the barriers and drivers of stakeholders to reduce whole life carbon emissions in renovation projects and a tool that helps in overcoming these barriers and enhancing the drivers respectively. These outcomes are hypothesized to show the importance of both the operational and embodied side of emissions for renovations. While the tool will be tailored towards the key identified stakeholders in this context, the outcomes can be used by all actors in the Dutch built environment value chain. Additionally, the outcomes could be of help for the World Green Building Council (WGBC), with its subsidiary the Dutch Green Building Council. This foundation is committed to making the built environment future-proof at a rapid pace. With their own vision on embodied carbon, called Whole Life Carbon, the foundation intends to bring the whole building and construction value chain together to collectively mitigate these emissions [7].

C. Research questions

Taking the steps in drawing more attention to the issue of embodied carbon and its relative importance against operational carbon, the main research question (RQ) is defined as follows:

RQ: ***"How can organizations involved in the Dutch built environment be stimulated to actively consider the balanced reduction of both embodied and operational carbon in their renovation projects?"***

Since the first part of this research is about determining the barriers and drivers experienced by stakeholders in this context, a couple of things need to be established. First of all, like mentioned before, the type of building and renovation, respectively, that is investigated needs to be chosen. In addition to that, it is of importance to note how the operational carbon needs to be considered in this situation. When carrying out renovation projects, the operational carbon over the remaining life cycle of a building changes. That is why an assessment of both the embodied and operational carbon within the renovation project is necessary. Finding the answers to the aforementioned problems is seen as a first step towards the goal of this research as explained above. Consequently, the following sub-questions have been defined:

SQ 1: *"How can the assessment of operational and embodied carbon in renovation projects be conducted according to literature?"*

SQ 2: *"What practical context should be the focus point for the to be developed tool?"*

These first two sub-questions can be answered by gathering secondary data from literature. After a demarcated context for reducing embodied besides operational carbon in renovation projects has been conclusively found, market players need to be prompted to reduce this overlooked part of emissions. Moreover, it is hypothesized that facilitating stakeholders with a tool giving them insights into this matter could be of value in the pursuit of more awareness and concrete actions in this field. To achieve this, additional sub-questions have been formed, which can be found below.

SQ 3: *"What stakeholders should the to be developed tool be designed towards?"*

SQ 4: *"What (inter)national policies exert influence on the identified key stakeholders regarding embodied carbon in renovation projects?"*

SQ 5: *"What barriers and drivers in the socio-technical system of renovations in the Dutch built environment need to be respectively overcome and enhanced for market players to not only actively pursue operational, but also reduced embodied carbon?"*

On the basis of these sub-questions, the necessary strategic and economic value of a balanced reduction of embodied and operational carbon will be established for the most important stakeholders in the context of renovation projects. Knowing this, the stakeholders can be interviewed to help the effective design of the supporting tool even more, after which the development of the tool itself can be carried out. In order to design the tool as effectively as possible, two more sub-questions have been formulated:

SQ 6: *"What are the requirements of the to be developed tool, taking into account the earlier identified barriers and drivers?"*

SQ 7: *"What would be a possible realization of the to be developed tool?"*

To answer the last sub-questions, interviews will be held, which supplemented by the earlier determined barriers and drivers elicits user requirements for the to be developed tool. Afterwards, the tool will be developed which implements the earlier described strategic value in new and existing projects of said stakeholders. The tool can be used for better and more sustainable decision making on the topic of renovations.

D. Thesis outline

The remainder of this thesis is structured as follows. It starts out with a gap identification in the current situation in section II. After that, a research approach for answering the sub-questions and ultimately the main research question is determined in section III. Relevant data is gathered from different sources in the secondary data analysis in section IV. Then, a stakeholder analysis is conducted in section V, followed by a policy analysis in section VI. The barriers and drivers resulting from the stakeholder and policy analysis respectively are presented in section VII. The interviews conducted with the key identified stakeholders and the results from them are found in section VIII, as well as the design choices made for the developed tool as a result of all steps taken before. The results from the data modelling approach, together with the process of illustrating the tool are presented in section IX. Conclusions drawn from the presented results are documented in section X. This thesis is finalized with a discussion on the conducted research and recommendations for further investigation of this problem context in section XI.

II Gap identification

A. Introduction

This chapter introduces the relevant background information required to establish an effective research approach. More specifically, the most important technical terms and concepts are operationalized in the context of this research. Additionally, the state of the art regarding tools for embodied and operational carbon is investigated to identify the gap between the current and desired situation.

The built environment, with the Dutch one being no exception, can be described as *"the summation of all human-made structures, infrastructure, and transportation systems"* [5, p. 166]. For the sake of the research boundary, however, the built environment is considered to be all buildings that have been constructed. Hence, especially given that the focus of this thesis will be on renovation projects, existing buildings are considered, while new constructions will be left out of this research.

B. Embodied carbon in life cycle assessments

By knowing the currently applied assessment methods of embodied and operational carbon for the life cycle of buildings, a better understanding of the context of this research is created. In order to fully understand that, however, the necessary knowledge on life cycle assessments should be acquired.

As mentioned in the previous chapter, the building and construction sector accounts for a significant part of (energy-related) emissions worldwide. Across this sector, awareness of the need to reduce environmental impact in order to remain relevant for the market is growing [13]. That being said, reducing this impact is still often sought after in only one of the many stages of a building, namely its use phase. With a reduced environmental impact of only the use phase, impacts of the other phases become relatively more significant [14]. For this reason, proper assessment of the under-shadowed part of environmental impact from buildings is necessary.

Both the embodied and operational carbon of a building, together referred to as whole life carbon [15], is commonly measured using a form of a life cycle assessment (LCA). The LCA is a method to systematically evaluate the environmental impacts of the whole life of a product or process [16]. It assesses the impact based on multiple environmental categories, of which carbon footprint, or global warming potential, is commonly incorporated [15]. Multiple researchers have reported a growth of interest in applying LCA methodology to projects in the construction sector for better environmental decision making and to monitoring all stages of the product life cycle [5, 16, 17].

An LCA lends itself for effective assessments due to flexibility in terms of method that is applied, while simultaneously being subject to international uniformity. In essence, many different LCA methods can be applied, though the ISO 14040 standards dictate the four stages of the LCA regardless, with the four stages being Goal and scope definition, inventory analysis, Impact assessment, and Interpretation [18]. The interpretation stage, being an important part of the whole process, is connected to all stages as an integrated part of the LCA. The interrelation between the four stages is displayed in Figure 2 as adapted from the ISO standard [19].

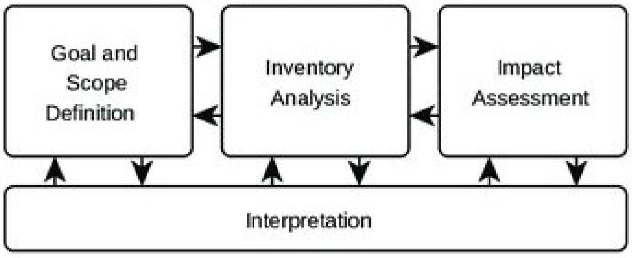


Fig. 2: The interrelation between the four LCA stages as defined by ISO 14040.

1) Goal and scope definition

The first phase of any LCA according to the ISO 14040 standard is the goal and scope definition. In the goal definition, the motivation for doing the LCA, together with the intended audience and applications are described. The scope includes the product system to be studied, together with its functions and system boundaries. Moreover, the scope defines a so-called functional unit, which can best be described as the *"quantified performance of a product system for use as a reference unit"* [18, p. 4]. The functional unit establishes a foundation on which different products can be compared considering how many times they can fulfil the unit.

The system boundaries define which parts of the life cycle and which processes belong to the analyzed system. In the construction industry, generally, four different system boundaries or scopes are considered. *Cradle to gate* considers only the extraction and manufacturing of materials and thereby solely includes the environmental impact of production. The *cradle to completion* scope goes one step further, covering all processes and impacts conducted to achieve the finalized product. *Cradle to grave* considers the whole life period of the product, from start to end, except for the possible recycling, reusing, or disposing of leftover materials after the product's original life. *Cradle to cradle*, on the other hand, facilitates a more cyclic approach to the LCA of a product, where it also considers the (negative) impacts of materials that can be reused or recycled [20].

2) Inventory analysis

Sometimes referred to as *"the most important stage in the process of LCAs"* [21, p. 1189], the inventory analysis is about defining and quantifying the incoming and outgoing flows of energy, greenhouse gases, and materials in all stages of the chosen scope of the product's life cycle. Typically, four steps are involved in performing an inventory analysis: the development of a flow diagram, developing a data collection methodology, collecting relevant data, evaluating and reporting results. In practice, it translates to data collection and analysis, which is frequently found to be the most time-intensive process of an LCA [22]. The relevant data can either be collected from direct measurements and calculations from the original source (primary approach) or literature and existing databases (secondary approach). The result of this step is a flow diagram considering all collected data together with the reported assumptions that substantiate the reported values.

3) Impact assessment

The final step of an LCA is the impact assessment. It is a step to evaluate the potential environmental impacts through the process of converting the results from the inventory analysis to insightful impact indicators [23]. The impact assessment itself consists of a couple of steps. First, the impact categories are chosen. Those categories can either be focused on the individual problem (midpoint, e.g. climate change or acidification) or on the area of protection (endpoint, e.g. human health or ecosystems). A combination of the two is also possible [24]. After impact categories are selected, which can either be end- or midpoints, the inventory data is assigned to one of the categories, i.e. they are classified [23].

The last mandatory step entails calculating the potential impact indicators and making the result characterized. Characterization of the impact indicators is based on the notion that every environmental effect can be expressed in terms of its reference (equivalent) substance. In other words, the contribution of a certain substance, in this case, emission, is compared to a common contributor to the chosen effect, in this example global warming. For that effect, the reference substance is carbon dioxide, which means that every substance contributing to global warming is expressed in kg CO_2 equivalents, factorized by the relative contribution of one kg of that substance in comparison to CO_2 [25]. This explains why most if not all terms in the discussion of global warming refer to carbon: it is the internationally accepted reference emission of all other substances contributing to global warming due to its prominent presence within that effect.

Normalization of, grouping, and weighting impacts are optional measures that can be taken to gain more valuable insights into the raw data. Normalizing the data means that the impact indicators are subjected to reference conditions, which results in the practitioner being able to better interpret the results. Sometimes, this process is also called benchmarking. Standard references might include the impact per geographical zone, person, or sector [26]. Grouping and weighting are both more subjective matters in which the severity of the different impacts are related to the practitioner's worldview.

C. Embodied carbon in buildings

Now that an understanding of the LCA method and its underlying theory is established, it becomes of importance to see how this method is applied to building in real-life situations. By investigating this, potential data sources for the tool can be identified more effectively, which is expected to enhance the applicability of the proposed tool.

For buildings specifically, the detailed standard for applying the different LCA methods to buildings is the internationally renowned EN 15978 standard. EN 15978 is in line with the ISO 14040 standard, meaning that any EN 15978 compliant assessment is inherently compliant to the ISO 14040 standard. It distinguishes the phases of a building by defining five life stages as follows [14]:

- Product (A1-A3). This covers processes such as extraction, transportation, and processing of natural resources to make them usable for construction.
- Construction process (A4-A5). In the construction process, all construction and installation-related activities are grouped, including transportation from the point of manufacturing to the

building in question.

- Use (B1-B7). This includes the use of all construction-related products and services as well as maintenance, repair, replacement, and refurbishment of (parts of) the building.
- End of life (C1-C4). This part covers all activities related to the decommissioning of the building. Transportation of rejected materials and products, as well as the processing of those materials and products, are part of the End of life phase.
- Benefits and loads (D). The last phase covers all positive impacts due to the reuse, recovery, and recycling of products and materials outside of the original building's life cycle.

The modules and stages within this standard are shown in Figure 3 [27]. From these stages, the operational carbon emissions are defined as *"those caused by the energy consumed by building-integrated technical systems during the operation of the building"* [28, p. 14]. While being the most affecting ones overall, this means that components B6 and B7 cover all operational emissions. Therefore, all other stage modules, with the corresponding impact of resource extraction and processing, construction, renovation, and demolition, cover the embodied carbon emissions of the building [29]. Phase D, or the Beyond building life cycle phase, are generally not taken into account when assessing embodied carbon, to prevent double-counting of so-called negative emissions when a product is (partially) used for several life cycles [15].

Considering all of the previously mentioned phases gives the most comprehensive picture of the environmental impact. Be that as it may, in practice, most LCAs do not include every stage. Instead, boundaries are identified in the form of scopes, as explained before. The four scopes in the EN 15978 standard are defined as cradle to gate A1-A3, cradle to completion A1-A5, cradle to grave A1-C4, and cradle to cradle A1-D [30, 31].

This research, like mentioned before, will be focusing on renovation projects, which means the analyzed buildings will have already been constructed. For that reason, it should be noted that the components A1-A5 of the building, which cover all steps up to the use phase of, are of less relevance for this study. That being said, the components A1-A4 of the newly applied materials are, naturally, relevant for the total environmental impact of a renovation. Considering that renovation projects might include replacing old materials, and thus having to dispose of, recycle or reuse them, the components C1-C4 (end of life) are deemed relevant.

D. LCA tools

By performing a state-of-the-art investigation on current tools on the market for this problem, the novelty of the to be developed can be guaranteed in a more substantiated way. That is why, in this section, the most important existing LCA tools for buildings are laid out.

Recent research has argued that the attention on embodied carbon should increase as low carbon building design and more sustainable use phases have become more and more popular [32–34]. Researchers studying this topic have focused on underlining the significance of embodied carbon [35], making it more measurable [36], and determining the relative magnitude of it in office and commercial buildings [37] through the use of LCAs. The focus of these studies has been largely on data acquisition. After the acquisition, inventory data can then be used for environmental impact

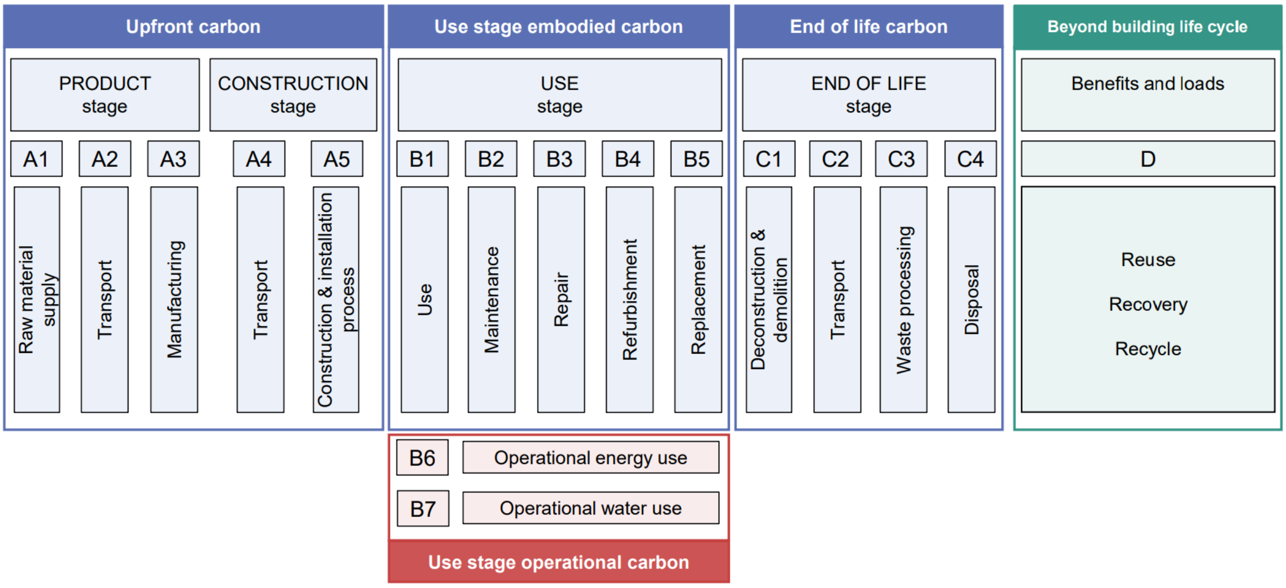


Fig. 3: Life cycle modules according to the EN 15978 standard.

databases or Environmental Product Declarations (EPDs). The latter can be defined as independently verified and registered documents containing reliable information on environmental impact of products in a credible way [38].

Putting LCAs to practice, one can identify the environmental impacts of products, among which buildings. That being said, performing complete and complex LCAs for all material and/or products every time a new building is constructed or an existing building is renovated is an arguably lengthy and possibly even redundant task. The development of LCA tools has thus been an uprising activity to incentivize the integration of sustainable design in different life stages of a building. With these tools, evaluating climate impact can be done in a relatively convenient fashion because of the exact values being available per type and amount of material used, based on different databases or EPDs. And whilst the international standards as explained before help in making the essence of them the same, different building assessment tools approach this task from different perspectives [39]. In this section, without the author presuming it to be fully comprehensive, an overview of the most noteworthy environmental assessment tools regarding embodied carbon and construction is given. A few of the tools are described in detail to demonstrate the diversity of perspectives that were taken into account when developing them.

One Click LCA is a licensed web-based environmental assessment software that helps calculate and reduce the environmental impacts of building and infra projects, products, and portfolios [40]. It can be used in the context of different environmental certification schemes such as BREEAM and LEED. By having data from different databases and EPDs available in their tool, which can be extended by users themselves, it can cover all relevant components of the EN 19578 standard regarding embodied carbon. For projects in the Netherlands, One Click LCA uses databases from the Dutch organizations INSIDE/INSIDE, Milieu Relevante Product Informatie (MRPI), and Stichting Nationale Milieudatabase (NMD) [41].

Gemeentelijke Prestatie Richtlijn (GPR) Software is a Dutch piece of software designed for the sustainability assessment and scoring of both residential- and service buildings, according to the aforementioned MPG calculation method. The software and corresponding calculations give insight into, amongst other environmental impact themes, the embodied and operational carbon of a building, and simultaneously ranks it based on five themes: energy, environment, health, usability, and future value [42]. These rankings are inherently connected to the Dutch Building Decree, where a grade of 6 corresponds to the current expected sustainability level. The software itself is mostly based on data from the NMD. Notable about this tool is the way assessments can be upscaled from building level to portfolio or even whole areas. With different tools for different applications such as completely new buildings, specific renovation projects, and whole cities, the software covers a very broad spectrum of sustainability-related issues.

The Carbon Risk Real Estate Monitor (CRREM) assessment tool is the open-source Excel-based result of the eponymous EU-funded research project. It is based on a model developed to assess current and future carbon risk exposure in the real estate sector [43]. The tool is meant for asset owners and investors to understand the carbon risks inherent in their real estate portfolio, which it tries to clarify through science-based decarbonization pathways compliant with the Paris Climate Agreement. CRREM, while also briefly highlighting embodied carbon in the tool, is mainly focused on the operational side of buildings.

Another science-based tool is the Building Circularity Index (BCI). With it, people can determine the circular potential of new and existing buildings based on material use and *releasability* of materials [44]. Every product used in a building is rated in terms of circularity individually. The rating is conducted with distinctions between the origin, the future scenario, and the lifespan of materials. A score of 0,00 for the product means it is not circular and thus has a linear life cycle, while a score of 1,00 means it is fully circular. These scores indicate the CO_2 footprint of the building which in turn results in an overall circularity score.

COSIS, abbreviation for Cost Optimal Sustainable Investment Solution, is a tool developed by Arcadis to give insight into opportunities for sustainable investments in real estate. In accordance with existing blueprints and conducted technical inspections, a reference point of the investigated building is created. With that reference point, all possible combinations of relevant sustainability measures are calculated in terms of financial costs and embodied carbon. The tool is able to find the optimal solution with regard to the client's budget and ambitions.

Table I gives an overview of a selection of LCA tools applicable to buildings. In this overview, only tools that consider the impact of the whole life cycle of a building or product are shown. It should be noted that there are certainly more construction-ready LCA tools, but they are argued to not add significantly novel perspectives compared to the tools already discussed. Additionally, highlighting and/or discussing them all is out of the scope of this thesis.

TABLE I: Overview of LCA tools.

LCA tool	Country	Area of application	Data source	Access
One Click LCA	Unspecified	Construction	Multiple databases	License
GPR	The Netherlands	Construction	Nationale Milieudatabase	License
CRREM	Unspecified	Construction	CRREM database	Free
BCI	The Netherlands	Construction	Madaster database	License
COSIS	The Netherlands	Construction	COSIS database	Company-specific
GaBi	Unspecified	Unspecified	Multiple databases	License
SimaPro	Unspecified	Unspecified	Multiple databases	License
OpenLCA	Unspecified	Unspecified	Multiple databases	Free

E. Discussion of theoretical framework

The overview of embodied and operational carbon, the calculation of it and how current theories are put to practice all help in setting the first step towards answering the research question. The overview of technical terms and concepts are relevant to this research, as it helps shaping both the theoretical as the practical part in a more substantiated way. The overarching theory of LCAs is discussed and put in the context of the built environment. The EN 15978 standard, in compliance with ISO 14040, include the detailed guidelines of applying LCA methods to buildings. In the standard, multiple components are identified, which cover the environmental impact of the different stages of a building or product, depending on the practitioner's view. The application of LCAs to buildings by means of a tool has been done numerous times before, but none of the discussed tools seem to focus on both operational and embodied carbon. Instead, the tools solely focus on embodied carbon. As a consequence, no tool facilitates the ability to compare both kinds of emissions and to see the resulting environmental impact from them. There is thus novelty found in the development of a tool that does facilitate this, which indicates the relevance of this research.

III Research approach

A. Introduction

Now that the most important technical terms and definitions have been lined out and a gap has been identified between the current and desired situation, the chosen approach to tackling the problem at hand can be formulated. In this chapter, the approach to answering the sub-questions and the main research question is explained. This chapter thus serves as a justification of the design choices of this research, contributing to a structured and unequivocal research approach for this thesis.

B. Approach to answering the research questions

This research consists two parts. The first part is about understanding what can be done to let stakeholders consider embodied carbon in renovation projects next to operational carbon. This part is covered in the first five sub-questions, as each sub-question helps in formulating a better approach to this. The second part is about how to facilitate this approach with the aid of a tool, which is developed while bearing in mind the findings of the first part. The latter part of the research is thus conducted by answering the last two sub-questions. The totality of answers of all sub-questions combined gives rise to answer the main research question of this research.

1) Assessing embodied and operational carbon in renovation projects

In order for the tool to assess the emitted or mitigated emissions in a validated fashion, the assessment of embodied and operational carbon should be investigated. The answer for this theoretical question is expected to lie in secondary data found in literature and Dutch legislation. That is why data will be acquired from these sources to formulate an answer to this sub-question.

2) Identification of practical context

The second sub-question (SQ 2) is designed to find out what type of building and renovation respectively the focus for this research should be on, finding a practical context for the development of the tool. At first, the different types of buildings as defined by Dutch law are investigated. After making a distinction between the most important aspects of building types, a choice shall be made on what type to investigate based on their operational emissions and, more importantly, their mitigation potential. The choice being made for a specific type of building is hypothesized to result in more accurate and applicable insights from the subsequently performed analysis. In a similar fashion, to gain the most valuable insights from this research, a specific type of renovation for the chosen building shall be selected.

3) Identifying key stakeholders

After finding a practical context for the rest of this research and ultimate development of the tool, it is important to determine the most influential stakeholders of this context. Therefore, a stakeholder analysis will be conducted, after which said stakeholders can be categorized on the grounds of the Stakeholder Salience Model (SSM) by Mitchell et al. [45]. This model categorizes the stakeholders based on three attributes: the ability to impose their own will (power), their need for immediate action in the field (urgency) and the desirability or appropriateness of their involvement (legitimacy). Through identifying the possession or lack of attributes by stakeholders, eight different types can be defined. The SSM and corresponding types of stakeholders can be displayed in a venn diagram as seen in Figure 4 [45]. The exact goal of the stakeholder analysis is to find out what stakeholders would benefit most from the proposed tool and how the tool should be tailored towards them.

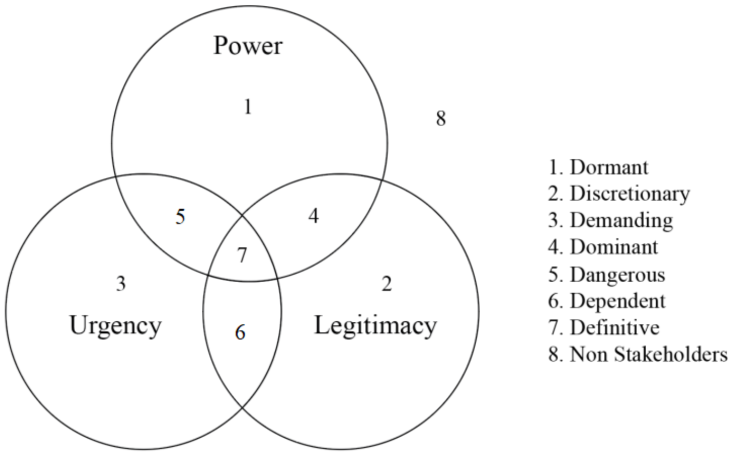


Fig. 4: The Stakeholder Salience Model.

4) Finding relevant national and international Policies

This research sets out to develop a tool that helps in overcoming barriers and enhancing drivers in the socio-technical context established by answering the first two sub-questions. After identifying and investigating the most important stakeholders in this context, a policy analysis is conducted to determine what (inter)national rules and regulations influence said stakeholders in this system. Together, the two analyses form the basis of establishing the aforementioned barriers and drivers.

Environmental policy has experienced a rapid growth globally over the last decades, making it necessary to assess the effectiveness of these policies on governments, NGOs, businesses and other organizations [46]. A policy analysis will be conducted, focusing on policies and regulations regarding embodied and operational carbon, specifically for renovations prompted by organizations in the Netherlands. Both European and Dutch legislation are highlighted, along with their causal effects on the Dutch market and implicitly the earlier analyzed stakeholders. Analyzing what policies or changes can be applied for the successful reduction of overall emissions while keeping the interests of stakeholders in mind allows for a bottom-up approach of identifying the most important barriers and drivers of this context.

5) Identifying barriers and drivers

By knowing the potential barriers and drivers experienced by stakeholders to reduce embodied carbon in their renovation projects, both the tool and this research of itself can prove more relevant. Identifying them allows for establishing user requirements of the to be developed tool. For the purpose of finding said barriers and drivers, the stakeholder analysis will be supplemented by a more in-depth investigation of the identified key stakeholders. Next to that, barriers and drivers will be identified from the policy analysis too. The two analyses together provide the opportunity to establish a broad understanding of the market around Dutch renovation projects. This way, the fifth sub-question of this research can be answered (SQ 5): *"What barriers and drivers in the socio-technical system of renovations in the Dutch built environment need to be respectively overcome and enhanced for market players to not only actively pursue operational, but also reduced embodied carbon?"*. As the answer to this question is found in multiple sections, SQ 5 will be answered in the results presented in section VII.

6) Tool development

A couple of steps are taken for the development of the tool. Firstly, a qualitative market research is conducted by means of interviewing the key stakeholders of this context, intending to benefit the design of the proposed tool supplementary to the earlier identified barriers and drivers. Together, the results elicit user requirements for the tool that are prioritized using the MoSCow method. Then, a regression model is built for the calculation of operational carbon emitted from buildings after a certain renovation. Data streams will be identified and combined in the tool. Lastly, databases that are deemed relevant will be accessed and implemented in the tool to achieve the desired outputs.

7) Interview methodology

As explained by Bryman in his book about social research methods [47], quantitative market research is concerned with the collection of numerical data, often collected through surveys, while qualitative research is generally about collecting data from interviews and observations. It is concerned with words, rather than numbers, hence making it different from a quantitative approach. In this context, Taylor describes interviews to be *"[...] the most commonly utilized qualitative data collection method"* [48, p. 39].

Rowley [49] defines three types of interviews used in research. The first one described is a structured interview. Much like a questionnaire, a logical order of questions is followed, without the interviewer changing the order in which questions are asked compared to the designed order, or them asking the interviewee to elaborate further throughout answering a certain question. Structured interviews require the interviewer to have a lot of knowledge beforehand to effectively gain the desired results. Unstructured interviews, on the other hand, let the interviewee speak freely with the exception of the interviewer giving some general pointers. This allows the interviewer to adapt the questions to the specific context they are working with. Lastly, the semi-strucutured type of interviews are mentioned. These interviews contain no more than 12 questions in a certain order, with potential sub-questions that the interviewer can use in order to retrieve more elaborate answers. Especially semi-structured interviews are mentioned among researchers to be a popular method of collecting data due to its effective, flexible, and versatile nature. For these reasons, the qualitative data collected in this research will be accompanied with results from semi-structured interviews. The questions for the interviews were created while taking into account the guidelines as proposed by Rowley [49].

The interviews can help in shaping both the results of this research and the design of the tool. In particular, the questions desired to be answered by investors is what could drive them and other market players to include embodied carbon in their sustainability-related decision making, as well as what can be made and done to stimulate said market players to actively keep track of this. To put it more in the context of this research: the goal of these interviews is to find out what barriers and drivers are experienced first-hand in the market and field of sustainability-related renovations and how these drivers can be utilized to impel for appropriate actions. Finding answers to these questions and implementing them into the development of the proposed tool is expected to enhance the tools effectiveness.

8) Determining user requirements

The barriers and drivers found through the stakeholder and policy analyses, together with the results of the conducted interviews, elicit user requirements for the functionality and design of the tool. A list of functional and non-functional requirements will be made on the basis of the earlier conducted research and prioritized through the MoSCoW method [50]. Often used in software development, the MoSCoW method prioritizes requirements based on whether the product *Must*, *Should*, *Could*, or *Won't* deliver the requirements. AbdElazim et al. describe the technique as a *"[...] reasonably simple way to sort user stories into priority order. [It is] a way to help teams quickly understand the customer view of what is essential for launch and what is not"* [51, p. 8]. By applying this prioritization method, the design of the tool can be done more effectively.

9) Data mining approach

The next step is being able to determine both the operational carbon before and after the renovation of the building, as well as the embodied carbon emitted by realizing this renovation. For the embodied carbon, a database of materials and their environmental impact shall be sought after and utilized. The operational carbon can be determined by means of implementing a data mining algorithm on annual consumption data of existing dwellings.

To ensure the validity of data being used for the data mining algorithms, it is of importance that the data set is as clean as possible. A clean data set entails different aspects. Among other requirements, the most important ones are that empty data entries, if any, are processed properly and that the right selection of features is made to accurately predict the value of choice.

To determine what features exactly are of importance to predict the annual gas consumption of a dwelling, a correlation analysis will be conducted. Reducing the amount of dimensions based on their correlation to the annual gas consumption can give a better predicting model.

What should be noted though, is that features with a linear correlation (i.e. a correlation value of 1) should be left out of the training set altogether. Such a feature for instance includes the energy index of the dwelling. The annual gas consumption and energy index are naturally highly correlated, which would pose a risk of the model giving too much weight to that particular feature.

After the data has been processed and cleaned, it can be used as input for a data mining algorithm to predict the desired value. In this case, the value is the annual gas consumption of a dwelling. Data mining methods have been proven to offer high-accuracy predictions for energy consumption by different researchers [52, 53]. Among those methods is the Support Vector Regression (SVR), an application of the Support Vector Machine proposed by Vladimir Vapniks [54], which has been said to be an effective method for energy consumption prediction.

A support vector regression is a type of linear regression. It is a popular choice for predictions and curve fittings of regression types [55]. Rather than a simple linear regression, the support vector regression allows for an error margin ϵ to tune the model to a desired accuracy as to not over- or underfit it[1]. Additionally, a tolerance for outliers in the data set can be taken into account through the tolerance value ζ. The importance of such outliers are determined with the cost parameter C, which is a value chosen by the practitioner.

A one-dimensional example of a SVR is shown in Figure 5 [57]. In this figure, the data points are the predicted values, while the solid black line represents the reference data. The two dotted lines represent the error margin ϵ. The deviation of outliers from the margin is denoted by ζ. The resulting hyperplane from this data can be denoted by the simple equation $y = \mathbf{w}X + b$, where $\mathbf{w}$ are the weights of the different features X, and b is the intercept at $X = 0$. In the case of predicting energy consumption based on data from a dwelling, y is the energy consumption predicted from data X by multiplying it with the respective weights $\mathbf{w}$ and adding the bias b. The weights and bias are the parameters determined by the model during its training.

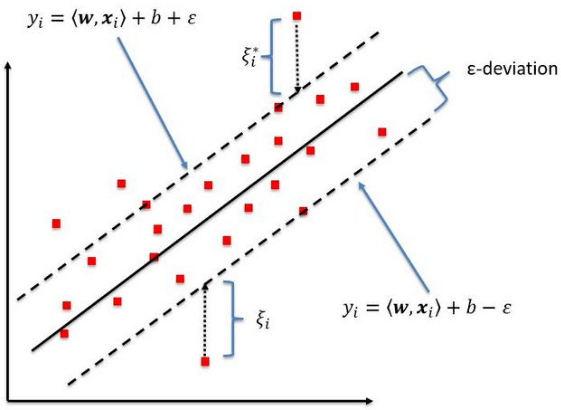


Fig. 5: An example of a one-dimensional support vector regression model.

A portion of 70% of the entries will be used for training the model, while the other 30% is used to evaluate it (testing). The cost parameter C and the kernel function[2] are determined by conducting grid searches and finding the most optimal results through them.

The model will be trained and evaluated on the basis of its mean absolute error (MAE) value, root mean squared error (RMSE) value, and coefficient of determination (R^2). These three statistical phenomena are often used in data science practices to evaluate regression models and their predictions compared to the best fit line, i.e. if all predictions exactly matched their target value [59]. The RMSE can best be explained as the standard deviation of all distances of the predictions to the earlier described fit line [60]. The MAE, on the other hand, is the mean of the absolute values of the individual prediction errors [61]. Lastly, the R^2 value describes the correlation of the predicted data points with respect to their actual value, ranging the correlation from 0 to 1 [62]. Knowing the definition of these three statistics, it becomes clear that relatively low values for both the RMSE and MAE with an R^2 value close to 1 are desired.

[1]Over- or underfitting in regression algorithms entails that a model has been trained either too well or too little on the given sample data. Whereas an overfitted model gives too much weight to noise or random fluctuations, leading to less accurate predictions outside of the training data set, an underfitted model is unsuited for predicting any desired value [56].

[2]The kernel function assists in mapping a data set to a higher dimensional space to obtain a better interpretation of the regression model. Examples of such transformations are applying a linear, polynomial, or Gaussian function to the data for a better fitting model and thus more accurate results [58].

10) Tool illustration

In order to illustrate its effectiveness, the tool will be applied to two different renovation scenarios. By doing this, insight is gained into the proportion of embodied and operational carbon for the chosen type of buildings and renovations. This is done in the section presenting the results of this research, section IX. The scenario studies are meant to show the effectiveness and necessity of tools that can evaluate both operational and embodied carbon in renovations, such that the actual outcomes of renovations can be evaluated more accurately by the relevant stakeholders. This is expected to allow for enhanced decision making regarding renovations, especially in terms of sustainability. After doing the scenario studies, the main research question (RQ) can finally be answered, which is done in the section with conclusions, presented in section X.

C. Research design

This research is divided into several research stages, each with their own activities. The sub-questions and overarching main research question will be answered at the hand of these stages. An illustrative overview of the research design is seen in Figure 6.

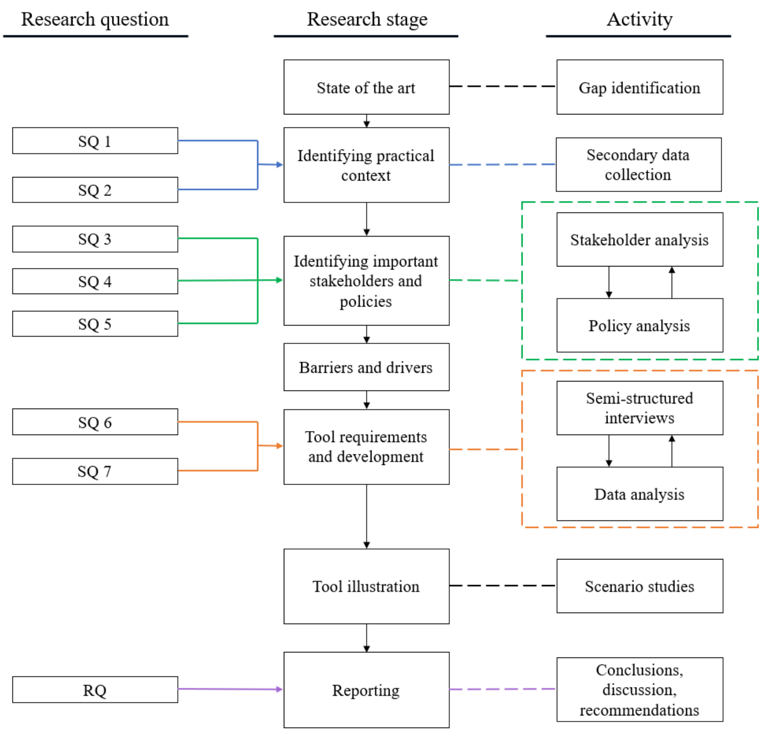


Fig. 6: Research design model.

IV The Dutch built environment

A. Introduction

In this section, secondary data is obtained from literature to answer the first and second sub-question (SQ 1 and 2), establishing a practical context to further advance his research. The formation of this practical context to develop the tool in gives direction to an otherwise very broad field of research.

B. Calculation of embodied and operational carbon

To start off this research, it is important to understand how operational and embodied energy are linked to the resulting carbon emissions from them. This helps in answering the first sub-question (SQ 1): *"How can the assessment of operational and embodied carbon in renovation projects be conducted according to literature?"*. The embodied carbon part of a building can be determined by means of assessing the production, use, and waste management of its different parts and materials. Determining the operational carbon emitted by a building, however, requires a notably different approach. The one thing that both assessment have in common is that, for a proper assessment of the impact of utilized energy, a carbon conversion factor is necessary.

Carbon conversion factors are values that relate the type of used energy to the amount of CO_2 equivalent substances emitted from it [27]. Typically, this value is given in kg CO_2 eq./kWh. The exact value of conversion is subject to the location and time of execution of an energy-requiring process, meaning the values differ per region of the world. Often, these factors are defined by governments, as is the case in the Netherlands. Dutch legislation dictates the exact values of the different forms of energy carriers through the NTA 8800 standard [63], with the most notable being 0,34 kg CO_2 eq./kWh for electricity and 0,183 kg CO_2 eq./kWh for natural gas.

With especially the electricity grid becoming more and more sustainable, the carbon conversion factor for electricity is both observed and expected to diminish over the years. The Dutch research institute TNO [64] has established predictions on the basis of available data by CBS for the electricity carbon conversion factor in the Netherlands until 2030. To determine the primary fossil energy factor, TNO used the integral method for the efficiency of electricity, looking at trends for future energy generation. The integral approach resulted in the predictions as seen in Table II. While a predicted value for 2050 is missing in their approach, this value can be derived from the projected decrease of 95% by 2050 compared to 1990 as described above. For the sake of completion, this value has been added to the corresponding table. These predictions can be used for the yearly prediction of the electricity carbon conversion factor by means of interpolation.

The carbon conversion factor for natural gas, or 'aardgas' in Dutch, on the other hand, is expected to remain the same over the course of the years. While there can be said to be differences in nuance of what type of gas is used, how much energy it yields and ultimately what this means for the total emissions, the differences are hypothesized to be marginal. Throughout the remainder of this thesis, the value of 0,183 CO_2 eq./kWh is thus used for the use of gas from now until 2050. Interpolating the predicted electricity factor per year, combined with the constant natural gas factor, results in the data as shown in Figure 7.

TABLE II: Predictions of electricity carbon conversion factor by TNO.

Year	**2020**	**2023**	**2030**	**2050**
Conversion factor [kg CO_2 eq./kWh]	0.34	0.30	0.19	0.03

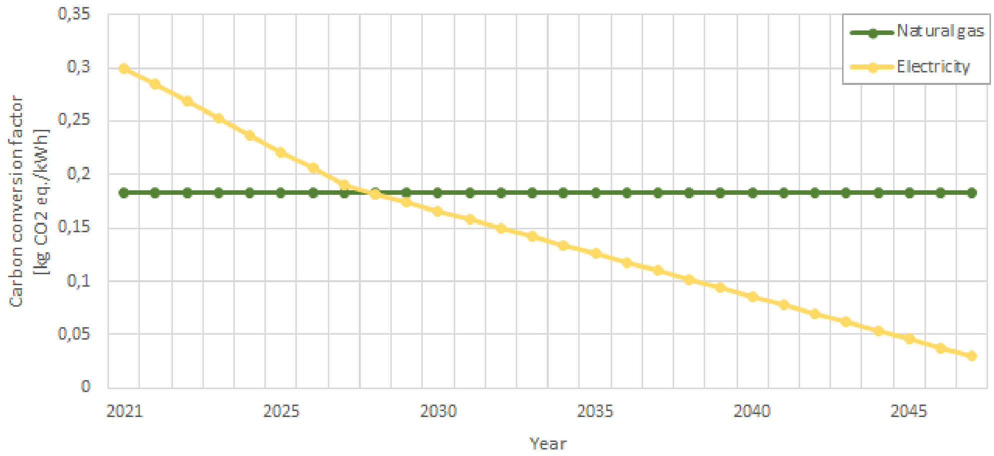


Fig. 7: Outlook of carbon conversion factors in the Netherlands.

Contradictory to what one might think at first, the operational carbon emissions of importance in renovation projects are the CO_2 emissions that are mitigated thanks to the conducted renovation. A financial analogy can be used to describe this phenomenon in a more elaborate fashion. The embodied and operational carbon in renovations can be thought of as two types of expenditure: the embodied carbon being the capital expenditure (CAPEX) or investment costs of a project, while the operational carbon entails the operational expenditure (OPEX). With an investment of embodied carbon, the operational carbon is reduced. This, however, arises the question of whether the 'investment' of carbon in the renovation of buildings is 'earned back' by the saving of operational carbon across the technical service life of the applied renovation material or the building itself.

Answering the first sub-question of this research (SQ 1): *"How can the assessment of operational and embodied carbon in renovation projects be conducted according to literature?"*, the calculation of operational and embodied carbon have been investigated. Dutch legislation prescribes the so-called carbon conversion factors, which indicate the amount of kg CO_2 eq. per kWh of energy. Electricity is said to emit 0,34 kg CO_2 eq./kWh while natural gas emits 0,183 kg CO_2 eq./kWh. As of now, natural gas is the more sustainable option in terms of CO_2 emissions per kWh. However, the emissions of the Dutch electricity grid is expected to diminish over the years, eventually passing emissions for natural gas. Next to that, with the coefficient of performance of modern heat pumps getting up to 4 [65], it would be inequitable to look only at this conversion factor to evaluate the sustainability of electricity.

C. Types of buildings

Given that this research will focus on the built environment of the Netherlands, an analysis of the specific environment is a requisite. As explained before, especially already existing buildings will be considered in this research. By finding a building type and renovation to focus the to be developed tool on respectively, the second sub-question of this research can be answered (sQ 2): *"What empirical context should be the focus point for the to be developed tool?"*

The focus of this thesis is on renovations of existing buildings, but combining different types of buildings is hypothesized to result in less accurate and meaningful results overall. That is why a choice should be made what type of building, with its corresponding renovation projects, will be investigated. In order to do this, the different types of buildings are identified along with the operational emissions per type.

The Dutch Building Decree (Bouwbesluit) distincts (partial) buildings in reference to their usage functions as described in paragraph 3 of article 1.1 [66]. An overview of the different user functions is shown inTable III. Generically, the functions can be divided into two categories: residential and services. In these categories, the residential function is the only one considered residential, meaning accommodations are categorized as services.

Residential entities account by far for the largest share of (partial) buildings, with a total of 7.966.331 against 1.157.582 non-residential ones as of January 2021, reported by Statistics Netherlands (Centraal Bureau voor de Statistiek, CBS) [67].

D. Operational emissions in the built environment

Figure 8 shows the distribution of primary energy consumption in the Netherlands [68]. Here it is seen that households, operating the residential buildings, have a rather notable energy footprint, which is still inextricably linked to the emissions of that category as explained in the previous section. Of the 2070 Peta Joules (PJ) of useful primary energy yearly consumed, 435 is used as power and heat by households. This accounts for 21% of the total yearly energy consumption across all domains. The other part of the built environment, in this diagram denoted as 'services', uses a mere 250 PJ, which is only 12% of the total useful primary energy. It is noted that a very small part of 'industry' should also be accounted for as non-residential buildings because of the industrial processes often happening in buildings, though no specific amount is mentioned. Consequently, this part is considered to be negligible.

The Dutch government at the time of writing this, installed as of 2017, adopted the National Climate Agreement in which a 49% reduction target for national emissions is translated into CO_2 Megaton (Mt) by 2030. The target is to have mitigated 7 Mt in operational emissions of the built environment by that time, taking the emissions in 1990 as a reference point [69]. With this reduction target in mind, a joint publication by Netherlands Environmental Assessment Agency (PlanBureau voor de Leefomgeving, PBL), TNO Energy Transition, Statistics Netherlands (CBS), the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO), and the National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu, RIVM) stated the actual reduction of emissions by 2019, with projections for 2025 and 2030 [70]. The data taken from this publication can be found in Table IV. Following this trend, the political reduction target of 7 Mt CO_2 equivalent by 2030 is expected to be met, with a total reduction of around 40% as compared to

TABLE III: Functions of buildings according to the Dutch Building Decree.

Usage function	Description
Gathering	Use function for the gathering of persons for art, culture, religion, communication, childcare, the on-site provision of food and drinks or for watching sports
Structure not being a building	Structure or part thereof, insofar that it is not a building or part thereof
Cell	Use function for compulsory residence of persons
Industrial	Use function for commercial processing or storage of materials and goods, or for agricultural purposes
Office	Use function for administration
Accommodation	Use function for the provision of recreational accommodation or temporary shelter to persons
Educational	Use function for teaching
Other use	Use function not described for activities in which the residence of persons plays a subordinate role
Sports	Use function for practicing sports
Shop	Use function for trading materials, goods, or services
Residential	Use function for living

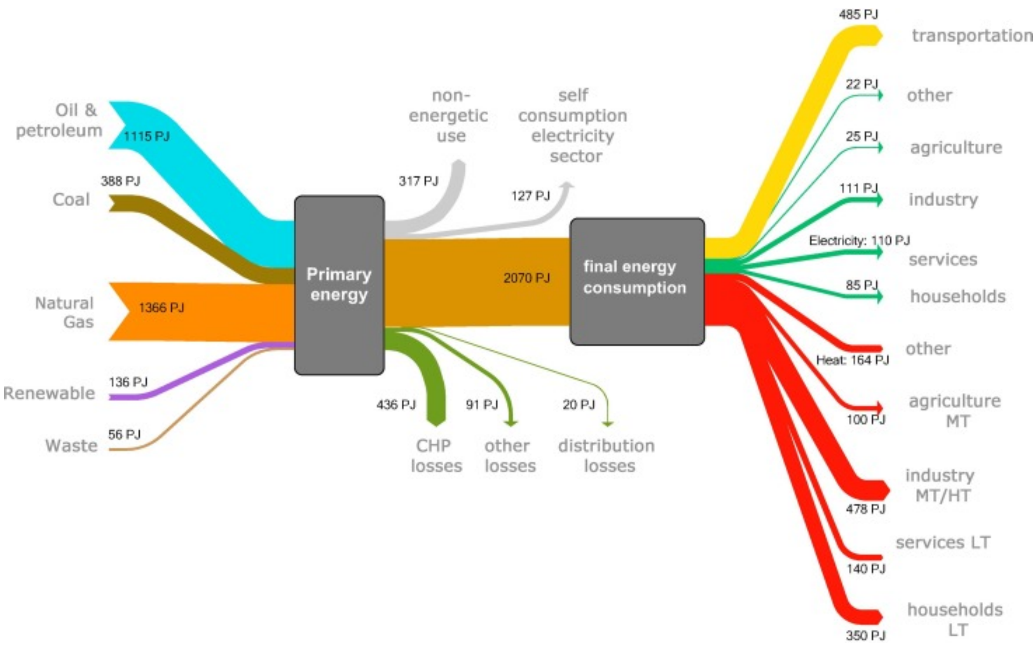


Fig. 8: Distribution of primary energy consumption in the Netherlands. At the final consumption, red is heat, green is electricity, and yellow is fuel.

1990 levels, with a total reduction of 95% by 2050. In the report, it is mentioned that households are accounting for around 70% of operational emissions from the built environment, making it a significant contributor. This claim is further confirmed by the Dutch Economic Institute for Construction (EIB), which reported a portion of 65% of operational emissions for which households were accountable based on data from 2014 [71]. Additionally, the previously discussed distribution of primary energy consumption reports an overall percentage of energy consumption by households accounting for 63,4% of the built environment. Observing that all three percentages fall within the range of 60 to 70 per cent, this research will consider a value of 65% to be the share of energy-related emissions from households.

TABLE IV: Total operational emissions of the Dutch built environment per year with projections into the future.

Year	**1990**	**2015**	**2019**	**2025**	**2030**
Emissions [Mt CO_2 eq.]	29.9	24.5	23.3	20.3	18.6

It is clearly observed that residential buildings make up for the highest amount of operational emissions. Zooming in on the specific differences between dwellings, Statistics Netherlands defines five types. The types, together with the mean annual energy consumption in 2020 as determined by Statistics Netherlands can be found in Table V [72]. They also found that, in 2016, the largest portion (42,5%) of Dutch residents lived in so-called terraced houses [73]. Terraced houses are those dwellings that are part of a row of attached houses. Within the type of dwelling, two sub-types are noted: the ones in between two houses and the ones at the end of a block (corner house) [74].

TABLE V: Mean energy use of dwellings per type in 2020, determined by Statistics Netherlands.

Dwelling type	**Gas consumption [m^3/year]**	**Electricity consumption [kWh/year]**
Apartment	750	1990
Terraced house (in-between)	1050	2850
Terraced house (corner)	1250	2970
Semi-detached house	1450	3290
Detached house	1910	4040

Considering the mean energy consumption of the different types of dwellings, and knowing the significant portion of Dutch residents living in terraced houses, it is hypothesized that the most positive impact can be made when focusing on these types of dwellings. While it may be true that in (semi-)detached houses on average more energy is used, the total amount of emissions potentially mitigated by focusing on terraced houses is expected to be larger due to the sheer amount of them being available. It is expected that, from the two sub-types, the in between type occurs multiple more times than the corner type. Accordingly, the focus of the rest of this research and thus the focus of the developed tool will be on this type of dwelling.

E. Renovation projects in the Netherlands

Now that the building type of focus is determined, a specific type of renovation shall be chosen to further develop the practical context of this research. By doing so, a more precise and demarcated direction can be chosen for the resulting tool, meant to stimulate market players to consider embodied carbon in renovation projects.

Renovation or retrofit is an important measure to reduce energy consumption and emissions in existing buildings [75], but can entail several actions. To be precise, a free translation of article 7:220, section 2 of the Dutch Civil Code (Burgerlijk Wetboek) dictates that renovation of residential buildings implicates *"[...] either demolition accompanied with new construction or partial renewal through alteration or addition."* [76]. In essence, this means that any type of renewal, alteration, or addition to a building or parts attached to the building (e.g. kitchen or toilet) is considered a renovation in the Netherlands. While it can be argued that the replacement of for instance a kitchen can help in mitigating operational emissions of a building, it is most likely not the main purpose of said renovation.

Keeping in mind the discussion of the above paragraph, the goal of this research is to facilitate more accurate sustainable decision making in the context of building renovations. Besides the type of building, the possible renovation projects conducted on the particular building is of importance for the balanced assessment of embodied and operational carbon. The particular renovations of interest are the ones that reduce the operational emissions of buildings. That is why a selection of renovation types should be made in which the most notable emission-mitigating renovations are included.

1) Making a selection of renovation types

The term 'renovation' involves a wide variety of alterations to a building and not every renovation might be as interesting for this research. Consequently, first, a boundary shall be established that eliminates the lesser sustainability-related renovations from the ones that are more relevant. Ultimately, the tool resulting from this research is meant to apply to all kinds of renovations, but for the data analysis part, the most meaningful results are hypothesized to come from renovations with a sustainable starting point. Accordingly, the renovations of focus are those that are meant to decrease the operational energy consumption of a building.

For existing residential buildings in the Netherlands, Arcadis, on behalf of the RVO, maintains an extensive database of the investment indicators of all possible energy-saving renovations [77]. This data is publicly available and can be requested by consumers to gain insights into the potential costs of a renovation resulting in higher energy efficiency. An overview of all measures listed in this database can be found in appendix A. These measures can be grouped in the following categories, as done by the independent environmental information organization Milieu Centraal [78]:

- Facade insulation
- Floor insulation
- Roof insulation
- Insulation glass
- Heat pump
- Solar water heater
- Biomass heater
- Solar panels
- Ventilation
- Consumption managers
- Heat recovery shower

From this list, three main types of renovation are identified: Insulation, primary energy measures, and secondary energy measures. An overview of the three main types with their respective measures is seen in Table VI. Looking at these renovations, it can be said that insulation in already existing buildings mainly focuses on the reduction of heat consumption - assuming that the buildings are heated with non-electrical technologies. Primary and secondary energy measures, on the other hand, might have a broader focus by tackling both heat and electricity consumption depending on the applied measure. This would be the case, for instance, if a heat pump would be combined with solar panels to electrify the dwelling and simultaneously reduce the necessary carbon-emitting electricity. That being said, research by Singh and others [79] shows that the adoption of heat pumps is subject to the quality of insulation per dwelling, which means that not all homes are equally fit for them. Furthermore, it is hypothesized that the renovation of a dwelling through insulation is a more effective type of renovation than the other options. For these reasons, the focus of this research will be on thermal insulation-type renovations, through which the heat requirement of a dwelling is reduced.

TABLE VI: Energy saving measures divided in three main categories as done by the researcher.

Category	**Insulation**	**Primary energy measures**	**Secondary energy measures**
Measures	Facade insulation	Heat pump	Ventilation
	Floor insulation	Solar water heater	Consumption managers
	Roof insulation	Biomass heater	Heat recovery shower
	Insulation glass	Solar panels	

2) A dive into thermal insulation renovation

The thermal energy consumption of a building is strongly dependent on the performance of its external walls, roof, and floor. Research has consistently proven that adding (better) thermal insulation to buildings is an effective measure to reduce the overall energy consumption because of more efficient winter heating and summer cooling [80–83]. The actual effectiveness of doing this, that is to say, the effectiveness of thermal insulation renovation, is evaluated on the basis of the applied material's thermal conductivity (k) and thickness (L). With these values, the R-value, or thermal resistance, of the material can be determined using Equation 1 [82].

$$R = \frac{L}{k} \tag{1}$$

In this equation, the thickness of the material L is described in meter, with the thermal conductivity k (sometimes denoted by λ) having the unit W/mK. From this, the unit for the thermal resistance R is found to be m^2K/W. The thermal resistance of the material can be understood as the ratio of the temperature difference between the two faces of a material to the rate of heat flow per unit area [84], thus a higher R-value means a better insulation. Naturally, from the definition it is understood that applied material with a lower k insulates more effectively. Equally, when the material is applied with a higher thickness L in total, the insulation becomes better. Especially for the thickness of insulation material, many researchers have focused on optimizing the value in terms of costs and environmental benefits [82, 83]. In the Dutch building sector, the thermal resistance together with the type of insulation material are used to identify and distinguish the used type of insulation. This is for instance seen in the Nationale Milieudatabase, where the environmental impact of the insulation is determined by means of its material type, thickness, and thermal resistance [85].

The other, often used, type of coefficient is the so-called heat transfer coefficient U. It is the inverse coefficient of the thermal resistance, giving it the relation as seen in Equation 2. The unit is correspondingly W/m^2K.

$$U = \frac{1}{R} \tag{2}$$

It goes without saying that insulation is usually applied along with two or more layers of a building, each with their own heat transfer coefficient/thermal resistance. The two outside layers, being into contact with air at a certain temperature, have an extra type of heat transfer coefficient: the convective transfer coefficient denoted by α or h, with its unit also being W/m^{2}K [86]. It can be described as the mode of heat transfer between a solid surface and the adjacent liquid or gas and correspondingly has a thermal resistance which can be found through Equation 3.

$$R = \frac{1}{h} \tag{3}$$

An example of the overall temperature profile of a wall with three layers of which the middle one is insulation would look like the one seen in Figure 9 as adapted from [87]. In this figure, five thermal resistances are identified: the convective resistances at the outer ends of the wall, and the conductive resistances of the materials themselves. The total thermal resistance is then obtained by using the equation as seen in Equation 4.

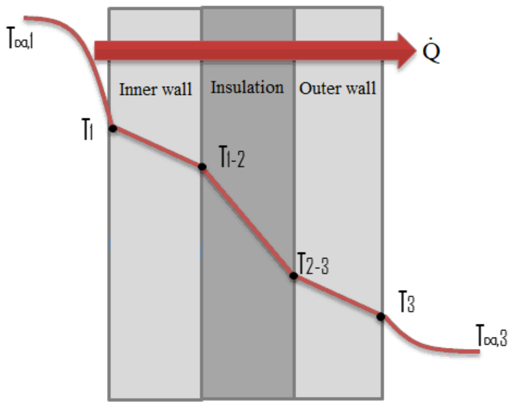


Fig. 9: An example of a multi-layered insulated wall.

$$R_{\text{tot}} = R_1 + R_2 + R_3 + R_4 + R_5 = \frac{1}{h_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} + \frac{L_4}{k_4 A} + \frac{1}{h_5 A} \tag{4}$$

The overall heat loss $\dot{Q}$ for this wall is then obtained from the relation as seen in Equation 5 where $\dot{Q}$ is given in W. ΔT is the difference between the two extreme temperatures, in this case $T_{\infty,1}$ and $T_{\infty,3}$

$$\dot{Q} = \frac{k_{\text{tot}} A \Delta T}{L} = \frac{\Delta T}{R_{\text{tot}}} = \frac{T_{\infty,1} - T_{\infty,3}}{R_{\text{tot}}} \tag{5}$$

When a renovation is carried out and better insulation is put in between the two existing layers of wall, the total thermal resistance of the wall rises, leading to a lower overall heat loss. This results in less heat being necessary for buildings and thus a lower share of operational carbon being emitted by the building. The difference in overall heat loss is defined by Equation 6. Especially this part is of importance for this research, as a balanced reduction of embodied and operational is sought after. Applying the aforementioned knowledge to renovations means that the heat loss of a building before and after a renovation can be determined. In combination with knowing the embodied carbon being emitted by the actual renovation, informed decisions about to be realized renovations can be made in terms of total saved carbon.

$$\Delta\dot{Q} = \dot{Q}_{\text{old}} - \dot{Q}_{\text{new}} = \frac{k_{\text{tot,old}} A \Delta T}{L} - \frac{k_{\text{tot,new}} A \Delta T}{L} = \frac{\Delta T}{R_{\text{tot,old}}} - \frac{\Delta T}{R_{\text{tot,new}}} = \frac{(R_{\text{tot,new}} - R_{\text{tot,old}})(T_{\infty,1} - T_{\infty,3})}{R_{\text{tot,old}} R_{\text{tot,new}}} \tag{6}$$

There is much more to be said about the different type of materials, their thermal conductivity, and thus their effectiveness in insulating a building. One could for instance choose to consider the radiation heat transfer as well, but going more in-depth than has been done here would be out of the scope of this thesis and is therefore left to the enthusiastic reader to find out for themselves.

When renovating a building, the insulating material is produced, transported and applied. Often the building undergoing renovation already has insulation - it would have a lower thermal resistance, otherwise, the renovation would be counterproductive - which needs to be removed and either disposed of, recycled, or reused. Referring back to the aforementioned EN 15978 standard, the following is noted about replacements:

"Replacement is limited to the installation [of] an item that has the same function as the item it replaces because the original item has reached the end of its technical service life. Replacement may also be undertaken for other reasons such a 'fashion' (e.g. flooring or decorative surfaces being replaced before the end of their service life), if this is a planned action. Thereby, replacement can be distinguished from refurbishment and from replacement of parts of an item, which can occur during planned maintenance, but which is not a full replacement of the item" [30, p. 135].

When a building's insulation is replaced, chances are the end of the technical service life of the original insulation has not been reached yet. Arguably, the renovation can be said to be for another reason than that, with the main purpose being 'sustainability'. The action itself is considered planned, for the reason that unplanned actions in the context of a building are defined as *ad hoc* manners in response to breakdowns or user requests [88]. Hence, the replacement of insulation, albeit without the original material reaching the end of its service life, is assessed in component B4 'replacement'. The boundary for replacing products in a building is dictated by EN 15978 to include the production and transportation of the new parts, the process of installing them, and waste management of the removed parts including their end of life treatment [30]. The embodied carbon contribution of the renovation then consists of the stage components A1-A5 of the new insulation and C1-C4 of the original insulation. If the building did not have insulation beforehand, meaning insulation is applied to the building for the first time, only the stage components A1-A5 of the new insulation need to be considered. Like mentioned before, the reuse and recycling of material generally do not negatively count towards the embodied carbon to prevent double-counting of negative emissions.

F. Discussion of findings

The analysis of renovation types for a dwelling in the Netherlands gives room to give an answer to the second sub-question of this thesis (SQ 2): *"What empirical context should be the focus point for the to be developed tool?"*. The Dutch built environment was investigated, in which multiple types of buildings were identified. The choice was made to focus on terraced dwellings, as it is expected to be the dwelling type with the highest potential to mitigate overall emissions in the existing built environment. For these dwellings, three main categories of renovation types are identified: thermal insulation, primary/direct energy savings, or secondary/indirect energy savings. From these three types, the thermal insulation category has been chosen to lie the focus of the to be developed tool on, facilitating market players in this field with the ability to reduce the embodied and operational carbon of thermal insulation renovation projects simultaneously.

Looking at the chosen renovation type, the choice was made to focus on thermal insulation, answering the second sub-question of this research. It was found that, according to the aforementioned standard, when considering replacement, the stage components A1-A5 of the new and C1-C4 of the original insulation need to be accounted for. When applying completely new insulation without the dwelling having it before, only the stage components A1-A5 of the new material are of importance for the assessment of embodied carbon. The mitigated operational carbon can then be determined at the hand of carbon conversion factors, which are established in Dutch legislation. For natural gas, the conversion factor is 0,183 kg CO_2 eq./kWh. For electricity, the factor is said to be 0,34 kg CO_2 eq./kWh.

While doing this research, it is of the utmost importance that the resulting tool of this thesis can be generalized later on, such that renovations other than insulation-related ones can be included as well. Though the focus of the conducted research will be on one type of renovation, only by making a tool that applies to many different situations, real impact can be made in the field of sustainability-related building renovation. In order to achieve this, the tool should allow for a convenient way for the user to specify what part and how much of that part of the building is being renovated. In the established practical context, the aforementioned features will thus be implemented on terraced in-between type dwellings and thermal insulation renovation projects.

V Stakeholder analysis

A. Introduction

From the practical context deducted in the previous section, an analysis of stakeholders regarding embodied carbon within this context becomes possible. Specifically, the drivers and barriers to reduce embodied carbon in thermal insulation renovations for terraced in-between dwellings are sought after for important stakeholders. By laying out the factors influencing market players to act on or refrain from reducing this embodied carbon, a strategy can be developed to overcome the present barriers and ultimately achieve truly sustainable decision making in this process. In order to be able to do that, though, the stakeholders in this socio-technical system should first be identified. This section presents the analysis of the stakeholders in this context on the basis of the Stakeholder Salience Model (SSM), answering the third sub-question of this research (SQ 3): *"What stakeholders should the to be developed tool be designed towards?"*.

The stakeholder analysis is followed by a deeper dive into the most important stakeholders, which helps in finding an answer to the fifth sub-question about the barriers and drivers for market players in this context (SQ 5). However, as the fifth sub-question will also be partly answered by the policy analysis, the answer to this question is presented in section VII.

B. Stakeholder identification and analysis

1) Governments and policymakers

The first identified stakeholders are governments and policymakers on all different levels in the Netherlands, such as municipalities, the Dutch House of Representatives and even the European Union. Governments and policymakers in this context are those that design, impose, and enforce the rules and regulations around renovation projects. The market value of reducing operational and embodied carbon is seen to be of (inter)national interest because of the aforementioned Paris Climate Agreement, next to the more detailed ambitions of different government organizations to bring down their carbon footprint. With these ambitions and reduction targets in mind, a certain amount of urgency arises to reduce overall carbon emissions, in which the construction industry of the Netherlands is a major contributor. Additionally, since governments make the policies that dictate what all other actors in this context need to comply to, they are clearly found to have the power to impose their own will, and potentially even force a market value from, for instance, the 'price on carbon'. That being said, they are less involved with the specifications of reducing emissions in this context, making them lack legitimacy. Governments are identified as dangerous stakeholders, of whom the needs should not necessarily be met, since they are not involved in the projects in which they are not also the occupant.

2) Investors

Parties investing in Dutch dwellings, like financial institutions or individual investors, are potentially quite an important type of stakeholder in this context. Investors are parties that utilize their financial assets for the purchasing or enhancing real estate without the intend of solving their own housing needs [89]. While they need to adhere to existing regulation, the interpretation and translation of these rules are determined by the ones paying for it. Hence, legitimacy and power are certainly attributes belonging to investors. Currently, with investors not consistently focusing on reducing operational and embodied carbon in a balanced manner, no urgency is identified in their behavior and/or position. However, the goal of this research is to find the urgency for investors to start doing so. Hence investors are expected to have a high amount of urgency for this market value, especially with potential regulations becoming more and more strict. This makes investors definitive stakeholders, the most important type according to the SSM. The requirements and needs of investors should therefore undoubtedly be taken into account within the context of this research.

3) Developers

Developers are the market actors that build, redevelop, or refurbish buildings in order to make a profit. They are involved in the project from start to finish, including acquisition of land, design, and construction. Currently, developers have not seen the necessity of reducing embodied carbon as an integral part of their decision-making apart from the MPG regulations [3], while they are the ones that have the most power in this field. Their legitimacy and urgency are found to be high, too, through their active involvement in the design and completion of renovations and the increased level of scrutiny of embodied carbon by policymakers [13], respectively. Consequently, developers are concluded to be definitive stakeholders too.

4) Designers

Investors and developers are the parties that start the phases preliminary to the realization of a project. Designers, on the other hand, become involved once the conceptual phase is nearly done. They are the ones driving the concept- and detailed design phases, conforming to regulatory codes and the requirements as set by the developers and investors. Being bound to the budget and expectations of the two aforementioned parties, they are less in control of the decision-making. Since designers are an indispensable part of renovation projects, their involvement in the decision-making is observed to be appropriate. Be that as it may, with the budget coming from, and significant parts of the profit going to, investors and developers rather than designers, there is less urgency for them to find the market value in reducing embodied carbon. These reasons combined make the designers discretionary stakeholders, having some, but limited, ability to steer projects through their design and advice.

5) Demolishers

Demolishers in renovations are those who dismantle, raze, destroy or wreck any part of a building in order to prepare it for the application of new materials. The emission of lower values of embodied carbon itself is not necessarily an important matter to them. Nevertheless, if more future-proof materials are used in buildings and the demolisher dismantles the building in a smart way, they can experience added value from selling the acquired high-grade building materials. As a consequence,

[3] The current MPG method is not enforced in the context of renovations and therefore not considered by the stakeholders.

both urgency and legitimacy can be attributed to this stakeholder. As the demolisher does not determine what new materials will be applied in a renovation, the power characteristic is not attributed to them. This makes demolishers dependent stakeholders, who could certainly benefit from a transition to lower embodied carbon emissions, but lack the power to enforce their stake.

6) Contractors

Contractors are a special case of stakeholders in this context, being involved in the final stages of a renovation. They plan and coordinate the realization of the renovation and must complete the project within the time and budget earlier established by investors and developers. As a central knowledge hub of the construction industry, contractors are the parties being able to control the supply chain and ultimately the carbon emissions from the materials. In terms of decarbonizing renovations, they have an indispensable role to play in reducing the emissions in their part of the equation, giving them both power and legitimacy in this context. The urgency for the market value of reducing embodied carbon is less observed by contractors, though, as this urgency depends on the investing and developing parties and their requirements and expectations. This makes the contractor a dominant stakeholder, whose needs shall be considered due to their high level of involvement.

7) Occupants

Occupants of dwellings are the final stakeholder that will be considered in this research. Presuming that the occupants of the dwellings are not the ones investing in it, meaning they are not the owner of the dwelling themselves but are rather renting them, they have limited legitimacy nor urgency for the embodied carbon in renovations to be reduced. What they can do, however, is impose their will through the collective effort of not renting dwellings that are not up to par in terms of embodied impact. That is, if they decide to do so, since there is no market-related urgency for them. One could argue that occupants might decide to act on their power, depending on causes or concerns on both a social and public level. This makes them dormant stakeholders.

8) Discussion of stakeholders

In this section, a grasp of the most important stakeholders regarding the economic and strategic value of embodied carbon in renovations has been given on a sector level. Answering the third sub-question of this research (SQ 3): *"What stakeholders should the to be developed tool be designed towards?"*: Stakeholders have been identified and classified according to the Salience Stakeholder Model. An overview of their classifications can be seen in Figure 10. Upon analyzing the stakeholders, investors and developers were found to be the most important, as they exert the most amount of influence in this context. Government and policymakers were identified to be dangerous stakeholders, who possess both the urgency for embodied carbon to have economic and strategic value and the power to create it through legislation. Contractors are the dominant type of stakeholder here, meaning they have a legitimate interest in the project and should therefore be managed closely. Demolishers are observed to be dependent stakeholders, who could experience added value from materials with a lower embodied carbon, if said materials would be reusable after obtaining them.

Now, it should be noted that one certain party can make up for two or more stakeholders, possibly giving them multiple attributes. For example, the Dutch government real estate company (Rijksvastgoedbedrijf) is the party that owns and maintains buildings belonging to the Dutch

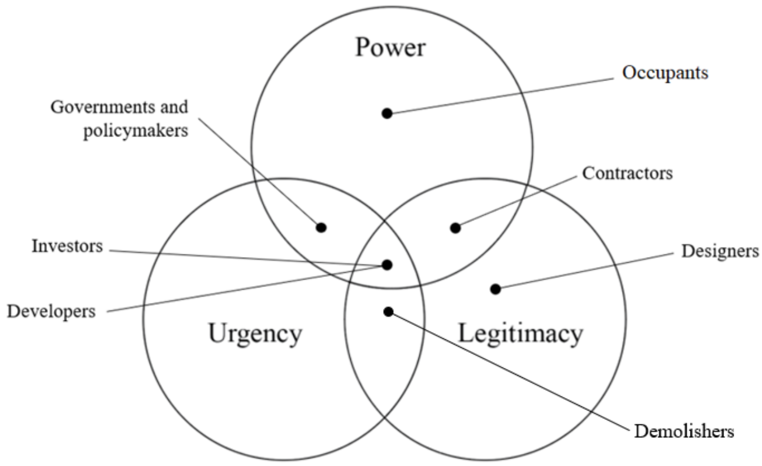


Fig. 10: An overview of the discussed stakeholders in the Salience Stakeholder Model.

government. If a dwelling of theirs - which they do own [90] - is renovated, the Dutch government would be policymaker, investor, and developer in one. This would give them all the traits to be a definitive stakeholder in this context.

There are certainly more stakeholders that can be thought of regarding embodied carbon. One could for instance think about material manufacturers. Though they would possible make for an interesting stakeholder in the investigated socio-economic system, exploring the manufacturing and supply chain side of this context is presumed to be a whole research in and of itself. That is why, for the sake of the scope of this research, they will not be considered as stakeholders, leaving the world of manufacturing with respect to embodied carbon one to be investigated.

C. Key stakeholders

Like explained before, investors and developers were identified to be the key stakeholders in this socio-technical system, with contractors being the only ones in the second most important group. Governments and policymakers are considered less important due to their attributes making them dangerous stakeholders in accordance with Mitchell's Salience Model [45]. Now, the question arises what lies beyond the general terms used for these stakeholders, seeing the interrelation between them and how they influence trends and developments in the market. This is the first step toward answering the fifth sub-question of this study (SQ 5): *"What barriers and drivers in the socio-technical system of renovations in the Dutch built environment need to be respectively overcome and enhanced for market players to not only actively pursue operational, but also reduced embodied carbon?"*. This section, together with the policy analysis, are used to answer the fifth sub-question.

1) Investors

The investors in Dutch dwellings can be of different natures. Differently oriented investors can be thought of, which can generally be described through two different attributes: non-profit and commercial. The non-profit part of the Dutch housing market is described by the EU as a Service of General Economic Interest (SGEI), which is completely made up of regulated social housing associations in the Netherlands [91]. The commercial part, however, consists of many different parties investing in middle range to full market dwellings with the intent to make a profit from them.

Parties that can be thought of in this context include financial institutions, like banks and pensions funds, and individual investors [92]. A scheme of the two different types of housing market investors is seen in Figure 11, based on the description and scheme by Barros [93].

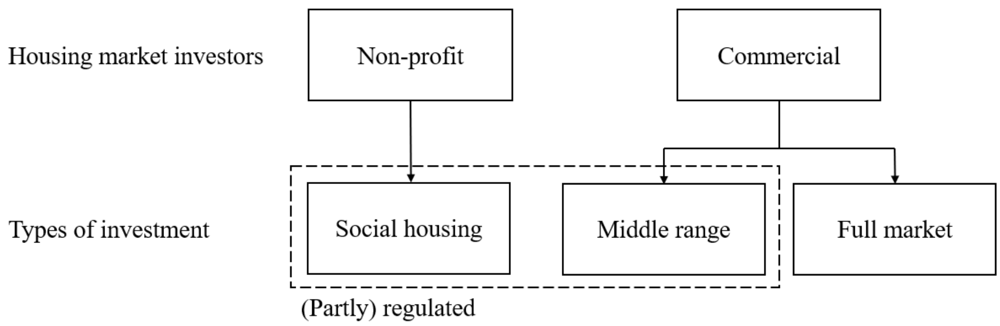


Fig. 11: Investors in the Dutch housing market.

Seeing that non-profit organisations in the housing market already have ulterior motives instead of improving their market positions through the buildings they invest into, especially the commercial market players are of interest in this context, taking in mind the goal of finding economic and strategic value for reducing embodied carbon. The importance of environmental issues regarding buildings is being acknowledged more and more by commercial institutions. Private investors of real estate have been trying to achieve these goals recently through the so-called Environmental, Social, and Governance (ESG) considerations, which are increasingly applied as non-financial factors that play a role in risk and growth assessments of potential investments [10, 94].

Following the increasing concerns among people and institutions on the topic of global warming, the ESG objective is becoming a significant focus point in asset acquisition and management. In order to make decisions and the risks or challenges involved measurable, ESG rating agencies assess corporate sustainability performance of businesses based on their investments and policies [95]. An example of such an agency is Sustainalytics, which measures a company's exposure to industry-specific ESG risks and evaluates how well a rated company is managing those risks. They have become a global leader in this field thanks to the agency not restricting itself to a specific geographic region [96]. Over time, ESG ratings have evolved into an important reference for corporate sustainability assessments.

Still, in terms of ESG performance, a lot of uncertainty is present. Avramov and their fellow researchers describe this phenomenon as follows: *In the absence of a reliable measure of the true ESG performance, any attempt to quantify it needs to cope with incomplete and opaque ESG data and non-structured methodologies. A meaningful illustration of uncertainty about the ESG score is the pronounced divergence across ESG rating agencies"* [97, p. 2]. The uncertainty experienced by investors on the ESG ratings has been proven by them to result in less sustainable investments because of negatively affected risk-return trade-off, social impact, and economic welfare.

This uncertainty is not the only factor leading to investors turning away from sustainable buildings or investments. The contemporary argument for a reduction of embodied carbon from buildings are primarily rooted in environmental and social, rather than economic terms. High capital costs and long payback times are feared among the investing stakeholders within renovation projects [6, 10]. Zhang et al. [98] found that the narrow understanding of economic viability for more sustainable buildings result in concerns about financial performance, which has been undermining the adoption of 'green buildings'[4]. They argue that commercial players in the market need to be persuaded into seeing that 'going green' can be as economically viable or even more so than using traditional building methods.

The fact that investment enterprises do not see the economic viability of more sustainable material for renovations can have numerous reasons. Most sustainability-related measures require initial investments during construction and realization, making the incremental costs for buildings higher. Dwaikat and Ali [101] investigated 17 empirical studies on the topic of green building cost premiums. The results show that the upfront costs for building owners and investors range between -0,4% and 21% of the less sustainable options. Only two of the investigated sources show a decline in costs, leaving a considerable majority to report higher required initial investments. Although they mention that literature on this topic has not reached maturity yet, it is concluded that little evidence supports the argument that green buildings would cost less than their conventional counterparts. It should be taken into account that the greater part of these studies come from cases in the United States of America and it can certainly be argued that economic factors playing a role in that country significantly differ from the ones in the Netherlands. Nonetheless, while research on the topic of Dutch green building projects could not be found, the same trend is expected to be found there, if one were to investigate it. Specifically, it is expected that little to no evidence would suggest that low- or zero-carbon materials would be beneficial to initial investment costs, as no research to date has significantly proven that this would be the case anywhere.

Above mentioned economic viability of using more sustainable materials against conventional materials is arguably only the case if the same renovation is considered. Naturally, a decision could be made for using less materials altogether. By doing that, the renovation itself would be less effective, but the net amount of carbon emissions could be lower because of the reduced embodied carbon. This way both financial and environmental gain is achieved.

Moreover, an analysis on ESG data as conducted by Auer and Schuhmacher [96] has shown that environmentally positive investments in the European financial sector lead to a similar financial disadvantage as compared to conventional investments. In this research, the 'financial' sector includes a number of investor types, among which banks, insurance organizations and investors in real estate. The researchers report their findings as robust evidence that investments based on environmental considerations in Europe do not necessarily result in a market advantage. With the growth of financial institutions staying the same through both conventional and sustainable pathways, combined with the initial investments for buildings becoming higher due to costly low-carbon materials, the overall financial profit experienced becomes lower than when choosing not to partake in this development.

2) Developers

Developers can be said to be the intermediary of property projects, being in contact with both investors and contractors. They are said to be one of the most powerful actors throughout the building and construction value chain, due to them standing in between and interacting with multiple stakeholders [7, 15]. Building and construction developers have the following responsibilities as seen

[4]The term 'green buildings' covers a broad range of sustainable measures taken in the construction sector, including but not limited to the reduction of noise, dust, waste and water pollution, incorporating sustainability in every phase of the building process [99]. By default it also considers a reduction of embodied carbon in the construction and renovation phases of buildings [100], thus rendering the term relevant to this research.

in the list below [102]. From this list, it becomes clear why developers would have a legit saying in the reduction of embodied carbon, given that they are involved in such a significant part of the value chain.

- Searching for adequate building locations in the case of a new building;
- Conducting feasibility studies;
- Making designs and plans that fit the investors' need;
- Making plans and budgets for the project;
- Communicating with stakeholders throughout the whole value chain;
- Managing consultants, architects and contractors;
- Selling the property, if applicable;
- Consulting the potential buyers of the property, if applicable;
- Managing and checking project-specific budgets.

Zhang et al. [98] report that, especially for developers, the economic viability of 'going green' is still a disputable topic. One of the main reasons mentioned for this is the fact that incremental costs of sustainable buildings are endured by developers, while the benefits, if any, are experienced by the occupants. Additionally, as explained by Deng and Wu [103], the purely financial benefits from opting for sustainable building design for developers can only come from the buildings' occupants, which would be at most a portion of the total benefits compared to the costs. In the corresponding paper by Deng and Wu, it is concluded that developers might not obtain meaningful economic returns from their efforts.

Especially in the case of reducing embodied carbon in renovations, other than ESG related targets, no benefit is gained by any stakeholder resulting from opting for less carbon-heavy materials. And, even if there is an advantage to using those (or less) materials, the observed benefit-cost mismatch between developers and occupants makes it so that most developers have not seen the economic viability of it. This dilemma of not receiving all benefits while being responsible for all costs may discourages developers from further participation in future sustainability-related investments.

With that being said, one might question whether there even is a benefit to be found for developers reducing embodied carbon in renovation projects. A couple of benefits can be noted, though. When choosing for more sustainable materials for renovations, a higher score in certain building certifications, such as BREAAM, WELL, or LEED, can be obtained. This in turn results in an increased market value, as described and concluded by Eichholtz et al. [104]. Deng and Wu conclude, in this context, that *"residential property developers [...] can be expected to be able to capture more benefits from their green investments in the future, when green building development is familiar to more market participants and made use of"* [103, p. 43]. Moreover, an enhanced internal and external corporate reputation is mentioned as a benefit, albeit an intangible one since it cannot directly be expressed in financial terms.

3) Interrelation of stakeholders

The interrelation between investors, developers, and occupants is identified to be one of the key interaction mechanisms in this market, of which the diagram corresponding to this interrelation is shown in Figure 12.

From this figure of interrelations, a couple of things become clear. Firstly, the investment of reducing

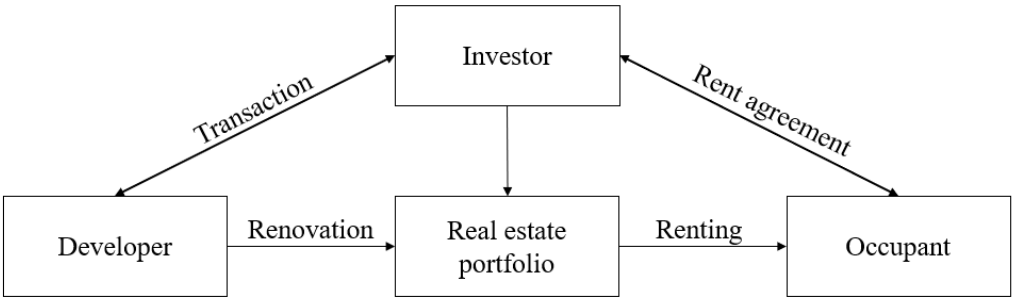


Fig. 12: Interrelation of the most important stakeholders regarding sustainability-related renovations of dwellings.

embodied carbon in renovations starts with one stakeholder, while the financial benefit is obtained by another. That being said, although the renovation itself results in added benefits for the occupant -e.g. less operational costs, increased comfort [103]-, the reduction of carbon throughout the process of that particular renovation does not. Hence, the occupant is might be willing to pay extra for the experienced benefits, but the incremental costs of investment for less carbon-heavy materials might be of less concern to them. Secondly, with the investor being the intermediary of the three stakeholders mentioned in this model and ultimately deciding what happens to a building due to their financial power, they can be said to be the most important actor in this socio-technical system. That is why the focus of the remainder of this research and the proposed tool will be on these stakeholders. According to the definition as laid out by CBS, the institutional investors of dwellings can be pension funds, insurance companies and investment funds except for money market funds [105]. Notable institutional investors in the Netherlands include parties like Rabobank, ABN AMRO, Delta Lloyd, Syntrus Achmea, and Amvest [106].

VI Policy analysis

A. Introduction

The previously conducted stakeholder analysis discusses the key stakeholders in the earlier established practical context of this research. This section consists of a policy analysis that highlights the main developments for the reduction of embodied carbon in the Netherlands and how it affects said key stakeholders. This section thus aids to answer the fourth sub-question stated in this research (SQ 4): *"What (inter)national policies exert influence on the identified key stakeholders regarding embodied carbon in renovation projects?"*. It also serves as an additional step of exploring all factors that are related to the successful integration of reduced embodied carbon in renovation projects, finding barriers and drivers for the aforementioned stakeholders in this context. This, in turn, helps answering the fifth sub-question (SQ 5): *"What barriers and drivers in the socio-technical system of renovations in the Dutch built environment need to be respectively overcome and enhanced for market players to not only actively pursue operational, but also reduced embodied carbon?"*. By seeing what efforts are made and how they are handled at the moment, informed decision making with respect to the timing and magnitude of sustainable investments can be made. As explained before in the stakeholder analysis, both the policy and stakeholder analyses are considered relevant for answering the fifth sub-question. That is why the answer to this question has been formulated in section VII.

B. European legislation

The term "decarbonization" has gained more and more interest from policy makers, from businesses, and in academia throughout the whole of Europe. The Intergovernmental Panel on Climate Change (IPCC) explains the term as *"the process by which countries, individuals or other entities aim to achieve zero fossil carbon existence"* [107]. Within the European Union (EU) Several efforts are made by different parties to reduce carbon emissions in, and ultimately decarbonize, the built environment and construction industry. One of the ways that have often been mentioned in international policies for acquiring this goal is to renovate buildings.

1) European Green Deal

In the recently released European Green Deal proposal of the EU, it is mentioned that the current European renovation rate should at least be doubled in the next ten years in order to reach the EU's energy efficiency and climate objectives [108]. The commission working on the proposal alludes to having the ambition to renovate 35 million buildings by 2030. Although one might expect the execution of this ambition to result in more sustainable buildings and less operational energy use, not every renovation's primary goal is to achieve that, as explained before in section IV. Adding to that, different member states of the EU have their own interpretation of what renovation entails, which might lead to even more skewed sustainability-related results in this context. Therefore, not the amount of renovations is important for a more sustainable built environment emitting fewer greenhouse gases, but rather the type and effect of the performed renovation. Counting renovations with another main purpose than making a building more sustainable towards the goal of renovating 35 million buildings would not be in accordance with the newly adopted Green Deal and would defeat the purpose of having such policy.

What is more noteworthy, though, is the policymakers' prospect of reducing so-called "whole life-cycle carbon emissions" in buildings. Quoting the stated plans in section 3.5 of the policy: *"[the Commission] will address the sustainability performance of construction products in the context of its revision of the Construction Product Regulation and it will develop by 2023 a roadmap leading up to 2050 for reducing whole life-cycle carbon emissions in buildings. The Commission will also accelerate work with standardisation organisations on climate resilience standards for buildings"* [109, p. 16]. By the end of 2024, the commissions plans on reviewing material recovery targets for construction and demolition waste, after which specific measures will be taken that stimulate the reuse and recycling of building materials.

This passage in the policy highlights a predicament present in the current embodied carbon situation. There is a clear lack of certainty in terms of amount and type of whole life-cycle carbon emission reduction. Hence, even if organizations would lay their focus on reducing embodied carbon in renovation projects in anticipation of future policies, it is unclear whether these efforts would be enough or even in the right direction. Not only that, but given the high complexity of stakeholder interrelations regarding this issue, a diffusion of responsibility may be the outcome of institutional ambiguity in the upcoming policy. Relating this to the nine lives of uncertainty in decision making of Dewulf and Biesbroek [110], different frames about the policy or how they should be applied might result in organizations exploiting this ambiguity by bending its meaning to their own advantage. It might even be so that the upcoming policy is stated in such a way that interpretations of it result in limited to no responsibility for the stakeholder reviewing them. This would in turn mean that, at least from the point of policy, the stakeholder would experience no strategic value by reducing embodied along with operational carbon. Applying the concerted strategies for mitigating this risk entails aligning interpretations of rules between stakeholders. Additionally, through multiparty negotiations, internationally renowned non-ambiguous policies can be established that drive the involved market players to reduce the carbon footprint of their renovations.

2) Emissions Trading System

The European Emissions Trading System (ETS) is a market-based institution established to reduce carbon emissions on an international level. It has been a flagship "cap-and-trade" system used by governments to set an allowable total amount of emissions over a set amount of time (cap), issuing tradable emission permits to emit the set amount (trade). These permits can be used as currency in carbon markets. When organizations reach a deficit of permits as compared to their total emissions, they are obliged to buy extra permits from the carbon market, compensate through offset credits, or pay a heavy fine [111]. Since there is a decreasing maximum number of permits given out each year, permits to emit CO_2 equivalent greenhouse gases become worth more and more. As a consequence, emitting organizations are prompted to make informed decisions about investment strategies regarding their emissions[112, 113]. With an annual reduction factor of 2,2% of total permits handed out starting in 2021, the decrease in carbon cap within the market has been accelerated by 26% as compared to 2013-2020, making it an even more pressing matter.

Currently, the European ETS is limited to the following sectors [111]:

- Electricity and heat generation;
- Energy-intensive industry sectors including oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals;
- Commercial aviation within the European Economic Area;
- Production of nitric, adipic and glyoxylic acids and glyoxal;
- Production of aluminium.

These sectors together cover around 50% of the total carbon emissions in the EU. As can be noted from the list above, the production of materials for buildings (e.g. steel works, metals, cement, glass) are covered under the established ETS. With the price of permits increasing fivefold from 2013 to 2018, coal power emissions have fallen by 43%, which is said to be largely resulting from the ETS and its price increases [114]. Supporting this claim, Bayer and Aklin [112], in their article on the results of the EU ETS, show that especially since 2013 the average treatment effect of the EU ETS has become increasingly negative, depicted in Figures 13a and 13b. It is hypothesized that particularly the steady decrease of available carbon emission permits, inextricably linked to an increase in price, are an acceleration to the average treatment effect.

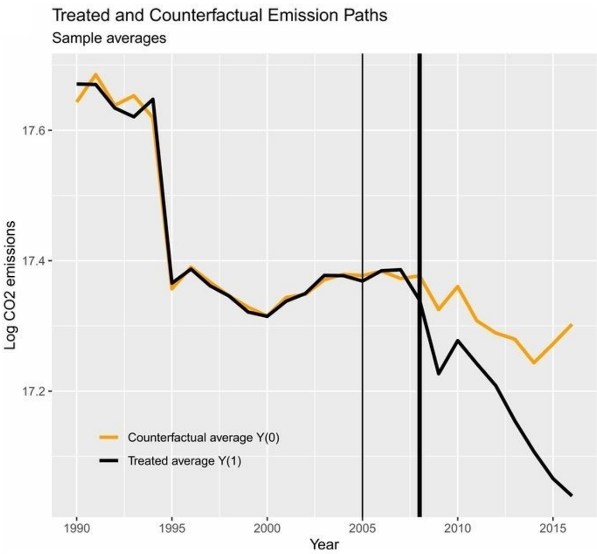
This trading system, despite observers expressing their skepticism about the system and its seemingly low carbon prices [112, 115, 116], has been proven to positively affect the reduction of carbon emissions in the EU. By increasing the price of carbon emission permits, market players are prompted to invest in their energy sources and/or efficiencies, making the overall embodied carbon of resulting products lower. Accordingly, a higher market share of products with a low embodied carbon value make the adoption of these products more convenient for both investors and developers.

C. Dutch legislation

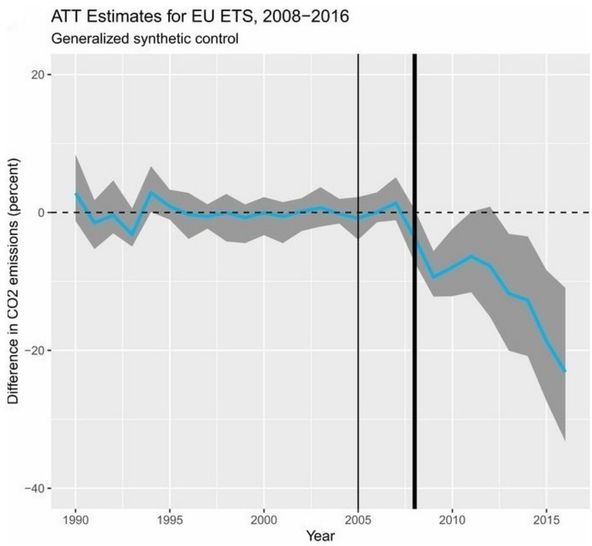
1) Energy labels

In the Netherlands, one of the main methods of assessing a building's sustainability is by determining its energy label. With an established energy label, occupants, potential buyers and sellers can immediately see how energy efficient a dwelling is, and what can be done to make the dwelling more energy efficient [117]. The labels range from category G (worst) to category A++++ (best) on the basis of a so-called 'energy index', which is calculated through the total primary energy demand. The exact method for calculating a dwelling's energy index is documented in the NTA 8800 standard [118]. For every step in getting a better label (e.g. from 'G' to 'F' or 'A' to 'A+'), sustainability related measures have been determined. The Dutch government obliges everyone looking to sell, rent or deliver a dwelling to determine its energy label through accredited parties [119].

Majcen et al. [120] have proven that, while not entirely accurate, there is a clear relation between the annual energy consumption of a building and its energy label. The discrepancy between the theoretical and actual gas consumption per energy label is seen in Figure 14. Moreover, as the researchers laid out in their paper on the topic of the Dutch energy label system, the labelling of energy performance of dwellings plays a crucial role to reduce operational energy consumption. By making the sustainability performance of a building measurable, the government can pose rules to follow in order to promote and stimulate renovation work and the construction of highly efficient



(a) Effect of the EU ETS over time. The mean CO2 emissions paths for actual (black line) and counterfactual (yellow line) emissions.



(b) The estimated average treatment effect of the EU ETS (blue line) and bootstrapped 95% confidence intervals (grey area).

Fig. 13: The overall effect of the EU ETS measured over the years. The thin and thick vertical black lines in both figures mark years 2005 and 2008 respectively.

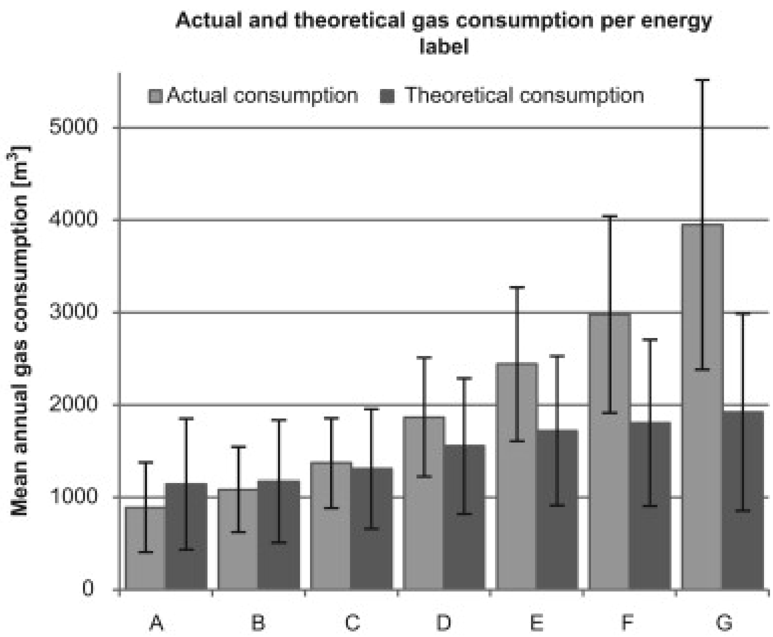


Fig. 14: Actual and theoretical gas consumption in m^3 per m^2 of dwelling area per label.

buildings. An example of the opportunities it brings is seen in the Dutch office building real estate sector, in which the government obliges everyone to renovate their office buildings to label 'C'. If this measure is not successfully realized by 2023, the office building in question cannot be utilized anymore [121]. This places incentive on stakeholders to renovate their buildings in order for them to be future-proof. Next to that, a stakeholder-specific strategy can proof valuable in terms of this energy label, seeing that governments are obliging parties to improve the energy efficiency of their buildings.

Next to the obligatory incentive posed by the Dutch government, an increase of a building's energy label has been linked to an increase in value for that piece of real estate. Van Eersel [122] showed through statistical analyses that the tightening of the Dutch energy label obligation in 2018[5] has had an increasingly positive impact on the rental value of offices. Next to that, Chegut et al. [124] found that for data from 2015, a better energy efficiency of dwellings in the Netherlands has a significant relationship to higher external valuations. Consequently, stakeholders are incentivized to renovate their real estate such that their portfolio is valued better in the building market, next to the fact that they need to keep up with increasingly stricter policy measures.

While the introduction of this energy rating system for dwellings can be argued to be an effective development, prompting market players to keep the value of their real estate up to date, it is observed that the system focuses solely on operational energy use. In other words, the system is disregarding the carbon emissions from the sustainability measures taken to achieve a certain energy label. It then poses no surprise that stakeholders choose to partake in reducing their operational, rather than their embodied emissions, instead of doing both in an optimized manner. Because of the disregarded initial emissions of renovations, the embodied carbon could diminish or even outweigh the mitigated operational carbon over the relevant lifetime of the renovation materials. Additionally, the incentive to achieve the highest possible energy label posed by this system could stimulate stakeholders to implement renovations with a marginal operational emissions mitigation, but with a high amount of embodied emissions.

Additionally, the incentive for stakeholders to renovate to a certain energy label without considering embodied carbon could result in them using more materials than would be optimal both in terms of sustainability and investment. Naturally, using less materials reduces the initial investment necessary for a renovation. That being said, with the current energy labelling system, not a minimal amount of emissions is being pursued, but rather a minimal amount of operational emissions.

2) MPG

The Dutch government is making efforts to incorporate the environmental impact of materials into sustainable decision making in the built environment. An example of such an effort is the MilieuPrestatie Gebouwen (MPG) calculation method. The MPG calculation results in the environmental impact of all building life cycle stages as seen in EN 15978, except for modules B6 and B7. These two stages, like mentioned in the theoretical framework, describe the impact of energy instead of materials. The calculation itself can be done by performing LCAs for the used materials or by using the embodied carbon data registered in the Nationale Milieu Database (NMD), or a combination of both [9]. In the words of the Dutch Enterprise Agency (RVO), *"the MPG of a building is the sum of shadow costs of all materials applied to that building. [...] The materials*

[5] In 2018, the Dutch government tightened the legislation of energy labels, such that parties are obliged to disclose the label for every mutation or transaction of their real estate [123].

replaced throughout the lifetime of a building should be considered too" [9]. Currently, the MPG is only applicable to new office buildings bigger than 100 m^2 and newly built houses, but the Dutch government is looking into how this legislation can be applied to renovation projects for existing buildings as well [125].

The truthfulness and thereby the effectiveness of the MPG, however, has been disputed by renowned market- and research-oriented parties. An example of such criticism is found in the report by TNO about the carbon storage potential of natural wood [126]. In this piece, the writers highlight the fact that negative emissions from growing wood is not taken into consideration by the current MPG method, as in accordance with the European-wide agreements on LCA methods. In order to determine the severity of this mismatch between actual and reported emissions, a case study was conducted on three different construction procedures and the reported emissions with or without accounting for the stored carbon. They concluded that, considering a material lifetime of 100 years, a halving of emissions is observed if the storing potential of natural wood is considered compared to not doing so. In the case of cross-laminated wood, the net reported emissions even become negative, meaning more carbon is stored than emitted.

With the current MPG method as it is, potential negative emissions from natural materials are not taken into account, making them just as unsustainable as human-made materials without such impact, like concrete. The choice of not considering the positive environmental impact of materials can be argued to give an inequitably negative stigma to those materials, while in reality they are more sustainable than the MPG lets them seem. As an exemplary result, still a lot more concrete is used for the structure of Dutch buildings as opposed to wood [127].

D. Sustainable certification schemes

As can be observed from the policy assessment so far, policymakers see the significant role the built environment plays in reducing carbon emissions on a large scale. The desire for international standards and social brand recognition in this field led to the global adoption of sustainable building certification methods. Such methods are increasingly being used to mainstream green building practices, with institutions and governments making it required building performance standards [128]. With it, buildings can be evaluated, enhanced, and sustainability can be promoted through these methods. The most notable certification methods currently used for residential buildings in the Netherlands are the Building Research Establishment Environmental Assessment Methods (BREEAM, or BREEAM-NL) and Leadership in Energy and Environmental Design (LEED) [128, 129].

Sustainability rating systems such as BREEAM and LEED consider three stages, similar to some of the stages in a life cycle assesment [130]:

- Classification: determining the impact category based on various in- and outputs;
- Characterization: identifying the impact of each in- and output with relation to the categories;
- Valuation: weighting the categories in comparison to each other.

Through this process, a building can be rated on different effects, leading up to a total score for the sustainable aspects of that particular building.

The economic value of high scores by these assessments has been investigated by Chegut, Eichholtz and Kok at Maastricht University [131]. They conclude that, for the United Kingdom at least, the rent of buildings having a high BREEAM scoring tend to be higher than those with a lower scoring or none at all. They state that due to *”institutional demands investors and tenants face from corporate social responsibility initiatives, government regulations and globally binding carbon reduction commitments”* [131, p. 24], a growing demand for ”green” real estate is observed.

1) BREEAM

The BREEAM-NL In-Use scoring, particularly meant for residential renovations in the Netherlands, is done by summing the credits achieved for each (environmental) category. The percentages of credits achieved per category are then multiplied by the weighting per category, with the categories and weightings shown in Table VII for the asset itself [132].

TABLE VII: Categories and weightings of the BREEAM-NL In-Use scoring system.

Category	**Available points**	**Weighting**
Management	0	0
Health and Wellbeing	38	18,5%
Energy	63	27%
Transport	23	6%
Water	29	9,5%
Materials	17	11%
Waste	18	14,5%
Land Use and Ecology	6	4,5%
Pollution	16	9%
Total	**208**	**100**
Exemplary Performance	8	8%

Notable is the fact that the category ”Management” has no points available for the asset, given that management of a dwelling is considered as a different form of assessments with its own weights. Looking at the assessment of embodied carbon, while the ”Materials” category seems to be weighted relatively high, it is important to consider the definition of that category and what it consists of, along with how points are achieved in this category. A total of 17 points can be earned with this category, which is considered the fourth most important one in terms of weighting. 7 of those points are earned by coming up with a timely renovation plan to prevent negative impact on the environment and the financials. 6 points are earned by implementing *”facilities to facilitate the reuse, repurposing or recycling of waste”* while using the building [132, p. 130]. The final 4 points can be given to those that have a proper building passport, or EPDs from the different materials. These last 4 points, together with the first 7, are thus the ones that are granted for considering embodied carbon in renovation projects.

What is learned from the description of the Materials category, is that just under two thirds of the total amount of points (i.e. 64,7%) considers embodied carbon, in a category that is already diluted by other, seemingly more important ones like (operational) Energy, Waste, and Health and Wellbeing. Especially the Energy category is here of relevance. It consists solely of points allocated to decreasing the operational carbon of the building. Together with the fact that Energy already has a higher weighting value, it accounts for a much more significant part than embodied carbon. Therefore, the embodied carbon of materials can quite easily be ignored by the stakeholders due to the overshadowing of it by other, more impactful categories and/or parts thereof. Conclusively, for embodied carbon to become of higher strategic value, a more significant allocation of points in the

BREEAM-NL In-Use Dwellings assessments could help.

2) LEED

Similar to the BREEAM method, LEED assesses the environmental performance of buildings based on multiple categories through points, adding up to a total amount of 110. The method utilizes nine major categories for this, as seen in Table VIII. The total number of points earned determines the level of certification, with a total of 0-39 for no certification, 40-49 Certified, 50-59 Silver, 60-79 Gold, and 80+ Platinum .

TABLE VIII: Categories and weightings of the LEED scoring system.

Category	**Available points**
Integrative Process	2
Location and Transportation	15
Sustainable Sites	7
Water Efficiency	12
Energy and Atmosphere	38
Materials and Resources	10
Indoor environmental quality	16
Innovation	6
Regional Priority	4
Total	**110**

In this assessment, there is no weighting of categories, meaning that the weighting is determined by the amount of points allocated per category. When considering embodied carbon, the points for reducing this are accredited in the Materials and Resources category. Of the total 13 points to be possibly earned in this category, 5 are accredited to reduction of building life-cycle impact, 2 for facilitating EPDs, 2 for sourcing of raw materials, 2 for the sustainable usage of material ingredients, and 2 for construction and demolition waste management [133]. In this case, the totality of the points are allocated to the proper consideration of embodied carbon in buildings. However, the amount of points allocated to the operational carbon of the building is more than twice as high, while it has earlier been established that the ratio of embodied to operational carbon in buildings is 1:2. Therefore it can be said that the embodied carbon of a building is also rather underrepresented in this sustainability rating system.

E. Discussion of policy analysis

National and international policies, in conjunction with sustainability rating systems relevant to Dutch market players involved in renovation projects were analyzed. First, an overview of the most important EU- and Netherlands-wide policies were identified and examined in the stated context, with how said policies influence the Dutch renovation market and its key stakeholders. Afterwards, a closer look at relevant sustainability certification schemes for buildings was given. This was done to formulate an answer to the fourth sub-question of this research (SQ 4): *"What (inter)national policies exert influence on the identified key stakeholders regarding embodied carbon in renovation projects?"*. The answer to this question is formulated below. The fifth sub-question, about the barriers and drivers of this context (SQ 5), will be answered in the Results section as explained before.

Observing the findings in this policy analysis, a couple of conclusions can be drawn. In European legislation, the European Green Deal as it stands is expected to potentially not affect the short-term adoption of less carbon-heavy materials and processes due to its lack of decisiveness. This could, naturally, be solved by the to be developed roadmap planned for 2023 and the measures on construction and demolition waste and recovery planned for the end of 2024. It is up for speculation whether these actions by the commission in question, if carried out in time at all, would result in the key stakeholders of this context being more stimulated to reduce embodied carbon in renovation projects. That depends on both the earlier addressed wording, as well as the proposed incentive for using materials and processes with a lower environmental impact.

The Emission Trading System as enforced by the European Union is observed to be of influence to the key stakeholders too. Data found on the progress of CO_2 emissions as a result of the exerted ETS proves the positive impact it has already made, while critique has been expressed by researchers on the still low permit price. The current trading system is hypothesized to keep having a positive influence on the emitted carbon from the production of new materials and, as a result, on the embodied carbon of said materials.

For the Netherlands specifically, the Dutch energy labelling system was put in place to stimulate institutions and individuals to reduce the operational energy consumption of their homes. The introduction of this system is seen as a positive development, but the focus of it is completely on the operational energy and thus operational carbon. Hence, embodied carbon is currently not regarded as important by the imposed labelling system, which means it could possibly have a negative effect on the embodied carbon of renovation projects.

The current MPG method, used for the assessment of environmental impact for new offices bigger than 100 m^2 and newly built houses, is a potential stimulant for the use of materials with high overall embodied carbon values. The reason for this is that it disregards negative emissions from naturally growing materials like wood. Accordingly, the MPG method is expected to negatively affect the adoption of materials with a lower embodied carbon value in Dutch renovation projects.

Finally, the two investigated sustainability certification schemes, BREEAM-NL and LEED, show a disproportionate allocation of points with regard to embodied and operational environmental impact. This incentivizes stakeholders to focus their attention and resources on other sustainability measures than embodied carbon, such as the operational energy consumption of a building. Therefore, the examined certification schemes are hypothesized to negatively affect the adoption of methods for mitigating embodied carbon.

VII Barriers and Drivers

A. Introduction

By conducting an extensive stakeholder analysis, the key stakeholders of the research context have been identified and classified according to the Salience Stakeholder Model. From this analysis, the most important stakeholders were found to be investors and developers. It was chosen to direct the focus of this research mostly towards investors, designing the tool tailored towards their needs. (Inter)National policies and sustainability certification schemes relevant for the Dutch renovation market were studied to see if and how they influence these stakeholders in their decision making. The two analyses together, supplemented by the results of the semi-structured interviews documented in section VIII, allows for the identification of the most important barriers and drivers of this context.

To answer the fifth sub-question of this research (SQ 5): *"What barriers and drivers in the socio-technical system of renovations in the Dutch built environment need to be respectively overcome and enhanced for market players to not only actively pursue operational, but also reduced embodied carbon?"*: The resulting barriers and drivers from the analyses are presented here.

1) Stakeholder related barriers

For investors, the so-called Environmental, Social, and Governance (ESG) considerations are an increasingly significant part of their business activities. These ESG objectives include non-financial factors considered when risk and growth assessments of potential new investments are conducted. However, given the current uncertainty around ESG performance and its effect on profit-minded organizations, these stakeholders tend to invest in less sustainable options because of otherwise negatively affected risk-return trade-off, social impact, and economic welfare.

The more apparent barrier for investors and developers both, though, is seen in the seemingly negative effect on the upfront costs of sustainable real estate investments. All investigated research on this topic found that, for environmentally positive investments, a higher initial amount of capital is necessary. According to Brown et al. [134], high upfront costs associated with low carbon technologies is a barrier often experienced in such cases. Specifically this barrier seems to result in the stakeholders being hesitant to reduce their embodied emissions when renovating a dwelling. It can be argued that, when embodied and operational carbon are deemed equally important in this socio-technical system, the initial investment of a renovation could become lower than when solely focusing on the energy label of a building. This mentality currently remains unsupported by enforced policies and regulations. As a consequence, aforementioned barrier could be overcome when a more holistic approach to emissions of buildings is adopted by all relevant stakeholders, especially the Dutch government and its policymakers.

The final barrier observed in the stakeholder analysis is identified when looking at the interrelation of stakeholders as shown in Figure 12. Here, a clear case of misplaced incentive is observed, where the financial and regulatory efforts performed by investors and developers result in added benefits for the occupant of the dwelling. That being said, especially in the case of reducing embodied carbon, little benefit is hypothesized to even be experienced by the occupant.

2) Stakeholder related drivers

Two drivers are identified by means of the stakeholder analysis. With these drivers, the potential barriers can be overcome such that stakeholders might see the value in reducing embodied carbon emissions when carrying out renovations.

The first driver found in the stakeholder analysis are about ESG considerations becoming more important for all kinds of business operations, including sustainable investments. By defining uniform assessments on how ESG reports can be assessed by market parties, it can acquire a significant amount of relevance in achieving more sustainable renovation projects. For this, independent parties working on frameworks to assess ESG considerations in the context of renovation projects might be of help.

Another driver is hidden in the barrier of higher initial investment costs. It needs to be said that, while the costs of sustainable investments might be higher, if embodied carbon is taken into consideration by sustainability assessors more frequently, the resulting market value of dwellings due to their increased BREEAM-NL or LEED score may be a driver for stakeholders to accept the seemingly high initial investment. That is, as long as it results in a favourable return on investment. Especially in the future, it is expected to be financially advantageous to invest in sustainable buildings, since awareness on green building development is increasing and could result in more stringent assessment methods or carbon pricing. Next to the financial benefit, an added positive result can be enhanced internal and external corporate reputation.

3) Policy related barriers

From the conducted policy analysis, a couple of aspects of the (inter)nationally established rules and regulations were found that could potentially discourage key stakeholders to invest in a lower carbon footprint for their renovations.

One of the main barriers found in European legislation is the often ambiguous or vague language and goal-setting of policies defined by European Commissions. A predicament like such is for instance found in the European Green Deal proposal, where a lack of certainty and decisiveness gives prominent stakeholders little handles to work with. Next to that, organizations not acknowledging the added value of reducing embodied carbon for themselves might twist the interpretation of the policies such that responsibility claims become unnecessary.

Identifying a nationally experienced barrier, the imbalance of focus on the operational emissions of a building by means of the energy labelling system can be said to have a negative effect on a stakeholder's ambitions in this field. Currently, a lot more economic value is found in renovating dwellings to a certain energy level as opposed to truly making a sustainable impact. It can be argued that making a dwelling future-proof - renovating it to a level where applying a heat-pump or district heating becomes possible - would be a good option to be more sustainable nonetheless. That being said, not considering and thus not rewarding the reduction of embodied carbon through this labelling system gives stakeholders a negative incentive to reduce embodied carbon in their renovation projects altogether. Moreover, with current renovations solely being focused on achieving higher energy labels, potentially more materials are used than necessary. This poses both a financial and environmental disadvantage to investors as compared to considering both embodied and operational carbon as equals.

A third barrier found in the policy analysis considers the MPG method as currently implemented by the Dutch government. Like explained in the corresponding section, the negative emissions and positive environmental impacts from naturally grown materials are not taken into account by the method, resulting in an inequitably negative stigma on materials that are better for the environment than they initially seem. Subsequently, market parties emit more embodied carbon than factually necessary because of the possibly untruthful reporting of environmental impact by the MPG.

The fourth and final barrier detected in this piece considers sustainability certification schemes, like BREEAM-NL and LEED, giving insignificant allocations of points to the consideration of embodied carbon. Due to this, the reward of making a building ”green” is achieved more efficiently by laying more focus on other factors than the embodied carbon part. The discussed certification schemes give market players incentive to focus on those aspects of a building that are generally perceived as sustainable, but it has been proven that embodied carbon is underrepresented in these systems.

The main themes observed in these four barriers can be linked to the categories for carbon lock-in barriers to deploying climate change mitigation technologies as laid out by Brown et al. [134]. By doing this, three main themes stand out for this analysis specifically. First, both statutory and regulatory barriers are recognized. The first barrier category in this context is thus unfavorable regulatory policies, discouraging the reduction of embodied carbon while encouraging a potentially misplaced focus on singular sustainability measures like operational carbon. Alongside this barrier goes the barrier of regulatory uncertainty, which is especially observed in the Europe Green Deal. On the other hand, unfavorable statutory policies and uncertainty are present, as there is a lack of modern and enforceable building codes and uncertainty of developments in this field to actively pursue reduced embodied carbon. Finally, the market risks, being the low demand of materials with reduced embodied carbon, can be said to be one of the themes.

4) Policy related drivers

In the earlier mentioned European Green Deal, it is mentioned that the Commission working on it is looking into ways to standardize material recovery targets for construction and demolition waste. Knowing that EU-wide legislation will be realized in the near future, market parties can use this to their advantage to become an innovator in the field of recycling and reuse of building materials. By doing so, the parties in question can attain the advantage of being first mover in a rather competitive market. Hence, the knowledge that new rules will be set up, along with the fact that market players can gain a serious strategic advantage in this field, can be seen as a driver.

The European Trading System, while not always critically acclaimed, has proven to be an effective system for the reduction of overall emissions throughout numerous industrial sectors. Seeing the ambition of the EU to reduce emissions in all markets they have influence on, it is only to be expected that the price of carbon permits will increasingly become higher. As a consequence, stakeholders choosing to be one step ahead of this development may undergo better prices for carbon mitigation technologies as opposed to those that wait. This can can be argued to be a potential driver for such stakeholders to make the decision to act now, rather than later.

Lastly, a potential driver might be found if the Dutch government decides to consider embodied carbon the issue it proves to be in both the energy labelling system and the MPG method. When such actions are taken, stakeholders will be incentivized to aim for an actual reduction of carbon emissions over the lifetime of a building, as has been the case for operational carbon since the introduction of energy labels.

VIII Tool development

A. Introduction

With the goal of underlining the importance of reducing both embodied and operational carbon in renovation projects in the Netherlands and stimulating market players to do so, a data analysis of existing residential buildings will be conducted to be able to predict the operational carbon savings after renovation. The resulting model for this can then be implemented to develop a tool that can be used to ensure better informed decision making regarding operational and embodied carbon in dwelling renovations. The earlier determined drivers and barriers of reducing embodied carbon in thermal insulation renovation projects are used alongside the results of the interviews documented in this section to define user requirements for the to be developed tool. By doing this, the sixth and seventh sub-question of this research can be answered (SQ 6 & 7): *"What are the requirements of the to be developed tool, taking into account the earlier identified barriers and drivers?"*, and *"What would be a possible realization of the to be developed tool?"*, respectively.

B. Interviews

Interviews were held with the key identified stakeholders of this context: investors. This is the first practical step taken to the successful design of a tool that aids stakeholders to consider embodied carbon as an integral part of their sustainability considerations regarding renovation projects. In other words, the interviews serve as a support to comprehensively answer the sixth sub-question of this research (SQ 6): *"What are the requirements of the to be developed tool, taking into account the earlier identified barriers and drivers?"*. Like mentioned before, semi-structured interviews were held with said investors based on the guidelines by Rowley [49]. The setup for the interviews can be found in appendix C. The interviews were held in January 2022.

1) Interview results

Three interviews were carried out with sustainability experts of institutional investors who are focused on the built environment. The experts worked at ABN AMRO, ING, and Rabobank. The main findings are presented below.

The general theme observed in these interviews is that embodied carbon is not considered as much by the investors, occupants, and developers because of its current non-existence in (inter)national legislation. The introduction of the Dutch energy label system provides an understandable scheme on the basis of which stakeholders can set their ambitions and give each each other benefits, be it financial or intangible. But, like mentioned before, this system is solely focused on operational carbon. Embodied carbon is not something that many stakeholders understand. A lack of accessible insights into it with for instance 'embodied carbon labels' or something of the like, makes it so that they cannot consider it as easily as other sustainability aspects of their building.

From the interviews, it became clear that most if not all people understand that sustainability measures are necessary. Rigorous actions taken by the investors on sustainability related issues were generally received positively, meaning the necessity of becoming more sustainable is clear to most. The underlying motivation for doing so, however, differs among stakeholders. Reported motivations not focused on sustainability of itself include keeping shareholders of their institution content, being future-proof for upcoming legislation, and keeping up with the ever more sustainable becoming real estate market.

The interviewees collectively advocated for a standardized system in which both embodied and operational carbon emissions become measurable. The initiator of this standard could be governmental parties or a nationally renowned coalition such as the Dutch Green Building Council (DGBC). Alongside that though, the investors mentioned that financial aspects of any type of investment matter quite a lot, hence preferably an additional financial component should be included. With such a system, a common understanding is established that allows for discussion and speculation on the potential impact of dwelling renovations, both financially and environmentally. Moreover, with this system, the issue of embodied carbon is brought to the attention of a more widespread audience, facilitating the possibility for more people to consider it when renovating a building.

Answering the sixth sub-question of this research (SQ 6) *"What are the requirements of the to be developed tool, taking into account the earlier identified barriers and drivers for the stakeholders?"*: the tool should contain both financial and environmental output to provide a more holistic view of the value of renovating the dwelling in question for the investor. It should be accessible for a wide range of people to maximize its effectiveness, hence the input should be limited to the key necessary technical information.

C. User requirements

The barriers and drivers, supplemented by the results of the conducted interviews, elicit user requirements for the functionality and design of the to be developed tool. The requirements have been identified based on the earlier conducted research and prioritized through the MoSCoW prioritization method. An overview of the determined requirements is seen in Table IX

TABLE IX: Functional and design requirements of the tool.

No.	Requirement	Priority
1	The user can choose between different types of renovations on different scales.	Must
2	The tool shows the embodied and operational carbon effects of the chosen renovation.	Must
3	The tool shows the monetary (dis)advantage of carrying out the chosen renovation.	Must
4	The tool calculates the energy label of the dwelling after conducting the renovation.	Should
5	The tool shows what parameters can be altered by the user.	Should
6	The user can conveniently input the renovation paramaters without having to use plain text input.	Could
7	The tool appeals to the user aesthetically.	Could

D. Data and modeling

1) Data description

The data used for the modeling segment of this research comes from the Dutch Enterprise Agency (RVO). This data set consists of complete and accurate data of dwellings serving as reference houses for the Dutch built environment [135]. In the data set, different features of such a reference building are given. The most important features of the data set are listed below.

- Dwelling type (e.g. terraced dwelling);
- Sub type (e.g. corner dwelling);
- Construction period;
- Roof type (tilted/flat roof);
- Types of windows used (e.g. double sided glass);
- Dimensions of outer walls, windows, floor, roof, door;
- Thermal resistance of all parts;
- Presence of crack sealing (yes or no);
- Energy label/index;
- Yearly gas consumption;
- Type of boiler;
- Presence and dimensions of attached greenhouse;
- Ventilation type.

Key to the to be developed tool is that it can predict the annual emissions, or operational carbon, of a dwelling before and after its renovation. Consequently, the choice is made to build a regression model for predicting the annual gas consumption of a building (target) based on the available other data (features). The operational carbon can then be determined through the carbon conversion factor as explained before. The embodied carbon, on the other hand, is taken from the data available in the aforementioned Nationale Milieu Database (NMD) [85] listing the embodied carbon of materials. The overarching scheme for the data structure is shown in Figure 15.

Data about the materials inside of the building, and therefore the embodied carbon of removing said materials, is unfortunately not available in the given data set. Because of this, no estimation can be made about the emitted greenhouse gases by removing and/or replacing the existing materials. That is why, for now, the focus will lie solely on the new materials and their effects.

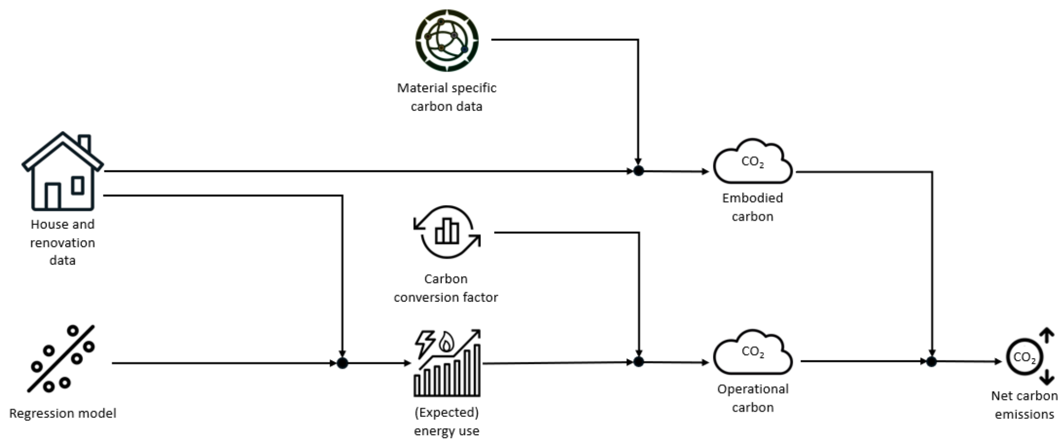


Fig. 15: Overarching data structure. The utilized databases are the ones from RVO (house and renovation data) and NMD (material specific data).

2) Data pre-processing

Firstly, knowing the theory behind the chosen renovation from the earlier answered sub-question (SQ 2), the thermal resistance and dimensions of the outer walls, windows, floor and roof are processed to form the heat transfer coefficient in W/K. As was investigated earlier, the thermal resistance and heat transfer coefficient of a material are inversely related. Adding the surface of the material to that, the amount of heat flux from inside to outside of the dwelling can be determined. And, while the temperature difference between the dwelling and outside world are unknown, the regression model can be trained to find the correlation between the heat transfer of all parts of the dwelling and its annual gas consumption.

3) Platform

Pre-processing the data, building the regression model and analyzing its results have all been done by using Python, an interpreted high-level programming language useful for different purposes and especially fit for data analyses [136]. The Python program was developed and run in a Google Colab virtual environment. The code for this experiment can be found in appendix B.

4) Data experiment

To achieve more accurate and thus usable results, the different types of dwelling were split up. For this experiment, a support vector regression model (SVR) was made for terraced houses. From the description of the data it becomes clear that the data set has multiple potentially important features, which can be of more or less relevance when looking at the annual gas consumption. The feature reduction method based on correlation resulted in a slimmed down version of the original data set per category. It was determined that, for terraced houses (in between two houses), the following features are significant to predict the annual gas consumption at the hand of this regression model:

- Presence of crack sealing (yes or no)
- Type of boiler
- Heat transfer coefficient of the floor
- Heat transfer coefficient of the roof
- Heat transfer coefficient of the front and rear facade
- Heat transfer coefficient of all simple glass
- Heat transfer coefficient of side facade (if applicable)
- Heat transfer coefficient of all insulated glass
- Heat transfer coefficient of the door

The kernel function and cost parameter of the outliers were determined at the hand of a grid search. A linear kernel function with a cost parameter of 5 was found to be the most optimal possibility for the given values.

E. Tool design

Keeping the goal of this research in mind, a tool shall be made that enhances the informed decision making of investors, developers, and occupants on sustainable renovation measures. All the steps taken before in this research serve as handles to bring this tool to its successful conclusion.

From the earlier done analyses, a couple of things stand out that are of importance for the tool. Firstly, it should be noted that reducing embodied carbon shall not be seen as a separate goal next to operational carbon. In the end, truly sustainable renovations can only be realized when both embodied and operational carbon are considered. Secondly, different databases should be utilized for the proper calculation of operational and embodied carbon. The RVO reference dwelling database and Nationale Milieu Database are key to the effectiveness of this tool. Lastly, different stakeholders find value in different aspects of a renovation, and thus the financial prospects of such a renovation should be disclosed in the tool.

The tool will be spreadsheet-based and made in Microsoft Excel. This program allows for convenient structuring of data gathered from one or multiple sources in order to gain useful insights from it [137]. With it, tools can be made that are user friendly, easily adaptable to a specific scenario, and conveniently extendable to different topics or data sources. Especially given that the tool being made has more appliances than only thermal insulation renovations, it is essential that other sustainability-related renovation appliances can be added in a convenient fashion.

1) Functional and technical design

Three groups of emissions have been determined to be of importance for the technical and functional design: the original operational carbon of the dwelling, the operational carbon after completing the renovation, and the embodied carbon emitted by conducting the renovation. The first type of operational carbon can be taken from the operational energy given in the RVO reference dwelling database in combination with the earlier established carbon conversion factor. The second group of operational carbon emissions is calculated by using the earlier implemented regression model together with the data of a dwelling as found in the RVO database. Lastly, the embodied carbon emitted by the renovation is determined by combining the renovation data, the dwelling data of the RVO database and the embodied carbon data from the NMD.

Ultimately, there are four different elements of data to this tool, as laid out below.

- Input data, such as the type of dwelling, the construction period of that dwelling, and the to be realized renovation;
- External data or calculation sources, like the databases from RVO and NMD, and the regression model;
- Calculation (sub)elements that can be applied through the input data and external data sources;
- Output data, such as the net carbon emissions of a renovation in 2050, and the net financial return on investment in the same period.

The four types of elements as defined are combined for the successful calculation of the outputs. The tool structure built up from those four types is seen in Figure 16.

A final step to make the results of the tool applicable in real-world situations. In order to do this, the calculation of the dwelling's new energy label will be implemented as well. The tool will be doing said calculations on the basis of the heat transfer coefficients and surfaces of the different materials as specified in the RVO database, in compliance with the aforementioned NTA 8800 standard.

2) Use case

Three different types of thermal insulation renovations - roof, floor, and facade - have been implemented in an Excel-based tool. A screenshot of the resulting tool can be seen in Figure 17. In

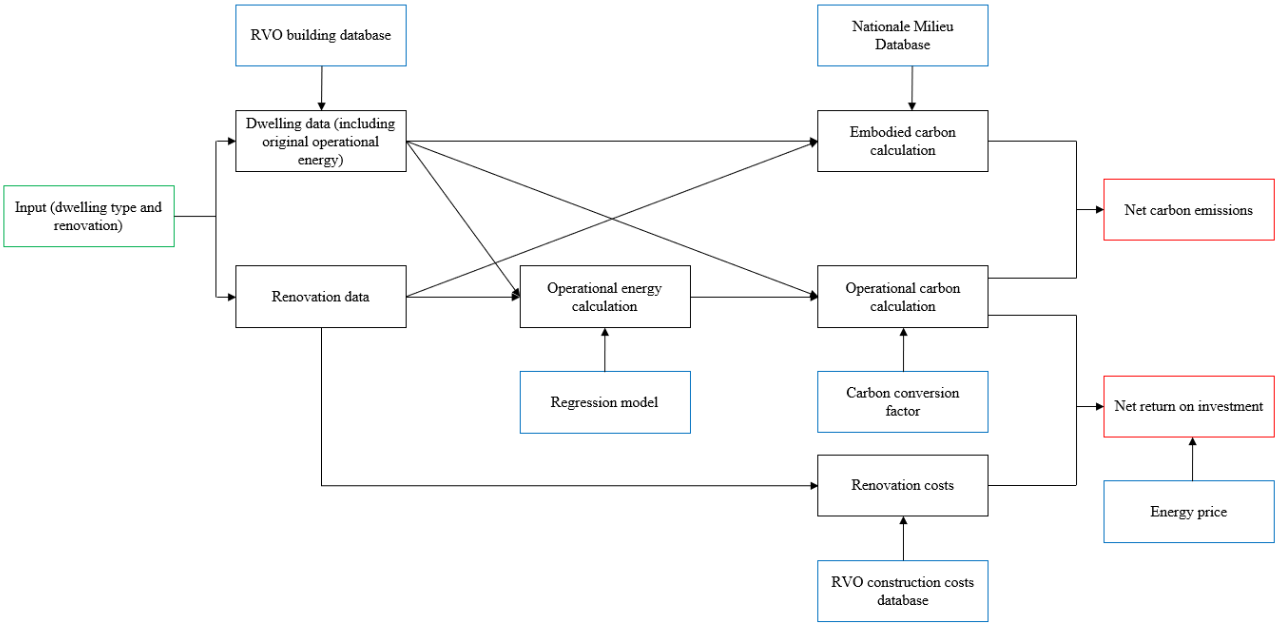


Fig. 16: Tool structure consisting of the different data elements. Green elements are inputs, blue ones are external data sources, black ones are calculations/calculation elements, and red ones are outputs.

this figure, five components are of importance. The first one, SELECTEER WONING, allows the user to choose a reference dwelling from the RVO database. The three input variables are the type of dwelling, its construction period and optional sub type. The three consecutive components to the right of that one let the user choose whether and what kind of renovations are applied. The tool allows for one to three accumulating renovations, each focusing on one of the three earlier mentioned renovation types. Below the green elements that the user has to fill in, the architectural specification of the dwelling is given. As can be observed in the figure, the data of the renovated component changes per 'renovation column', resulting in a lower heat transfer coefficient for that component and overall coefficient of the dwelling (UA). On the far right, the resulting initial investment and the courses of the financial net return on investment and resulting carbon emissions from 2021 to 2050 are shown.

The tool itself, like explained before, is tailored towards the needs of investors focusing on dwellings. Investors can use this tool to evaluate the planned renovation on the basis of its environmental and financial return on investment. Currently, the tool's database consists of reference dwellings, but it allows for changing the data of the reference dwelling to a specific case if desired.

The tool is suitable for investors who want more insight into the overall expected impact of their renovations, both financially and environmentally. It is expected to be most effective when applied after the initial renovation planning and inventory determination. Following the renovation process as laid out by Thuvander et al. [138], the tool would be most suitable to use during the *Pre-investigation / Design - alternative solutions* phase. By using the tool in this phase, the impacts of different renovations can conveniently be estimated, after which the preliminary costs calculations and the ultimate decision to design can be made. The investor using the tool as such can have several purposes with its results. The investor could choose for a financially optimal scenario, an environmentally optimal one, or a balanced one. In other words, the renovations chosen could return the highest amount of investment available through all renovations, or it could mitigate the highest amount of carbon emissions as a result of the renovation, or it could do a bit of both. It is then up

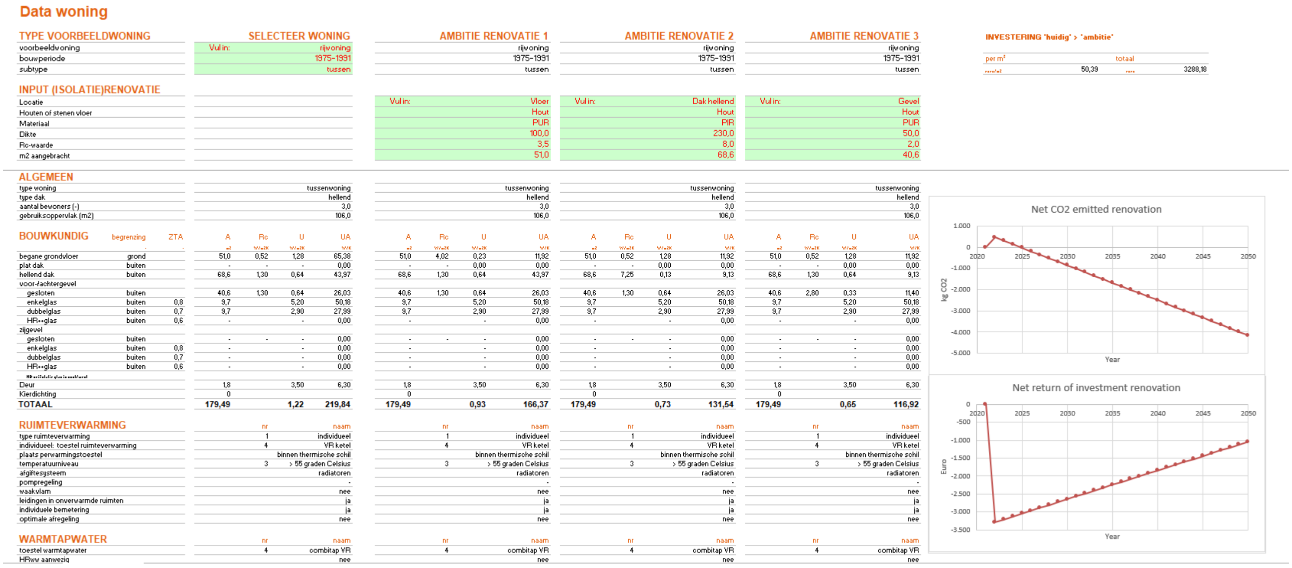


Fig. 17: Screenshot of the resulting tool. The green color highlights the components which the user can alter through drop-down menus or simple text input.

to the investor to decide what renovation (combination) is carried out. Ultimately, it is expected that both a positive financial and environmental return of investment are desired by the investor.

3) Data availability

When the renovation type and material have been selected, the NMD can be accessed for embodied carbon data. Generally speaking, for insulation material, the embodied carbon in the NMD is given in kg CO_2 eq/m^2 of material for a specific R_c value and thickness. Some materials have been submitted to the database having different R_c values and different thicknesses, making the embodied carbon of that material per m^2 different. It naturally matters how much of the material is applied and what its insulation value is in order to gain insights in the operational and embodied carbon aspects. That is why six different inputs have been identified, which should be filled in by the user for the tool to do its job properly: the type of dwelling, its construction period, the type of renovation (e.g. floor, walls, or roof), the material used, the thermal resistance of that material, and the amount of square meter applied to the dwelling. When the user selects a certain material, options will be given on the R_c value and the thickness based on what is available in the NMD. When a new type of material is chosen that has a different available thickness or R_c value, the user will be prompted to change the value using the corresponding drop-down menu by the input line becoming purple and a message appearing directly below the menu. The drop-down menu only gives available values for the chosen renovation, making it impossible for the user to update the incorrect values in this field. The same type of error is encountered when the user chooses a different dwelling component and the chosen material, R_c value, or thickness is not available. Additionally, this error occurs when the user inputs an amount of square meters larger than amount the dwelling component consists of. The error message and corresponding action is shown in Figure 18.

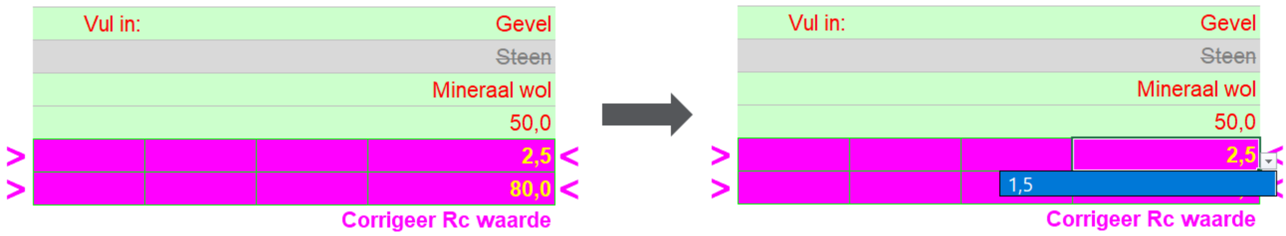


Fig. 18: Screenshot of error message in purple, which translated states to correct the R_c value. The user can then use the built-in drop down menu to correct it. In this example both the R_c value and applied amount of square meters are incorrect. When corrected, the error message will prompt the user to alter the amount of applied square meters.

Ideally, the RVO database would have included the insulation material currently present in the chosen dwelling. Unfortunately, no data of such nature is available in the database. Consequently, no proper estimation can be made for the embodied carbon of removing and processing the original insulation material (module C1-C4). For now, that part of the emissions is left out of the equation. If the data for that would be available, though, the estimation of embodied carbon emitted by applying the chosen insulation would have been even more accurate.

4) Evaluating the tool based on user requirements

After integrating all elements of the tool, the tool is evaluated to see if all earlier determined user requirements are met. Table X shows which requirements were met and which were not. Whether the tool appeals to the user aesthetically is up for debate. But, given that the focus of this research was on the functionality of the tool to begin with which can arguably be perceived in the look and feel of the tool, the requirement is concluded to not be met. That being said, as is observed in the corresponding table, all *Must* requirements were implemented. Conclusively, a minimum viable product is achieved at the hand of these requirements.

TABLE X: Requirements evaluation of the tool.

No.	Requirement	Priority	Requirement met?
1	The user can choose between different types of renovations on different scales.	Must	Yes
2	The tool shows the embodied and operational carbon effects of the chosen renovation.	Must	Yes
3	The tool shows the monetary (dis)advantage of carrying out the chosen renovation.	Must	Yes
4	The tool calculates the energy label of the dwelling after conducting the renovation.	Should	Yes
5	The tool shows what parameters can be altered by the user.	Should	Yes
6	The user can conveniently input the renovation paramaters without having to use plain text input.	Could	Yes
7	The tool appeals to the user aesthetically.	Could	No

IX Results

A. Introduction

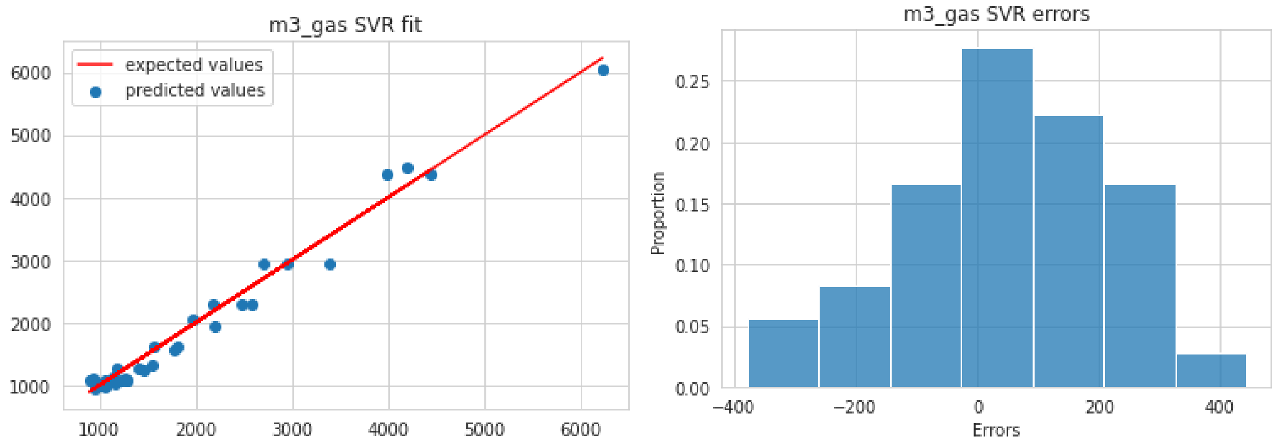
This section describes the results acquired by conducting the data analysis and tool development of this research. Goal of this section is to highlight the findings from the performed analysis and to illustrate the designed embodied carbon tool at the hand of two case studies that show the area of application of the tool.

B. Data analysis results

With the features and parameters selected as explained in the research approach, a support vector regression model was implemented. The Python code for this can be found in Appendix B. The results of the model and its performance are laid out in this section.

1) Resulting regression model

The predictions of 30% of the total data set as done by the model are plotted against the expected values in Figure 19a. Figure 19b shows a histogram of the error values of the predictions against their actual value. In Table XI, the previously described statistical metrics of the trained model are given.



(a) Scatter plot of predictions against actual values. (b) Histogram of error values achieved by the trained SVR.

Fig. 19: Resulting SVR model performance for predicting annual gas consumption of terraced houses.

2) Discussion of model results

Looking at the results of the support vector regression model as shown in the corresponding table and figure, a couple of observations can be made. The RMSE, MAE and R^2 values are considered

TABLE XI: Statistical metrics of the trained SVR model predicting annual gas consumption of terraced houses.

Metric	**RMSE**	**MAE**	**R^2**
Value	182,74	148,07	0,977

quite favourable in terms of performance. Especially an R^2 value of 0,977 can be said to be quite good, as acceptable values are often taken to be at least 0,80 [62]. Additionally, knowing the mean annual gas consumption reported in the data set to be 1957,61 m^3 per year, the RMSE and MAE values can be deemed acceptable for the prediction of annual gas consumption based on the used features of a terraced house. Finally, since the error histogram resembles a normal distribution, according to the Central Limit Theorem[6], the model can be argued to have been implemented successfully.

Conclusively, it can be said that, for the development of a tool that can approximate annual gas consumption based on data from a dwelling in combination with a thermal insulation renovation, the implemented SVR model is a proper instrument to predict it.

C. Tool validation

Data of dwellings, materials, energy, and carbon have been collected from different sources and combined into an Excel-based tool to gain insights into the balance between operational and embodied carbon for renovation projects, as well as their financial impacts. The goal of this tool is to facilitate better informed decision making for market players planning and conducting renovations to make them truly sustainable. Additionally, the tool makes insights into the two kinds of carbon accessible to a broader range of stakeholders than currently is the case, as now mainly sustainability and MPG experts in the Netherlands are able to work with them. In order to prove the necessity of this tool and its subsequent effectiveness, a case study is conducted with two different renovation scenarios. Two different dwellings with their own characteristics are chosen and renovated to show the discrepancy there can be in terms of assumptions and actual outcome. Using this tool, stakeholders can prevent such discrepancies from happening.

1) Renovation scenario 1

In scenario 1, a terraced house (in-between type) built between 1975 and 1991 is considered. Currently, it resides among the dwellings having an energy label of D. The relevant specifications for this dwelling can be found in Table XII. Knowing it has a relatively low energy label, a renovation is carried out to increase the label from D to C. With the purpose of achieving that, the insulation for the ground floor and the facade are replaced. In the ground floor, a 130 mm thick layer of PIR will be added with a thermal resistance of 5,5 m^2K/W. The facade will be renovated with a 50 mm thick layer of PUR, having a thermal resistance of 2,0 m^2K/W. After filling in the particulars of the insulation renovation in the tool, the tool calculates the new specifications of the dwelling, which are found in Table XIII.

[6]The Central Limit Theorem, applied to machine learning, states that *"... when we add a large number of independent random variables to a data set, irrespective of these variables' original distribution, their normalized sum tends towards a Gaussian distribution"* [139]. Knowing that the independent variables are deterministic in this case, the stochastic part of the model consists of the error values, which should therefore be normally distributed.

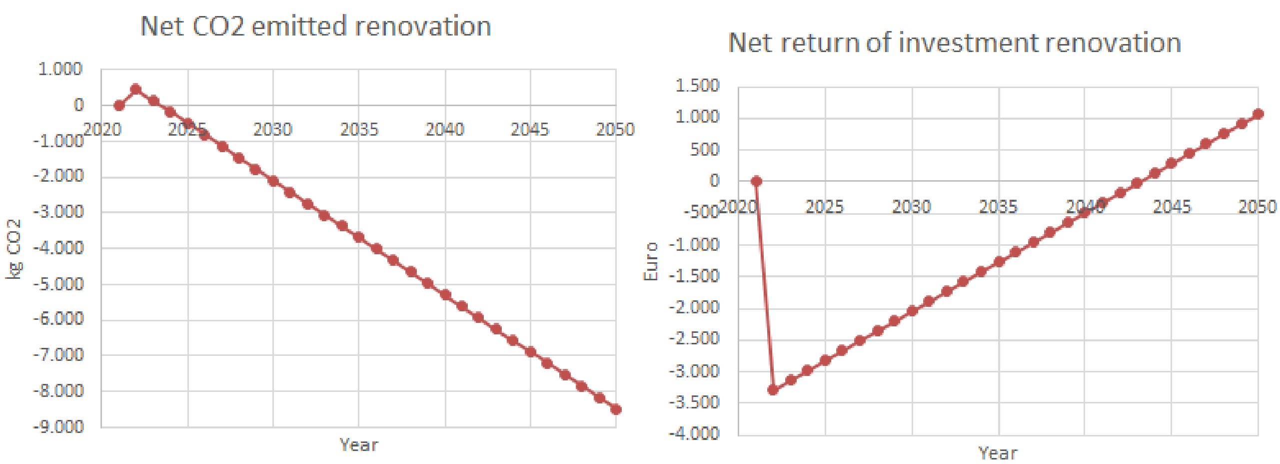
TABLE XII: Dwelling 1 specifications.

Component	Area [m²]	U value [W/(m²·K)]	UA value [W/K]
Ground floor	51,0	1,28	65,38
Facade	40,6	0,64	26,03
Roof	68,6	0,64	43,97
Singular glass window	9,70	5,20	50,18
Double glass window	9,70	2,90	27,99

TABLE XIII: Dwelling 1 specifications after renovation scenario 1.

Component	Area [m²]	U value [W/(m²·K)]	UA value [W/K]
Ground floor	51,0	0,16	8,12
Facade	40,6	0,28	11,40
Roof	68,6	0,64	43,97
Singular glass window	9,70	5,20	50,18
Double glass window	9,70	2,90	27,99

The tool combines the embodied carbon data of the two materials over the whole surface of the floor and facade respectively, and calculates the amount of embodied carbon emitted. The implemented regression model calculates the resulting operational carbon per year from the new dwelling specifications, after which the net amount of emissions can be plotted as seen in Figure 20a. Additionally, the total costs of the renovation and energy savings due to the higher energy efficiency are determined, resulting in a net return on investment over the course of the years, which is plotted in Figure 20b.



(a) Net carbon emissions of renovation scenario 1.

(b) Net return on investment of renovation scenario 1.

Fig. 20: Resulting carbon emissions and energy return on investment of renovation scenario 1.

Looking at both plots, it is observed that, in terms of net carbon emissions and return on investment, the renovation results in a positive outcome. This can be attributed to the fact that poorly insulated dwellings experience significant positive effects from any type of insulation renovation. As a consequence, the renovation is both sustainable and financially beneficial, making this an attractive renovation to carry out.

2) Renovation scenario 2

Scenario 2 again considers a terraced dwelling (in-between type), this time built in the period of 1992-2005. Due to its relative newness, the dwelling has better insulation parameters than the one in scenario 1, giving it energy label B. The specifics of the second dwelling are shown in Table XIV. This dwelling will also be renovated with the purpose of achieving a higher energy label, after which it will henceforth have energy label A. For this, the ground floor, facade, and roof need to be renovated. The facade and ground floor renovations are conducted with the same materials as done in scenario 1. The roof is renovated with a 230 mm thick layer of PIR, which has a thermal resistance of 8,0 m^2K/W. The details of the newly renovated dwelling can be found in Table XV

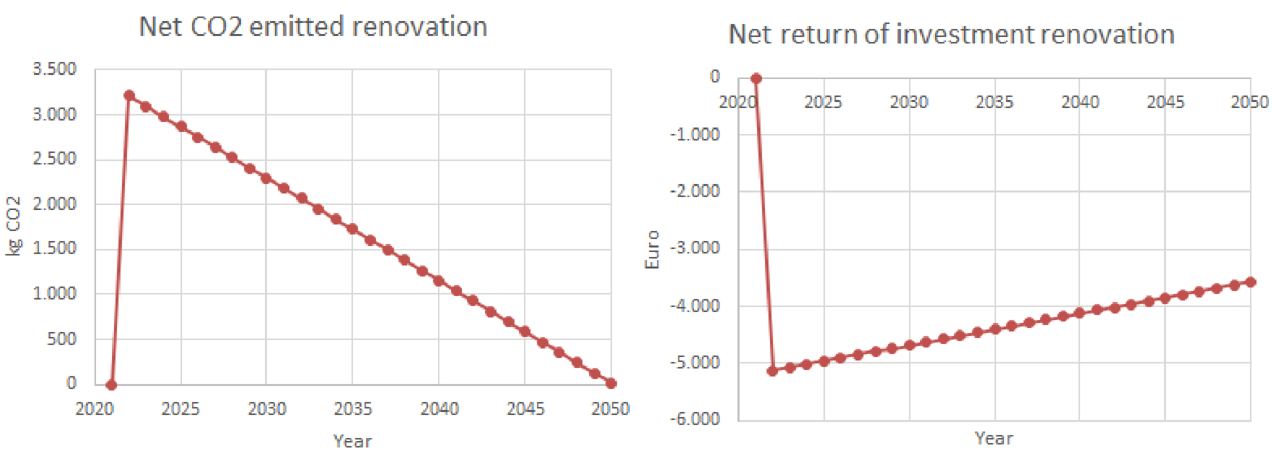
TABLE XIV: Dwelling 2 specifications.

Component	Area [m^2]	U value [$W/(m^2{\cdot}K)$]	UA value [W/K]
Ground floor	56,0	0,36	20,07
Facade	49,9	0,36	17,89
Roof	56,1	0,36	20,10
Double glass window	21,80	2,90	63,22

TABLE XV: Dwelling 2 specifications after renovation scenario 2.

Component	Area [m^2]	U value [$W/(m^2{\cdot}K)$]	UA value [W/K]
Ground floor	56,0	0,12	6,76
Facade	49,9	0,21	10,42
Roof	56,1	0,09	5,20
Double glass window	21,80	2,90	63,22

The tool once again calculates the relevant carbon emissions and savings, as well as the resulting operational energy and costs. The courses of the net carbon emissions and net return on investment as a result of this renovation are plotted in Figure 21a and Figure 21b, respectively.



(a) Net carbon emissions of renovation scenario 2.

(b) Net return on investment of renovation scenario 2.

Fig. 21: Resulting carbon emissions and energy return on investment of renovation scenario 2.

What can be seen immediately is the financial savings through the higher energy efficiency not weighing up to the necessary initial investment of the renovation. More notable, however, is the fact that the net emitted carbon stays positive over the whole course of 2021 to 2050, resulting in a net amount of emissions of 16 kg CO_2-eq up until then. Therefore, the renovation can be said to have a negative impact on the environment as opposed to not renovating the dwelling.

Insights like these are generally not acquired when a renovation is carried out. The reasons for this have been highlighted in this report before, but amount to an imbalance of focus on the operational and embodied carbon by all relevant stakeholders. The current emphasis of government and market parties on the Dutch energy labeling system, without them regarding the hidden environmental impact of the used materials, gives a false pretense to said parties of performing sustainable and future-proof actions.

X Conclusions

IN this thesis, research was carried out on the topic of embodied carbon in Dutch renovation projects and how stakeholders can be motivated to consider this part of emissions more. By doing this study, a tool was developed to facilitate this new philosophy on emissions in the built environment, retaining the goal of highlighting the necessity of reducing total life cycle emissions in the built environment and prompting market players to see this necessity. This section facilitates answers to the posed questions of this research. By answering the individual sub-questions, an answer to the main research question can be found. The main research question posed in this research is formulated as follows:

RQ: ***"How can organizations involved in the Dutch built environment be stimulated to actively consider the balanced reduction of both embodied and operational carbon in renovation projects?"***

To answer the research question, seven sub-questions are answered:

SQ 1: *"How can the assessment of operational and embodied carbon in renovation projects be conducted according to literature?"*

The first sub-question is answered by the secondary data found through literature in section IV. Data was collected for the successful assessment of carbon emissions for both natural gas and electricity. Carbon conversion factors were found that prescribe the amount of emissions per kWh of energy. Dutch legislation defined the electricity emits 0,34 kg CO_2 eq./kWh while natural gas emits 0,183 kg CO_2 eq./kWh. It is expected that natural gas will eventually surpass electricity in terms of emissions per energy unit because of the Dutch electricity grid becoming more and more sustainable. Next to that, the conversion from electricity to heat is done with coefficients of performance far above 1, making the comparison of the carbon conversion factors for natural gas and electricity inequitable. Since heat from natural gas would thus be the highest contributor to operational emissions, the initial focus of the developed tool is on dwellings utilizing natural gas.

SQ 2: *"What empirical context should be the focus point for the to be developed tool?"*

The answer of the second sub-question is also presented in section IV. Acquiring secondary data from literature resulted in the findings that residential buildings account for the highest amount of operational emissions with a share of 21% of the total yearly energy consumption across all domains as described in this section. Specifically, it was chosen to focus this research on terraced houses, given that this is the most occurring type of dwelling in the Netherlands. The second sub-question is answered as follows: three main categories of renovation types are identified for terraced houses. From these three types, the thermal insulation category has been chosen to investigate further. A deeper dive into the engineering aspects of thermal insulation applications was done and data was gathered for the embodied carbon, costs, and heat transfer coefficient of numerous materials and appliances. It is expected that this kind of sustainability-related renovation projects is an effective starting point for the proposed tool.

SQ 3: *"What stakeholders should the to be developed tool be designed towards?"*

The answer to the question regarding the relevant stakeholders of this context is answered in the stakeholder analysis in section V. From the stakeholder analysis, with a deeper dive into the key stakeholders, the market regime of sustainability-related thermal renovation is identified. Commercial investors in different forms are typically the ones most in control of what happens with real estate. Such investors can be individual actors that desire the highest return on their investment, or institutional investors who either renovate their own buildings or financially support aforementioned individual actors to renovate (financier). Both types of investors can have a positive effect on the embodied carbon in renovations. For instance, a financier can put lower interest rates on loans that are used for renovations that limit both operational and embodied carbon in the process. The direct investors, on the other hand, have the power to choose what materials and how much of them are applied. Moreover, the determine what type of renovation is realized, meaning they can actively pursue a minimum amount of carbon emitted by keeping track of the potential footprint of their seemingly sustainable endeavours. Notable investors of the like include Rabobank, ING, Delta Lloyd, and Amvest. Similarly, construction developers opt for the materials and processes that deliver the highest return on investment due to the most financial value being encapsulated in those choices. They determine what kind of services and materials are offered to investors through their catalog of options. Currently, developers have been said to not necessarily pursue the options where the most carbon is reduced.

SQ 4: *"What (inter)national policies exert influence on the identified key stakeholders regarding embodied carbon in renovation projects?"*

The answer to this question is found in section VI. Without the author presuming to be fully comprehensive in this field, relevant European and Dutch policies were investigated and how they influence key market stakeholders in this context. The European Green Deal and Emission Trading System are concluded to respectively negatively and positively influence the decision making of stakeholders regarding reduced embodied carbon in renovation projects. The Dutch energy labelling system and MPG method are expected to both negatively influence this process. The two investigated sustainability certification schemes, BREEAM-NL and LEED, could have a more positive influence if the allocation of points was more in line with the proportion of embodied as opposed to operational carbon.

SQ 5: *"What barriers and drivers are there to be found for parties in the socio-technical system of renovations to actively pursue not only operational but also reduced embodied carbon in the built environment?"*

Barriers and drivers for the key stakeholders were found through both the stakeholder analysis and policy analysis, which are elaborately described in section VII. In terms of barriers, vagueness in sustainability-related policy and assessment methods, higher initial investments and misplaced incentive are observed as a result of the Stakeholder Analysis. From the Policy Analysis, additional barriers were found in regulatory and statutory policies. Additionally, the Dutch energy labelling system, as well as sustainability certification schemes such as BREEAM-NL and LEED, have been found to lie their focus more on operational than embodied carbon in a disproportional manner. Finally, the Dutch MPG method is said to give skewed results for certain materials because of potentially flawed carbon accounting, making the embodied carbon of actually sustainable materials seemingly higher than is really the case.

The drivers from the Stakeholder Analysis, on the other hand, include increasingly important ESG considerations, a higher potential market value of buildings in the future, and enhanced corporate reputation. The Policy Analysis showed that the European Green Deal, when carried out properly in terms of material recovery standards, can be of strategic value for institutions to act upon. Moreover, the European Trading System being in place gives them incentive to do so already. Finally, the Dutch MPG method and energy labelling system can become a driver in this context, when government parties start seeing the potential of reducing embodied carbon for their national decarbonization goals.

SQ 6: *"What are the requirements of the to be developed tool, taking into account the earlier identified barriers and drivers?"*

To answer the sixth sub-question, interviews were held with the key identified stakeholders of this context, investors. The results of the interviews, together with the predefined barriers and drivers as highlighted in section VII, resulted in user requirements that were prioritized using the MoSCoW method. Not all user requirements were met, but all top priority requirements were, meaning a minimum viable product was achieved. The most important requirements were about the tool being able to show both the environmental and monetary value of a renovation, as well as the user being able to choose different types of renovations and materials to see the difference between them.

SQ 7: *"What would be a possible realization of the to be developed tool?"*

In order to answer this question, the gained knowledge on the socio-technical system of embodied carbon in renovation projects through analyses and interviews was applied to develop a tool that facilitates insights into the financial and environmental performance of thermal insulation renovation plans. A support vector regression (SVR) model was built to predict the annual gas consumption of a dwelling based on the conducted renovation, which, combined with embodied carbon data from the NMD, makes it possible to balance embodied and operational carbon for that project. Furthermore, the expected financial return on investment over the years up until 2050 is calculated for the user. With both these outputs, informed decision making becomes more accessible in terms of sustainable and financial considerations when planning a dwelling renovation. Adding to the context-dependable applicability of the tool, the tool included the calculation of the potential energy label of the dwelling after renovation.

The implemented SVR model was evaluated based on its mean average error (MAE), root mean square error (RMSE) and coefficient of determination (R^2). With a MAE of 182,74, a RMSE of 148,07, and an R^2 of 0,977, the regression model can be said to be implemented successfully and predict the annual gas consumption of dwellings rather accurately. The SVR model as is was thus incorporated in the tool.

The developed tool was illustrated through two scenario studies. The first scenario showed that a renovation of a terraced house from energy label D to label C is both financially and environmentally feasible. The net emitted carbon and net return on investment showed that such a renovation would be beneficial for both the renovator and the environment. The second scenario considered a terraced house that was renovated from energy label B to label A. Because of the amount of necessary materials for a relatively marginal step in energy label, the net carbon and net return on investment both turned out to have a detrimental impact. By using the tool, renovations that seem environmentally friendly but might not be in reality can be evaluated before they are conducted, giving the key stakeholders a more comprehensive idea of the impact they are making with said renovations.

Answering the main research question of this research, there are many factors that can contribute to organizations involved in the built environment to be stimulated to reduce not only operational, but also embodied carbon. Financial, environmental, and non-tangible strategic value was identified in the form of net return on investment, enhanced corporate reputation and favorable policy regulations. What is currently observed in the Dutch playing field for renovations, though, is the evermore present imbalance of focus on operational carbon by government parties, rewarding those that strive after complying with these rules while missing potentially more sustainable opportunities along the way. Changing this would go a long way in motivating said stakeholders to adopting more sustainable renovation methods. Next to policy, other barriers and drivers were identified for stakeholders to consider embodied carbon in their renovation decision making, after which a tool has been developed that stimulates them to actively do so. The effectiveness of the tool was evaluated on the basis of two scenario studies, showing the necessity of such accessible instruments. The true value of reducing embodied carbon can further be stimulated by government parties and policymakers alike, by making the embodied carbon aspect of renovations and dwellings as important as this research has proven it to be.

XI Discussion and recommendations

A. Discussion

Some limitations were observed in the tool development method that has been presented. The first limitation is found in the used dwelling database. In an ideal world, both the embodied carbon of applying the new thermal insulation, as well as removing and processing the old insulation shall be accounted for. The data set used in this research did not facilitate that possibility. This could have significant effects on the calculated net emitted carbon as the embodied carbon becomes higher due to this. Consequently, potentially interesting renovations that are assessed by this tool currently may still seem more sustainable than they are.

A second limitation point regarding the dwelling data is that it originates from 2011. With a dynamic system such as the Dutch built environment, the data might already be a bit out of date. Doing this research has nonetheless proven to be insightful, but a more up-to-date database would make the developed tool more applicable to real-life scenarios.

Lastly, while this tool serves as a stepping stone for better decision making regarding renovations, not all types of thermal insulation renovations were included. Currently, the roof, floor, and facade can be put in the tool. That being said, there are other options for better insulation and thereby a potential increase in energy label, such as replacing singular windows with insulated ones. Adding such features would have made the tool even more usable to determine what sustainability measure would have the best environmental and financial impact.

1) Scientific contribution

Many different LCA tools to assess the impact of new and existing buildings already exist. Nevertheless, such tools have a singular focus: the renovation itself. Mitigated environmental impact as a result of the renovation was not included in the LCA tools described in the theoretical framework of this thesis. As a consequence, this tool aims to bridge the gap between theoretical and practical environmental impact of renovations, both embodied and operational. The rest of this research shows what could stimulate or discourage prominent stakeholders to apply the whole life carbon thinking in general, with or without facilitating this way of thinking with the proposed tool. With some adjustments and additives, the tool itself could serve as a solid instrument to reduce overall emissions of existing buildings in multiple contexts.

Earlier conducted research on this topic has mainly focused on two aspects. The first one is about quantifying embodied carbon through the use of LCA methodologies, while the second one is about reducing the quantified embodied carbon by proposing alterations in the construction value chain [140–142]. While this is arguably of significant value for the shift of focus from only operational to both operational and embodied carbon, a hiatus is observed in the available research. It is not only of importance how embodied carbon should be reduced, but also why stakeholders should care about it in the first place. This research has focused on finding economic and strategic value in the whole life carbon thinking approach for said stakeholders, giving them incentive to put this mindset to practice. Hence, this research fills the earlier mentioned hiatus such that a more holistic understanding of this topic is obtained and taking appropriate action becomes more attainable.

B. Recommendations

There are some points that can be focused on to increase the scientific and societal value of this research. The first one includes researching effective ways of how European and Dutch policies should be changed in order to reward those market players reducing their embodied emissions. The study presented in this thesis shows that positive impact can be made by this and interviewees have agreed that policymakers should be the initiators in this field. The specifics and possibilities of such policies should therefore be investigated further.

If one were to continue the development of the proposed tool, it is highly recommended to acquire more data about the reference dwellings than currently used. Specifically, the original materials present in the dwelling before renovation would make the estimation of embodied carbon emitted more reliable. In that way, also the module components C1-C4 of the old material can be taken into account, which would potentially put some seemingly sustainable renovations on the wrong side of the environmental equation, hence this recommendation.

As a last recommendation to further research, it would be of immense value to also incorporate other sustainability measures in the proposed tool. One could think about the embodied against operational carbon of renovating a building to a state where a heat pump could be used, which is then implemented. With additions like these, a more holistic approach becomes possible for stakeholders that need to make decisions regarding this topic. Ultimately, a single easy-to-use tool that incorporates all relevant factors in this context is hypothesized to not only prove effectively in terms of engineering, but could disrupt the Dutch and maybe even the European real estate sector as a whole, establishing a new way of thinking about sustainability.

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Appendix

Appendix A: Energy Saving Measures

KRUIPRUIMTE

Bodemisolatie (Rc=3,0): schuimbeton (d=300mm) - 500kg/m^3
Bodemisolatie (Rc=2,5): EPS chips (d=300mm)

VLOEREN

Vloerisolatie (Rc=3,0): resol isolatie (d=65mm) bovenzijde houten begane grondvloer - afwerking plaatmateriaal
Vloerisolatie (Rc=2,0): minerale wol isolatie (d=100mm) onderzijde houten begane grondvloer
Vloerisolatie (Rc=2,5): minerale wol isolatie (d=100mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=2,0): EPS isolatieplaten (d=100mm) onderzijde houten begane grondvloer
Vloerisolatie (Rc=2,5): EPS isolatieplaten (d=100mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=3,5): PUR isolatie (d=100mm) onderzijde houten of steenachtige begane grondvloer
Vloerisolatie (Rc=3,5): PIR isolatie (d=100mm) onderzijde houten begane grondvloer
Vloerisolatie (Rc=3,0): PIR isolatie (d=80mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=3,5): PIR isolatie (d=90mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=4,0): PIR isolatie (d=100mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=4,0): PIR isolatie (d=100mm) onderzijde steenachtige vloer
Vloerisolatie (Rc=5,5): PIR isolatie (d=130mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=4,0): resol isolatie (d=100mm) onderzijde houten begane grondvloer
Vloerisolatie (Rc=4,5): resol isolatie (d=100mm) onderzijde steenachtige begane grondvloer
Vloerisolatie (Rc=3,0): thermoskussen (d=300mm) onderzijde houten of steenachtige begane grondvloer
Zolderisolatie (Rc=2,0): minerale wol deken (d=100mm) los over vliering - vliering onbeloopbaar
Zolderisolatie (Rc=2,5): EPS drukvaste isolatie (d=100mm) bovenzijde houten zoldervloer - zolder beloopbaar

DAKEN

Dakisolatie (Rc=3,5): PIR renovatie dakelementen (d=75mm) buitenzijde hellend dak
Dakisolatie (Rc=6,0): PIR renovatie dakelementen (d=130mm) buitenzijde hellend dak
Dakisolatie (Rc=8,0): PIR renovatie dakelementen (d=175mm) buitenzijde hellend dak

Dakisolatie (Rc=3,0): PIR isolatie (d=80mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=4,0): PIR isolatie (d=110mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=5,0): PIR isolatie (d=140mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=6,5): PIR isolatie (d=185mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=7,0): PIR isolatie (d=200mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=8,0): PIR isolatie (d=230mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=4,0): resol isolatie (d=100mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=5,0): resol isolatie (d=130mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=6,0): resol isolatie (d=160mm) binnenzijde hellend dak - afwerking gipsplaten
Dakisolatie (Rc=2,5): foamglas isolatie (d=100mm) op bestaande dakbedekking plat dak - ballastlaag hergebruiken
Dakisolatie (Rc=3,0): EPS isolatie (d=100mm) op bestaande dakbedekking plat dak - ballastlaag hergebruiken
Dakisolatie (Rc=3,0): EPS isolatie (d=100mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=3,0): minerale wol isolatie (d=100mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=3,5): PIR isolatie (d=80mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=4,0): PIR isolatie (d=100mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=6,0): PIR isolatie (d=160mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=7,0): PIR isolatie (d=185mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=8,0): PIR isolatie (d=210mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=4,0): resol isolatie (d=90mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=5,0): resol isolatie (d=110mm) buitenzijde plat dak - vervangen dakbedekking APP
Dakisolatie (Rc=6,0): resol isolatie (d=130mm) buitenzijde plat dak - vervangen dakbedekking APP

GEVEL DICHT

Gevelisolatie (Rc=2,5): minerale wol isolatie (d=100mm) buitenzijde gevel - afwerking sierpleister
Gevelisolatie (Rc=2,5): EPS isolatie (d=100mm) buitenzijde gevel - afwerking sierpleister
Gevelisolatie (Rc=4,5): resol isolatie (d=100mm) buitenzijde gevel - afwerking sierpleister

Gevelisolatie (Rc=1,5): minerale wol vlokken (d=50mm) in spouw
Gevelisolatie (Rc=1,5): EPS parels (d=50mm) in spouw
Gevelisolatie (Rc=2,0): PUR schuim (d=50mm) in spouw
Gevelisolatie (Rc=4,0): geïsoleerde MS-wand (d=100mm) binnenzijde gevel - regelwerk en gipsbeplating - behangklaar
Gevelisolatie (Rc=5,0): geïsoleerde MS-wand (d=125mm) binnenzijde gevel - regelwerk en gipsbeplating - behangklaar
Gevelisolatie: vulpaneel spouw - sandwichpaneel trespa 6 mm - 100 mm EPS
Gevelisolatie: vulpaneel spouw - isolatieplaat 100mm - multiplex
Gevelisolatie (Rc=4,0): PIR isolatie (d=100mm) binnenzijde gevel - regelwerk en gipsbeplating - behangklaar
Gevelisolatie (Rc=5,0): PIR isolatie (d=130mm) binnenzijde gevel - regelwerk en gipsbeplating - behangklaar
Gevelisolatie (Rc=7,0): PIR isolatie (d=185mm) binnenzijde gevel - regelwerk en gipsbeplating - behangklaar
Gevelisolatie (Rc=8,0): PIR isolatie (d=210mm) binnenzijde gevel - regelwerk en gipsbeplating - behangklaar

GEVEL OPEN

Voorzetraam enkel glas o.g.
Enkelglas
Isolatieglas (U=2,7) i.p.v. enkel glas
Isolatieglas gasgevuld (U=1,6) i.p.v. enkel glas
Isolatieglas luchtgevuld (U=1,6) i.p.v. enkel glas
Isolatieglas gasgevuld (U=1,3) i.p.v. enkel glas
Isolatieglas gasgevuld (U=1,2) i.p.v. enkel glas
Isolatieglas gasgevuld (U=1,2) i.p.v. standaard isolatieglas
Isolerende deur (Rc=1,45): afm.2115x830mm (opp=1,75m^2)
Triple glas gasgevuld (U=0,8) i.p.v. enkel glas
Triple glas gasgevuld (U=0,8) i.p.v. dubbel glas
Triple glas gasgevuld (U=0,8) i.p.v. HR++ glas
Triple glas gasgevuld (U=0,8) i.p.v. enkel glas, inclusief vervanging kozijn
Triple glas gasgevuld (U=0,8) i.p.v. dubbel glas, inclusief vervanging kozijn
Triple glas gasgevuld (U=0,8) i.p.v. HR++ glas, inclusief vervanging kozijn
Kozijn met geïsoleerd paneel (Rc=1,5) i.p.v. kozijn met ongeïsoleerd paneel
Buitenzonwering screens

SERRE, BALKON EN GALERIJ

Serre diep 3m1, enkelglas, polyester golfplaten, hoogte 2 bouwlagen, gehele breedte van de woning
ISO; Serre diep 3m1, enkelglas, polyester golfplaten, hoogte 2 bouwlagen, gehele breedte van de woning
Serre diep 3m1, enkelglas, polyester golfplaten, hoogte 1 bouwlaag, gehele breedte van de woning
Balkons dichtzetten
Galerij dichtzetten

LUCHTDICHTHEID

Aanbrengen kierdichting op alle ramen en deuren
Afdichting kozijn en dichte geveldelen

Afdichting aansluiting dak/gevel
Afdichting naden tussen dakplaten
Afdichting nok van het dak

VENTILATIE

Mechanische ventilatie
Vraaggestuurde ventilatie
CO2-gestuurde ventilatie
Gebalanceerde ventilatie met WTW
Gelijkstroomventilator
Gebalanceerde ventilatie met HR-WTW
Vraaggestuurde ventilatie o.b.v. CO2-meting (geavanceerde natuurlijke toevoer en mechanische afvoer)
Mechanische ventilatie met CO2 sturing i.p.v. 'gewone' mechanische ventilatie
Mechanische ventilatie met CO2 sturing i.p.v. natuurlijke ventilatie
Decentrale mechanische ventilatie

WARMTEOPWEKKING
WARMTEOPWEKKING LOKAAL

Lokale elektrische verwarming
Lokale gasverwarming
Infrarood panelen i.p.v. gaskachels
Infrarood panelen + electrische boiler i.p.v. HRcombiketel

WARMTEOPWEKKING CENTRAAL
INDIVIDUELE OPWEKKING

VR ketel
VRketel (i.pv. VRketel)
Combi Tap VR i.p.v. VRketel en keukengeiser
Combi Vat VR en indirect gestookte boiler i.p.v. VRketel en keukengeiser

HR100
HR100 Ketel (i.pv. VRketel)
HR100 Ketel (i.pv. HR100 ketel)
Combi Tap HR100 i.p.v. VRketel en keukengeiser
Combi Vat HR100 en indirect gestookte boiler i.p.v. VRketel en keukengeiser

HR104
HR104 Ketel (i.p.v. VRketel)
HR104 Ketel (i.p.v. HR100 ketel)
Combi Tap HR104 i.p.v. VRketel en keukengeiser
Combi Vat HR104 en indirect gestookte boiler i.p.v. VRketel en keukengeiser

HR107
HR107 Ketel (i.p.v. VRketel)
HR107 Ketel (i.p.v. HR100 ketel)
HR107 Ketel (i.p.v. HR107 ketel)
Combi Tap HR107 i.p.v. VRketel en keukengeiser
Combi Tap HR107 (i.p.v. Combi Tap VR)
Combi tap HR107 i.p.v. gevelkachels en keukengeisers

Combi tap HR107 i.p.v. collectieve ketel + keukengeiser
Combi tap HR107 i.p.v. collectieve combi-tap VR
HR107 combiketel i.p.v. warmtelevering

HR107 met boiler
HR107 ketel met warmtepompboiler i.p.v. gevelkachel en keukengeiser
HR107 ketel met warmtepompboiler i.p.v. VRcombi
HR107 ketel met warmtepompboiler i.p.v. HRcombi
HR107 ketel met warmtepompboiler (ind.) i.p.v. collectieve VR/HR ketel met coll. tapwater
HR107 ketel met warmtepompboiler (ind.) i.p.v. collectieve VR/HR ketel met ind. Tapwater
HR107 ketel met zonneboiler (i.p.v. Combi Tap VR)
Combi Vat HR107 en indirectgestookte boiler i.p.v. VRketel en keukengeiser

COLLECTIEVE OPWEKKING

VR KETEL
Collectieve VR ketel i.p.v. collectieve VRketel
VR COMBIKETEL
Collectieve Combi Vat VR en ind. gestookte boilers i.p.v. collectieve VRketel en keukengeisers
Collectieve Combi Tap VR en circulatieleiding i.p.v. collectieve VRketel en keukengeisers

HR100
Collectieve HR100 ketel i.p.v. collectieve VRketel
Collectief Combi Vat HR100 en ind. gestookte boilers i.p.v. collectieve VRketel en keukengeisers
Collectieve Combi Tap HR100 en circulatieleiding i.p.v. collectieve VRketel en keukengeisers

HR104
Collectieve HR104 ketel i.p.v. collectieve VRketel
Collectief Combi Vat HR104 en ind. gestookte boilers i.p.v. collectieve VRketel en keukengeisers
Collectieve Combi Tap HR104 en circulatieleiding i.p.v. collectieve VRketel en keukengeisers
Collectieve Combi Tap HR107 en circulatieleiding (i.p.v. collectieve VRketel en keukengeisers)
Collectieve Combi Tap HR107 en circulatieleiding (i.p.v. collectieve VR combi-ketel)

HR107
Collectieve HR107 ketel i.p.v. collectieve VRketel
Collectief HR107 Combi Vat en ind. gestookte boilers i.p.v. collectieve VR ketel en keukengeisers
collectieve HR ketel met collectieve tapwater i.p.v. Collectieve VR ketel met collectieve tapwater
Collectieve HRketel met individuele keukengeisers i.p.v. Collectieve VRketel met individuele keukengeisers

Collectieve HRketel met individuele elektrische boiler i.p.v. Collectieve VRketel met individuele elektrische boiler
Collectieve HR ketel met individuele warmtepompboiler (i.p.v. collectieve VR/HR met collectief tapwater)
Collectieve HR ketel met individuele warmtepompboiler (i.p.v. collectieve VR/HR met individueel tapwater)
Collectieve HR combiketel met zonneboiler (oppervlakte zonnecollector 4,74m^2) i.p.v. warmtelevering

HYBRIDE WARMTEPOMP

Hybride warmtepomp lucht-water + HRketel (ind.) i.p.v. gevelkachels+keukengeiser
Hybride warmtepomp lucht-water en HRketel (ind.) i.p.v. VRketel
Hybride warmtepomp lucht-water (ind.) bijplaatsen bij HR107-combi ketel
Hybride warmtepomp lucht-water (ind.) i.p.v. collectieve HR installatie

LUCHTWARMTEPOMP

Warmtepomp lucht (ind.) i.p.v. VRketel
Warmtepomp lucht combi -buitenopstelling (ind.) i.p.v. VRketel en keukengeiser
Warmtepomp lucht combi en WP boiler (ind.) i.p.v. lokale verwarming
Warmtepomp lucht combi en WP boiler (ind.) i.p.v. CV ketel en keukengeiser
Warmtepomp lucht combi (ind.) i.p.v. coll. VR/HR met coll. tapwater
Warmtepomp lucht combi (ind.) i.p.v. coll. VR/HR met ind. tapwater
Warmtepomp lucht combi - Buitenopstelling (ind.) i.p.v. VRketel en keukengeiser
Warmtepomp lucht combi - Buitenopstelling (ind.) i.p.v. CV installatie
Warmtepomp lucht combi - Buitenopstelling (ind.) i.p.v. CR/VT-combi installatie
Warmtepomp lucht combi (ind.) i.p.v. warmtelevering
Warmtepomp lucht (coll.) i.p.v. VRketels
Warmtepomp lucht combi (coll.) i.p.v. collectieve VR/HR met collectief tapwater
Warmtepomp lucht combi (coll.) i.p.v. collectieve VR/HR met individueel tapwater

HT WARMTEPOMP

HT warmtepomp i.p.v. HRketel
HT warmtepomp i.p.v. gaskachels en geisers

BODEMWARMTEPOMP
INDIVIDUELE OPWEKKING

Warmtepomp bodem (ind.) i.p.v. gevelkachels en keukengeisers
Warmtepomp bodem (ind.) i.p.v. VRketel
Warmtepomp bodem combi (ind.) i.p.v. VRketel en keukengeiser
Warmtepomp bodem combi (ind.) i.p.v. lokale verwarming
Warmtepomp bodem combi (ind.) i.p.v. gevelkachels en keukengeisers
Warmtepomp bodem combi (ind.) i.p.v. VRketel en keukengeiser
Warmtepomp bodem combi (ind.) i.p.v. cv installatie
Warmtepomp bodem combi (ind.) i.p.v. collectieve installatie
Warmtepomp bodem combi (ind.) i.p.v. warmtelevering

COLLECTIEVE OPWEKKING

Warmtepomp bodem (coll.) i.p.v. VRketels
Warmtepomp bodem (coll.) en individuele warmtepompboiler i.p.v. collectieve VR/HR met coll. tapwater

Warmtepomp bodem (coll.) en individuele warmtepompboiler i.p.v. collectieve VR/HR met ind. tapwater
Warmtepomp bodem (coll.) i.p.v. individuele installatie
Warmtepomp bodem (coll.) i.p.v. warmtelevering
Warmtepomp bodem (coll.) voor egw i.p.v. individuele installatie lokaal
Warmtepomp bodem (coll.) voor egw i.p.v. individuele installatie cv
Warmtepomp bodem combi (coll.) i.p.v. collectieve VR/HR met collectief tapwater
Warmtepomp bodem combi (coll.) i.p.v. collectieve VR/HR met individueel tapwater
Warmtepomp (coll.) i.p.v. warmtepomp collectief
Warmtepomp water i.p.v. VRketel
Warmtepomp water combi i.p.v. HRcombi ketel
Warmtepomp water (coll.) i.p.v. VRketels

HRe KETEL

Hre i.p.v. lokale verwarming (gevelkachels)
Hre combi i.p.v. VRketel met geiser
HRe combi i.p.v. combi tap VR
HRe combi ketel i.p.v. collectieve VR/HR met coll. tapwater
HRe combi ketel i.p.v. collectieve VR/HR met ind. tapwater

BIOMASSAKETEL

Pellet cv-ketel
Biomassaketel (ind.) voor RV en tap i.p.v. gevelkachels
Biomassaketel (ind.) voor RV en tap i.p.v. CV
Biomassaketel (ind.) voor RV en tap i.p.v. collectieve installatie met ind. tapwater
Biomassaketel (ind.) voor RV en tap i.p.v. collectieve installatie met coll. tapwater
Biomassaketel (ind.) voor RV en tap i.p.v. warmtelevering
Biomassaketel (ind.) voor RV en tap i.p.v. gevelkachels+keukengeiser
Biomassaketel (ind.) voor RV en tap i.p.v. individuele HRketel
Biomassaketel (ind.) voor RV en tap i.p.v. collectieve HRketel
Pelletketel (ind.) i.p.v. individuele installatie lokaal
Pelletketel (ind.) i.p.v. individuele installatie CV
Pelletketel (ind.) i.p.v. collectieve installatie

WKK

Gebouwgebonden WKK i.p.v. VRketel en keukengeiser

WARMTE DOOR DERDEN

Warmte door derden i.p.v. VRketel en keukengeiser
Stadsverwarming i.p.v. CV-ketel en keukengeiser
Stadsverwarming i.p.v. collectief
Warmtelevering LT - (stadsverwarming i.p.v. elke individuele installatie)
Warmtelevering LT - (stadsverwarming i.p.v. elke collectieve installatie)

WARMTEAFGIFTE

Radiatoren $T>55$
Radiatoren T=35-55
Radiatoren $T<35$
Vloer/wandverwarming $T>55$
Vloer/wandverwarming T=35-55

Vloer/wandverwarming T<35
Luchtverwarming T >55
Luchtverwarming T=35-55
Luchtverwarming T <35

PV CELLEN

Multikristallijne PV-cellen (oppervlakte 6m^2)
Multikristallijne PV-cellen (oppervlakte 15m^2)
Multikristallijne PV-cellen met hoge opbrengst (oppervlakte 6m^2)

PVT PANELEN

PVT zonnepanelen en WP i.p.v. HR combi-ketel
PVT zonnepanelen en WP i.p.v. gaskachels en geisers

ZONNEBOILER

Zonneboiler standaard (oppervlakte zonnecollector 2,37 m^2)
Zonneboiler standaard (oppervlakte zonnecollector 2,5 m^2)
Zonneboiler standaard (oppervlakte zonnecollector 5,0 m^2)
Zonneboiler groot (oppervlakte zonnecollector 7,11 m^2)
CV-Zonneboiler compact (oppervlakte zonnecollector 2,37 m^2)
CV-Zonneboiler standaard (oppervlakte zonnecollector 4,74 m^2)
CV-Zonneboiler groot (oppervlakte zonnecollector 7,11 m^2)
Zonneboilercombi (oppervlakte zonnecollector 4,74 m^2)
Collectieve zonneboiler (oppervlakte zonnecollector 7,11 m^2)
Collectieve zonneboiler + collectieve HR-ketel 300kW i.p.v. collectieve installatie
Collectieve zonneboiler + collectieve HR-ketel 300kW i.p.v. individuele installatie
Collectieve zonneboiler + collectieve HR-ketel 300kW i.p.v. warmtelevering
Stadsverwarming LT + collectieve zonneboiler i.p.v. collectieve installatie
Stadsverwarming LT + collectieve zonneboiler i.p.v. individuele installatie
Stadsverwarming LT + collectieve zonneboiler i.p.v. warmtelevering
Windenergie d.m.v. rotor bladen
Windenergie d.m.v. bol rotor

WARM TAPWATER

Keukengeiser i.p.v. keukengeiser
Badgeiser i.p.v. keukengeiser
Gasboiler i.p.v. keukengeiser
Elektrische boiler i.p.v. keukengeiser
Warmtepompboiler i.p.v. keukengeiser
Close-in boiler i.p.v. keukengeiser
Beperken leidinglengte warm water
Waterbesparende douchekop

AFVOEREN

Douche WTW
Douchebak WTW

BEMETERING

Individuele bemetering gasmeter

Individuele bemetering warmtemeter
Individuele bemetering elektrameter

DIVERSEN

Vervangen van afleverset voor ruimteverwarming
Leidingisolatie ruimteverwarming
Leidingisolatie tapwaterverwarming
Pompschakeling op CV installatie
Optimale afregeling CV installatie

Appendix B: Python code

Listing 1: Code for the support vector regression used to predict the annual gas consumption of dwellings.

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import re
from sklearn.model_selection import train_test_split
%matplotlib inline

# import data
df = pd.read_excel('/content/woningen_verbruik.xlsx', index_col=0)

# Look for missing values
fig = plt.figure(figsize=(12,6))
sns.heatmap(df.isnull(), yticklabels=False, cbar=False, cmap='viridis')

df.dropna(inplace=True)
# Choose the type of dwelling the model is trained for
# options: rijwoning, 2 onder 1 kap woning, vrijstaande woning,
   galerijwoning, portiekwoning
df_werkelijk = df['woningtype'] == 'rijwoning'
df = df[df_werkelijk]

#Drop unneccessary columns that should not be used for training
df = df.drop(['prim_rv', 'deur_u', 'prim_tap', 'prim_hulp', 'prim_licht',
    'prim_tot', 'vloer_rc', 'vloer_opp', 'hellend_dak_opp','
   hellend_dak_rc',
              'voorachtergevel_opp', 'voorachtergevel_rc', 'zijgevel_opp
                 ', 'zijgevel_rc', 'enkelglasvoorachter_opp', '
                 enkelglasvoorachter_u', 'enkelglasvoorachter_zta',
              'dubbelglasvoorachter_opp', 'dubbelglasvoorachter_u', '
                 dubbelglasvoorachter_zta', 'hrppglasvoorachter_opp', '
                 hrppglasvoorachter_u', 'hrppglasvoorachter_zta',
              'enkelglaszij_opp','enkelglaszij_u', 'enkelglaszij_zta', '
                 dubbelglaszij_opp', 'dubbelglaszij_u', '
                 dubbelglaszij_zta', 'hrppglaszij_opp', 'hrppglaszij_u',
                 'hrppglaszij_zta',
              'deur_opp', 'deur_u'], axis=1)

#See what data is left
df.info()

sns.set_style('whitegrid')

# plot the gas consumption
predicting_value = 'm3_gas'
fig = plt.figure(figsize=(12,6))
sns.distplot(df[predicting_value], bins=30, kde=True)
```

```
# correlation between overall gas consumption and features
cutoff = 0.5
corr_results = df[df.columns[0:]].corr()[predicting_value][:]
print(abs(corr_results) > cutoff)
print(type(corr_results))
corr_results = pd.DataFrame(abs(corr_results.to_frame().T) > cutoff)

#Drop all features that do not have a correlation of more than 0.5 or
   less than -0.5
keeps = np.zeros(len(corr_results.iloc[0][:]))

for i in range(len(corr_results.iloc[0][:])):
  if corr_results.iloc[0][i] == 0:
    keeps[i] = False
  else:
    keeps[i] = True

headers = list(df.columns.values)
keeps = [i for i, headers in enumerate(keeps) if headers]
keeps = [headers[i] for i in keeps]

# These are the features that are worth training with
print(keeps)
# Remove the rest of the features
df = df[keeps]

# Drop features that should not be used for prediction, as there is a
   linear correlation between them
if predicting_value == 'kg_co2':
  df = df.drop(['m3_gas', 'energie_index'], axis = 1)
elif predicting_value == 'm3_gas':
 df = df.drop(['kg_co2', 'energie_index'], axis = 1)
elif predicting_value == "energie_index":
 df = df.drop(['kg_co2', 'm3_gas'], axis = 1)

# Plot correlation matrix
plt.figure(figsize=(22,15))
sns.heatmap(df.corr(),annot=True,cmap='viridis')

# Importing libraries for SVR
from sklearn.model_selection import GridSearchCV
from sklearn.svm import SVR
from sklearn.preprocessing import StandardScaler
from sklearn.utils import shuffle

# Permute the data
df = shuffle(df)

# Divide data in features and targets
```

```
X = df.drop(predicting_value, axis=1).values
y = df[predicting_value].values

# Divide the data set in train and test data
X_train, X_test, y_train, y_test = train_test_split(X,y,test_size=0.3,
   random_state=42)
print(X_train.shape)
print(X_test.shape)

# Scale the data
sc_X_train = StandardScaler()
sc_X_test = StandardScaler()
X_train = sc_X_train.fit_transform(X_train)
X_test = sc_X_test.fit_transform(X_test)

# Do a grid search to find the proper C value and kernel function
parameters = {’C’: [0.5, 1, 5, 10, 20, 50, 100],
              ’kernel’: [’linear’, ’poly’, ’sigmoid’, ’rbf’]}
grid_search = GridSearchCV(estimator = SVR(),
                           param_grid = parameters,
                           scoring = ’neg_mean_absolute_error’,
                           cv = 5,
                           n_jobs = -1)
grid_search = grid_search.fit(X_train, y_train)
print(f"Best MAE: {grid_search.best_score_ * (-1)}")
best_params = grid_search.best_params_
print(f"Best parameters: {best_params}")

regressor = SVR(kernel = best_params[’kernel’], C = best_params[’C’])
clf = regressor.fit(X_train, y_train)
predictions = regressor.predict(X_test)
print(clf.coef_)
print(clf.intercept_)

#Histogram of error values
errors = y_test - predictions
sns.histplot(errors, stat=’proportion’)
plt.title(predicting_value + ’ SVR errors’)
plt.xlabel(’Errors’)
plt.grid(b=True, linestyle=’-’)
plt.show()

# Plot the predictions as done by the model
from sklearn.metrics import mean_squared_error, mean_absolute_error,
   r2_score
plt.scatter(y_test,predictions, label=’predicted values’)
# Plot the perfectly fit line (target values)
plt.plot(y_test,y_test,’r’, label=’expected values’)
plt.legend()
```

```
plt.title(predicting_value + ' Support Vector Regression')
plt.grid(b=True, linestyle='-')
plt.show()
print('mean absolute error: ', mean_absolute_error(y_test, predictions))
print('r2_score: ', r2_score(y_test, predictions))
print('root mean squared error:', mean_squared_error(y_test, predictions,
    squared=False))
```

Appendix C: Interview setup

Below is the setup for the semi-structured interview conducted with three stakeholders as explained in section VIII.

1 Introductie

2 Kun je in het kort omschrijven wat je functie precies inhoudt?

3 Wat kan je vertellen over de duurzame bedrijfsvoering van je organisatie?

4 Hoe ambitieus zou je zeggen dat duurzaamheid wordt aangepakt in jouw organisatie?

4a) Hoe vertaalt dit ambitieniveau zich naar projecten?

5 Wat doet jouw organisatie op het gebied van renovaties?

6 Welke verduurzamende maatregelen worden door je organisatie bij renovatieprojecten zoal doorgevoerd/geadviseerd om door te voeren?

6a) Op basis waarvan wordt de keuze gemaakt om deze, en niet andere, maatregelen door te voeren/te adviseren?

7 Hoe heeft wet- en regelgeving invloed op de keuzes die jullie maken m.b.t. verduurzamende maatregelen bij renovaties?

8 Wat weet je over de term ‘embodied carbon’?

9 Op wat voor manier houd jouw organisatie rekening met embodied carbon?

10 Wat denk je dat er gedaan kan worden om jouw organisatie te stimuleren om embodied carbon (meer) te overwegen bij projecten?

11 Wil je nog iets toevoegen?

12 Afsluiting