Harmonizing heritage and sustainability : Exploring the potential of bio-based Materials in heritage preservation

"The building is to form an example for future architecture on how to work, design and live with bio-based materials."

| Abstract

The construction sector is responsible as one of the largest emitters of carbon and nitrogen, and as a user of water. In addition, it is a linear construction process that creates new materials from non-renewable resources. Furthermore, the built environment in the Netherlands is becoming overcrowded and there are insufficient regulations for the preservation of historical buildings. The aim of this research is to apply bio-based materials in the conservation of historical buildings for a circular and sustainable renovation. For this purpose, the following main question has been formulated: "How can bio-based materials enhance sustainability and circularity in architectural renovation while prioritizing the conservation & preservation of architectural heritage?".

Foundation of the research are the 10 R's of circularity, BREAAM and LEED. In addition, software was used to select materials and properties based on sustainability parameters. Combined with a heritage assessment, it indicates which materials can be used in the conservation and renovation of heritage buildings.

This research has yielded a practical tool designed to enhance the sustainability and circularity of architectural renovations with a focus on bio-based materials. This framework also addresses the preservation of heritage qualities of buildings. Moreover, the outcome of the introduced tool contributes to the reduction of carbon and nitrogen emissions, as well as water consumption. It also actively supports the transition towards a circular building process through the use of new materials made from renewable resources.

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Harmonizing Heritage and Sustainability

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Introduction

| Concepts & Relations

Within this research, there will be looked at the various bio-based materials that could be considered for use in contemporary building processes, with a focus on heritage.
To this purpose, the following keywords have been compiled that define the research.

| Bio-based materials | Heritage preservation | Circularity | Sustainability | Material properties |

| Problem Field

In today's urban environment, we run into a number of problems that pose a bottle neck problem for building development (of housing) in the Netherlands. Today's construction industry constructs buildings in a traditional way, being a linear process, using conventional building materials such as concrete and steel (Gagg, 2014). These building materials are newly produced for the sector from mostly non-renewable raw materials (Ethical Unicorn, 2020). In addition, most of these building materials are not reused or not sufficiently reused after their lifetime in the specific building. These form a number of the reasons why the construction sector is responsible as one of the largest carbon and nitrogen emitters and users of water in the world (Ethical Unicorn, 2020). Re-use initiatives and circular construction methods are attempts that seek to stem the tide of this straight-line economy by re-using building materials after they have done service in existing buildings. Thus, fewer building materials are destroyed, but the production of new, non-renewable building materials can also decrease this way. This will benefit to the construction sector in order to be more sustainable. Although, at the front end of the process, the same non-renewable building materials are still being used which have a negative impact on the emission volumes and thus the climate.
In addition, the Netherlands has a large number of structures with heritage values.
These buildings are valued for their appearance and style of bygone days. Furthermore, the Netherlands are reaching a ceiling for the expansion of cities into the urban outdoor space (Nederland is druk en vol (column), 2018). As a result, more and more solutions are being sought to densify within the urban limits and, as a result, existing buildings are being preserved and equipped with, as an example, extra floors to contribute to the growing demand for housing. Additionally, entire blocks and neighboorhouds are being redeveloped to densify the area, but also keep the rich (green) collective outdoor space (We moeten de stad op een aantrekkelijke manier zien te verdichten, 2022). Developments such as these ensure that the green environment outside cities can be preserved and that the expansion of cities is done more efficient within the area of the existing municipality.
But even these construction and densification processes are often still part of a linear building process that does not, or poorly, use renewable materials, or materials with low carbon and nitrogen emissions. This makes development socially and urbanely more and more sustainable, but from an environmental point of view, there is still a long road ahead.

What if the front end of the construction industry with non-, or poorly, renewable building materials changes? Using bio-based materials can go a long way in reducing emissions from the construction sector and contribute to a sector that deviates from traditional linear construction processes. These bio-based materials can help the construction sector transform itself into a circular sector, thus making a positive contribution to the set climate goals (Chayaamor-Heil et al., 2023b).

Incorporating bio-based materials into heritage preservation and architectural restoration emerges as a sustainable and forward-looking strategy. These materials, sourced from renewable origins, seamlessly blend historical authenticity with ecological responsibility (Melià et al., 2014). By seamlessly integrating bio-based elements like natural wood, lime, or earth-based plasters into heritage structures, we not only pay homage to their original construction techniques but also champion their enduring protection. These materials often possess innate qualities that rejuvenate aging edifices, bolstering their resilience against environmental pressures while ensuring the timeless cultural significance perseveres for future generations (Ben-Alon et al., 2019). In this endeavour, bio-based materials align the cause of heritage preservation with contemporary sustainability objectives, elegantly harmonizing tradition and innovation in the realm of architectural conservation.

| State-of-the-art:

Already existing research concerning bio-based materials goes in three different main directions.
The bulk of research is about materials that change our daily lives by making waste biodegradable. This in order to reduce pollution (Al-Tayyar et al., 2020). It is also used for countering oil pollution and the materials used for the oil production (Doshi et al., 2018).
Further, research was conducted to evaluate various bio-based materials to see how well they perform in terms of thermal and sound insulation, etc. This was done in comparison to conventional building materials (Zhu, 2014).
Another source was found that goes into a LCA (life cycle assessment) between 3 buildings that are conventional, CLT and 'increased bio' (Peñaloza et al., 2016).
This shows that bio-based materials are being researched from multiple angles and that their applications are broader than just the building sector. Namely, these studies already show that the LCA of an 'increased bio' building is much better than that of a conventional building (Peñaloza et al., 2016). Bio-based materials have also been found to serve as a good substitute for the materials currently used to clean up oil pollution. In fact, these clean-up materials were found to be polluting themselves (Doshi et al., 2018).

What is still missing in research field is a linkage of these different topics to each other. Various materials are checked, but not brought together in a whole overview. In addition, it would also add value if there were insight into which bio-based materials could serve as substitutes for certain conventional building materials.
Finally, an extension of assessments of already existing bio-based buildings is of added value to gain more insight into the various building-technical and architectural possibilities with these bio-based materials.

| Aims & Objectives:

The aim of this research is to create a list of different bio-based materials and their material properties, which are selected by using a certain set of criteria that are elaborated up on later in this research. In addition, these bio-based materials are going to be linked to conventional materials in order for the research to also serve as an auxiliary tool in substitute materials selection. This is to show the potential bio-based replacement for the conventional building

material.
Furthermore, case studies are used to show the selected bio-based materials in buildings. From this, one can learn what the different application possibilities are and secondly, this serves as inspiration for designers to implement these materials in future projects.

| Research Question:

In order to reach the aims & objectives stated above, the following main question and sub-questions have been drawn up to provide a complete picture:

Main question:
"How can bio-based materials enhance sustainability and circularity in architectural renovation while prioritizing the conservation & preservation of architectural heritage?"

Sub-questions:

- What criteria should there be stated in order to select bio-based materials suited for location specific architectural heritage renovation?
- What are the distinct categories and characteristics of bio-based materials available for architectural renovation and how can their performance be assessed and compared?
- What are the cultural and historical considerations when selecting bio-based materials for heritage preservation in architectural renovation and how can already existing architecture show the possibilities of applying bio-based materials?
- What are the implications for architectural heritage renovation when transitioning from traditional building materials to bio-based materials?

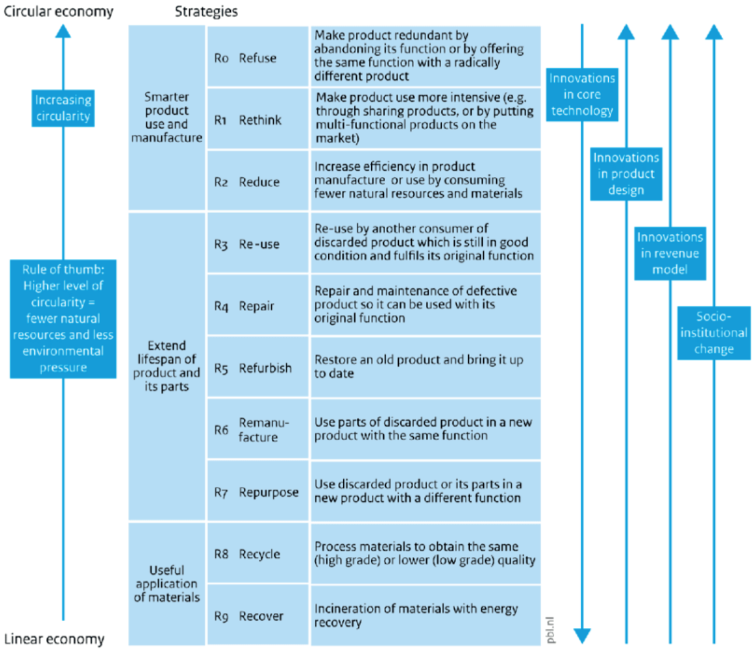
The first idea for the influence of this research on the design later on is to work with a building where new additions and interventions are as much as possible made with bio-based building materials and where the design can draw inspiration from these natural materials in order to cut down on emissions, waste materials and linear processes but still maintain the heritage value and image of that building and adding a new layer of heritage to this existing structure.
To see the approach for answering each of these research questions, see appendix 1: research table at the end of this document.
Furthermore, the envisioned design case on which the results of the research will be tested first can be found in the appendix.

The building is to form an example for future architecture on how to work, design and live with bio-based materials.

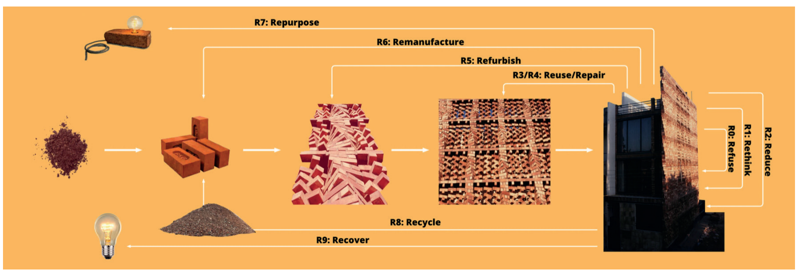
Methodology

| Theoretical Framework:

To connect the research to existing theories that are already published in the field, the 10-R method on circularity has been selected in order to place the material selection tool onto that specific ladder. With that, the tool becomes an auxiliary to the ladder in order to reach the potential proposed by the 10-R strategies.
The graph below shows the 10-R's of circularity (Potting et al., 2017). Below that is another image that shows what each of the R's could mean for a building (What the R?! – the 9R framework and what you should know about it, 2023).
This 10R system also works in preserving heritage values in a building. Potting et al (2017) states that R0, R1 and R2 are the most preferred stages to reach, because waste is minimalised and the existing building is optimally used. To add on that, What the R?! (2023) shows in their image that these cycles prove to be the shortest and best for preserving the building. This research also focusses on integrating heritage in order to make restauration and preservation more sustainable and circulair, so using the 10R system as a theoretical framework to further build the research on will be a good starting point for both development of the envisioned results as well as additional information on the 10R value system.



Circularity strategies within the production chair, in order of priority, Potting et al., 2017



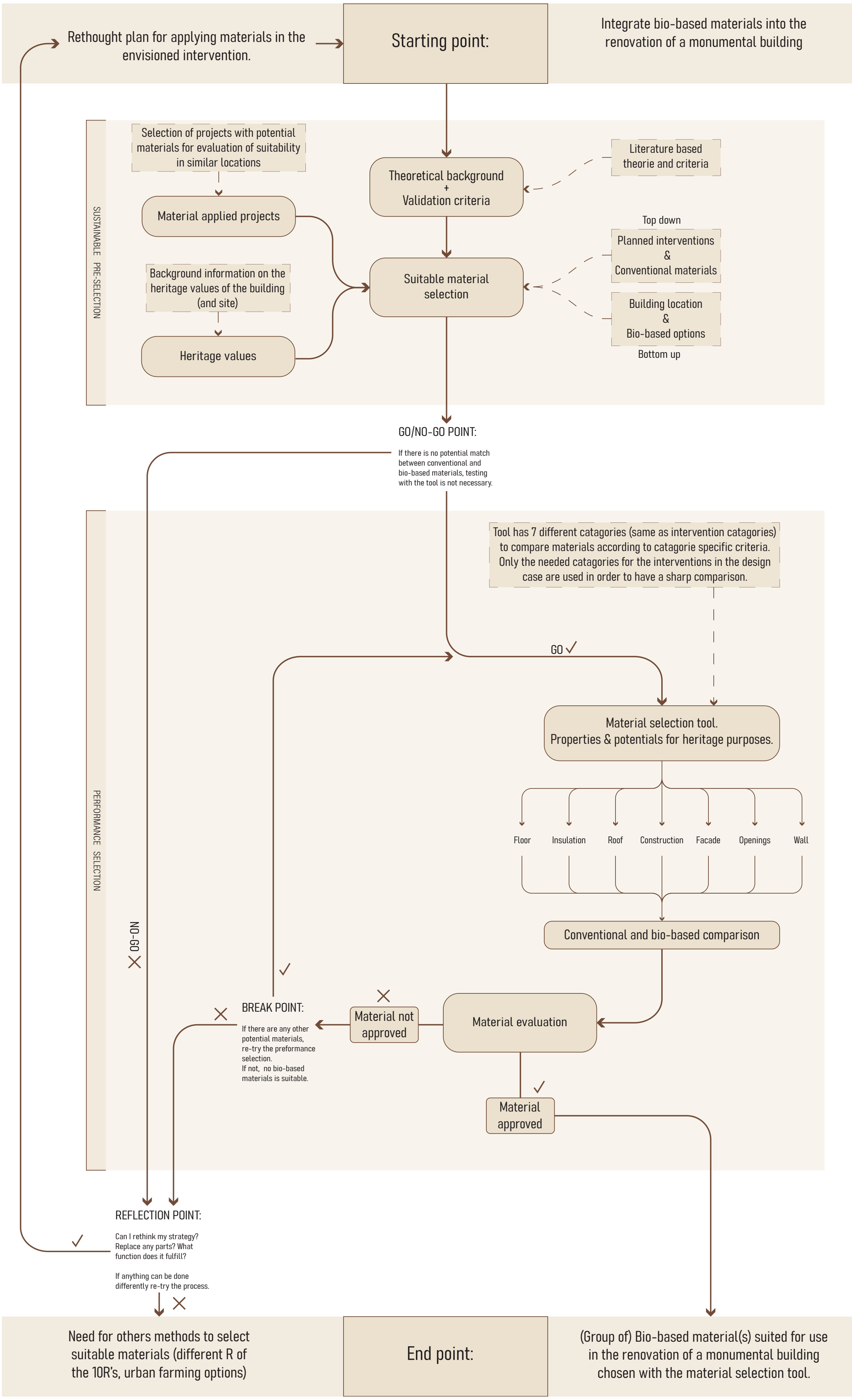
10-R framework as used on an building level, What the R?! – the 9R framework and what you should know about it, 2023

Furthermore, the criteria systems of the BREEAM and LEED are used in this research in order to help develop the criteria for evaluating materials. These are used as sources of information to base further statements on and therefore are not used as a framework, but rather as a substantiation to the formed criteria in this research that make up the foundation of the envisioned tool.

| Methods:

For this research, the idea is to use sources that provide insights into the different kinds bio-based materials available, their parameters for comparison, any heritage values and projects where certain bio-based materials are applied. That would give the first part of the research insight into the overall possibilities, options and criteria to pay attention to. Then, further investigation into the use of those materials can provide the needed information on the possible needed changes to the existing techniques used in construction. This will form a sustainable pre-selection that allows to assess the worth (or not) of applying bio-based materials before testing which is actually suitable for application.
Therefore giving a total overview of usable materials, but also in depth assessment of the extent to which these materials are suitable for use in preserving heritage and making the construction sector more sustainable.

Keeping this in mind, two methods are anticipated to gather the necessary information for the study. The initial approach involves creating a comprehensive framework of information across different subjects to establish a sustainable pre-selection, as outlined in the framework on the right. This interdisciplinary framework is developed using various literary resources. The outcomes of the sustainable pre-selection involve, first, the formulation of validation criteria based on a theoretical background. Secondly, the process includes selecting suitable materials by forming a database with parameters to evaluate bio-based materials for application. This selection process will be expanded with insights into heritage values, building applications, and material-applied projects. The resulting database will include potentially suitable materials with background information on applying materials while respecting the heritage value of a building. It will also provide insights into specific heritage values to consider when altering a building and showcase architectural projects that have already used specific bio-based materials, offering valuable insights into their practical application.
The second method delves into the practical facet of this research. Leveraging the established database, a tool can be formulated to facilitate material selection for application in a project. This second segment serves as a performance selection, offering users the capability to assess material suitability and, if not, assisting in determining the correct utilization of the tool. Furthermore, this performance entails an examination of the implications for building techniques and potential adjustments the sector may need to accommodate.
The performance selection, as depicted in the framework on the right, follows a circular process to identify a suitable material. Within this circular trajectory, three breakpoints are identified. Initially, before commencing the selection cycle, a GO/NO-GO point is established. If the database reveals no materials suitable for testing with the tool, initiating the testing process becomes futile. This leads to the REFLECTION POINT, designed to assess the appropriateness of the approach. Minor adjustments to the approach at this juncture can potentially yield a positive outcome. The circular process also encompasses a BREAK-POINT. If a material is deemed unsuitable for application, the BREAK-POINT offers two alternatives. If no more potentially suitable materials are available, the process transitions to the REFLECTION POINT. Alternatively, if there are still potentially suitable materials, the circular process recommences to evaluate the material's approval.Overall, this makes the research both theoretical and practical. This is because the dual framework provides an auxiliary direction for applying bio-based materials in different situations. In addition, it is practical because it also immediately shows how it can be used in practice by providing the various material applied projects and helping with applying materials into projects.



Methodological framework, B. Turkstra, 2023

| Sources:

Firstly, the data needed consists of information and properties about the materials to make an informed consideration about their usability. In addition, sources are needed to help determine the application and which conventional building material it can replace. Furthermore, resources to help formulate the criteria are also needed. Finally, projects that apply the materials should be selected to see what can be learned from them for further design assignments. This gives a total of 4 different types of data to be collected. The first two mentioned are sought by consulting literary sources and books. The latter will come from comparing different projects to find suitable ones for this research.

| Hypothesis:

A hypothesis was also drawn up for this study, to have clarity on what the expected outcome of this study could possibly be. This hypothesis serves as an aid for reflection later on this research.
The earlier shown methodological framework gives as result a tool for material selection and evaluation. The expectation is that this tool is able to combine information from literature and relevant case studies, heritage values and building applications together in order to provide the answer of which materials are suited for application in the specific design case.
This would mean that the effectiveness of the tool will influence the outcome of the research.

| Case Study:

Projects that use the materials that can be found in the database were chosen for this research. These are projects located in western Europe, or an area with the same climate as the design location of this research, each using one or more bio-based materials in the building in its own way. The buildings differ in function and size so that different applications can be compared to provide a full conclusion. The chosen climate area for the case studies comes from the location of the chosen design case, being Amsterdam West (see the added Design location Determination booklet). These case studies will later be evaluated. The results per case study will provide additional information that can be used in the evaluation tool in order to select the best materials needed for the design case in question. These projects are collected in a database that is connected to the materials.

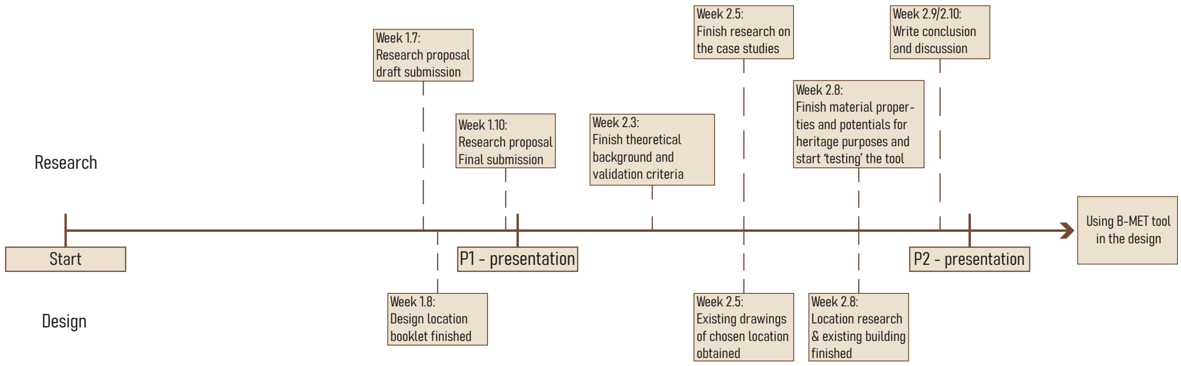
| Scope:

This research will be done in the 20-week time frame from September 2023 to January 2024. The research provides a tool that is not bound to any location or scale. It is to be implemented into a design location. Here it can provide materials specific to the building. The outcome of materials is unique for every location the tool is used for. For now, a number of case studies and a framework with a small amount of materials will be examined, allowing a qualitative look at these materials for a proper assessment of them and also a valuable assessment of the tool and the potential it has for actually evaluating bio-based materials.

Furthermore, no surveys are conducted that could be time-consuming for the study, which helps with containing the time required. On the other hand, as many sources as possible are consulted to make the information as objective as possible on the subject and ensure that the knowledge gained can be applied. This is sought to be done within the stipulated time period.

| Process & Timeline:

For the process and timeline of this study, the timeline below has been created to provide a guide through the study. This seeks to give clarity and structure to the research. The goal, is that it allows information to be gathered from every point of view without major quantity differences, so that the conclusion that follows from the research is as objective as possible.



Timeline, B. Turkstra, 2023

| Risks & Mitigation:

In terms of lockdown and limitations to working off-site on this research, it has few bottlenecks to consider. This is because much of the research comes from looking up sources. In addition, the relevant architectural firms can be contacted for further information on various case studies. If it is necessary to consult libraries, this should be done in a timely manner, also for the benefit of the research. The design of the research, in case it is necessary, also provides the space to integrate more materials as well as case studies that may strengthen or weaken the possible outcomes.

Results

| Sub-question one:
What criteria should there be stated in order to select bio-based materials suited for location specific architectural heritage renovation?

Selecting bio-based materials for location-specific architectural heritage renovation necessitates the establishment of clear criteria for evaluation and selection. To this end, the analysis of key papers, "Sustainability and Green Building Rating Systems: LEED, BREEAM, GSAS, and Estidama Critical Analysis" by Awadh (2017) and "Critical Review of the Material Criteria of Building Sustainability Assessment Tools" by Park, Yoon, and Kim (2017), yields seven essential criteria: Resources, Location and Transportation, Water Consumption, Embedded Energy, Living Environment, Ecology and Pollution and finally life cycle. These seven criteria will be explained further in detail later on.

The BREEAM (Building Research Establishment Environmental Assessment Methodology) was introduced in 1990 as a comprehensive tool to evaluate various aspects of building performance. It assesses buildings across categories such as Management, Health & Wellbeing, Energy, Transport, Water, Materials, Waste, Land use & ecology, Pollution, and Innovation. Since its inception, BREEAM has certified over 535,000 buildings, with 2,217,000 buildings seeking certification. While predominantly used in the UK, BREEAM has a global presence, with certified buildings in 74 countries and a network of 2,600 licensed assessors (Townsend & Townsend, 2023).

LEED (Leadership in Energy and Environmental Design), launched as a pilot program in 1998 by the U.S. Green Building Council, mirrors BREEAM's commitment to environmental awareness. The LEED rating system encompasses categories like Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental Quality, Innovation, and Regional Priority. Buildings are rated as Certified, Silver, Gold, or Platinum based on the points they accumulate. LEED has evolved since its pilot, adapting to emerging building techniques and maintaining relevance. In addition to its general rating system, LEED offers specific methods tailored for diverse building types, including Neighbourhood Development, Homes, Existing Buildings, Operations & Maintenance, and Schools, each addressing unique considerations (LEED Rating System | U.S. Green Building Council, n.d.).
Both BREEAM and LEED emphasize continuous updates to reflect advancements in sustainable practices and to align with changing building technologies.

Upon explaining the BREEAM and LEED rating methodologies, the delineation of crucial considerations in evaluating buildings becomes apparent. This holds significant relevance in establishing criteria for the research on selecting bio-based materials.

Awadh (2017) underscores a critical perspective by asserting that the attainment of a green building certification does not invariably signify the realization of environmental objectives. The primary factors contributing to a potentially obscured sustainability outcome, as highlighted by Awadh, are financial-driven implementation and prescriptive application of GBRS. The study posits that financial considerations take precedence over a sincere commitment to achieving environmentally sustainable structures during the pursuit of a green building certificate. Furthermore, Awadh explicates that both BREEAM and LEED operate within a framework characterized by a checkbox approach, emphasizing certification achievement. This checkbox approach, as noted, can lead to a 'masked sustainability outcome,' wherein the building may appear environmentally sound on paper but may not fully manifest its sustainable potential in reality.

In parallel, Park, Yoon, and Kim (2017) contribute an additional layer of insight by contending that prevailing assessment methods, while focusing on environmental factors, tend to marginalize economic and social values, which are equally paramount. Considerations such as justice, wellbeing, diversity (social), and life cycle cost, sustainability, and durability (economic) are posited as integral but often neglected facets in the current evaluative frameworks (Park, Yoon, and Kim, 2017). Consequently, the research advocates for an expanded analytical paradigm, introducing a triple bottom line encompassing social, economic, and environmental parameters for a comprehensive assessment of all material-related items.

In summary, both studies accentuate the imperative for a more comprehensive evaluation of green building certification methodologies. The delineation of parameters by Park, Yoon, and Kim (2017), coupled with the financial-driven and prescriptive implementation elucidated by Awadh (2017), collectively paints a picture of a green building certification landscape where theoretical propositions may diverge from practical outcomes. The need for an expanded evaluative framework is underscored, necessitating the inclusion of economic and social values alongside environmental considerations. This imperative resonates throughout the literature, emphasizing the importance of recalibrating existing paradigms to ensure a more holistic and accurate reflection of a building's sustainability performance.
Therefore, in order to assess materials in a proper manner to ensure the best suited material is selected, the following criteria, based on the BREAAM and LEED will be used in the practical development of the research:

Resources:

Sustainable sourcing of bio-based materials is of importance, with a focus on preserving natural resources and minimizing ecological disruption. Evaluation of resource sustainability encompasses factors like resource renewal rates, responsible extraction practices, and impacts on biodiversity..

Location and Transportation:

Opting for locally sourced materials or employing low-emission transportation practices reduces carbon emissions and thus the environmental footprint, aligning with heritage preservation and environmental sustainability.

Water Consumption:

The selection of materials with reduced water footprints contributes significantly to water conservation and sustains renovation efforts.

Embedded Energy:

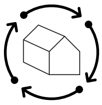
Opting for materials with lower energy requirements during production is instrumental in minimizing carbon emissions and upholding environmental responsibility.

Living Environment: 

Architectural heritage renovation projects aim to establish comfortable and health-conscious living environments. The choice of bio-based materials should take into account their influence on indoor air quality, thermal performance, and overall occupant well-being.

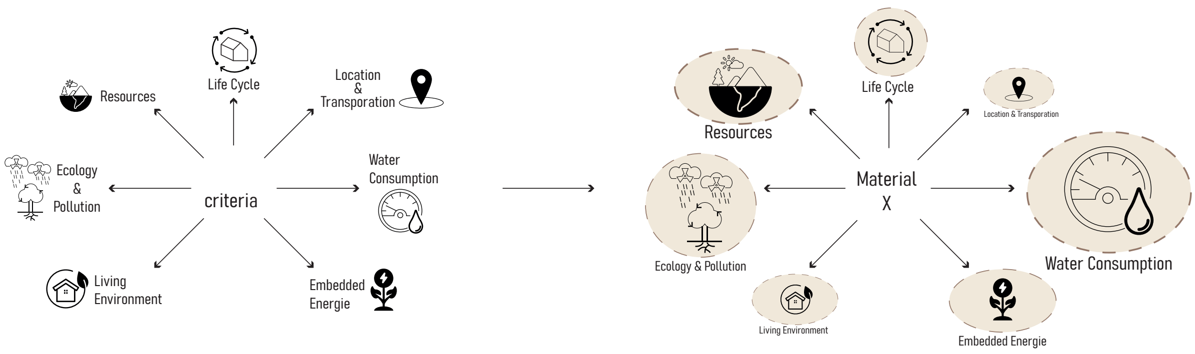
Ecology and Pollution: 

Bio-based materials should not pose threats to local ecosystems or contribute to pollution throughout their lifecycle. The selection of bio-based materials should prioritize options that minimize ecological disruption and prevent harmful pollutants from entering the environment.

Life Cycle: 

Assessing the life cycle of materials ensures that they not only serve the immediate renovation needs (long- or short term solution) but also stand the test of time, reducing the long-term environmental impact and costs associated with maintenance and replacement.

In the image below, these seven criteria are shown in a diagram. Also visible in the image is that each specific resource can have a mixed amount of influence on whether the material is suited for application.



Material evaluation criteria

A potential bio-based material is tested based on the stated criteria in the research. These are not all of the same importance. This depends per material. For a possible distribution of the importance, there can be looked at the image below.

Priority of every criteria for chosen material

In this diagram, a possible distribution of the importance of each criteria is shown for a specific material. This distribution is unique and will be different for each material. Furthermore, the same material can have a different diagram depending on a different design location.

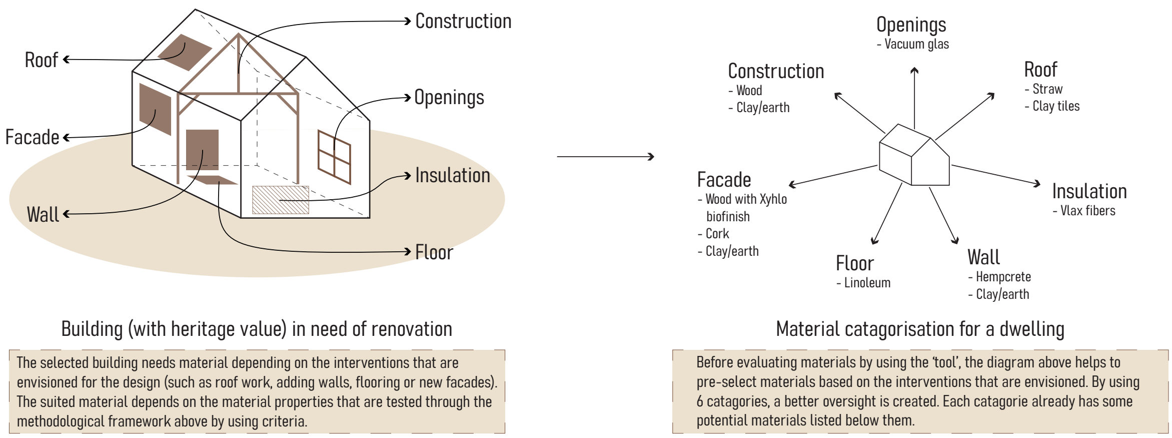
Material evaluation, B. Turkstra, 2023

These criteria, when employed in a structured manner, ensure that the materials chosen for architectural heritage renovation not only preserve the historical significance of the structures but also adhere to sustainable practices and principles. They help strike a balance between heritage conservation and environmental responsibility.
In the quest for sustainable architectural heritage preservation, these criteria and tools serve as valuable guides, paving the way for informed decisions and responsible choices.

| Sub-question two:
What are the distinct categories and characteristics of bio-based materials available for architectural renovation and how can their performance be assessed and compared?

To achieve suitable materials that can be applied in architectural heritage restorations/conversions, it is of great value to select parameters by which to determine whether a material is suitable. Before there is the possibility of attaching such value to a material, it is first important to look at the different material categories a building has. In the book 'Fundamentals of building construction' by Allen and Lano (2019), the entire building process is categorised into materials and methods. It also maps out in which parts of the building various categories are located. Based on the work in the book by Allen and Lano (2019), 7 different categories have been compiled that divide a building. These are as follows: wall, structure, roof, facade, openings, insulation and floor.

With this classification, a building is divided into useful segments for making considered choices of a suitable material. An example for the usefulness of this subdivision comes from the study by Ertemir and Edis (2022). That study looks at mapping inspections for heritage buildings and thus an emphasis on facades. This research already clearly shows that it is not necessary to look at the entire building. In addition, the research also shows the usefulness of a clear division to have, in conjunction with such inspections, an overview by category of work done to a heritage building.
In the following image, the 7 categories are made visible through the use of 2 diagrams



Material catagorisation, B. Turkstra, 2023

The seven categories are formed in such a way that an entire building can be compiled with all of them. The division was made on the main function a category has. As an example, the main function of the structure is to keep the building standing. As opposed to insulation, which ensures a pleasant indoor climate throughout the year.
To compile a list of materials and variables for each category, an Excel file was prepared (see appendix) using information obtained from the Granta Edupack software package (Ansys, 2023.

This package uses information obtained from Cambridge. Cambridge Engineering Selector, which later became CES EduPack and eventually GRANTA EduPack, was originally developed as part of the first computer-based teaching project at the Engineering Department of the University of Cambridge.
In this programme, material properties can be searched and compared with other materials. This can be done based on different material properties. For this study, a number of parameters

applicable to all categories were selected. These are as follows:

- A renewable resource
- CO^2 footprint, production
- CO^2 footprint, recycling
- Embodied energy, production
- Embodied energy, recycling
- Water Usage
- Production location
- Downcycle/recycle
- Price

In addition, parameters applicable to a specific category have been identified for each category. These individual parameters are substantially different from each other. As an example, the following parameters have been selected for the insulation category versus the construction category:

Insulation category:

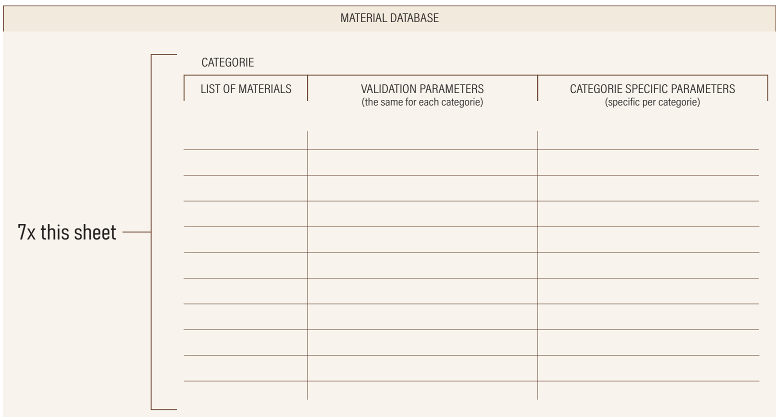
- Lambda value
- Thermal resistivity
- Thermal conductor/insulator
- Sound insulation
- Sound absorption

Construction category:

- Yield strength
- Young modulus
- Tensile strength
- Density
- Compressive strength
- Bending strength

This maintains the same values for each category for ecological and economic aspects in order to make a comparison. The category-specific parameters have been established to allow a bio-based material to be compared with its conventional alternative. In doing so, the objective is to allow the research to work more broadly. This is in line with Park, Yoon and Kim's (2017) conclusion for a 'triple bottom line'.

The image below shows a simplified version of the database behind this study. This clarifies how the survey stores the data and works with it.

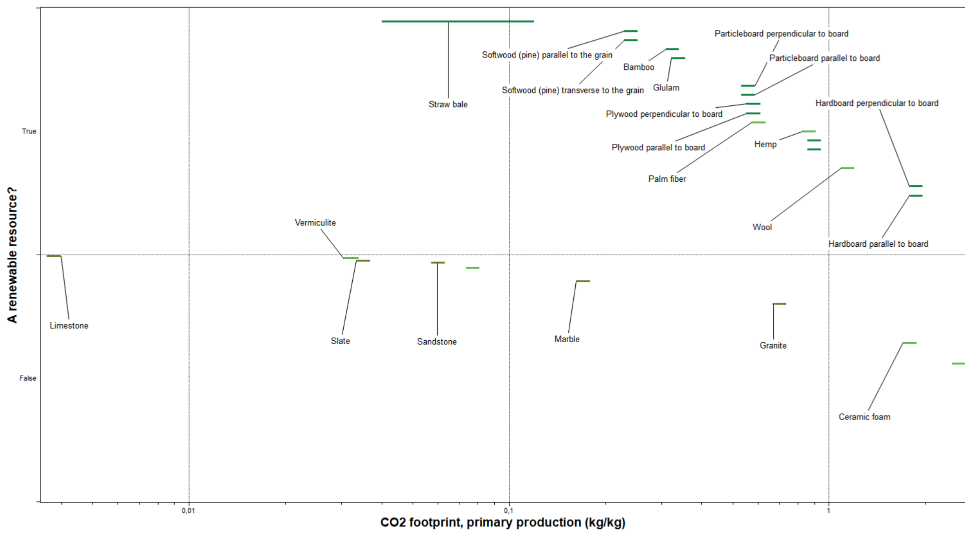


Simplified diagram of the materials database

The database consists of seven sheets. One for each of the 7 defined material categories. For each sheet, there is first a section with parameters that are the same for each category. These are established using the validation criteria. In addition, there are specific parameters established for each category that apply to that specific category but do not add value to another. Parameters are not a one-off herein and may occur across a number of categories.

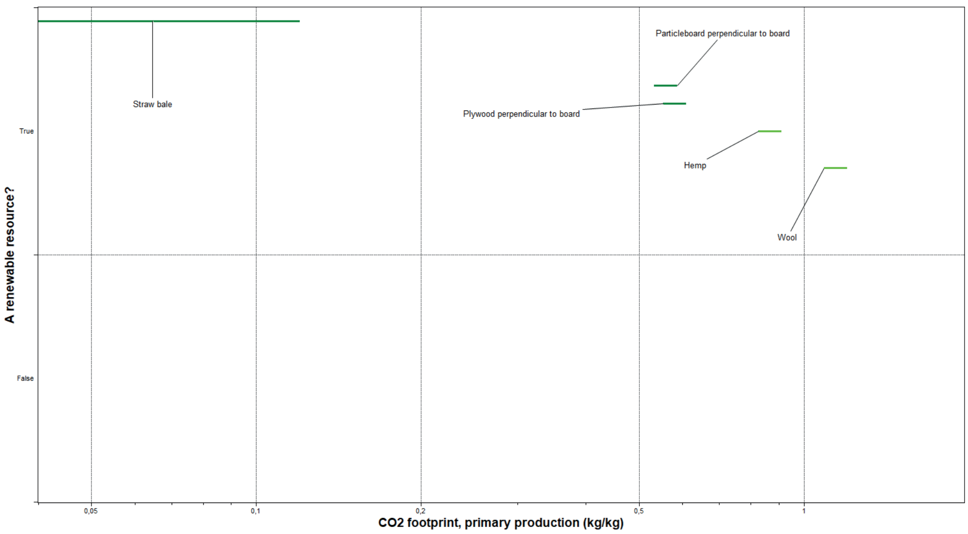
Simplified database diagram, B. Turkstra, 2023

Following are a number of images showing how the different materials for the database were determined using the Granta Edupack software. By first applying the general validation parameters, a batch of materials is collected from the software. In the following diagram, these materials are visualised. The two main parameters are shown on the X-axis (CO^2 footprint) and Y-axis (A renewable resource). The remaining parameters are added as additional filters in order to apply all selected validation parameters. In the image below all the materials that passed are shown. Additionally, natural stone (such as limestone and slate) are also considered possibilities. Although not a renewable resource, the remaining parameters and their lifespans allow these to be considered as optional materials.



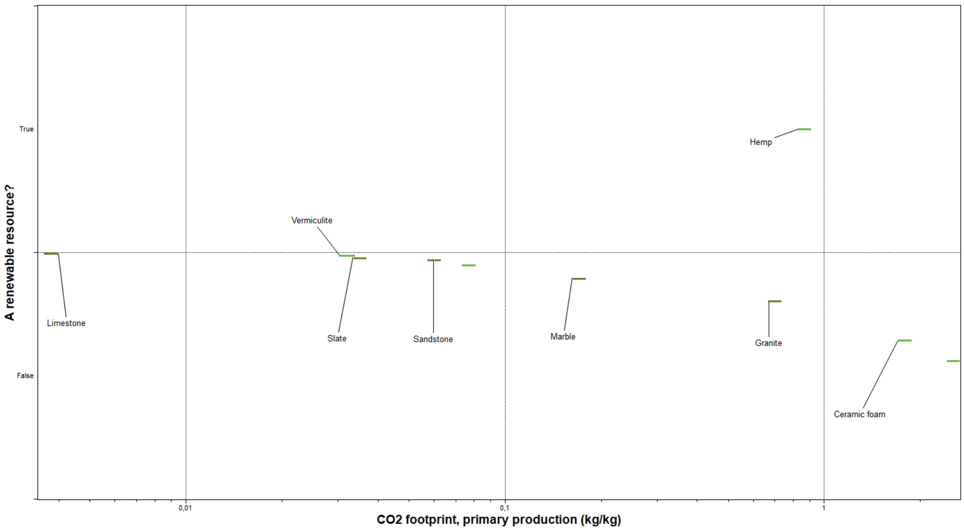
All materials suitable for use in the tool, Ansys 2023

Insulation categorie:
Applying the insulation category parameters (thermal resistance, thermal conductor/insulator, sound insulation and sound absorption) yields a total of 5 potentially suitable materials (see diagram below). In addition to these materials, sea grass was also selected as a potential material. Further research into materials not included in Granta Edupack yielded additional materials for a number of categories.



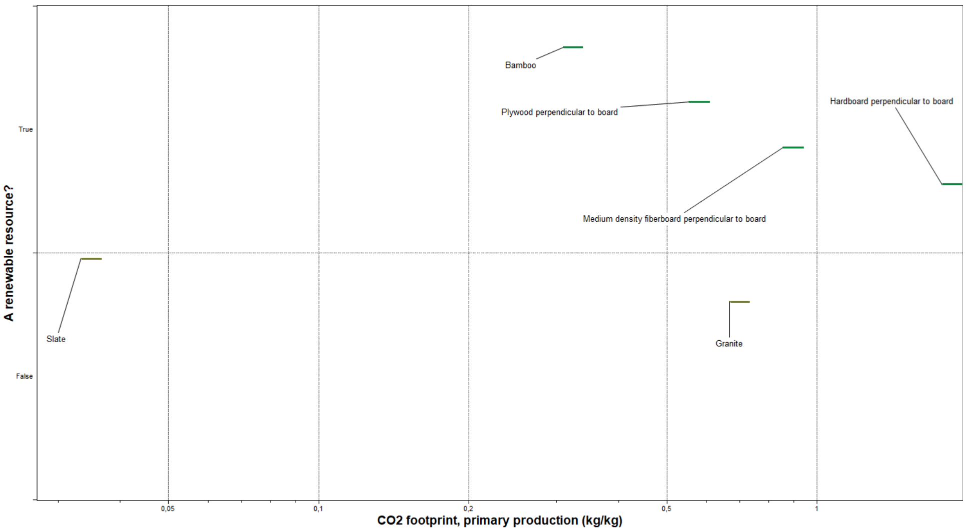
Insulation categorie, Ansys, 2023

Facade Categorie:
Applying the parameters of the facade category (UV radiation, water absorption, wear resistence and frost resistence) yields a total of 8 potentially suitable materials. The database also includes wooden facade elements protected with bio-based wood oil protection (Xyhlo biofinish). Wooden facade elements are not selected as suitable by the software as the material does not score sufficiently by itself on the set requirements of water and freeze damage/absorption. However, these can be used to excellent effect from a bio-based perspective when combined with a suitable protective coating.



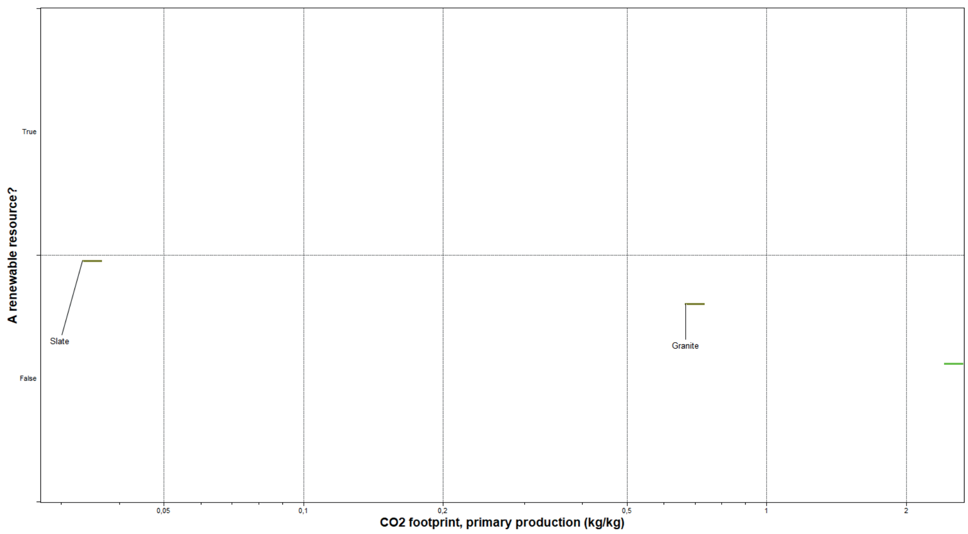
Facade categorie, Ansys, 2023

Construction categorie:
Applying the construction category parameters (yield strength, Young modulus, tensile strength, density, compressive strength and bending strength) yields a total of 6 potentially suitable materials. This shows that for both facade materials and construction materials, stone is a suitable material for application. This material group is not renewable, but with its long lifespan and high scores for structural load-bearing walls, it has a valid reason for application in the database.



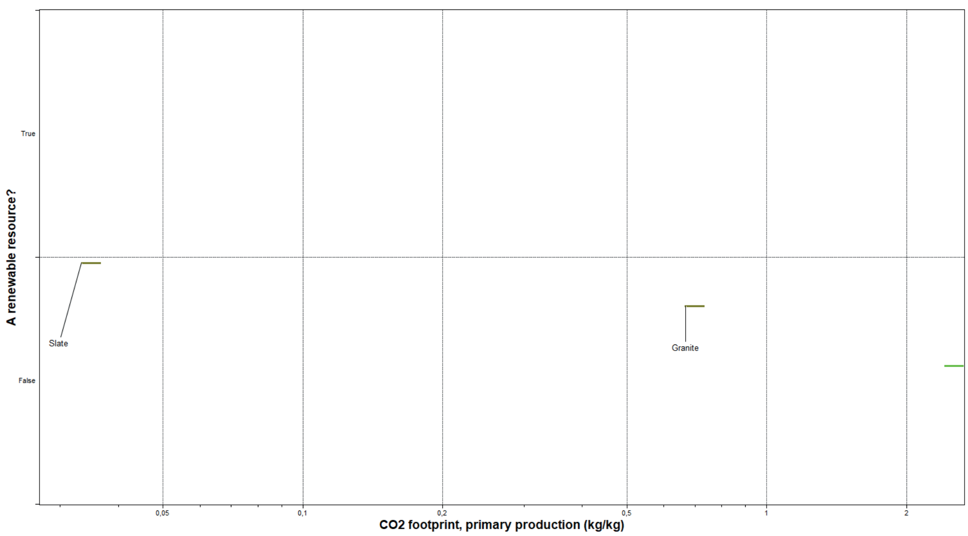
Construction categorie, Ansys, 2023

Roof categorie:
Applying the parameters of the roof category (UV radiation, water absorption, wear resistence and frost resistence) yields a total of 2 potentially suitable materials. These materials are both stone types. Further research has also added reeds as a roofing material. The parameters of this category are similar to those of the facade. In the case of roofing materials, the parameters have the toughest requirements. This is because the category has to cope with the greatest amount of weather influences.



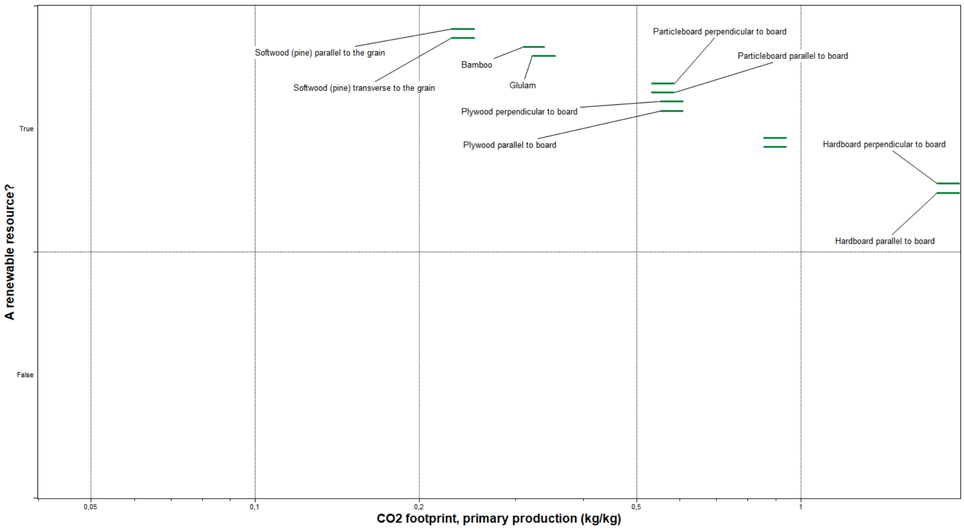
Roof categorie, Ansys 2023

Floor categorie:
Applying the parameters of the floor category (sound absorption and wear resistence) yields a total of 2 potentially suitable materials. These materials are both stone types. The limiting parameter for materials here is wear resistence. This quickly excludes various materials from the software. Further research has also added wood flooring and marmoleum as a potential material.



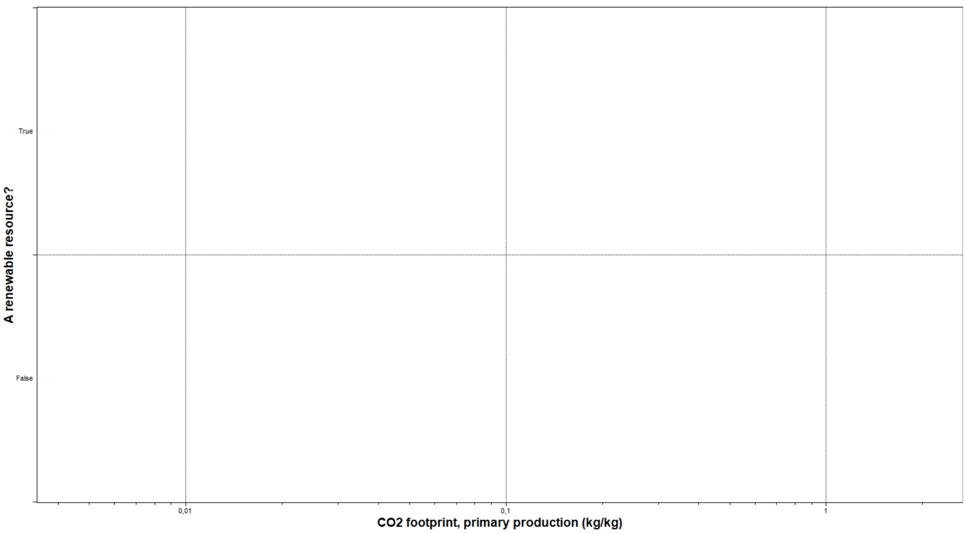
Floor categorie, Ansys, 2023

Wall categorie:
Applying the parameters of the wall category (sound absorption, sound insulation, water vapour permeability, compressive strength and bending strength) yields a total of 10 potentially suitable materials. These materials are all wood species. An addition to this is hemp as a building block. The software only calculates with hemp as a fibre and mainly insulating applications. The application as a building block is not included in the software.



Wall categorie, Ansys, 2023

Openings categorie:
Applying the parameters of the openings category (transparency, thermal resistivity and thermal conductor/insulator) does not provide suitable materials. This is due to the transparency parameter. The materials that come out of the validation parameters do not have transparent properties. In order to have (one or more) materials for each sheet in the database, glass types were selected that fit within the validation and specific parameters.



Openings categorie, Ansys, 2023

The final database does not include all the materials that have been generated by the Granta Edupack software. Further checking of material properties shows that a number of materials are used for other applications. One example is medium density fibreboard in the construction category. In practice, this material is suitable for making furniture and as a finish for walls. The structural properties of the material do not extend beyond this type of application.
Materials have therefore been double-checked after they have been listed in the tables to ensure that each material in the database is actually suitable for the category in which it is listed.

Ultimately, there are a number of comments to be made when using the software. Since it tests materials for their individual performance, it is therefore more likely to exclude materials from possible application. Consequently, a validation of the software will be valuable to ensure that it does not allow unintentional errors in the selection procedure.
Furthermore, as mentioned earlier, the category of stony materials has been added to the possible groups of materials. Stone types appear to have very low energy and emission emissions and water use in the production process from the Granta Edupack software (Ansys, 2023). In addition to the fact that these materials also have a low cost price per KG compared to other bio-based materials, their lifespan is also considerably long. This makes it interesting to use these materials due to their long lifespan and low maintenance requirements. This completely natural material can aslo be easily reused. Due to these qualities and material properties that Granta Edupack demonstrates (Ansys, 2023), the decision has been made to make these materials part of the materials selection database. It is therefore of added value to check the parameters that have been selected for applicability and to determine whether materials that are excluded should actually be excluded or not.

In summary, the following can be said about bio-based materials. Based on Allen and Lano (2019) and the example research by Ertemir and Edis (2022), dividing a building into its different components has added value. For this purpose, 7 categories have been drawn up in this study: roof, facade, wall, construction, openings, insulation and floor. Further research using the Granta Edupack software shows that materials are suitable for use in 6 of the 7 categories. These have been combined in a database with additional materials that are not included in the Granta Edupack software database. What is striking from working with the software is that water resistance and wear resistance are two strict requirements that quickly rule out materials.
In addition, materials are excluded from an application because they do not meet the requirements in their pure form. In reality, these are used in combination with a protective agent. This is also good to take into account when selecting materials as a combination of materials can also be suitable as an application.

| Sub-question three:
What are the cultural and historical considerations when selecting bio-based materials for heritage preservation in architectural renovation and how can already existing architecture show the possibilities of applying bio-based materials?

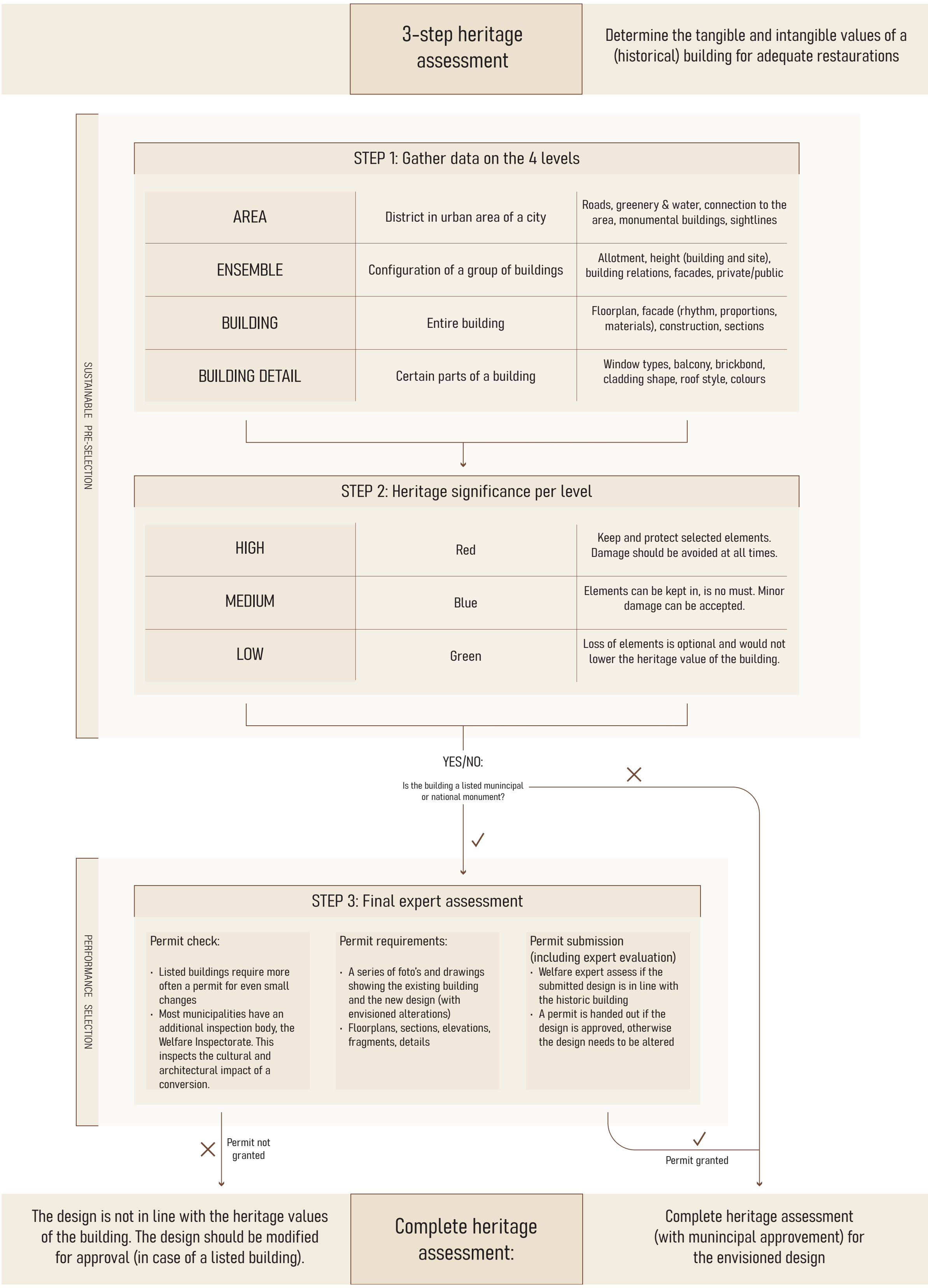
In the european union, much of the housing stock was built before 1970. 25% of the stock was built before 1945 and 50% was built before 1970, to be precise. This means that half of the housing stock was built before there were any regulations regarding thermal qualities of a building (Kranzl et al., 2014). Kranzl et al. (2014) furthermore points out that, due to the size of the (historical) housing stock, it contributes to a large extent to the energy consumption of the built environment.
In previous attempts to make this housing stock more sustainable, the focus was not so much on historical qualities of these buildings, but mainly on making them more sustainable and ready for future use. As a result, the risk of loss of historical qualities is high and should therefore be protected in future developments.
When preserving buildings with heritage values, the starting point is often 'do only what is necessary to preserve the property'. This contrasts with the urgency to make the built environment sustainable for the 2050 climate goals. As a result, a so-called balance between quality and quantity is usually sought after in order to keep costs manageable, living environment sufficient and heritage value somewhat in tact (Bond & Worthing, 2016).
Therefore, when preserving homes from this stock, attention should be paid to both energy sustainability and heritage significance.

In addition, several guidelines have so far been drawn up at European level. One is the NEN-EN 16883:2017 (Koninklijk Nederlands Normalisatie-Instituut, 2017), as well as the EFFESUS project (Eriksson et al., 2014) from the EU. Goals of these projects and regulations are to develop a methodology that use energy efficient applications that go hand in hand with heritage values. Although these initiatives and guidelines address the lack of guidelines and regulations in the determination of historic qualities and look for a solution to make the sustainability of the historic housing stock better, there are 3 minus points that are not taken into account in these methodologies (Havinga et al., 2020).

1. Methods to assess heritage significance
2. Specific results of these assessments
3. Evaluation of these assessments

Based on these findings, Havinga et al. (2020) started making a significance assessment. This aims to address the regulatory flaws and integrate them into a better approach. Nevertheless, there are a number of concerns in making this evaluation that should be included as preconditions. A significance evaluation in this form to heritage values can never be exact and unquestionable. In addition, this study works with interviews with experts in the field of heritage values. These experts are expected to draft their findings with respect and thoughtfulness for the context (Havinga et al., 2020).

This research will build on the evaluation by Havinga et al. (2020). The scales that apply as well as the levels of significance are a valuable starting point for determining heritage values within this research as a base layer of information when selecting appropriate materials. As the diagram below shows, there are 3 steps in the heritage assessment.



3-step heritage assessment, B. Turkstra, 2023

First of all, data gathering. Data is collected at four levels (area, ensemble, building and building detail) to map the building and site. The second step is significance. Three colours are used to indicate which parts of the building are of higher value. The third step is the final valuation by an expert. This follows if the building is registered as a monument. A permit procedure should

be followed to obtain a licence for intentional work on the building in relation to the design. If this is the case, there will have been an assessment of the heritage value of the building, what the most important aspects of the building are, and whether the new design will have a negative impact on the heritage value of the building.
In addition, steps one and two are part of a sustainable pre-selection as defined in the theoretical framework. Together with the material application projects, they provide the necessary background information. Step 3, on the other hand, is part of the performance selection, as it focuses on the design and thus the use of the selected materials, and whether this sufficiently safeguards the heritage qualities in case a review by the Welfare Authority is required.

With the validation criteria, a database of potentially applicable (bio-based) materials and a heritage assessment, there is a clear basis from which to start testing materials for suitability in a design. The final step in creating a complete foundation is to add reference projects using the materials in the database. Based on the results of the Granta Edupack software (Ansys, 2023), it has become clear that not every material that meets the theoretical requirements is suitable for application in practice.
Research by Akadiri (2015) shows that from a sustainable construction perspective, there is an increasing focus on the use of sustainable and/or bio-based materials. Akadiri (2015) further states that the main barriers preventing this from happening on a large scale are cost and lack of information about these materials. Additionally, research by Van Kesteren et al. (2008) and Bahrudin (2017) shows that the categorisation of materials and their production capabilities are being considered.
From this, it can be concluded that research is mainly conducted on the applications of materials and what they can lead to. In this research, different materials have been identified through the use of criteria, but the potential of these materials is determined by designs that have yet to be realised. It is therefore of added value to create a table of projects using one or more different (bio-based) materials from the database. This allows the user of the tool to look at references for the possibilities of a material and use them in the design process. To add to that, the used Granta Edupack software also shows the need for critial evaluation and validation of it's provided results. Therefore, having material applied projects at hand to further confirm the worth of a potential material is of added value for the later performance selection of a material. This table provides the information to answer the 'how' of the design by having reference projects in addition to a (bio-based) material.
The table of projects can be found in the appendices.

In summary, the European Union grapples with the intricate task of harmonizing energy sustainability with the preservation of its historical housing stock. Past sustainability efforts have neglected historical significance, putting heritage values at risk. Current guidelines, such as NEN-EN 16883:2017 and EFFESUS, aim to integrate energy efficiency with heritage, but lack specifics on assessment methods and results, and evaluation processes.
Based on Havinga et al. (2020), a 3-step heritage assessment was created that allows for a consistent approach for each different project. This methodology integrates sustainable pre-selection (through the use of different levels and significance per level) and performance selection (through the help of an expert assessment), offering a comprehensive framework for selecting suitable materials.
However, practical application hurdles persist, such as cost barriers and information limitations for sustainable and bio-based materials. Therefore it is a necessity to validate materials through reference projects to provide practical insights for users.

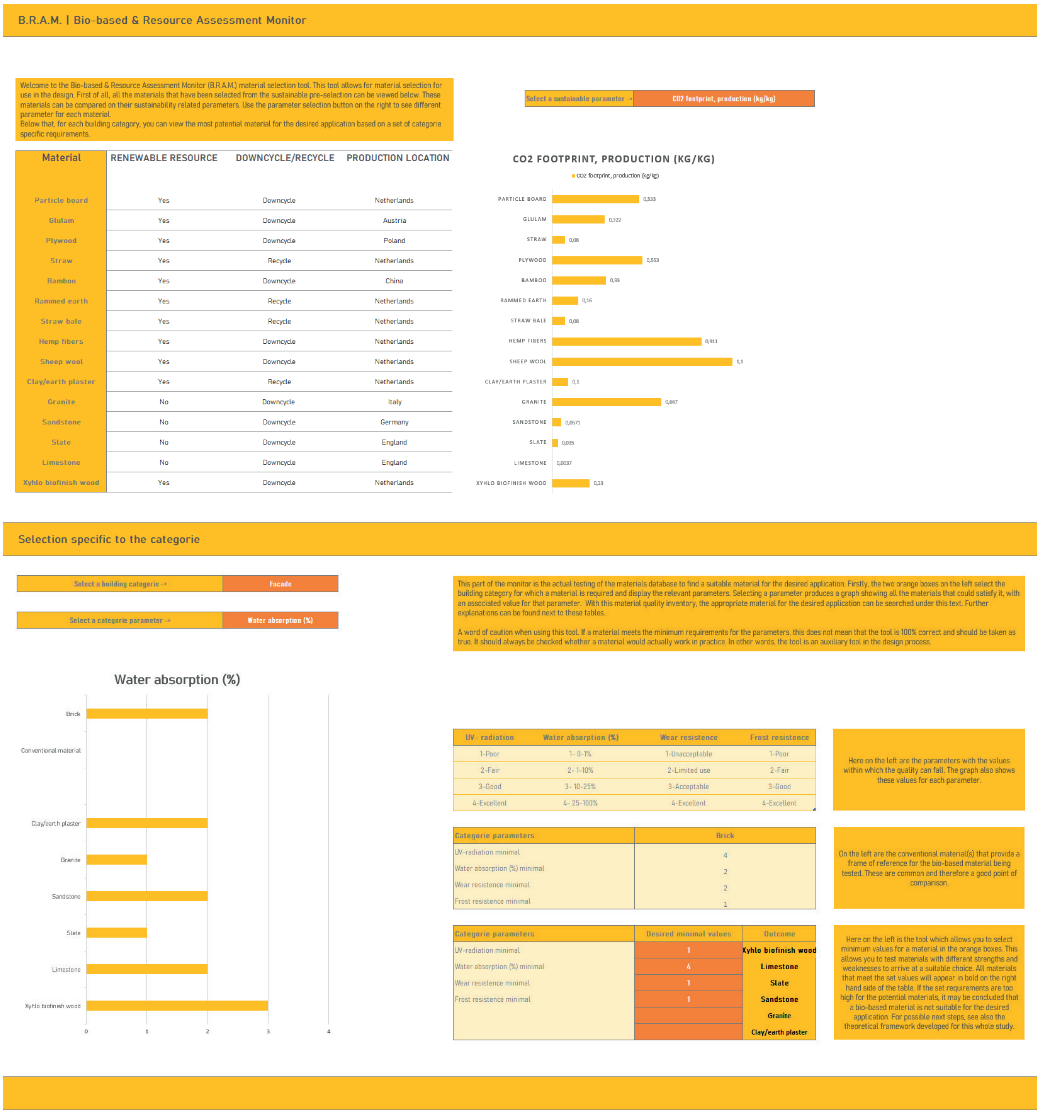
| Sub-question four:
What are the implications for architectural heritage renovation when transitioning from traditional building materials to bio-based materials?

Now that a complete sustainable pre-selection has been made, we can look at the process of selecting a material and its impact on design and industry. The basis for creating this tool is the database of materials created using Granta Edupack software (Ansys, 2023) and the established 7 material categories of a building. This static database now only forms materials that are not being used in any other way. In order to assess the impact of bio-based materials on heritage, this database should be used to develop a working tool that can select a potential material for the user.

To ensure this transition from a linear to a more circular building process, the materials tool was created in Excel, as shown below. This tool, the Bio-based & Resource Assessment Monitor (B.R.A.M.), works in 2 parts.

First, it makes the sustainable pre-selection transparent for all materials that could potentially be used. With a list of the selected materials, the user can compare them by selecting different sustainability aspects from a drop-down menu. An initial comparison per material is then made.

The second part looks at the requirements for a material by category. The first step is to select



Screenshot of the interface of the B.R.A.M. tool, B. Turkstra, 2023

a category for which a material is required. Following the same principle as in the first part, the performance of the possible materials can then also be compared per category-relevant parameter. It is then up to the user to define the requirements that the material should meet. By entering these figures, the tool will indicate which materials remain and are therefore potentially suitable for further use in the design.
For the sake of feasibility, it was decided for this study to fully develop one category to show how the tool works and, most importantly, that the tool works and selects a material. The façade category was chosen as the most interesting category for this purpose, because of the variety of materials available. Both bio-based materials and stone types, which, as mentioned earlier, were also selected for this research because of their suitable properties.
As can be seen, the user can see the performance of the materials in the graph combined with the legend. The conventional materials are also included to provide a frame of reference. In the bottom right-hand corner, the user enters the material requirement for each category-specific parameter. All materials that meet the requirement are then displayed next to it. The tool is structured so that it calculates that a material must meet each minimum requirement, working on an AND principle rather than an OR principle, which would select materials that do not meet all the requirements, but at least one.
Following below, a possible elaboration of the tool for the Facade category is shown. There are requirements that the material must meet and it can be seen that out of a total of 6 potential materials, only 3 meet the set limit. For example, Xylo treated wood is not one of the potential materials because it absorbs more moisture than the specified requirement. This minimum requirement may be because the designer wants a certain type of wall construction where the outer skin is not ventilated. Therefore, if the designer wishes to use Xylo treated timber, the

UV- radiation	Water absorption (%)	Wear resistence	Frost resistence
1-Poor	1- 0-1%	1-Unacceptable	1-Poor
2-Fair	2- 1-10%	2-Limited use	2-Fair
3-Good	3- 10-25%	3-Acceptable	3-Good
4-Excellent	4- 25-100%	4-Excellent	4-Excellent

Categorie parameters	Brick
UV-radiation minimal	4
Water absorption (%) minimal	2
Wear resistence minimal	2
Frost resistence minimal	1

Categorie parameters	Desired minimal values	Outcome
UV-radiation minimal	4	**Slate**
Water absorption (%) minimal	2	**Granite**
Wear resistence minimal	3	**Clay/earth plaster**
Frost resistence minimal	3	

Possible outcome of material selection for the facade categorie, B. Turkstra, 2023

construction of the entire wall must be considered to ensure that the moisture content of the timber can be managed. This shows that the use of the tool can potentially affect the structure of the design. When this is combined with the desire to preserve a heritage building, it is important to understand the existing situation and therefore the minimum requirements for a material. This knowledge can be extracted from the previously developed 3-stage heritage assessment.
A disadvantage of this tool is that a potential material still needs to be verified after it has been identified as applicable by the tool. The approval of a material in the tool is based on theoretical material properties that are not related to the practical environment in which a building is located. This environment is different for each building. The tool can only partially take this into account. Other circumstances may result in a different requirement for a parameter, but these are not directly related. Therefore, once selected by the tool, a manual check must always be carried out to ensure the actual applicability of a material.

There are several consequences of using this method for a heritage restoration. These consequences are summarised in the following 3 key points:

1. Possible changes to the existing structure/construction of the building, which may result in higher costs.
2. More stringent requirements for potentially applicable materials, which may limit the range of options available.
3. Results of the sustainable pre-selection process that are not in line with the results of the tool, which means that certain materials or even categories cannot be implemented with a bio-based material.

In order to arrive at a well-founded solution and still be able to use this tool, 3 considerations have been drawn up as possible outcomes. These do not guarantee a solution to the problem, but are a starting point for adapting the current linear way of thinking to a circular form.

1. Consideration of costs and benefits.
   In today's society, many initiatives remain unimplemented because the main consideration is the financial feasibility of the project. Park, Yoon, and Kim (2017) and Awadh (2017) also demonstrate in their research the need to look beyond the financial aspects of a design.
2. The requirements imposed on a building must be maintained. Creating an internal living environment that is of good quality for the user is a major priority. Because heritage buildings are often characterized by a poorer indoor climate because they were built in periods without regulations (Kranzl et al., 2014). It is therefore important that the requirements necessary for the building to comply with the regulations are critically examined and that they also provide a pleasant indoor climate.
3. A considered consideration must be made between the possible discrepancy in the existing heritage values that a building has and the future design with its own values that add a new historical layer, but do not necessarily leave all the values of the existing building intact. An assessment of the new proposal including a value for the future of the building could be taken into account when considering whether to apply a design.

In conclusion, the development of the Bio-based & Resource Assessment Monitor (B.R.A.M.) represents a significant step towards incorporating sustainability into the material selection process for heritage restoration. The tool provides a transparent and systematic approach that facilitates both the pre-selection of sustainable materials and the assessment of their suitability based on specific category requirements. The focus on the façade category demonstrates the tool's effectiveness in providing a clear overview of potential materials and their performance, to aid decision making by designers and architects. To address the implications of using the tool in practice, three key considerations have been suggested: a thorough evaluation of costs and benefits, maintaining the building's requirements for a quality indoor environment, and a thoughtful balance between existing heritage values and future design considerations. While these considerations do not provide a definitive solution, they offer a starting point for adapting the conventional linear approach to a more circular and sustainable form, paving the way for a conscientious integration of heritage restoration and contemporary design practices.

Conclusion

| Conclusion:

When looking back at the stated research question at the front of this research, which states: "How can bio-based materials enhance sustainability and circularity in architectural renovation while prioritizing the conservation & preservation of architectural heritage?", the following conclusions can be drawn to answer this question.

Firstly, it is important to clearly identify how bio-based materials can contribute to sustainable developments in the built environment. BREAAM and LEED already provide tools to develop a building in the most sustainable way possible, but the research carried out by Park, Yoon, and Kim (2017) and Awadh (2017) shows that these methods do not look at the problem broadly enough and leave room for improvement. They therefore propose the use of a triple bottom line, using social, economic and environmental parameters. A combination of these data provides a set of criteria to ensure that bio-based materials are selected with a minimum value for different sustainability requirements. These criteria are Resources, Location & transportation, Water consumption, Embedded energy, Living environment, Ecology & pollution and finally Life cycle. Taken together, these criteria lead to the conclusion that a minimum threshold is required from various social support bases to ensure that materials are actually positive for the environment and buildings.

In order to have a clear view on the quality control of materials, it is also essential to have an understanding of what different materials should comply with, what their properties are and how this can be compared. Based on the book "Fundamentals of building construction" by Allen and Lano (2019), 7 categories have been created that divide a building. These categories are as follows: Roof, Facade, Wall, Construction, Openings, Insulation and Floor. Practical research by Ertemir and Edis (2022) also points to the value and necessity of such a division in its application to heritage buildings.
By establishing categories for a building, materials that score sufficiently on the pre-established validation criteria can be assigned to the appropriate category.
The Granta Edupack software (Ansys, 2023) was used to test the materials. Firstly, a number of parameters were set for the sustainability criteria in order to select materials that achieved the set values. In addition, relevant parameters were set for each category to test which category a material was suitable for. These multiple rounds of material testing showed that bio-based materials are suitable for 6 of the 7 categories. In the openings category, there is currently no suitable material. It is also worth noting that the software only looks at individual materials and therefore rejects, for example, wood as a facade material because it would not be sufficiently weather resistant. This, combined with the water and wear resistance parameters, means that Granta Edupack can write off materials faster than necessary. In addition, Granta Edupack also depreciates stone materials. From the validation criteria previously set, these are still approved for testing as they score high on various criteria and are a natural material. This clarifies the requirements for materials and how they are tested for different usability needs.

Now that it is clear how bio-based materials can contribute to sustainability requirements, it is important to look at the conservation and preservation of the heritage values that characterise a building. Research by Kranzl et al. (2014) shows that 50% of the Dutch housing stock was built before 1970, and therefore before the introduction of any thermal qualities for a building. Furthermore, it is clear that previous sustainability improvements in this housing stock have not adequately addressed the heritage values of these buildings. European legislation that should point this in the right direction, such as NEN-EN 16883:2017 (Royal Dutch Standardisation Institute, 2017) and the EU's EFFESUS project (Eriksson et al., 2014), have various shortcomings, such as methods for assessing heritage significance to be demonstrated, as well as results and evaluations thereof, according to Havinga et al. (2020). Based on this need for consistent heritage assessments, a 3-step heritage assessment has been developed, which aims to identify and safeguard the heritage qualities of a building in future redevelopments. This assessment helps to preserve the essence of the existing building for future use, in addition to new materials.

Now that it is clear how bio-based materials can contribute to sustainability requirements, it is important to look at the conservation and preservation of the heritage values that characterise a building. Research by Kranzl et al. (2014) shows that 50% of the Dutch housing stock was built before 1970, and therefore before the introduction of any thermal qualities for a building. Furthermore, it is clear that previous sustainability improvements in this housing stock did not adequately address the heritage values of these buildings and therefore resulted in a loss of heritage quality in buildings. European regulations that should guide this in the right direction, such as NEN-EN 16883:2017 (Royal Dutch Standardisation Institute, 2017) and the EU's EFFESUS project (Eriksson et al., 2014), have various shortcomings, such as methods for assessing heritage significance and results and assessments that cannot be proven, according to Havinga et al. (2020). Based on this need for consistent heritage assessments, a 3-step heritage assessment has been developed for this research, which aims to identify and safeguard the heritage qualities of a building in future redevelopments. This assessment helps to preserve the essence of the existing building for future use, alongside the selection of bio-based materials for the conservation of these heritage buildings.

These results are summarised in the developed material selection tool: Bio-based & Resource Assessment Monitor (B.R.A.M.). This tool allows the user to view the materials in the database that meet the validation criteria. These materials are then assessed on the basis of their category-specific parameters, which are based on the parameters used in the Granta Edupack software (Ansys, 2023). The user of the tool selects the minimum requirements for the parameters and the tool then displays only those materials that meet these minimum requirements. In combination with the 3-step heritage assessment, it becomes clear whether the material is suitable for use in the design or whether a bio-based material is not suitable for the desired application.

This research has yielded a comprehensive set of criteria, recommendations, and a practical tool designed to enhance the sustainability and circularity of architectural renovations with a focus on bio-based materials. This framework also addresses the preservation of heritage qualities of buildings. Moreover, the outcome of the introduced tool contributes to the reduction of carbon and nitrogen emissions, as well as water consumption. It also actively supports the transition towards a circular building process through the use of new materials made from renewable resources.

| Discussion:

This research consists of two main parts regarding the use of sources. The first part consists of a sustainable pre-selection, based on literary sources from institutions such as universities and so forth. The results found are generalisable to a large part of the Dutch built environment, making the reliability of these sources and statements plausible. In addition, Granta Edupack software was used to develop a tool for selecting materials. However, it is important to note that the parameters used for this selection may not have been entirely suitable, which may have led to a loss of responses in the process.
Despite this finding, it can be concluded that the hypothesis of the study has been confirmed. The tool developed can select materials for use, largely thanks to the Granta Edupack software and the literary sources on which it is based. The research has the same aim as the 10 R's of circularity, and although the direct link is not clear, a comparison remains possible.
From a personal perspective, it has become clear that natural materials have significant and versatile potential for the future of the built environment, offering significant competition to conventional building materials due to their flexibility and properties.
The main limitations of the study are time and software skills. A deeper knowledge of the Granta Edupack software can lead to a better selection of materials and a more comprehensive database. Time was a limiting factor as the Excel tool was only developed for one category due to time constraints. For future research, it is recommended to start working with the software early to gain more experience.
From the research, it can be suggested that buildings with heritage value can be redeveloped more quickly with bio-based materials, given the demonstrated potential and harmony with heritage qualities. Future research can focus on refining the parameters for material testing and further developing the tool. It can also explore how the heritage assessment can be better integrated into the tool to create a tool that requires less manual input from the user.

| Reflection:

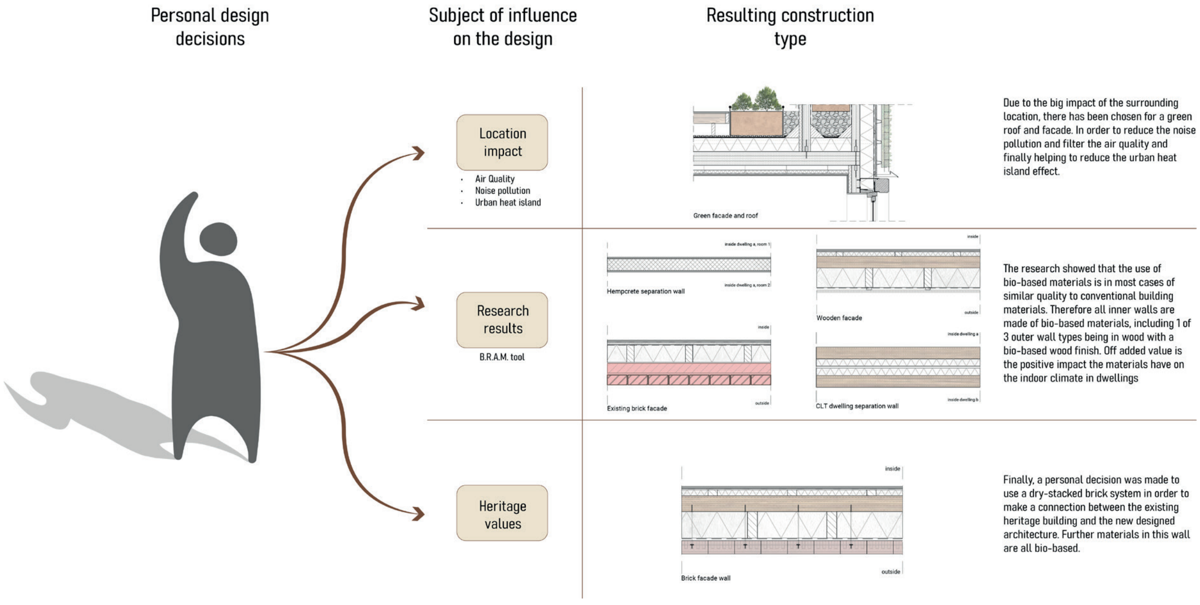
In a reflection back on the research in combination with the design that has been made, it is good to evaluate the worth of the research and what it in the end added in value for the final design.
Initially, research was not a major part of the design process for the outline design. This was because the surroundings had a major influence on the site itself and researching materials could not solve this overnight. As a result, I myself also noticed that the research came at a lower priority and was less involved. This does not alter the fact that the location research was not of great importance for the design. Without a proper analysis of the influences of the surroundings, the final project could never have achieved the depth and quality that I believe it now possesses. After the concept was completed and the design went into more depth, the research did become more relevant again to the story and quality in the building. Bio-based materials, besides being good for the environment, also appear to have a great positive impact on the indoor climate of homes. This made their application even more valuable. Then, by using the tool, I personally started looking at which materials would be suitable to make my building with and/or make it more sustainable. As the diagram on the right shows, a classification can be made for all the structures that will eventually be found in the building. One of these is based on site influence. That is the green roof and façade. The green facade is used all around on the outside of the complex to ensure that air is filtered and noise is dampened. So for this wall structure, location research proved to have the greatest relevance.

There is also personal preference that resulted in the brick construction. The tool showed that brick performs fairly equally to the other materials used in the design. In addition, the existing building consists of brick and it was decided from a personal preference to carry out one inner façade (courtyard side) with brickwork. This was done with a special technique that does not use mortar. The main relevance in this was the heritage value and the design choices I personally made in this as a designer.

Finally, in the middle row, you can clearly see the influence of the bio-based materials research on the applied structures in the building. All interior walls are made of bio-based materials that, according to the tool, perform best for the task at hand. A wooden façade was also realised using a bio-based wood finish. Herein also lies directly a minor drawback of the tool. It assesses materials individually for their performance, not in combination with other materials that perform better together such as wood and a protective agent. Additional research showed that wood facades with the bio-based finish used did not perform significantly worse than masonry, but did require re-treatment every 5 years. And finally, bio-based materials have allowed the existing building to be preserved in a way that best suits the existing building and leaves it intact as much as possible. By creating a front wall on the inside, a façade is created that can last for years to come and ensures that the building can be preserved.

To come to a conclusion, the research had a significant influence on the final design, but a clear hierarchy can be distinguished. The design has shown that conceptually, the research has little or no influence on design choices. The research only became relevant again later and that is good to realize, both personally and for the next user. On the other hand, I don't think this had a negative effect on the final design as incorporating suitable materials in the design process did not cause any problems for me personally.

The research has shown that it is possible to use bio-based materials and compare how well they perform compared to conventional materials. Now this has been taken a step further in the design and it has been shown that it is not only possible, but can also come together as a whole. The final design of 3 different walls, each with their own character that would not have looked like this without the research, form an ensemble containing an inner garden with a pleasant climate. The final project forms a Symphony.



Wall types based on subject of influence, B. Turkstra, 2024

Resources & Appendix

| Resources:

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| Appendix

Research question	Requirements	Ways of collecting	Ways of analysing	Expected results
What criteria should there be stated in order to select bio-based materials suited for location specific architecetural heritage renovation?	◦ Quantitative data on different ways and subjects to use criteria to evaluate materials	◦ Official documents provided by governments ◦ Reports on projects done according criteria	◦ Literature review of found information on relevance	◦ A list of criteria that help to evaluate materials on their sustainability
What are the distinct categories and characteristics of bio-based materials available for architectural renovation and how can their performance be assessed and compared?	◦ Material properties and potentials ◦ Ways of comparing materials ◦ List of potential bio-based materials	◦ Use of Granta software for material properties ◦ Producers of certain materials	◦ Use software/producers to find material properties to be able to compare and assess each materials value	◦ List of properties that materials can score on to show their potential ◦ Easily applied on multiple materials with the same properties
What are the cultural and historical considerations when selecting bio-based materials for heritage preservation in architectural renovation?	◦ Value assessments of heritage considerations	◦ Munincipality guidelines on heritage	◦ Literature study and comparisons on relevance of found values	◦ Set of restrictions/limitations that munincipality's give in order to maintain heritage value of the building
What are the implications for architectural heritage renovation when transitioning from traditional building materials to bio-based materials in terms of construction techniques and practices?	◦ Application of conventional building techniques ◦ Application of bio-based material building techniques	◦ Manufacturers of products/materials ◦ Standard details of applying	◦ Using details to learn how to incorporate ◦ Contact manufacturers	◦ Have potentially different ways of application visible ◦ Know how to integrate each material in a existing building
How can already existing architecture (through the use of case-studies) show the possibilities of applying bio-based materials?	◦ Relevant case studies for the envisioned design case	◦ Books and website that shows multiple projects	◦ Filter on desired material and comparing projects	◦ Information from reality on how materials are used and if they have proven their worth

Appendix 1:

Research table, Turkstra (2023)
In this, one can see the approach, requirements and results envisioned for each of the formulated research questions in this research.

Appendix 2:

The B.R.A.M. material selection tool made in excel. The file is added in the map with the name:
B.R.A.M. material selection tool.xlsx

Appendix 3:

Material applied projects database made in excel. The file is added in the map with the name:
Material Applied Projects.xlsx