Controlled Environment Agriculture to Renovation

Bio-base Materials from Element to Global Scale

Masters Graduation Thesis

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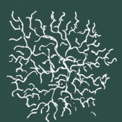


Title
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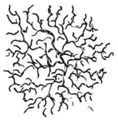


Abstract

In the global shift towards decarbonization of the built environment, the nearly Zero Energy Building (nZEB) goals in the Directive 2010/31/EU had been set as an achievable goal for the EU. By requiring all future constructions to utilize the integration of energy efficient services into the building as well as emphasize the reduction of embodied energy in building materials, the nZEB goals for existing buildings has continued to be a challenge. Within the Netherlands, large estates of post-war housing require the renovation for improved energy efficiency to meet the thermal performance set by the directive, however the low renovation rate of buildings has limited progress thus stunting the major shift towards a more sustainable existing built environment.

In the completed renovation projects, petroleum based materials have been utilized in most cases for insulation and particleboards. This raises the question of if the shift towards a more sustainable built environment that meets nZEB goals should still be utilizing materials that no longer meet the rationality of sustainable practices.

Through the use of Bio-base Materials, renovations have the potential of not only decarbonize aspects of the entire renovation project but also shift towards following a circular economy design approach. By replacing the traditional construction materials, bio-base materials have the possibility of large scale integration in the built environment through a modular panel renovation approach. Specifically focused on agricultural bio-base materials, allow for the possibility of acknowledging the four steps of circular design, origin, composition, assembly, and future. Within the framework of the circular design approach, it was acknowledged that the origin of agriculture bio-base materials have limitations of scalability as well as have the potential of damaging the local ecosystem and land use designations through the increased pressure for cultivation of bio-base materials from agricultural waste flows.

Although bio-base materials are inherently more sustainability sourced than traditional materials, by designing a controlled environment agriculture process for bio-base materials has been a radical and novel idea within the research for the guaranteed harvesting of bio-base material as well as integrated Water Energy Food Nexus concepts. By reducing water consumption of the bio-base materials in a Controlled Environment, as well as the by-product of grains, and increased efficiency, the application of the circular renovation design of the renovation elements acknowledges major parts of the WEF Nexus on a local and regional scale.

A Controlled Environment growing bio-base materials for renovation application is designed for the future resilience of the agriculture bio-base material industry as well as enables positive impact on a local social scale and suggests that the shift towards decarbonized built environment and material elements must require a considerable and radical shift in order to meet the sustainable future goals of 2050.

Key Words | Bio-base Materials, Exterior Renovation, Facades, nZEB, Post-war Housing, Controlled Environment Agriculture, Circular Economy and Design, WEF Nexus

Acknowledgments

With pleasure I finally present my thesis Masters graduation project, “Controlled Environment Agriculture to Renovation | Bio-base Materials from Element to Global Scale”.

At the beginning of the thesis, this project had been intended to be focused on vertical farming and the shift of changing the materialization of the vertical farm directly. But as many research projects go, the shift, ebb and flow had changed my topic. As I found myself peering into rabbit holes of different topics, I had notice my passion and progress in researching bio-base materials in general building applications. When I reflect on this thesis project, it has wandered from one aspect to the next while still picking up bits of new knowledge along the way. This is how I would have wanted it, regardless of the topic.

First, I would like to thank my supervisors, Andy Jenkins and Mo Smit, for the valuable guidance during the project. For all the time that they have placed into helping me sort out through the weeds of information found in the continued research progress. Andy, thank you for the seeing me through this journey that this thesis has been and for helping me develop the storyline of this project even through all the different research paths that I have taken. Mo, thank you for asking me the larger picture questions which challenged me to envision something more for this design project.

A very big thank you to my friends in the States and in Delft who have supported me every step of the way with late night FaceTime calls, walks around Delft and library sessions. I am extremely grateful for the community of peers and friends that I have around me and I relish in the colors and laughs that my life in Delft has because of them. A thank you to my mother and brother, who have been the ones to call when motivation was missing and for the laughs as I started talking in metric rather than in imperial units. And to my fourth-cousins, my new Aunt, Uncle and Cousins in the Netherlands, for being the local family support system that I needed.

Finally, I dedicate my thesis to my father, who was a constant person on my mind throughout the thesis project. Although he will never see the outcomes of my thesis project, I am so grateful that he was able to see the beginning of my Masters career at TU Delft knowing that moving to the Netherlands would be not only an educational experience of shifting my lens as a Civil Engineering Bachelors to a Building Technology Masters but also a personal journey of travel and family history.

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INTRODUCTION

By 2050, the global population is set to reach 9.7 billion people (UN, 2019), which suggests that in less than 30 years there will be an increase of approximately 1.95 billion people. As a result, this will also lead to an increase in food and housing demand, challenging growing cities to construct enough homes in already densely populated regions. All of these challenges must be acknowledged while adhering to emission reduction goals from the UN Paris Agreement. For many historic cities in the EU, meeting 2050 emission reduction goals translates to a demand for renovating older infrastructure (Housing Europe, 2021) to improve the energy efficiency of dwellings. Within the EU, these renovations are not only to meet UN goals but also to acknowledge more localised goals to meet nearly zero-energy (nZEB) as set by the Directive 2010/31/EU. To meet these goals, approximately 9.4 billion m2 of walls and roofs will require some kind of maintenance and renovation by 2050 (Goswein, Reichmann, Habert, & Pittau, 2021) and will cost the EU approximately 33 billion euros for building envelope renovation until 2050 (Housing Europe, 2021).

Although these renovation efforts are made to decrease emissions through energy consumption, approximately 5-15% of greenhouse gas (GHG) emissions are caused by material extraction, building material production, as well as construction and renovation of buildings. In response, the Circular Economy Action Plan was put in place, which promotes lifecycle assessments (LCA) and a circular economy approach in renovation (EC, 2020). By replacing commonly used building materials, bio-economy and bio-based materials are seen as a means to mitigate GHG from the building industry as well as a means of carbon sequestering during renovation projects and following circular and bio-economy principles.

Research Introduction

Renovation of the building envelope, specifically the skin shearing layer, as suggested by architect Frank Duffy, poses an opportunity to replace commonly used building skin materials with bio-based materials, which can sequester carbon and reduce the overall emission impact of construction and materials (Pawelzik, Carus, Hotchkiss et al, 2013). However, shifting to the utilisation of bio-based materials for renovation will also increase the demand for growing bio-based material plants and crops. Relying on sustainable forest management and sustainable agriculture to harvest these products has the potential to reduce GHG emissions within the agriculture industry (Goswein et al, 2021). However, sustainable agricultural practices are not commonly occurring currently due to the commercialization and intensification of crops within the EU, leading to the dependency on pesticides and fertilisers.

The growing and use of bio-based materials within the built environment also calls to attention the impact that bio-based material crops have on land-use competition and could potentially lead to indirect land-use changes, ILUC, causing a shift from agriculture to alternative crop use. Land-use changes and conflicts are already occurring, like many industries, such as the production of biofuels from agricultural crops in efforts to decarbonize (Scarlat, 2019). As the most viable land type for transformation, in comparison with urban and transport land use, agricultural land for bio-based material crops will be entering into competition with photovoltaic farms and biofuel production crops, as well as food production. In the future where bio-base materials are commonly applied in the built envrioment, there will be a demand for land designated directly for the production of material.

Currently, bio-based materials made through agriculture byproducts or crops depend on the agriculture industry, which is oftentimes unsustainable and can lead to large scale environmental impact. Crops cultivated in open fields are subject to environmental hazards, such as flooding, drought and soil degradation, and have been increasingly commercialised due to demands for food, feed, and fibres (EPA, 2015). This has led to the dependency on pesticides and fertilisers causing further soil degradation (FAO, 2021).

Research Problem Statement

To declare agriculture bio-based materials a sustainable material for renovation, the method of growth and harvest of crops and by-products should be responsibly sourced, sustainable, and resilient to land competition and environmental hazards, which is not possible in the current state of the agriculture industry.

Design Problem Statement

Post-war housing dwellings utilizing MUWI system construction require a sustainable and modular renovation in order to meet nZEB goals for energy efficiency through the design of a productive bio-based material scheme utilizing localized material cultivation in vertical farming.

Hypothesis

MUWI post-war housing constructions are able meet thermal performance nZEB goals through panel renovations that are primarily assembled from responsibly sourced agriculture bio-based material grown in a localized CEA construction, which provides opportunity to foster resilience to land competition and environmental hazards while also acknowledging circular economy practices and the Water-Energy-Food Nexus.

SCOPE

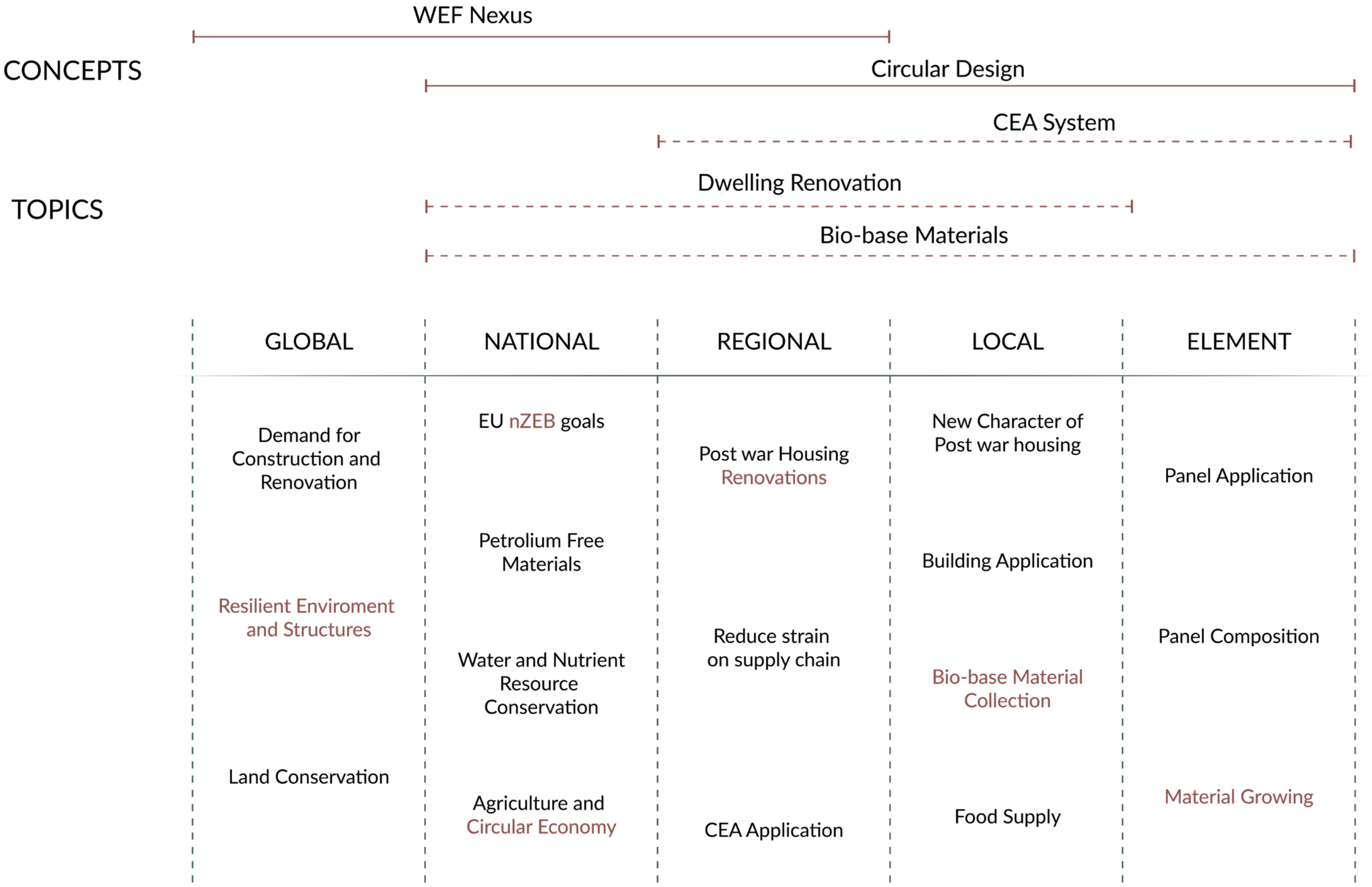


Figure 1 | Thesis Scope | Global to Element for Bio-base Materials in Renovations

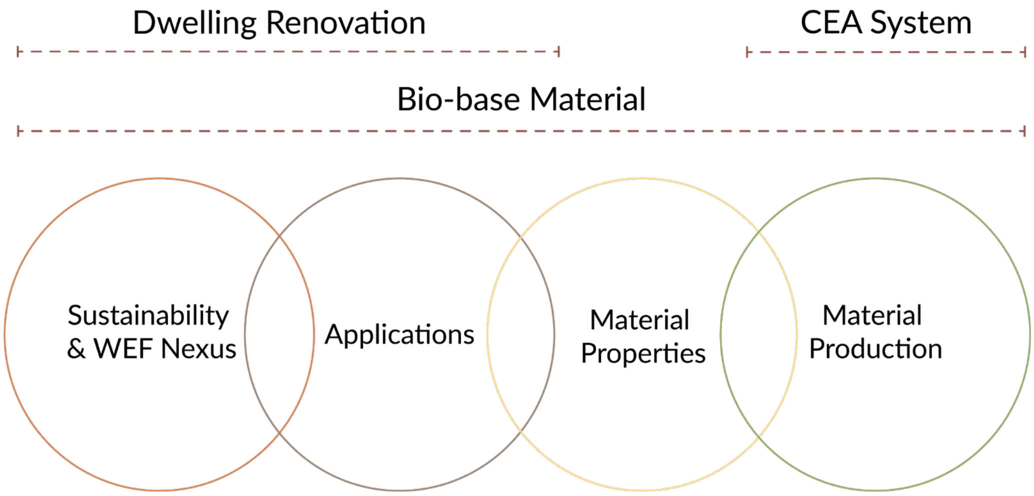


Figure 2 | Scope of Bio-base Materials Investigated

METHODOLOGY

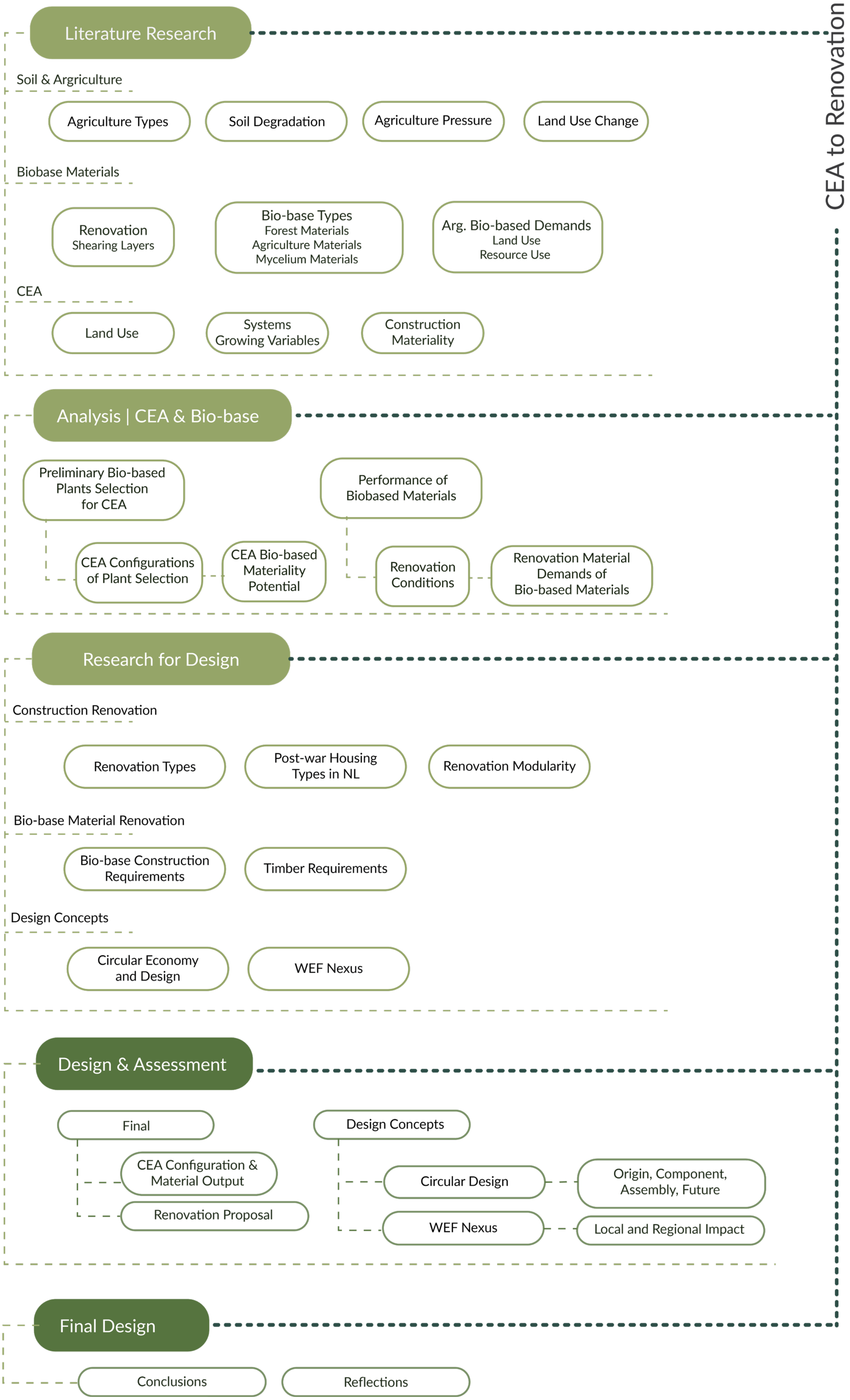


Figure 3 | Methodology Chart

Objectives

The objective of this research is to explore wheather vertical farming and other CEA practices are viable alternatives to traditional farming in areas where traditional farming is no longer a sustainable option for cultivating bio-based materials. These objective will be met during the analysis of research for design:

- Propose the use of a sustainable and circular CEA enclosure that is resilient to environmental hazards such as drought and soil degradation.
- Confirm that utilising a CEA system for bio-based material growth will reduce ILUC and resource competition with other industries and meet building material volume demands.
- Determine an array of bio-based materials that can be grown in a CEA system that can applied in a building renovation
- Design the assembly of a renovation panel utilizing bio-base materials and open construction
- Evaluate the demand yield for producing agriculture bio-based materials for proposed renovation panel that is to be produced in a CEA system

Research Questions

To what extent can CEA be a viable and more sustainable alternative to field crop and plant growth for agriculture bio-based construction materials for building renovations?
To answer the main research question the following sub-questions have been proposed to also have a greater understanding of the problem/challenge at hand. Each sub-question follows three main categories of research:

Agriculture

1 What are the current challenges and environmental hazards of open-field agriculture and how would that affect bio-based material crops?

2 How will agriculture-based bio-based materials compete for land use and prevent ILUC?

3 What are the current agriculture industry outcomes as well as future prospective if bio-based materials were to be an added demand on agricultural production?

Bio-based Materials

4 To what extent can bio-based materials be utilised in renovation?

5 How can bio-based materials meet required material properties for nZEB policy requirements in dwellings?

6 Will growing bio-based materials closer to urban areas improve accessibility to locally sourced building materials?

CEA

7 To what extent can bio-based materials crops and by-products be harvested from a CEA system?

8 What material components of a vertical farm could be transitioned to bio-based materiality?

Research Method

To answer the research question and sub-questions, the process will be divided into three major steps: Literature Research, Analysis, and Design & Assessment. Since this project is based on a theoretical approach and will not be directly tested, the final evaluation will describe if a CEA, bio-based material, and renovation nexus may or may not be feasible in practice through a feasibility study.

To evaluate this, a problem statement was thoroughly investigated to establish the need for agriculture to shift to CEA for a potentially more sustainable and responsibly sourced bio-based material growing and harvest process.

Strategies, system and design outcomes of a CEA environment for growing bio-based materials that are then processed and implemented in a designed building renovation. This will be done through the use of concepts such as the shearing layers, circularity for renovation, and bio-based materials, and bio-based material application in the final design of the CEA system and renovation case studies. The following are direct products that will be developed at the end of the thesis:

1. Evaluate the volume demand and sizing restraints of home renovations in the Netherlands with selected bio-based materials
2. Case studies with selected bio-based materials in renovation
3. CEA configuration and design that is suitable for the selected crops
4. Determine feasibility of the CEA for agriculture bio-based material crop growth through a technical, economic, and operational feasibility study

BIO-BASE MATERIAL APPLICATIONS

The “Materials as usual” scenario is not a viable option for the future of the construction sector that currently has the opportunity to develop novel materials to improve the quality of the built environment.

- Arup, *Urban Bio-Loop, 2017*

Bio-based materials are a major construction material that has been previously utilised in human history due to their ease of use and abundance for cultivation (Jones, 2017). As the structural expectations and forms of buildings have changed, natural building materials have been replaced with synthetic and mined materials, such as steel, concrete, glass, and insulation foam. These materials are now considered common and have dominated the built environment material pallet. As our built environment transformed with these new types of materials, the CO2 emissions from the construction industry also increased and now comprises over 40% of global emissions and hold large quantities of embodied carbon in materials (Blok, 2019).

To reduce CO2 emission impact and to transition to a material that is more renewable, bio-based materials have again become an attractive alternative (Jones, 2017). Many of the positive outcomes of selecting a bio-based material over a common material include changing the user's experience of a space, sustainability, and having similar or better application performance (Jones, 2017).

Renovation Shearing Layer

Alternative bio-based material applications include the use of plant residue for aggregates, boards and panels, cladding and roofing, flooding, insulation panels, structural elements and substrates. For this study, bio-based materials for the refurbishment of homes will be focused on and communicated through Steward Brands Shearing Layers Diagram as a guide of outlining the possible layers that bio-based materials can become a part of (Brand,1994). Although there are many applications of bio-based materials in the structure shearing layer of buildings such as timber and biowaste for cement construction, these layers do not require replacement as often as the more interior layers (Pereira-Roders, Post, & Erkelens, 2005). The skin shearing layer is expected to have a lifespan of approximately 20 years before the renovation is required. Renovation is focused on the layers that require replacement during a structure's life span. The term renovation technically can only apply when 25% or more of the building envelope surface undergoes renovation (Gvozdenović, Zeiler, Maassen, 2014).

In order to improve the energy efficiency of the current housing stock, renovations focus on improving insulation as well as the durability of exterior and interior surfaces (Hoppe, 2012). Studies have concluded that the skin layer contributes approximately 30-40% of the environmental damage of a building operation (Menna, Asprone, Jalayer, Prota, et al., 2013), while other studies have found that the skin layer could contribute up to 70% of the environmental impact (Pushkar, 2015). Through the adaptation of new insulation and heating technology, a building's lifespan can be extended. The renovation process is however not limited to just insulation but will also include the installation of new OSB board and gypsum wall or flooring finishings.

Acknowledging that over 9 billion m2 of walls and roofs, part of the skin shearing layer, will need to be renovated in the EU by 2050, bio-based replacements for common materials have the potential to sequester some of the building's embodied carbon (Gosweinn et al., 2021). The production and application of common construction and thermal insulation materials, such as rockwool and Polyurethane Insulation (PUR) require intensive fossil fuel consumption during production (Tettey, Dodoo, Gustavsson, 2014). This means that material selection is vital for sustainable construction. For this reason, the skin shearing layer, which has an approximate lifespan of 20 years for commonly used materials, will be focused on for renovation with bio-based materials (Menna, et al., 2013).

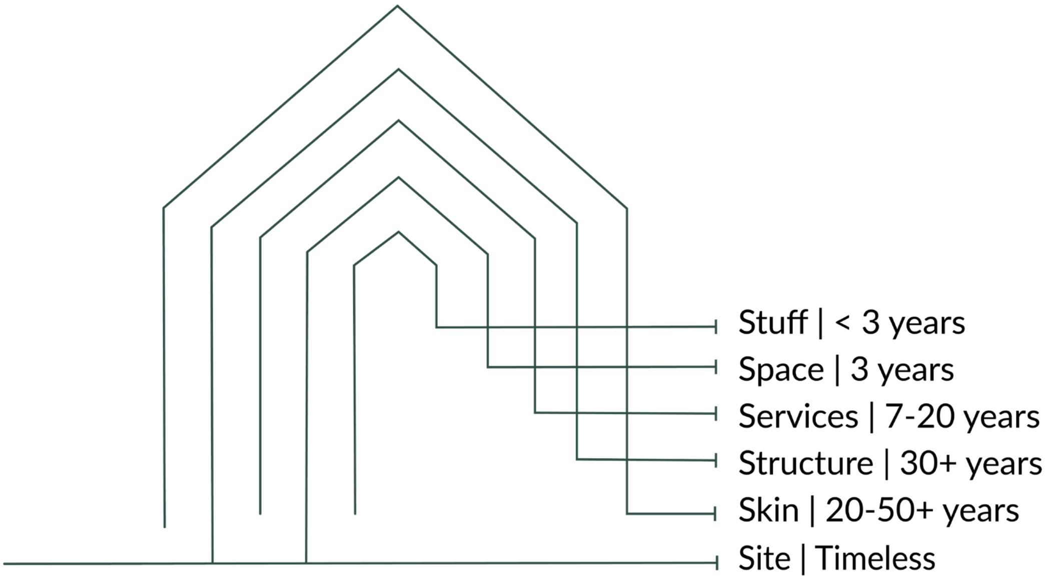


Figure 4 | Shearing Layers in Construction

Figure 5 | Figure of all the bio-base materials section

Types and Avaliability of Materials

Bio-based materials can be derived from different resources. Acknowledging that some bio-based materials also come from earth or animal products, such as clay and wool, this research will focus on plant based bio-based materials. Within plant-based products, classifications are forest, agricultural and fungi materials. These materials can be combined with bio-based additives as well as recycled or composted (Jones, 2020) in efforts to maintain a circular economy of materials.

Compilation of Bio-based Materials

In an effort to further understand the availability of bio-based materials, a compiled list of 135 different bio-based plants were compiled. Plants were considered if they had textile or building application examples. Within the list, product properties, applications, manufacturing, growing climate, and commercial products were added as data fields.

The following knowledge was acquired in the research process:

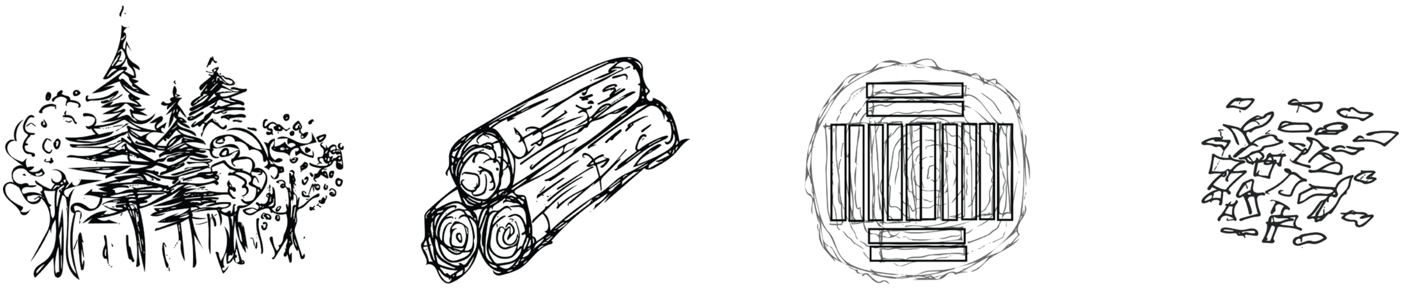
- Different parts of the crop can be utilised for different bio-based material functions
- Many bio-based materials are a form of composite with bio-adhesives or adhesives
- Timber has limitations of being degraded at the end of life due to structural lamination needed for construction
- Agricultural crops have the potential of generating food as well as bio-based materials as by-product
- Cellulose or tree pulp are primary by-products of paper mills which can be utilised in recycled functions

Forest Materials

Of the forest materials, raw timber, timber-based composites and cork applications were outlined. Many of these materials are utilised in the structure and skin shearing layers of a building. By utilising a timber frame, construction can save up to 50% of the embodied carbon in comparison with traditional residential building materials (Monahan & Powell, 2011).

Within the skin shearing layer of a building, Oriented Strand Board, OSB, Plywood, Fibreboards or Particleboards are utilised for wall or flooring construction. These products are already a common practice in the construction and renovation of buildings. Many of these wood panels utilise resins and adhesives to manufacture, which are not always compostable. Through sustainable forest management and sourcing, timber is a viable future construction product that is able to sequester carbon during its use.

Within the literature research, one of the aims is to identify bio-based products that are able to be grown in a controlled CEA system, trees were eliminated from the list of potential bio-based materials. These were eliminated due to long growing periods over one year, the extensive root system required for viable timber for construction, as well as the limitations of growing trees in soilless agriculture. This however does allow for the possibility of tree saplings to begin their growing stage in a CEA environment.



Origin Composition Assembly Future

Figure 6 | Processing Chain for Agriculture Materials

Agriculture Materials

Agriculture by-products and agriculture crops as bio-based materials for construction is a potential field of expansion. In most agriculture emission studies assume by-products are left on the fields to improve soil quality after farming or are completely overlooked in LCA studies (Goswein et al, 2021). However, after further understanding of the biocycles of agriculture, it was found that ⅓ of the straw can be taken out of the agricultural system for further function application rather than left on fields (Goswein et al, 2021). Within the EU, agriculture crops primarily consist of cereal crops, wheat, rye, barley, oats, maize, rice, and rapeseed and the expected crop yield is approximately 260.4 million tonnes of cereal by 2030 (EC, 2020). utilising the approximation of the straw-to-cereal ratio of 0.848 (Goswein et al, 2021), approximately 73.6 billion tonnes of straw could potentially be harvested for product use within the EU.

A total of 63 bio-based materials were compiled from agricultural plant fibres, agricultural byproducts, and bioplastics made from agricultural residuals. From this list, the materials only suited for textiles were removed as well as materials that depend on additional processing for production. Due to height limitations, tall grasses like typha and Elephant grass were eliminated as well as plants that have not been grown in hydroponic or aeroponic conditions. From the finalised list of potential crops, there is a combination of agricultural byproducts as well as agricultural crops, therefore farming and land use must be considered if bio-based materials are to place additional strain on the agricultural industry demands.

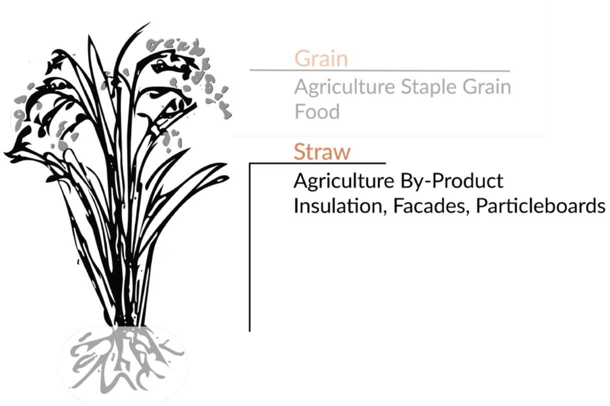


Figure 7 | By-product extraction for Agriculture Bio-base Materials

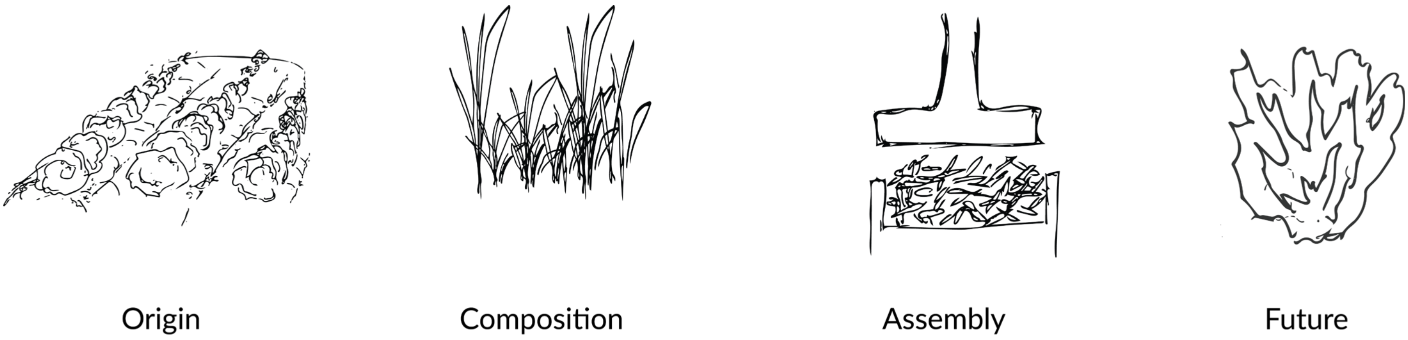


Figure 8 | Processing Chain for Agriculture Materials

Fungi Materials

Alternative plant based bio-based materials that do not fall under the category of forestry or agriculture is Fungi. Mycelium is the vegetative growth of fungi and has been gaining attention within the built environment academic and commercial field (Jones, Mautner, Luenco, Bismarck, & John, 2020). As the root structure of mushrooms, the white fibres are able to quickly fill and bind a growing medium together to create a composite material (Biohm, 2020). The outcome is a natural material that does not require binding resins or adhesives due to the strength of the root structure, which can be utilised as an insulation material or building block through load transferring of the growing medium fibres (Arup, 2017). The growing medium can be sourced from local agriculture waste, such as wheat straw or rice husks (Camere & Karana, 2018) and growing time within the medium is comparable or shorter than plant growth time. High pressure and heat are utilised to stop the growth of the mycelium within the medium. In comparison with other bio-based material manufacturing processes, it is quite simple (Jones, et al., 2020) (Camere & Karana, 2018). Additional research and applications have utilised live mycelium for timber staining to improve the durability of outdoor facades (Fungi Force, 2020). Mycelium composites are still in the research and development phase and require additional testing to understand the material properties in many environmental conditions. It is seen that the target use of mycelium will be in insulation, panelling, and flooring, all of which are found in the skin shearling layer during renovations (Jones, et al., 2020). Already organisations like Cradle-to-Cradle have acknowledged the circularity and potential this composite has for reducing building emissions from materiality (Camere & Karana, 2018).

Based on the research of CEA systems, it is acknowledged that mycelium and other fungi pose a potential risk for hydroponic systems since they could contaminate the water and nutrients used for crops. There are design mechanisms that are used in CEA systems, such as painting seedling mats black to prevent algae or fungi growth. The separation of mycelium in a CEA system from more water based crops is critical.

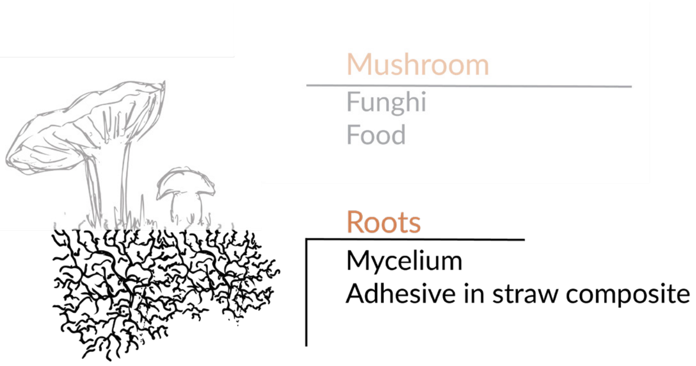


Figure 9 | By-product extraction for Fungi Bio-base Materials

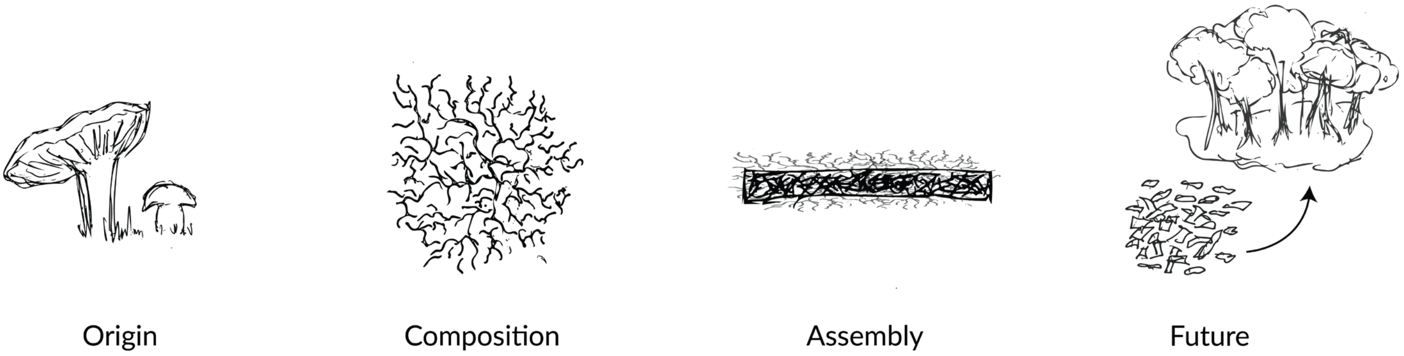


Figure 10 | Processing Chain for Fungi Materials

Dandelions

In construction materials, rubber is produced from either synthetic or natural sources. Dandelions rubber the case of natural rubber, the sap of the rubber tree is collected and manufactured for utilization however faces over-exploitation as well as deforestation. Found in the Brazilian Amazon River region (Venkatachalam, Geetha, Sangeetha, Thulaseedharan, 2013), research of other plant sources have been investigated as a means of reducing the demand on rubber trees without moving to petroleum based synthetic rubbers. Currently, Russian dandelion, *Taraxacum kok-saghyz*, rubber is already being applied to automobile tires from Continental Tire and has been proven to be effective in most manufacturing industries (Cornish, 2017). Rubber is extracted from the sap of the dandelions, which are also able to grow hydroponically. The process of collecting the rubber can be done without damaging the plant and is ideally collected in a similar fashion as hydroponic trays. This allows the ease of harvesting the necessary rubber within a CEA growing format.

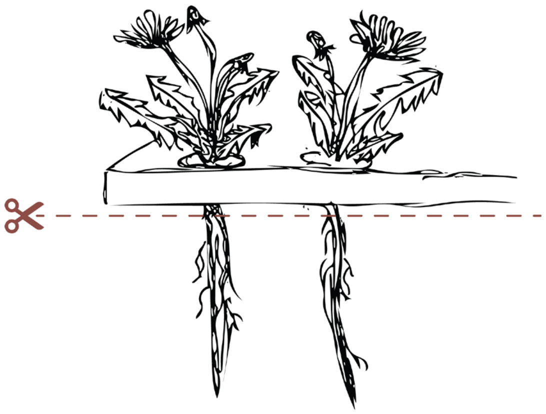


Figure 11 | Dandelion extraction process, utilizing the sap of the dandelion without damaging the plant

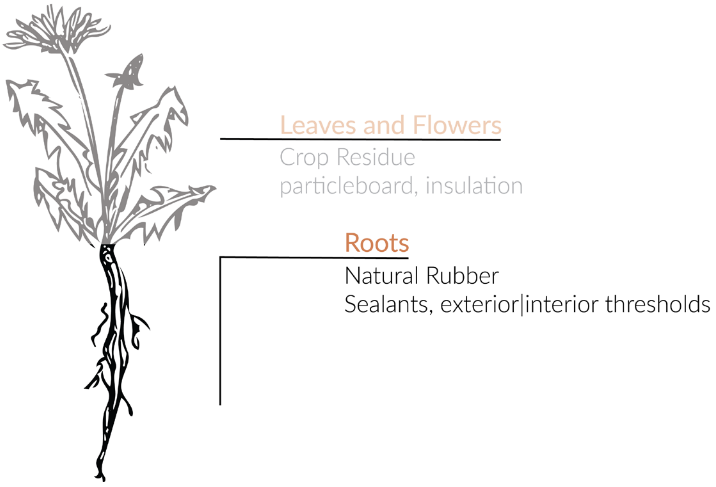


Figure 12 | By-product extraction for Dandelion Bio-base Materials

Industrial Hemp

One key crop that had consistently appeared in CEA and bio-based material research was hemp. As a crop that has been utilised as a major construction material through hempcrete (Arup, 2017) and hemp insulation panels. Due to the rapid acceptance of this bio-based material within the academic field, research has found that hemp could also quickly substitute timber framing and cement blocks (Yadav & Agarwal, 2021). In the growing process, hemp can also be used in the phytoremediation of degraded land through the removal of contaminants in the soil as well as replenishing the quality of soil in temperate climates (Göswein et al, 2021). Unfortunately, hemp is limited in many countries around the world due to legislation, therefore, stunting the potential growth in agriculture (Göswein et al, 2021).

There are many misconceptions surrounding hemp, as its direct counterpart is also known as marijuana, a psychoactive recreational drug with varying legal status around the world. Both have the same botanical name, Cannabis Sativa, but are grown in different conditions and have been through selective breeding to be considered to be two different strains (Johnson, 2019). Industrial Hemp for construction material is required to be grown in the soil and must grow to heights of approximately 350-500 cm for proper structural fibre cultivation (Arup, 2017). Although cannabis sativa has been successfully grown in hydroponic conditions, industrial hemp plants are planted less densely so the plant becomes bushy with many leaves with wide branching while marijuana's high THC content is concentrated primarily in the flowers by limiting plant branching (Johnson, 2019). Placing industrial hemp in a vertical hydroponic growing condition could potentially be detrimental to the potential of the plant to be utilised for construction. For this reason, hemp is not a selected plant to be utilised for CEA bio-based material growth.

Circularity and Bio-based Materials

Within the circular economy framework, the bio-economy of materials focus on biological materials that can be reabsorbed into the ground as biological feedstock at the end of use without toxic traces (EdX, 2020). Although bio-based materials have considerably lower values of embodied carbon, they still rely to a certain extent on processing, such as drying, sawing, adhesives, and packaging (Byrd, 2005). In addition, many of the agriculture by-products or crops utilised for bio-based materials rely on the use of fertilisers and pesticides (Brunklaus, Riise, 2018). This is a major challenge as sustainable architects and designers shift to bio-based materials without realising that there are negative implications that could be further intensified by increasing the demands on agriculture. For bio-based materials to be part of the circular economy, the material origin must also align with sustainable practices (Ellen MacArthur, 2017)

As a means of accounting for the envreionemntal impact of materials, embodied energy of the production and global warming potentials are investigated. Usually claims state that timber does not have any GHG emissions due to the sequestration of carbon in the material during the growing period. This however does not acknowledge the timing of carbon uptake, since many bio-based materials are actually only sequestering carbon for a temporary period (Pittau, Krause, Lumia, Habert, 2018) and that temporary carbon storage does not always lead to emission reductions. When bio-based materials inevitably reach the end of the lifecycle and there is the uncertainty of the state of the earth when these materials do need to release the sequestered CO2 (Pawelzik, Carus, Hotchkiss, Narayan, et al, 2013). By utilising Cradle to Cradle, a circular economy concept, the vision is to also continue the use of biological materials to avoid the unproductive release of the sequestered carbon. This with the use of LCA also helps identify the environmental impacts of material during its early development stages, such as growing resources needed and soil degradation (Pawelzik, et al, 2013). Utilizing the idea of circularity, allows designers to also reach more sustainable goals as well as acknowledge practical challenges for bio-based materials in the management of End of Life (EoL) CO2 emissions (Brunklaus & Riise, 2018).

Material	Root Depth < 50 cm	Plant Peak Height < 100 cm	Grown in CEA system	Bulk Growth and Cultivation	Growing Time ~1 year	Bio-based Material for Construction
Flax	🟩	🟩	🟩	🟩	🟩	🟩
Mycelium	🟩	🟩	🟩	🟩	🟩	🟩
Dandelions	🟩	🟩	🟩	🟩	🟩	🟩
Barley	🟩	🟩	🟩	🟩	🟩	🟩
Rice	🟩	🟩	🟩	🟩	🟩	🟩
Wheat	🟩	🟩	🟩	🟩	🟩	🟩
Rye	▨	🟩	🟩	🟩	🟩	🟩
Alfalfa	▨	🟩	🟩	🟩	🟩	🟩
Oat	▨	🟩	🟩	🟩	🟩	🟩
Hemp	▨	▨	🟩	🟩	🟩	🟩
Corn	▨	▨	🟩	🟩	🟩	🟩
Sunflower	▨	▨	🟩	🟩	🟩	🟩
Bio-PE	▨	▨	▨	🟩	🟩	🟩
Polylactic Acid (PLA)	▨	▨	▨	🟩	🟩	🟩
Strach Blends	▨	▨	▨	🟩	🟩	🟩
Peanuts Husks	▨	▨	▨	🟩	🟩	🟩
Potato	▨	▨	▨	🟩	🟩	🟩
Abaca	▨	▨	▨	▨	🟩	🟩
Agave	▨	▨	▨	▨	🟩	🟩
Bagasse, Sugarcane	▨	▨	▨	▨	🟩	🟩
Banana Fibers	▨	▨	▨	▨	🟩	🟩
Coconut Fiber	▨	▨	▨	▨	🟩	🟩
Coconut, Green	▨	▨	▨	▨	🟩	🟩
Palm	▨	▨	▨	▨	🟩	🟩
Pineapple	▨	▨	▨	▨	🟩	🟩
Alginate, Brown algea	▨	▨	▨	▨	🟩	🟩
Seaweed, Green algea	▨	▨	▨	▨	🟩	🟩
PHA	▨	▨	▨	▨	🟩	🟩
Leaves	▨	▨	▨	▨	🟩	🟩
Acetylated Fibers	▨	▨	▨	▨	🟩	🟩
Bulrush	▨	▨	▨	▨	🟩	🟩
Henequen/ Sisal	▨	▨	▨	▨	🟩	🟩
Jute	▨	▨	▨	▨	🟩	🟩
Kenaf	▨	▨	▨	▨	🟩	🟩
Ramie	▨	▨	▨	▨	🟩	🟩
Ratan Fibers	▨	▨	▨	▨	🟩	🟩
Rattan	▨	▨	▨	▨	🟩	🟩
Roselle fiber	▨	▨	▨	▨	🟩	🟩
Cellulose Algae	▨	▨	▨	▨	🟩	🟩
Cellulose Fungi	▨	▨	▨	▨	🟩	🟩
Lignin	▨	▨	▨	▨	🟩	🟩
Lignocellulosic	▨	▨	▨	▨	🟩	🟩
Bamboo	▨	▨	▨	▨	🟩	🟩
Guayule	▨	▨	▨	▨	🟩	🟩
Reed	▨	▨	▨	▨	🟩	🟩
Sabai, Grass	▨	▨	▨	▨	🟩	🟩
Sudan Grass	▨	▨	▨	▨	🟩	🟩
Elephant Grass	▨	▨	▨	▨	🟩	🟩
Esparto	▨	▨	▨	▨	🟩	🟩
Kapoc	▨	▨	▨	▨	🟩	🟩
Manila hemp	▨	▨	▨	▨	🟩	🟩
Mesta	▨	▨	▨	▨	🟩	🟩
Silvergrass	▨	▨	▨	▨	🟩	🟩
Sorghum	▨	▨	▨	▨	🟩	🟩
Totora Grass	▨	▨	▨	▨	🟩	🟩
Typha	▨	▨	▨	▨	🟩	🟩
Coffee	▨	▨	▨	▨	▨	🟩
Cork	▨	▨	▨	▨	▨	🟩
Timber and Wood Products	▨	▨	▨	▨	▨	🟩

Figure 13 | List of Potential Bio-base Materials for application and Criteria for feasibility

AGRICULTURE BIO-BASE MATERIAL CHALLENGE

“[We] assume most of the climate change—that we unquestionably face—is due to fossil fuel emissions. But it is in direct conflict with reality when we consider agriculture is contributing as much to climate change, and possibly even more than fossil fuels“

- Allan Savory, 2014

“Crop failures will become more frequent in places in which they are now considered rare, and will become the rule rather than the exception in places in whchi they now regularly occur”

- Dickson Despommier, 2010

Currently most agricultural practices have focused on food and feed yields to feed the growing global population as well as livestock. In this section, agriculture will be described primarily in the context of food and feed to show the potential of each method of agriculture to accommodate future bio-based materials crop extraction and byproduct use.

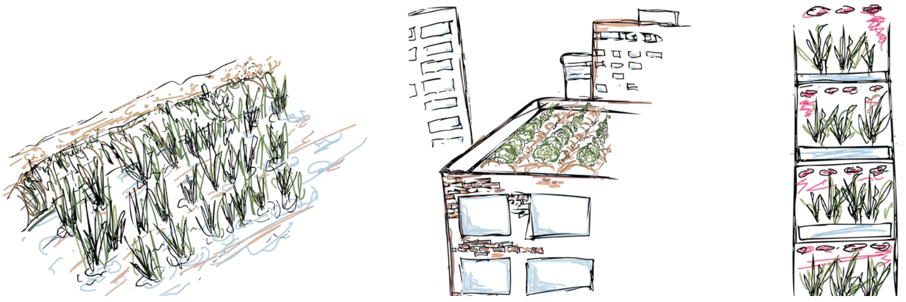


Figure 14 | Agriculture Typologies | Open Field, Urban Agriculture, Controlled Envrioment Agriculture

Agriculture Typologies

Open Field

Agricultural farming has progressively changed with modern advancements and now incorporates the use of extensive tilling and pesticides on open fields. Most utilised crops in temperate regions, such as Western Europe and the United States, include wheat, maize, barley, rapeseed, sugar beets, and potatoes. This region is also considered to be the most productive agricultural climate (Dastrup, 2015). Currently, the driving force in agriculture is the global demand increase of food and fibre due to the growing world population (Olesen and Bindi, 2002) as well as increased demand for biofuels. In addition, conflicts occuring globally places strain on the global food and fibre supply chain. The result is usually increasing pressure on the land, water resources as well as distribution of goods.

Although this is the most traditional and known form of agriculture, the open fields in recent years have been vulnerable to increasing continuous extreme weather events that cause lower harvestable yields and reduction of suitable areas for traditional farming. This is increasingly seen in research showing that the global stock of arable land for agriculture has been declining between 1961 and 2013 (FAO, 2016) causing further strain on the agriculture industry. For this reason, most farmers in developed countries receive a yearly subsidy to guarantee income regardless of the yield production, which drives the consumer price down for crops like corn and cane sugar (Dastrup, 2015). For this reason, there is also an excess of these crops which exceed local demands and creates a mono-crop culture focused on “cash crops” that are subsidised.

Urban Agriculture

Currently consuming 70% of the global food supply-demand, urban dwellers have depended on the consumption of processed foods and lack ease of access to fresh foods (FOA, 2019). However, the demand for fresh foods in urban areas has increased, causing an increase in the density of food that has to travel large distances to reach the plate of an urban dweller. This distance is accounted for as "food miles" and many urban agriculture practices aim and claim to reduce these distances and CO2 emissions that come with transport (Philips, 2013). Urban agriculture practices are usually found in the heart of the city to meet the food demands of city dwellers and was previously practised as a means of establishing and feeding large civilizations in countries such as Egypt and China over 10,000 years ago (Philips, 2013). Unfortunately, much of the farmland around major modern cities are not particularly fertile after generations of over-farming the land. After the utilisation of innovations to increase the productivity of a farm, like the tractor and fertilisers, the fertility of the soil has decreased (Hemenway, 2015) or has been converted to urban land. To mitigate soil stress and increase access to fresh foods, urban agriculture focuses on creating agriculture forms that do not depend on large land uses (Pötz, Bleuze, Sjauw et al, 2012). Rooftop farming and raised bed community gardens, which depend on urban infrastructure and land, are more sought out forms of urban agriculture as a means of greening cities and for sourcing fresh foods closer to city inhabitants (Pötz, 2012).

There are three outlined urban agriculture systems that can be implemented in urban areas: plant-factory with artificial lighting (PFAL) and rooftop farming (Al-Kodmany, 2018). PFAL's also fall under the term of Controlled Environment Agriculture, CEA, systems, which are discussed in further detail in the next section. CEA's can be found in urban settings but also do not completely depend on urban infrastructure. Examples like the 0.6 ha Brooklyn Grange rooftop garden on the former Brooklyn Navy Yard in New York City now yields approximately 11,000-13,000 metric tons of organic vegetables per year and has set an example for NYC's newest zoning code addition, Zone Green (Harada & Whitlow, 2020). Zone Green aims to ease city approval for rooftop gardens and other forms of productive green space and to allow urban agriculture to become a norm. New York City has the potential of 1,246 ha of rooftop gardens like Brooklyn Grange (Nowak, et al., 2018).

Controlled Envrioment Agriculture

Recognized as different terms, such as greenhouse, plant factory, indoor farming, or vertical farming, CEA has revolutionised the methods of farming from outdoor settings to indoor controlled climates. The level of climate control varies from Plant factories with Artificial Lighting (PFAL) to smart greenhouses found in peri-urban and urban areas (Opitz, Berges, Piorr, et al., 2016). Growing systems include the use of Aeroponics, Aquaponics, and Hydroponics with a stacked bed design or the use of cascading raised beds (Shamshiri, et al., 2018). Each system has been developed to control growing conditions, such as growing medium pH, water distribution, plant nutrients, lighting characteristics, temperature, CO2 concentration, and humidity within an indoor enclosure. By being able to monitor and artificially create ideal growing conditions, crop production levels can be optimised for higher yields for year-long growth and harvesting periods.

Agriculture Pressures

Yield

In order for agriculture to meet the demands of food, animal feed, biofuels, and now bio-based materials, there will be additional agricultural pressure to have productive fields and large yields on the limited arable land available. Already to optimise crop production, farmers utilise genetically modified crops, utilise irrigation systems as previously mentioned, pesticides, and fertilisers. However, it has been found that biomass crops that do not utilise fertilisers also decreased in yield to approximately 2 Mg/ha/year while well managed plantations with fertilisers have values closer to 15 Mg/ha/year (Nonhebel, 2005). In a certain sense, crops that are intended for the decarbonization of the energy and material industry have the potential to be the product of intensive fertilizers, over tilling, and pesticides, effectively leading to environmental hazards. It is noted that there in most tradditional open field agriculture practice, synethic featilisers are utilised. In comparison with organic fertilisers, synthetic have a higher envrionmental impact In the case of bio-based materials, although the intention is to reduce the CO2 emissions of building material products which will in turn would decrease the overall emissions of the construction and renovation industry, it cannot be neglected in the dynamic LCA to account for the negative environmental impact of bio-based materials that are grown and cultivated in an open field setting.

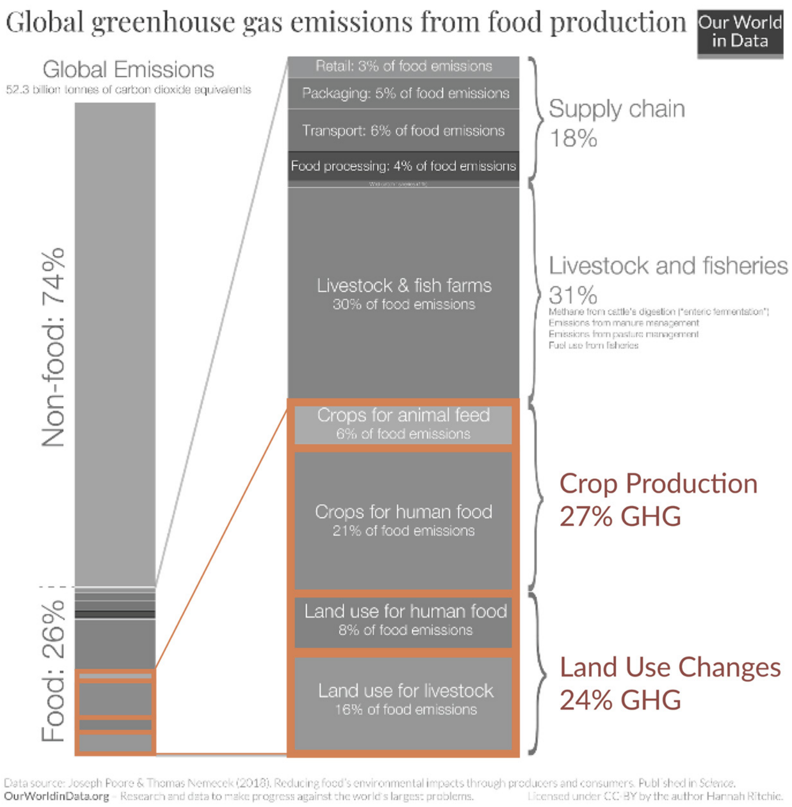
Financial

Many farmers receive subsidies in order to promote the growing of cash crops such as corn. Planting crops with subsidies is a financially secure decision but does create an imbalance of crops harvested to the actual demand of the consumers. In the Netherlands, crops that receive subsidies are wheat, barley, and sugar beets (Hermans, Naeff, & Terluin, 2006) since 2000 but have worked toward reducing subsidy dependency. At this time, subsidies and forms of financial security are not yet formalised within urban agriculture and vertical farming. In addition, open field farmers do not have a financial incentive to grow bio-based oriented crops (Dastrup, 2015), therefore will not have a direct motivation to transition their crop use from traditional and cash crops. A similar challenge is occurring with biomass generation and the introduction of the EU Renewable Energy Directive in 2009, which has resulted in more incentive to sell crop yields to the energy and fuel industry (Vural, et al., 2021) in efforts towards energy transition. This then reduces the availability of biomass for non-incentivized bio-economies such as bio-based materials.

Agriculture Emissions

The current rhetoric surrounding climate change has focused on reducing CO2 emissions and promoted there is a focus on reducing embodied carbon in our construction materials and processes, as previously mentioned in the bio-based material section. But what failed to be highlighted when discussing carbon sequestration and end of life stage (EoL) of bio-based materials is that carbon itself is a necessary part of agriculture and ecosystem life cycles. Although it has been outlined that many of the bio-based materials can sequester carbon from the atmosphere, the soil has more carbon storage potential than the atmosphere and plants combined. Unfortunately, these soil life cycles are interrupted during farming and other agricultural practices, causing the release of more CO2 into the atmosphere. For this reason, permaculture has been seen as the most sustainable form of agriculture and is one of the primary methods of addressing the climate crisis (Project Drawdown, 2020) but unfortunately permaculture is not easily scalable and many farmers opt for financially stable commercialised options.

Currently food production emissions account for approximately 26% of the GHG emissions globally and 9.1% of those emissions are directly from crop agriculture (Poore, Nemecek, 2018). These emissions account for the conversion of forestland to crops and use of pesticides and unsustainable agriculture practices. Within the EU, agriculture accounts for arppoximately 11% of GHG in 2016 (Fernandez, 2016) but is only a mere fraction of actual emissions due to the fact that EU imports a large quantity of agriculture and food products through international trade, displacing CO2 emissions consumed by Europeans onto providing countries (Poore, Nemecek, 2018).



Data source: Joseph Poore & Thomas Nemecek (2018). Reducing food's environmental impacts through producers and consumers. Published in Science.
OurWorldinData.org – Research and data to make progress against the world's largest problems. Licensed under CC-BY by the author Hannah Ritchie.

Figure 15 | Chart Agriculture Emissions from Open Field Agriculture from Crop Production and Land Use Change (Sourced from Poore, Nemcek, 2018)

Environmental Hazards

In addition to the CO2 emissions that are released by the agriculture industry, there are several environmental and climate aspects that impact and are closely related to current unsustainable farming practices. As previously mentioned, the introduction of bio-base materials would increase yield pressure on the dwindling and competitive land uses. In addition, it has been mentioned that the building industry's effort of decarbonization through the utilisation of bio-based materials is fragile and is highly dependent on the success of open field crops. Unfortunately, open field crops are subject to the following environmental hazards that are capable of destroying entire fields of crops before harvest.

Soil Degradation

Currently agriculture has shifted from small farms to commercialization for yield optimization through the use of fertilisers and intensive nutrients causing soil degradation, which is the loss of moisture retention in soil to the point it becomes a coarse and dry texture. The degradation of soil is a long term challenge for agriculture especially in areas with high erosion risks, such as Indonesia, India, and the Philippines (Sulaeman, Westhoff, 2020). Because water cannot infiltrate into the soil due to its texture, it can cause damaging flooding and further decrease soil fertility as the water erodes any remaining nutrients in the soil. Similarly, degraded soil is subject to wind erosion due to the lack of vegetation and nutrients, causing the cascade of continuous degraded soil. Policies and methods, such as the Effective Disaster Risk Reduction, DRR (FAO, 2021) are now utilised by modern farmers to prevent and manage soil erosion and extreme agriculture conditions. But with the increasing number of commercialized land areas utilising extensive tilling and pesticides, flooding caused by agricultural runoff and desertification of land has continued to increase which in turn has and will continue to lead to further soil degradation.

Flooding

Flooding disasters cause 19% of all crop and livestock loss globally and the average number of flood events in a year has gone from 30 per year in the 1970s to an average of 180 per year in the 2000s (FAO, 2021). Flooding can be seen as the extreme climate disaster event while seawater rise is the slow-onset event that will affect agricultural land long-term. Flood events have been known to further divide socio-economic classes and cause a shift in agriculture type that households and farmers rely on. In the case of the coast of Vietnam, relative prosperity indicates whether they have access to fertile high ground agricultural land while farmland around the coast has been completely inundated with saltwater, forcing the coastal region to depend on low-income salt-making. The lack of income in these areas further perpetuates increased vulnerability to future storms (Fayazi, & Bornstein, 2021).

Drought

As the primary cause of agricultural production loss, drought and desertification of crop land causes approximately 34% of the production losses (FAO, 2021). Drought is seen as the extreme climate event while desertification is seen as the slow onset and effect of constant drought. Although every environmental hazard had a lasting impact, it is droughts that have caused the most serious famines and displacements of communities (FAO, 2021). As the leading driver of climate refugees, households move across borders in search of better land that has not been affected by intense desertification to grow on. This kind of process has occurred in the past, as seen by the American Dust Bowl, where thousands of farmers retreated due to the lack of fertile land and hazardous living conditions caused by desertification of crop land (Riebsame et al., 1991). This is currently being seen in the Mediterranean, Africa's Sahara and Sub-Saharan desert, and American Plains. By 2050, 50 million people in Bangladesh, Egypt, China and India are predicted to be vulnerable to desertification and potential displacement due to environmental hazards (Government Office for Science: London, 2011).

Agriculture Competition

The production of raw material for bio-based materials will require the allocation of land, resources, and collaboration from the agriculture industry. Of the 13.2 billion hectares of arable land on the planet, 12% is being utilised for crop cultivation (Dastrup, 2015). In areas like South and Southeast Asia, West and Central Europe, and the Americas, agricultural land use is the leading land function while areas like Northern Africa are not able to cultivate high crops yields due to soil degradation and drought. In areas like this, farmers cannot depend on natural rainwater for their crops and have to utilise irrigation systems connected to rivers and lakes to accommodate water scarcity and drought (Dastrup, 2015).

As the world population increases, there will be additional pressure on the productive land that is available. This also means that bio-based materials are entering a land use competition between the agricultural bio-economy and energy industry, which now includes land use for biofuels and photovoltaic (PV) farms. The complexity of land use can be shown in concepts like land use nexus framework and “land use efficiency” (Pawelzik, et al., 2013) which have been utilised to understand the effects of land use and to visualise the impact of land exploitation and indirect land use change, ILUC, where forest or ecologically valuable land is converted to agriculture land to make up for the conversion of agriculture land to different functions such as urban sprawl, photovoltaics or for biomass energy.

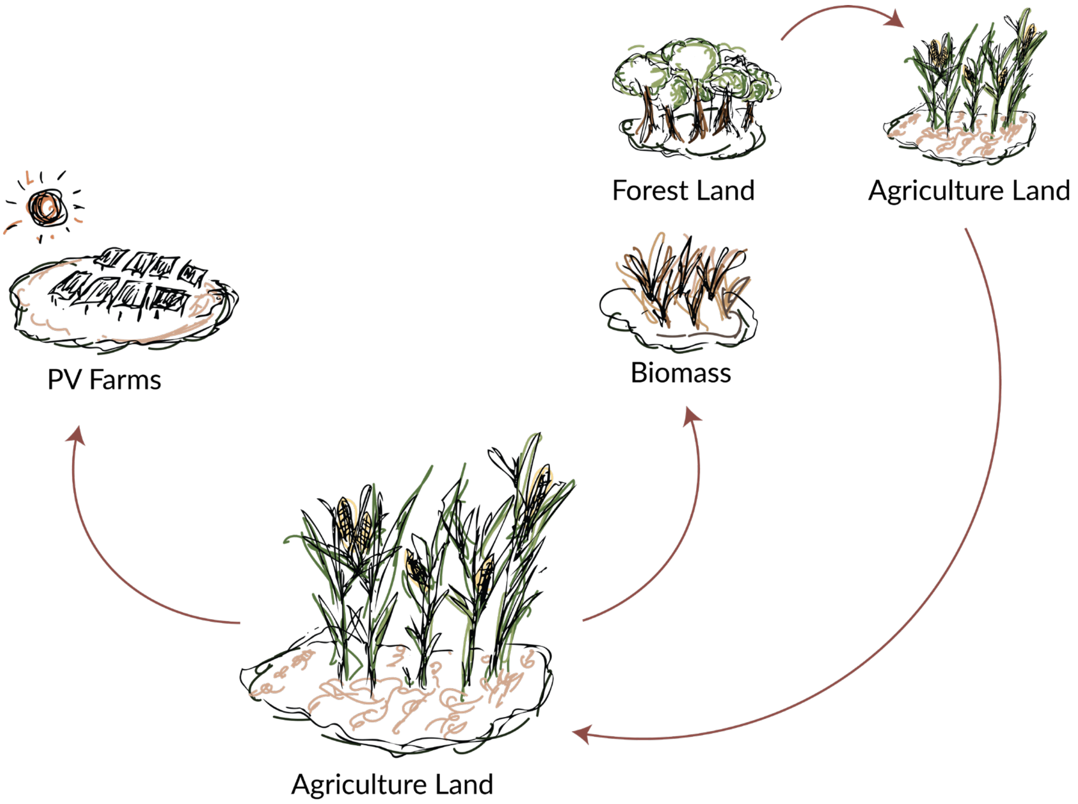


Figure 16 | Indirect Land Use Change Scheme

Urban Sprawl

As the primary driver for land development, the urban sprawl of cities has caused the loss and replacement of agricultural land for urbanization. Ironically, population growth in urban areas increases the demand for agricultural products but decreases the arable land available surrounding cities (Smith, Gregory, Van Vuuren, Obsterteiner, et al., 2010). For this reason, farmers have intensified their crop yield per hectare which commonly leads to the use of fertilizers. Although policies are put in place to prevent the conversion of farms to urban land, much of the challenges come with forest land being converted to agriculture because of the increasing urban demands. The natural competition between agriculture and forestry begins with the consumption of meat products and the need for agricultural feed for the animals. For this reason, urban agriculture has increasingly been considered as a sustainable practice to reduce the demands of currently allocated agricultural lands. Within the EU, the forest area has increased in recent years with reforestation efforts while agricultural available land is shrinking (Göswein, 2021).

Photovoltaics

Transitioning to renewable energy has been the means of reducing the overall dependency on fossil fuels, however, geographical characteristics and land use for agro-forestry and nature conservation have limited the land for collecting photovoltaic energy (Dias, Gouveia, Lourenço, Seixas, 2019). It was concluded that additional designated land would be needed in the EU in order to provide enough solar renewable energy. However, in order to expand, this means competing with agricultural crops and forest lands, which was investigated specifically in a case study in the municipality of Evora, Portugal (Dias, et al., 2019). In this case study, it was found PV utility scale projects, smaller plots of PV, were more effective than large scale PV farms which reduce land competition. Photovoltaics will be a renewable energy source that will compete with agriculture land for bio-based materials. However, it is important to note that utilising a CEA system would reduce the land pressure by reducing the land demand for the same crop yield but will increase energy demand therefore PV reliance will increase. Design projects have also proposed agri-voltaic systems, the combination of solar photovoltaic panels over food crops as a means of not having to trade off between the two different industries (Dias, et al., 2019). Unfortunately, this concept is only functional for crops that have a certain level of shade tolerance (Dinesh & Pearce, 2016).

Biomass

In previous accounts of the shift of agricultural crops to biomass, feild dedication solely for bio-fuels has caused major food crises' due to competition and demand shift of resources causing an increase in food prices (Göswein et al, 2021). The development of biofuels in the later 2000s had caused strain on food production in Brazil in exchange for allocating a large partition of cereal crops towards biofuel rather than food (Scarlat, 2019). This highlights the social implications of ILUC, when shifting crop use and allocation. Biomass specifically requires the structural plant material, such as cellulose, proteins and fats, which are also utilised for bio-based materials (Nonhebel, 2005). In addition, biomass, the largest source of renewable energy within the EU (Scarlat, 2019), depends on the use of by-products of cereal crops like wheat and barley straw, which are major components of bio-based materials.

However it has been found that when crops are utilised for biomass energy, more land is needed to meet energy demands than food. This is approximately 10 times more area for energy than for food in best case scenarios or 20 times more land required in worst cases. This is based on energy and food demands of a single person, where 10 MJ of food per person per day only generates 3.6 GJ of energy per year from biomass when a single person demands approximately 35 GJ per year (Nonhebel, S. 2005). In addition, bio-based materials potentially have a larger environmental benefit than biofuels by having larger potential in reducing GHG emissions and its capability to promote a circular economy approach (Vural Gursel, Quist-Wessel, Langeveld, 2021).

In comparison with biofuels, which has alternative renewable energy sources such as PV, bio-based materials are specifically design for processing biomass feedstocks and cannot be produced from alternative materials, meaning the building material industry would have to return to current material use if the biomass suddenly becomes unavailable (Vural, et al., 2021). This clearly illustrates that agriculture bio-based materials are highlighly dependent on the allocation of land use strictly for material production. In addition, with increasing environmental hazards, bio-based materials currently do not have a climate resilient alternative, exposing that the bio-economy of bio-based materials is fragile.

RE-ENVISION AGRICULTURE WITH CEA

Agriculture Resilience

With the increasing events of flooding and drought events, global communities are being forced to adapt and attempt to prevent further impact of environmental hazards (Chikumbo, Lewis, Canard, Norris, 2015). The terms sustainability and resilience are utilised as methods of responding to these events, one to take preventative measures and the other as a means of reacting. It can be found that some countries prioritise one methodology for cultural or financial reasoning. Although both concepts are dependent, where sustainability is used to prevent environmental hazards and resilience is the means by which people react to the hazards, resilience can be used as means of learning from the past to create functioning systems for the future.

Creating robust-yet-flexible systems for disaster response and prevention is synonymous to resilience. To design for the variability of conditions rather than assuming what the conditions may be, allows for systems to improve because they do not mask the stressors and rather allow them to happen at whatever scale. As described in the previous section, sea water rise has forced communities either to move to higher ground, or alternatively, has urged resilience through the implementation of floating agriculture beds, as found in Bangladesh (Asad, Ahmed, Vaughan, von Meding, 2021).

Unfortunately, currently the agriculture industry struggles to absorb and recover from the shocks and stresses of the environmental hazards. A long term solution, many farmers is to turn to permaculture as means of improving the soil and to create more resilient agricultural land, but this occurs over a span of years to have enough fertile soil for harvesting crops (Hemenway, 2015) and does not provide aid or food in the weeks and months of after a natural disaster or environmental hazard. Unfortunately, in the cases of flooding and droughts, there is no means of recovering the crop once it is destroyed for the season leading to financial and production insecurity in the agriculture industry.

Bounce Back Better

In situations of major environmental hazards, many communities strive to implement a sense of normalcy into their communities. The first large-scale effort in disasters is to find interim solutions for food and shelter within the first hour and days of the disaster event (Chikumbo, et al., 2015). In an abstract manner, victims of environmental hazards do not necessarily only want a house to protect them from outside elements but to have a home that provides the resumption of daily life (Mannakkara, Wilkinson, & Potangaroa, 2018). In the light of an environmental hazard and the need to rebuild a community also allows for a potential catalyst for change. Rather than to "bounce back" with the utilisation of familiar technologies and strategies to return to the original state, which in turn could also increase community vulnerability for future disasters, "bounce forward" reinforces the desire to strengthen institutions. To make a vulnerable community see that resilience is not to just bounce forward and move on from the disaster but to see the disaster as an opportunity to adopt new changes (Manyena, O'Brien, O'Keefe, Rose, 2011).

After the major tsunami of Japan in 2011, the surrounding rural areas of Fukushima, which was once utilised for agriculture, were completely flooded by saltwater. In these conditions, 5% of the agricultural land was not to bounce back and prevented residents from resuming their daily life. Before the tsunami, Dr. Kozai at Chiba University had developed an experimental vertical farm in 2010 and had been testing its ability to replace traditional farming practices. In response to the loss of agricultural land in Fukushima, Dr. Kozai proposed and successfully proposed the utilisation of vertical farming to the Japanese government as a means of "bouncing forward". From this point, vertical farming has gained more acceptance as a form of agriculture in Japan and now several widespread commercial vertical farms are fully functioning in Japan, most of which are more productive than traditional farming techniques. (Despommier, 2019)

Bio-based Materials and CEA Systems

The outcomes of the 2011 tsunami and use of vertical farming as response to the environmental hazard is an integral example of CEA being utilized as a means of bouncing forward with agriculture. Not only did the application of VF technology assist in alleviating the land use pressure caused by the loss of land to saltwater, but also introduces a system that is much more resilient to future environmental hazards. A CEA approach for growing bio-based material crops will provide a means of providing crop yields resilient to environmental hazards, securing guaranteed biomass for bio-based materials, and ensuring responsibly sourced crops that do not degrade soil quality or depend on fertilizers. In addition, CEA provides a possibility for redundant resilience, where farmers can diversify with different farming methods and means of revenue (Despommier, 2010).

Proposed Agriculture Resilience

To combine bio-base materials and CEA systems will acknowledge responsible agricultural practices as well as provide a means of more resilient agriculture alternative to guarantee both crops for the use of bio-based materials. Although the implementations of CEA would also provide resilience for crop growth for food, the aim of this research was to also figure the feasibility of configuring a CEA system suited for agriculture bio-based crop growth. By utilising a more resilient agriculture structure, bio-based materials in CEA can be considered as a key and more secure form of circular economy which guarantees the continuous availability of bio-based material stock (Brunklaus, Riise, 2018).

It can be acknowledged that although proposing one large CEA system to provide agricultural resilience to the greater Netherlands, the design of the system will serve a specific region of the country.

Comparing Resource Consumption

Land

CEA systems implemented in urban settings will have difficulty in purchasing land due to high land prices. However, it can be seen that the possibilities of CEA reducing ILUC and competition could outweigh those costs and lead to the possible continued reforestation and reestablishment of natural ecosystems that had been disrupted by the agriculture and building industry (Benke, Tomkins, 2017). CEA is advertised as a means of reducing land use for agricultural demands through the use of stacked levels of agriculture production (Philips, 2013). This can be compared to open field farming directly through potential yield per m2 to show productivity levels of farming processes. Initial research has shown that vertical farms are able to accommodate more plants per hectare than in greenhouses and open fields as well as produce more due to all year production capabilities (Bao, Lu, Zhao, Bi, 2018). This has however not been directly applied to crops for bio-based materials and there is limited research on the actual density of these crops in different growing settings. In this example, tomato plants are nearly 5 times dense than field farming and have an overall increased production output, as seen in Appendix.

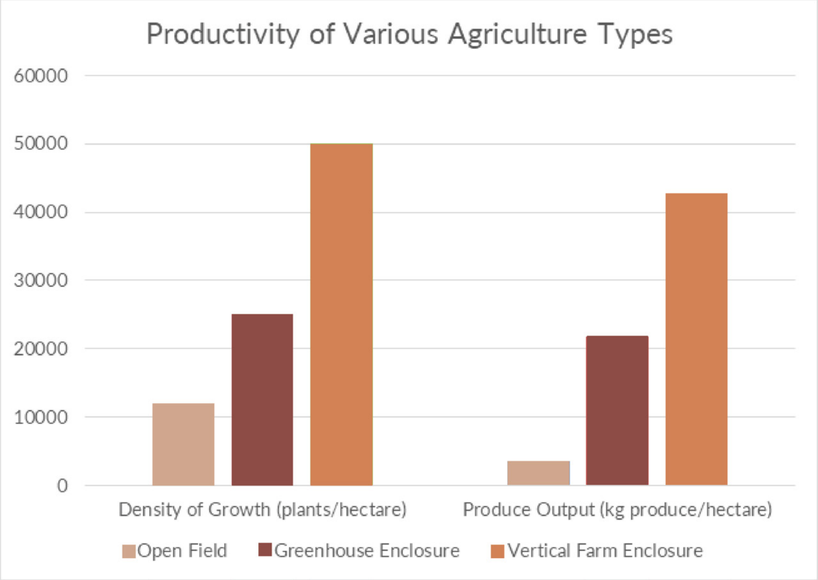


Figure 17 | Productivity of Open Field, Greenhouse Enclosure, and Vertical Farm Enclosure (Sourced from Graamans, Baeza, van den Dobbelsteen, et al., 2018 and Shamshiri, Kalantari, Ting et al., 2018)

Water

Additional resources that must be considered when investigating agriculture alternatives is the impact on water usage. On average, the CEA systems described have a water-saving value of over 80% when compared to traditional open-field farming. In the limited water that is required, rainwater collection from impervious urban surfaces, such as roofs can be reclaimed and utilised within the CEA system, thus reducing urban water runoff and increasing the water storage capabilities of cities (Philips, 2013). As water becomes more of a commodity in areas of drought, water conservation for agriculture will become crucial. Furthermore, variables such as fertilisers also decrease in comparison with open field farming. Table A.2, found in Appendix A summarizes resource use and productivity illustrates the reduced demands of water and fertilisers when vegetable crops are placed in a CEA system (Alshrouf, 2017). This illustrates the possibility of reducing the environmental demands of bio-based materials.

CEA Construction

The construction and operation of vertical farming in a CEA setting includes a structural, growing, water, and climate system. Since many of the materials are exposed to water for prolonged periods, materials for construction are primarily of metal and plastic components (Kozai, Niu, & Takagaki, 2019). With the intensive use of plastic for the nutrient solution distribution system, there is some concern about toxic phthalates seeping into irrigated water. To mitigate this PVC is usually treated with diluted sulfide solution (Despommier, 2010). The following are common components and materiality for a vertical farm, as seen in Appendix A Table A.3, as well as Figure 2.12 (Kozai, Niu, & Takagaki, 2019) and a proposed bio-based material alternative that can be explored as found in Appendix

The construction of the exterior building of a CEA system can either be transparent with natural light allowance or enclosed with only artificial lighting (Kozai, Niu, & Takagaki, 2019). In ideal situations, regardless of the construction of the exterior, the interior arrangement should be flexible, allowing for the adaptation of different crops and operational demands (Despoimmier, 2010). Transparent facades with clear plastic panels are recommended to reduce the use of glass. CEA enclosures that utilise only PFAL systems require a warehouse-like space with no windows and building insulation. In the construction of these enclosures, bio-based materials can be utilised for facade and interior finishes and insulate the skin shearing layer of the building. Overall, utilising more eco-friendly materials for the exterior and enclosure construction can also potentially present a means of reducing the building and construction emissions for the CEA system (Despommier, 2010).

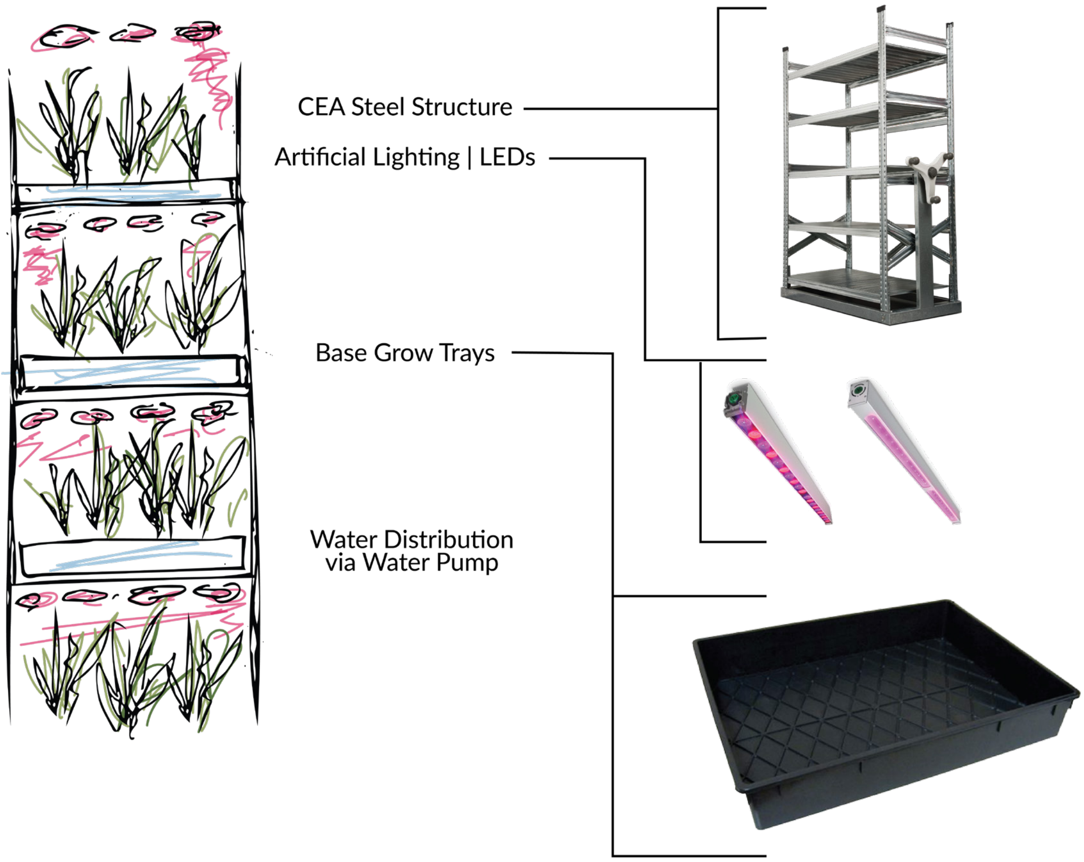


Figure 18 | Materials for CEA Construction

Operation

During the operation of CEA systems, growing conditions are created and controlled. Each condition can vary based on the crops being grown as well as can be altered for researching optimised conditions. As testing and research continue in vertical farm settings, lighting, ventilation, and temperature are seen as the key aspects of ensuring the efficiency of crop yield. Each crop also requires different growing conditions, especially root systems (Despommier, 2010), that should be monitored with sensor and feedback loops.

Variations of lighting colours and schedules have been found effective in simulating daylighting and promoting plant growth. Utilising light emitting diodes, also known as LEDs, have been specially designed to promote the photosynthesis of plants through the use of blue and red coloured lights (Despommier, 2010). Photosynthesis is driven primarily by blue and red lightwaves within the visible light spectrum, therefore exposing plants to these lightwaves will speed up the growing process more effectively than utilising the entire broad light spectrum, most of which are not effective for plant growth.

Lighting in a CEA system does emit excess heating, but when balanced with outdoor temperature, can provide the heat necessary for plant growth. Air conditioning and ventilation provides circulation as well as maintaining CO2 concentrations necessary for plants. Through the use of direct air capture for carbon enrichment, it has been found that increasing CO2 concentration from 400 to 1000ppm can stimulate plant growth by 21-61% for flowers and vegetables (Bao, et al., 2018). This produces an opportunity of sequestering emissions for any processing required to convert crops to building materials.

It has been determined that operations for CEA are complex and require more of an understanding of plant science and laboratory testing to determine feasible conditions specifically for bio-based material crops. For this reason, operations such as lighting schedule, nutrition cycle and ventilation will not be coordinated for the remainder of the project but will be assumed in optimised growing and energy efficient conditions for LCA calculations. Temperature, watering, and harvest cycles will be considered.

CEA Precedents

Construction of CEA buildings and configurations vary however, they all maintain the idea of optimising plant yield and space. Many successful examples of vertical farming have focused primarily on leafy greens.

Many vertical farms have focused on leafy greens and have multiple tiers of growing medium. This however can be limiting in crop possibilities since bio-based crops commonly require more than 0.3m of growing height and an additional 0.2 for lighting and structure frame between tiers (Kozai, Niu, & Takagaki, 2019). In the field of medical cannabis, there are more examples of taller crop growth, approximately 1.4m in between tiers. This CEA configuration and height is better suited and is comparable for bio-based material crop growth. Utilising indoor growing of cannabis as an example of CEA for taller crops, additional research into their configuration as an example will be done in the next phase of design.

Table 1 | CEA Case Studies investigated

Farm Name	Location	Primary Crop	System	Land Area (m2)	Floor Area of the system (m2)	Ceiling height (m)	# of tiers, between frames (m)
AeroFarms	New Jersey, USA	Baby Leafy Greens	Aeroponics	14000	6503	11	12
60cGrowWise	Eindhoven, NL	Research for multi veggies	Hydroponics		234	~4	4, 0.85 between
8o8	Yaizu, JP		NFT, hydroponic	10000	1000	6	12, 0,4 between
MedMen	California, USA	Medical Cannabis	Dutch Bucket	-	-	4	2, 1.4m

Crop Possibilities

A leading constraint in vertical farming is crop height limitations. Although the heights between each level of culture bed tiers can vary based on construction, it is recommended for PFAL's to maintain heights 30 cm or smaller for optimising growing space (Kozai, Niu, & Takagaki, 2019). As anticipated, stacking more culture beds and intensifying the density of plants will also increase the overall yield within the indoor space. In many PFALs, the focus is tomatoes, cucumbers and leafy greens such as spinach and lettuce as crops (Kozai, Niu, & Takagaki, 2019) as well as pharmaceutical herbs (Benke, 2017). As more crops and systems are validated through research for CEA application, design assumptions will evolve and accommodate potential new crops.

Although there are recommended height limitations, growing time can be considerably reduced for taller crops such as common open field cereals like corn. It has been found that corn can be grown hydroponically in large tubs with a yield of around three ears per plant, and a growing period of every eight to ten weeks, allowing for the possibility of five harvesting periods per year compared to one in open fields (Dsepommier, 2010). Additional staple crops that have found success in growing in hydroponic conditions are variations of wheat, rye, and barley (Mackowiak et al, 1989) as well as potatoes (Tibbitts, 1994).

Rice grown in an hydroponic system is the most similar to its traditional agriculture growing methods. Rice paddies are used to immerse the crop in water for more than half of the 120 day growing period as seen in and is harvested two times a year (De Wolf, 1980)

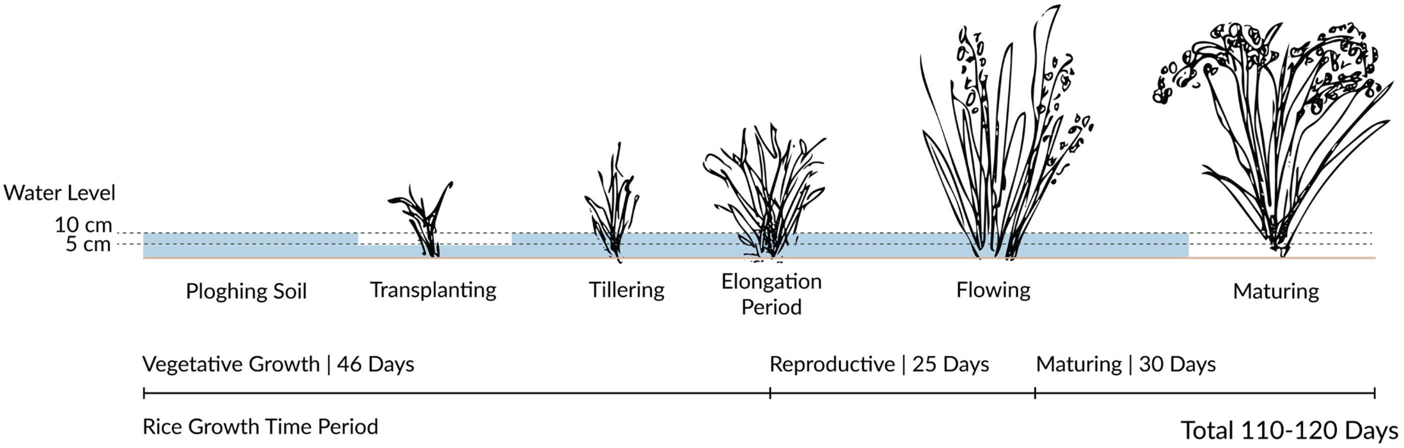
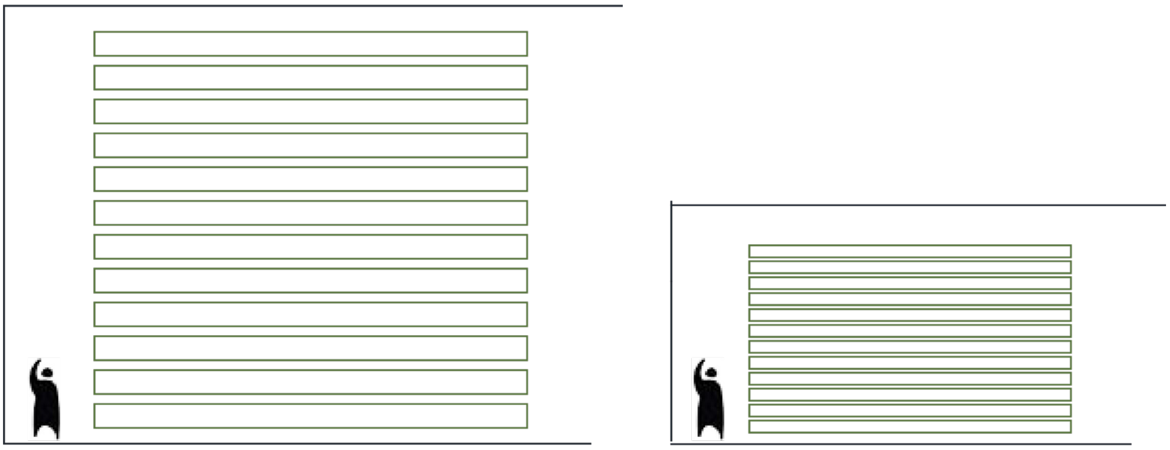


Figure 19 | Rice Growing Timeline in Traditional Rice Agriculture

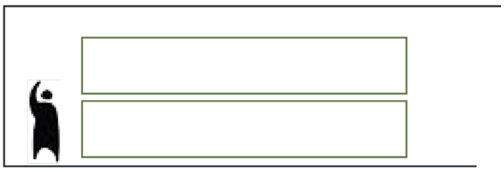
Rice in vertical farming has been studied at the Chinese Academy of Agricultural Sciences and has been found to efficiently reduce the breeding cycle and improved cultivation efficiency due to height densification of the plants in vertical farming. Rice grown in CEA conditions require approximately 28 days (Yamori, Zhang, Takagaki, 2014), thus increasing the number of harvests possible in a single year from two to four times with 5 times more cultivated material.

In order to maintain vertical farming principles of optimising for space, the growing height for this project was limited to below 100 cm for stacked farming. This is an effective height for a select group of crops, whcih can be utilized as bio-base materials in construction as well as allows for the accomodation of lighting and structural framing of the CEA tiers. Since there is a possibility of multiple harvests of a single crop within the CEA enclosure, crop yields could still exceed the yield in open fields. Through the research of bio-based materials, crop possibilities with bio-based material outcomes for the renovation were investigated and then selected.



AeroFarms | Leafy Greens | 60 cm

808 | Leafy Greens | 40 cm



MedMen | Medical Cannabis | 140 cm

Figure 20 | Building Heights and Tier Height for Example CEA Case Studies

SELECTED AGRICULTURAL BIO-BASE MATERIALS

Rice

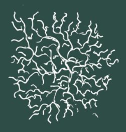
Barley

Flax

Wheat

Dandelion

Mycelium



Tree Saplings

Table 2 | Selected Agriculture Bio-base Material Crops | Growing Period Outdoors and Indoors

	Growing Period Outdoors					Growing Period Indoors	
Bio-base Source	Germination Period	Vegetative Period	Flowing Period	Maturing Period	Growing Period Outdoors	Growing Period Indoors	Number of harvests in a year
Wheat	13	60	80	25	178	71.2	5
Flax	10	50	25	35	115	46	8
Barley					120	48	8
Rice	10	46	25	30	120	48	8
Dandelions					63	25.2	14
Mycelium Composites	20	30		20	190	76	5
Tree Saplings							1

Table 3 | Selected Agriculture Bio-base Material Crops | Temperature Conditions

Bio-base Source	Germination Period	Vegetative Period	Flowering Period	Maturing Period	General Temperatures
Wheat	12 to 25	20 to 25			12 to 25
Flax	7 to 10	20 to 25			7 to 25
Barley	12 to 15	15 to 30			12 to 30
Rice		20 to 25			20 to 35
Dandelions	10 to 25	20 to 30			10 to 50
Mycelium Composites	17.5 to 20	24 to 27			24 to 27
Tree Saplings					

Figure 21 | (Previous Page) Selected Agriculture Bio-base Material Crops

Selected Material Characteristics

Utilising the selected crops, preliminary analysis of application in renovation was done. In research of each type of construction component, three different aspects were considered and then investigated for one construction component in the skin shearing layer. The three aspects cover processing, material characteristics, and material application requirements. For insulation, thermal conductivity and comparison of different material thicknesses were conducted. For flooring, processing of bio-based composites with mycelium is investigated. For Particleboards, characteristics and performance of cereal fibres for particleboards was investigated.

Processing | Mycelium

An example of processing bio-based material crops is mycelium, which can be utilized as a binding agent for bio-composite material such as rice. This composite is already being applied currently as a product by Mogu, a mycelium based bio-based material building material producer in Italy (Mogu, 2021). Currently their flooring technology utilises mycelium, cotton residue, and biomasses such as rice and is then finished with a bio-based PU coating made from plant oils.

Mycelium grows quickly and is able to take any shape needed for function. In addition, mycelium has relatively high durability and low processing energy requirements compared to other bio-based materials (Jones, et al., 2010) that have been selected as part of the CEA system. Based on personal experiment for testing the processing steps of novel bio-base materials, mycelium has possible scalability for composite bio-based materials within the skin shearing layer which require durability and waterproofing. As seen in Figure 2.21, the following are the steps required for mycelium composite processing:

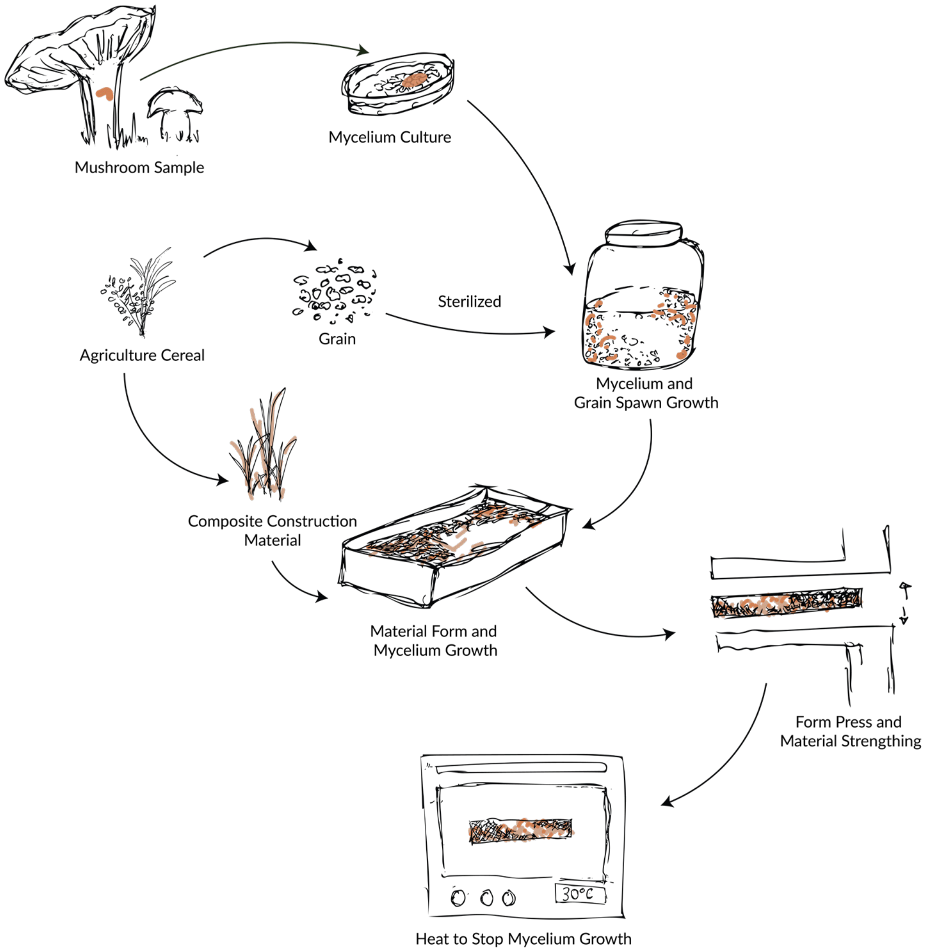


Figure 22 | Mycelium Processing Experiment | Scheme

Week 0

Week 1

Week 2

Week 3

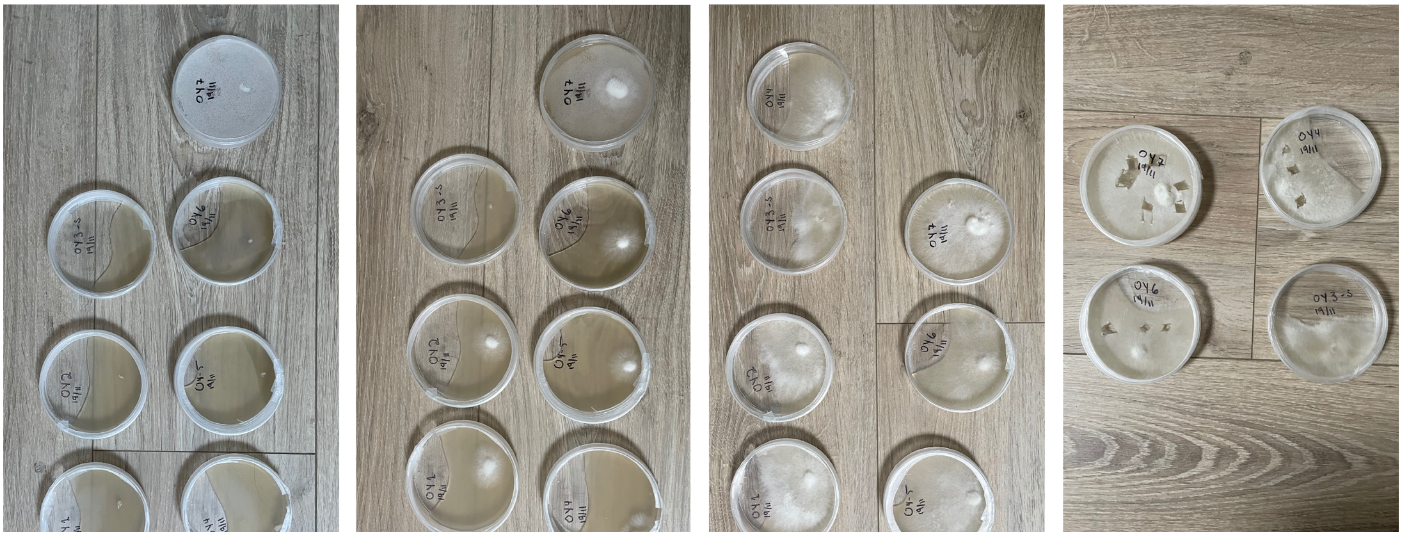


Figure 23 | Mycelium Processing Experiment | Mushroom Mycelium Culture Growth in Agar Petri Dish

Growing Medium
Vermiculite + Powdered Rice

Sterilization
Pressure Cook with cover

Cooling Period
Cool before placing Mycelium Samples

Inoculate with Sample
Place sample in jar and cover

Figure 24 | Mycelium Processing Experiment | Steps for Starting Mycelium Growth in Growing Medium

Figure 25 | Mycelium Processing Experiment | Complete Grain Spawn Growth of Mycelium

Material Character | Insulation

Due to the thermal and acoustic limitations of bio-based insulation materials, the thickness of these products needs to be much greater than their foam and plastic counterparts. This also means a greater quantity of material production to meet the same building requirement values. For this research, building codes from the Netherlands will be taken into account, however it is noted that R values will be changing based on location of construction and proposal. In addition, in efforts to meet the Directive 2010/31/EU on energy performance of buildings, buildings constructed after December 2020 within the EU member states are to be nearly zero-energy, nZEB. In response, insulation requirements have been revised to increase energy efficiency of buildings in heating and cooling seasons.

To meet the basic Energy Performance Level for walls, a required R value of 5.0 for all future building in the Netherlands (Gvozdenović, Zeiler, Maassen, 2014). Previous standards in the Netherlands had required 3.5, but have since changed in 2015 to an R value of 5. Currently the thermal resistance of walls in the current building stock in the Netherlands varies based on age of construction and has only been regulated since the 1970 oil crisis (Filippidou, Nieboer, Visscher, 2016). Older constructions have R-values varrying from 0.19 to 1.39 (Majcen, Itard, Visscher, 2016). See table 4 for R values based on construction year as well as diagram that illustrates how many buildings in the building stock in the Netherlands still require insulation upgrades.

More than 75% of the European building stock has been built before 1980, prior to the standardisation of energy performance regulations. This means that many of the residential buildings that now require renovation are also responsible for the majority of the energy consumption (Pittau, Iannanccone, Lumina, Habert, 2019).

Table 4 | R values of Existing Wall Construction Based on Year of Construction

	R-value of walls
Before 1970 (1)	0.19 - 1.39
1970 (1)	1.66
2014	3.5
2015 -2020 (2)	4.5
nZEB 2020 onwards (2)	5

Utilising the required R value of 7.0 for walls and the common utilisation of PUR insulation, a thickness of 150 is required. This R value was then utilised as a base number to compare required insulation thicknesses of each of the potential bio-based materials that are grown in the CEA design. Table summary can be found in Appendix A. The following equation was used to calculate required thickness to meet a similar R value needed for common insulation material, PUR foam, which has the highest thermal conductivity.

Equation 1 | Thermal Resistance per Unit Area Calculation Relative to U-Value

$$U\ Value = \frac{1}{R\ Value}$$

$$\left[\frac{W}{m^2\ K}\right] = \frac{1}{\left[\frac{m^2\ K}{W}\right]}$$

$$Thickness = R\ Value * Thermal\ Conductivity$$

$$[m] = \left[\frac{m^2\ K}{W}\right] * \left[\frac{W}{m\ K}\right]$$

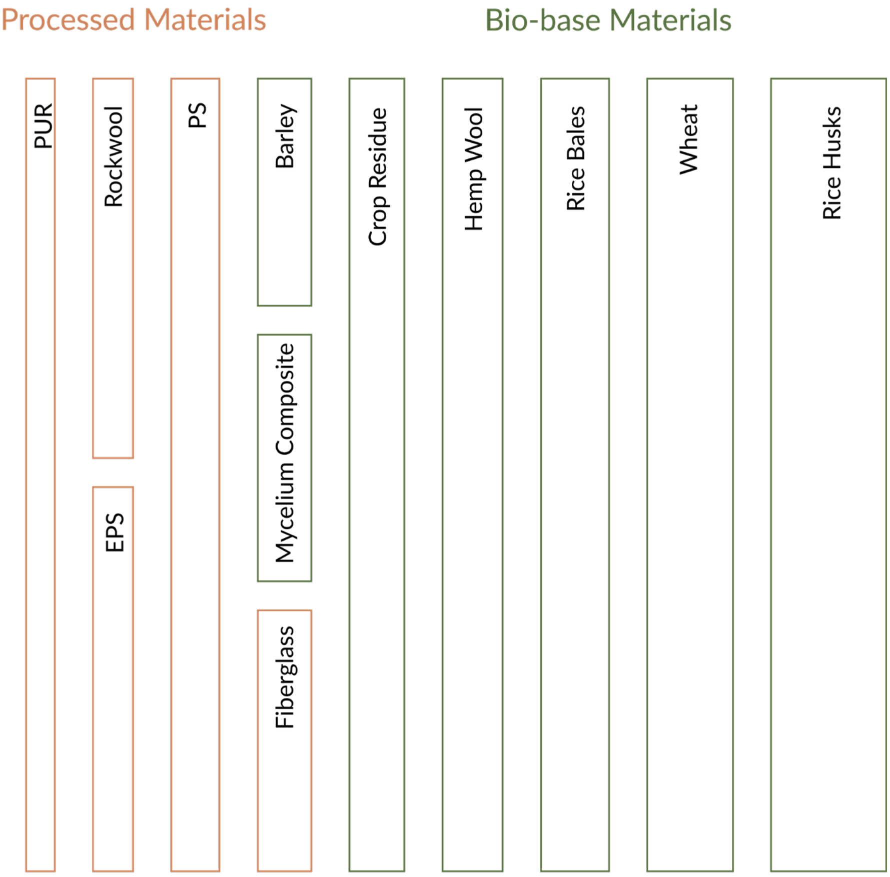


Figure 26 | Insulation Thickness | Processed Materials and Bio-base Material Comparisons

Material Requirements | Particleboards

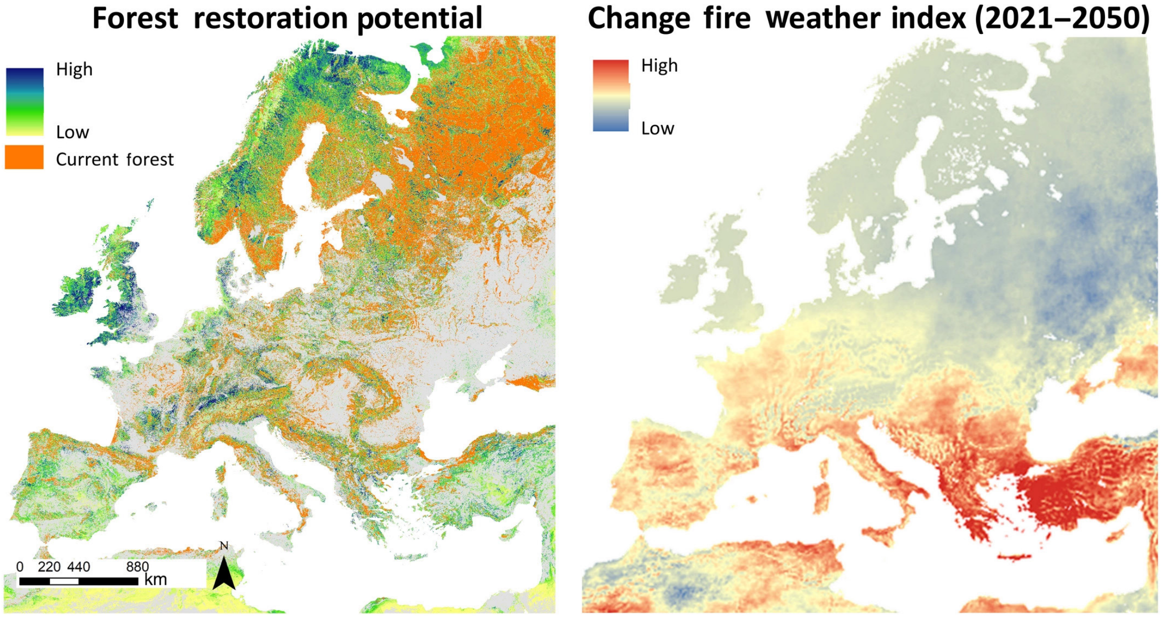
Particleboards have often been made of wood residue bonded with adhesives under pressure and heat and in some cases formaldehyde is utilised to improve water resistance. In 2014, the EU produced and utilised a volume of 28.4 million m3 of paticleboard and application demands are expected to continue to expand (Klímek, Wimmer, 2017). Particleboards are typically utilised as a structural component for interior finishes and require characteristics such as resistance to moisture and warping, lightweight, and durability. Due to price increase of raw wood chips, agriculture bio-based crops are an attractive material to replace traditional wood-based paneling (Papadopoulou, Chrissafis, 2017).

Characteristics of different particle board alternatives were compared to determine the feasibility of utilising agriculture bio-based boards as an alternative to wood particleboards. Material characteristics that were accounted for were Modulus of Rupture (MOR), Modulus of Elasticity (MoE), Internal Bond Strength (IBS) and Tensile strength. Data found in Appendix A concludes that bio-based material composites have potential of meeting particle board requirements and replace commonly used wood composites (Sandak, Sandak, Brezezicki, Kutnar, 2019).

Use of Timber

Considering timber construction and material use is an up and coming form of sustainable material use, material extraction of wood must still be acknowledged. Within the renovation panels, timber is utilized as battens and framing to maintain the structural integrity of the panel construction and is required in the renovation process. In addition, timber in proposed for façade application. Although timber cannot be grown directly in the CEA to maturity, the controlled environment provides a potential for seedling growth for future planting. In efforts of afforestation and reforestation, CEA provides a starting point for seedlings prior to soil planting. Within the CEA, saplings also have an opportunity to be grown based on Target Plan Concept (Montagnoli, Dumroese, Terzaghi, Pinto, et al., 2018) through the use of specified LED spectra. By utilizing specific LED for the tree saplings such as Pinus Sylvestris, Scotch Pine, and Picea Abies, Norway Spruce, specific ideal traits such as root depth and strength are fostered. From research of seedlings that are then planted outdoors, are able to be utilized for degraded forestland and harsh environmental conditions (Montagnoli, Dumroese, Terzaghi, Pinto, et al., 2018). Indoor seedling nurseries, such as farmboxfoods, have been focused on reforestation, starting with seedling growth in a density of 278 seedlings per m2 to then 435-726 trees per acre (Farmboxfoods, 2021). For this reason saplings are included within the designed CEA environment for the renovation of MUWI constructions.

There is however concern of forest diversity and the increasing demand of timber in construction. For this reason, it is recommended not only responsible forestry is practice for the harvesting of the timber for the panel construction and potential façade, but to also use tree plantations (Cunningham, Mac Nally, Baker, Cavagnaro, et al., 2015). The saplings that are grown in the CEA should be then grown in a tree plantation to guarantee the protection of existing natural forests as well as the existing biodiversity. Within the EU, the most popular and native trees are found to be *Fagus Sylvatica* (European Beech), *Fraxinus Excelsior* (Common Ash, European Ash), *Picea Abies* (norway Spruce), *Pinus Sylvestris* (Scotch Pine), *Quercus Petraea* (Irish Oak), *Quercus Robur* (English Oak), *Quercus Rubra* (Northern Red Oak), *Pinus Pinaster* (Maritime Pine). Within these tree types, the Scots Pine and Norway spruce are the most viable for panel application however require treatment prior to façade application. Thermal modification is recommended for pest and weathering prevention. Additional coatings can be applied to protect the timber further. Some of these coatings can include chemicals which would prevent further recycling and reuse of the materials (Campbell, 2018). For this reason, it is proposed that a mycelium coating finish, such as Xyhlo, to be utilized over the timber façade.


Forest restoration potential

Change fire weather index (2021–2050)

Figure 27 | Trees reforestation potential under the RSP8.5 Scenario of 2050, where the worlds average temperature will rise by nearly 9 degrees Fahrenheit (Hermoso, 2021)

RENOVATIONS

Renovations for nZEB

An investigation of renovations was done to find the current state and demand for dwelling renovations. Renovations have been recommended based on the nZEB suggestions that are outlined by the EU in hopes to reach the UN sustainability goals to reduce the human footprint by 2050 (Directive 2010/31/EU). The goal of renovations are to reduce the energy usage of buildings and create more passive homes through renewable strategies. This is usually seen with the perspective of energy use, but can also be applied to the materials that are utilized in the building, hence the application of biobased materials in renovations.

Following the nZEB requirements, existing dwellings should aim for R-Values of 3.5 to 7 on exterior facades as well as 3 to 5 for flooring and basements (Groezinger, et al., 2014). The values directly reflect how much the material can resist the exchange of heat. In order to meet these requirements for all buildings in the Netherlands, new construction will require design and material considerations from the initial stages of design to meet these required thermal values. However, this poses a challenge for renovations. Additional maintenance cost are needed and the existing construction design that does not accommodate additional insulation that is needed to me nZEB goal R-values.

As part of maintaining the circular economy, it is recommended to approach building design with the intention for renovation rather than for demolition (Ham, van Hulst, 2000). By investigating the construction and demolition waste flows (Gelderman, 2020) it is suggested that waste from dwelling demolition are usually recycled at low-grade recovery routes and are unsustainable in the long term. In order to maintain structural integrity, it is suggested that renovations are able to provide new revitalization and character of a building.

Current Post-war housing have an energy efficiency rating between E and D. The aim in the Netherlands was to improve the energy efficiency in all existing dwellings to an average energy efficiency of B by 2020 (Filippidou, 2016). This however was not met by the goal period of time, raising attention to the pace that renovations are occurring as the EU aims to meet the nZEB goals.

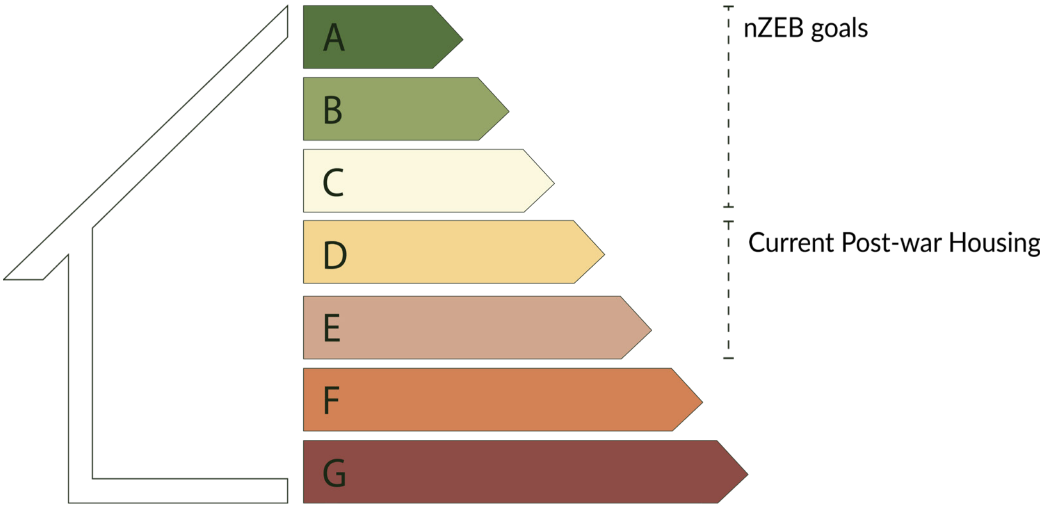


Figure 28 | EU Energy Efficiency Scale for current and nZEB goal dwelling ratings

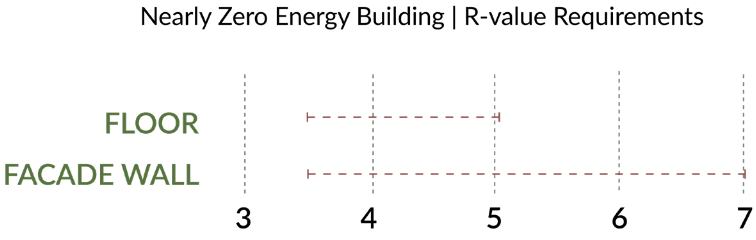


Figure 29 | nZEB R-Value Requirements for Construction

Renovation Defined

To first define what a renovation is and how it compares to other terminology such as rehabilitation, refurbishment, retrofitting, and renovation. These terms are sometimes used interchangeably however mean different constructions on a technical level. (Oorschot, 2019) (Shahi, 2020)

Renovation

the act or process of repairing and improving something, especially the quality of a building. Commonly done every 20-30 years and the aim is to improve energy efficiency

Retrofitting

the act of providing a machine with a part, or a place with equipment, which the machine or place did not have when it was first built. This mean be in the example of new heating and ventilation systems

Rehabilitation

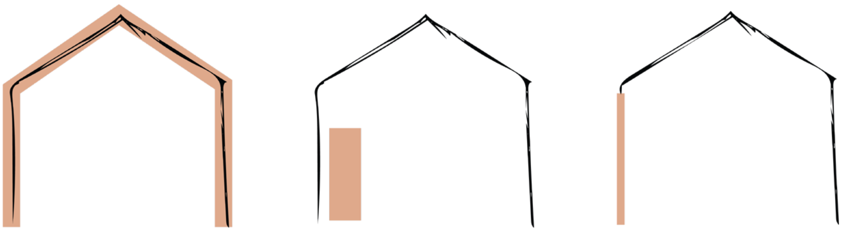
Repairing, altering, or adding to a deteriorating building to make it compatible for use again.

Refurbishment

Process of improving existing conditions of a building for the same existing functions.

Adaptive Reuse

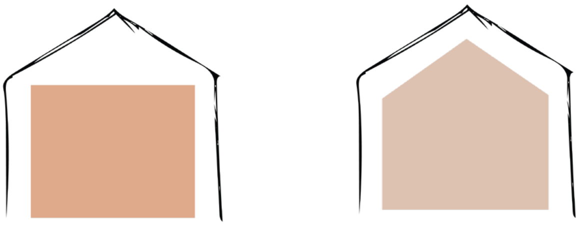
Reuse of a building by changing its function an maximizing the reuse and retention of existing materials and structures.



Renovation

Retrofitting

Rehabilitation



Refurbishment

Adaptive Reuse

Figure 30 | Schematic Diagrams of Renovation, Retrofitting, Rehabilitation, Refurbishment, Adaptive Reuse

Within these boundaries, the focus will be renovation, where the facade is the improving component towards changing the quality of the energy efficiency of the building. The priority of a renovation is to:

- Improve the integral indoor climate
- Improve skin of the building
- Reduce energy demands

Renovation Applications

Investigation of the renovation types that are done in the Netherlands first compared the components of a building that is being renovated. This research was then expanded to projects within the EU. Many exterior renovations that are being completed are on large scale high rise dwellings. This is occurring in combination with understanding that a high rise dwellings was a popular solution for the housing crisis post-war. Renovations that were found in the investigation included exterior and interior renovations.

Interior

Interior renovations is by definition, a renovation where only the interior is changed in the construction while maintaining all other features. This is also known as an box-in-box renovation. This is a popular choice for maintaining the exterior appearances of a building for historical preservation as well as a method of furnishing the interior spaces with a new character (Oorschot, De Jonge, 2019). This type of renovation is focused on the space plan within the steward brand shearing layers (Brand, 1994). Limitations include the fact that this type of renovation does not address thermal bridges that occur in the structure, which causes an increased need of material for the same thermal performance of an exterior renovation (Konstantinou, Knaack, 2011).

Figure 31 | Interior Renovation Case Study | Before and After Rozemaai Housing by Atelier Kempe Thill

Exterior

Exterior renovations are strategically done through updating existing balconies with a facade, replacing glazing with insulated glazing units, and insulated finishing system or a ventilated cladding added externally on top of existing facades. Due to its exterior feature, an exterior renovation is able to acknowledge more thermal challenges that a construction may have compared to an interior renovation (Havinga, Colenbrander, Schellen, 2020). An additional benefit is that usually in exterior renovations, inhabitants are able to stay in their dwellings during the time period of the renovation with some changes of living conditions, but relatively comfortable since inhabitants do not have to relocate (Loussos, Konstantinou, Van den Dobbelsteen, & Bokel, 2015).

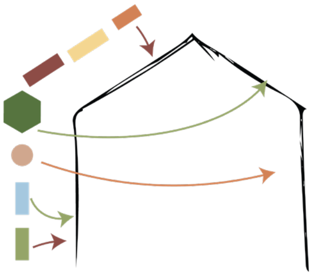
Figure 32 | Exteior Renovation Case Study | Before and After (Sourced from Philippe Ruault, 2020)

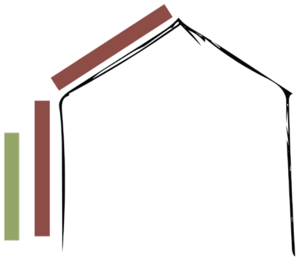
Deep Renovation

Between 1995-2015, housing corporations have utilized deep renovation as a method to renovate their building stock as a means to improve the quality of housing as well as energy efficiency (Oorschot, De Jonge, 2019). In combination of interior and exterior improvements, more than 75% of the building is usually replaced or updated (Shnapp, Sitja, Lausten, 2013). This however can be compared more similarly to exterior renovation but with the requirement that the building is not inhabited during renovation period.

Figure 33 | Deep Renovation Case Study | Before and After Sheffield Park Hill by Jack Lynn and Ivor Smith

Renovation Methods





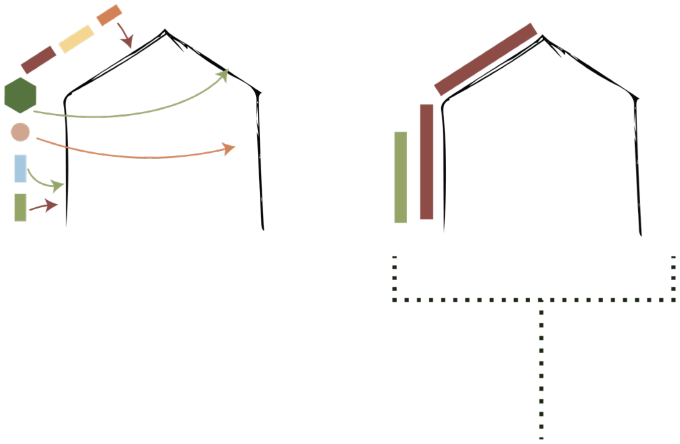
Design for Renovation

Design for renovation is defined as renovations that are specifically designed for building specific changes. Buildings that are being preserved for monumental or historical significance fall under this category (Oorschot, De Jonge, 2019). Renovations in this setting end up taking more time and can be quite expensive but more customized for the building situation. Enlarge, renovations that are designed are not suitable for large scale projects, such as the Park Hill renovation in UK by Sheffield and Hawkins Brown with Studio Egret West or the Rozemaai Housing in Antwerp Belgium by Atelier Kempe Thill. In these projects a design was created and then replicated repeatedly throughout the construction, thus creating some sense of modularity but without the intention of ease of construction (Hoppe, 2012). These housing projects were specifically for social or student housing and required an additional design process for changing aspects of the building. However the elevators, new balcony railing systems or additional systems added to the building were replicable. In this system, customization is a possibility while a simple panel renovation is more efficient but is missing personalized characteristics. For ease of construction, design for renovation is not recommended for standard construction in the Netherlands. For this reason, panel renovation was investigated further.

Panel for Renovation

For ease of application in different situations especially for standard building constructions, it is suggested that panel renovations are cost and material effective compared to a design for renovation cases (Loussos, Konstantinou, Van den Dobbelsteen, & Bokel, 2015. Additional examples are found of different renovation panels that are utilized within the EU. The renovations were done for both high and low rise buildings, while still allowing for resident occupancy during the renovation due to the minimal impact on the interior during the renovation. Panels are now being proposed to meet the EU thermal performance requirements with the terminology of “mass retrofit” of prefabricated elements.

Within the panel design, there are opportunities to introduce panel renovation with bio-base alternative for ease of application as well as introduction of bio-based materials as a standard material in any building with ease of application. There are challenges of accessibility for bio-base materials in many cases, but creating a complete panel that integrates semi-bio-base intervention also allows for the ease of application for designers and contractors that are looking for a simple and easy to utilize application. Panel components and assembly are selected as the best method of renovation with the application of Bio-based Materials.



Meets nZEB Goals
Allows for Occupancy
Ease of Construction
Modular

Figure 34 | Renovation Method Selected as Panel Construction

Panel Renovation

Precedents

Panel renovation design has been developing in research and application of both renovation and new construction design. In the industry currently, there is still investigation of effective means and methods which can be found in several different research papers and projects (Torres, Garay-Martinez, Gustavsson, 2014). The following are research precedents that have been utilized in creating the framework for renovations in MUWI construction.

Table 5 | Comparisons of Panel Case Studies

	Material Construction (INSIDE TO OUTSIDE)	Weight (kg/m2)	R-Value (m2K/W)	Mounting System
Gap3 Skin	Timber Support plate (19mm), Solar honeycomb (30mm), Cavity (29mm), Float Glass with timber frame (6mm)	35	0.77	Timber framing and Steel L sections
P2 ENDURE	Mineral wool (2cm), Gypsum fiber board (1.25cm), Mineral Wool between timber studs (20cm), HD board finish (1.5cm) Total 12.8cm, PUR Sealing tape between	52	4.34	Timber Substructure with anchor system with screws from Halfen, 50% shorter installation time
2ndSKIN	Sandwich insulation panels, cladding	-	-	Steel U profiles with wooden posts attached.
RC Panel	Vapour Barrier, OSB, EPS, Vapour Barrier, Brick finish Total 24.2cm	Less than 50	7.0	New construction or renovation utilizing Anchor
Bertim	Rockwool (5-2cm), Vapour Barrier(0.5cm), OSB (1.2cm), Rockwool with timber frame 62mm (14cm), Waterproofing sheet 15.2cm	-	5.2	Fix bracket plan with timber construction. Hung
Dextall	Stonewool insulation, acoustic steel, rainscreen cladding	-	-	Gasket dry connection
Plug and Play	Cavity (12.5cm), Insulation (15.5cm), Air chamber (6.4cm), Vapour barrier, Cladding, EPDM rubber insertions Total 23.6cm	Max 166.6 for hanging mechanism	11.1	Hanging and metal hanging point loads

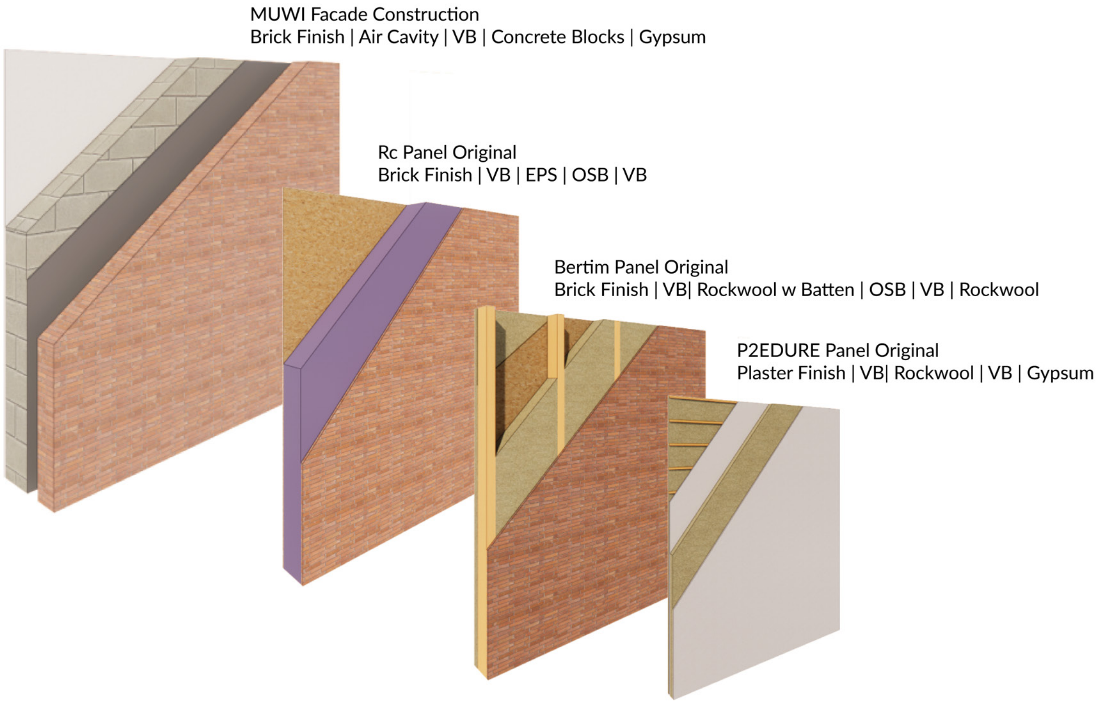


Figure 35 | Recreated Panel Case Studies

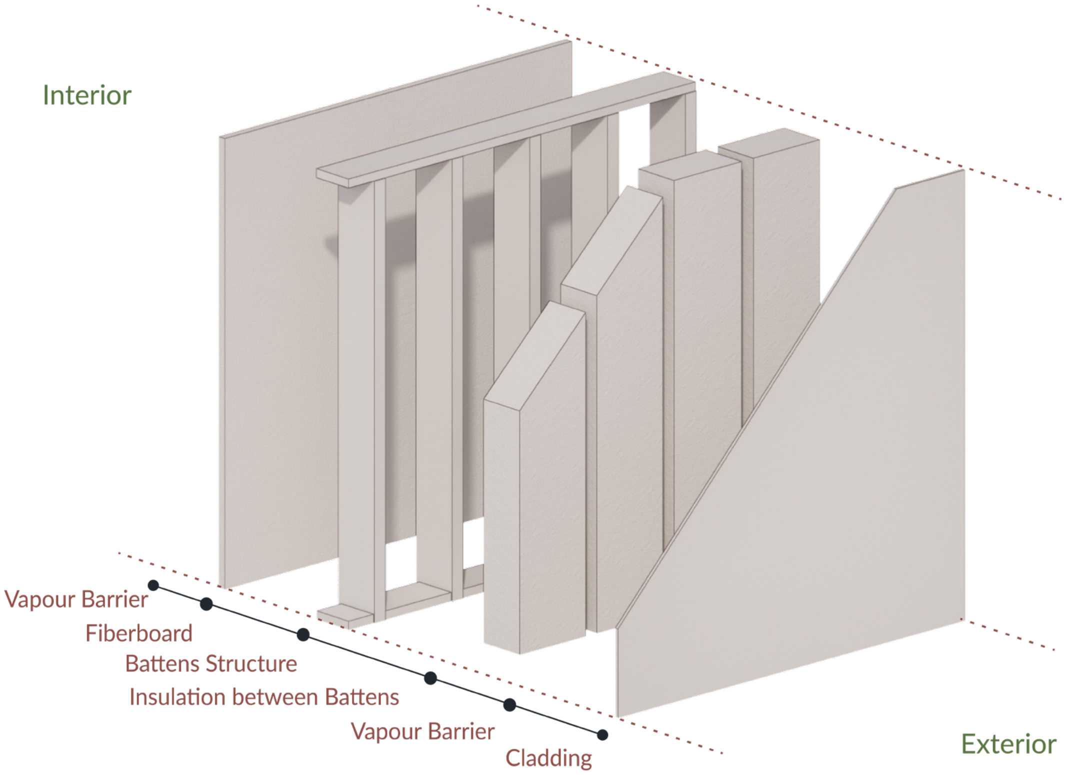


Figure 36 | Standard Panel Construction for Panel Case Studies

Table 6 | Summary of Renovation Case Studies

		Years				
		Construct	Renovation	Renovation Type	Building Type	Occupancy
Design Renovation	Old Thread Storage Building	1940	2019	Interior	Low Rise	X
	Rozemaai Housing	1970	2011	Deep	High Rise	X
	Marco Pololaan	1960	2015	All	Mid Rise	O
	Urban Renewal	1960	2004	Exterior	High Rise	O
	The Horsten	1970	2005	Exterior	Mid Rise	O
	Camera Obscuradreef	1965	2014	Exterior	High Rise	O
	Landlust	1930	2012	Interior	Mid Rise	O
	Park Hill	1957	2011	Deep	High Rise	X
	Prinsessenflats	1964	2022	Exterior	High Rise	X
Combo Renovation	BGDD	1970	2019	Exterior	Low Rise	O
	Le Lignon	1963	2021	Deep	High Rise	O
	2ndSKIN Research	1960	2018	Exterior	Mid Rise	O
Panel Renovation	Gap3 Skin	1960	2014	Exterior	Mid Rise	O
	PEER	1970	2017	Exterior	Low Rise	O
	P2ENDURE	1970	2015	Exterior	Mid Rise	O
	RC Panels	1965	2018	Exterior	Low Rise	O
	Bertim	1980	2021	Exterior	Low Rise	O
	Woodside Multistory	1960	2019	Exterior	High Rise	O
	Dextall	1950	2023	Exterior	High Rise	O

POST-WAR HOUSING RENOVATIONS

Currently, much of the post war housing in the Netherlands requires renovation due to the lifespan of building shearing layers. This is primarily proven through the understanding of the Steward Brand Shearing Layers, which outline that the skin of the building has a lifespan of approximately 20 to 50 years (Brand, 1994). For this reason, as well as the need for nZEB, the post war housing in the Netherlands will require renovation in the coming years. This also acknowledges the need for renovating the skin shearing layer of a building in order to increase its energy efficiency (Loussos, Konstantinou, Van den Dobbelsteen, & Bokel, 2015).

The construction of many post war housing buildings have a standard construction in order to be constructed in batch productively. This is primarily due to the major housing demand after WWII (Oorschot, De Jonge, 2019).

These buildings have a distinct characteristic of having a very simple character through the utilization of concrete and glass. The utilization of glass has a distinct characteristic which helps identify the typology of the post-war housing (Priemus, Van Elk, 1971). Each construction type is more specific based on the architect and contractor due to patents and rights to standard construction types.

Post-War Housing Constructions

Within the modern standardized housing that require renovations, there are three different types of constructions: stacked, cast in place, and heavy construction building types. Within these building types, there are standardized building plans and systems that are utilized by contractors for efficient mass construction. There are 33 listed common non-traditional systems of buildings (Priemus, Van Elk, 1971). This group of systems can be used to analyze and understand the variables between different systems that were utilized in the post-war construction period. It is important to note that even non-industrialized buildings that were constructed after the post war housing period, have a high degree of similarity with materials utilized and floor plan layouts.

Within this design research, it was evaluated that there are four different construction types that are the most popular in the Netherlands which are still standing today. In the building stock, MUWI system accounts for over 11%, RBM 7%, Coignet-groep 9%, and BMB 9% (Konstantinou, Knaack, 2011). For continued investigation of this project the four systems were evaluated with the intention to only select one type of system for the purposes of the bio-base renovation strategy.

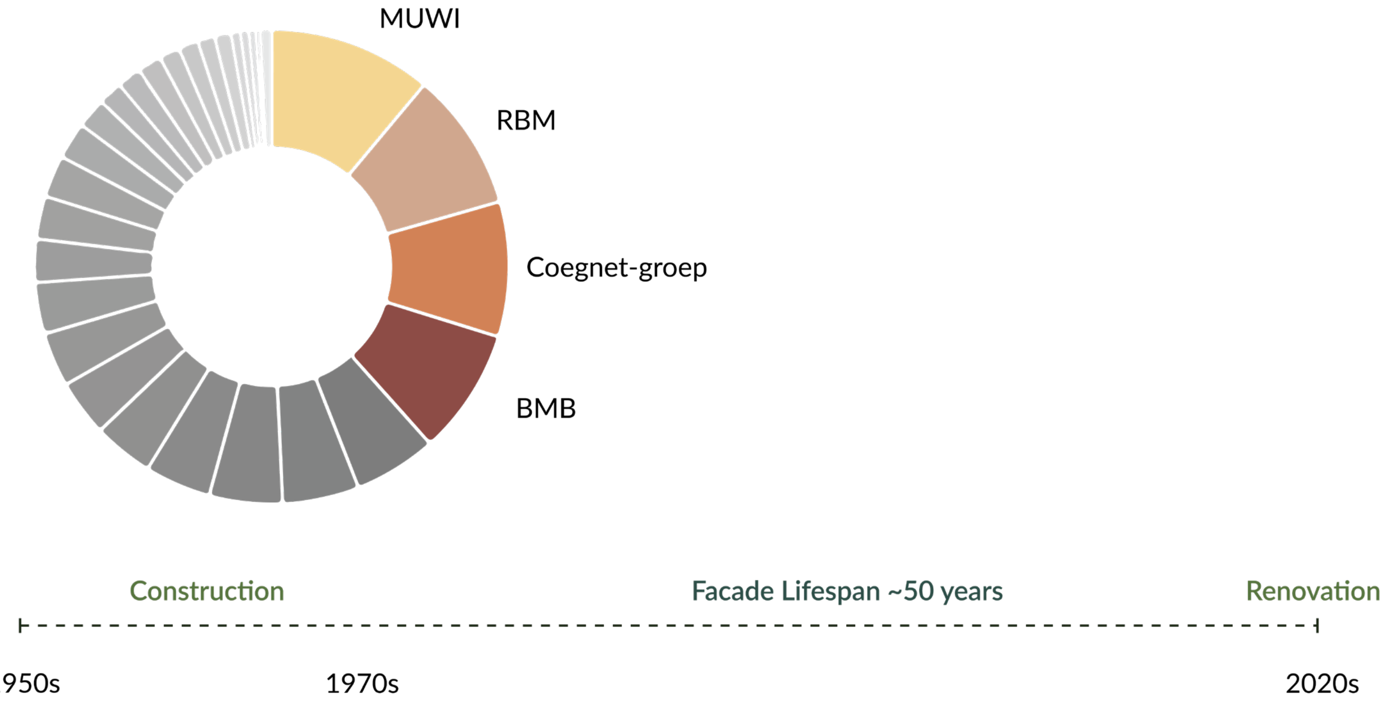


Figure 37 | Building Types in the Netherlands Constructed Post-War and Timeline for Renovation after Construction

MUWI, RBM, Coignet-Groep, BMB

Within the Netherlands, MUWI, RBM, Coignet-Groep, and BMB are the four most prominent construction types from the Post-War era. There are however limitations to the building construction that make renovations difficult to accommodate. When approaching a renovation of these buildings, a standard method can be implemented which follows the existing construction. Each of these construction types have different requirements and were compared in order to determine the most effective renovation that overcomes many challenges in a renovation scenario.

These comparisons look at the detail elements that are found in the construction type, see table B.3. It is important to note that each of these constructions have flat roofs but will not be touched upon in the renovation portion of the thesis.

Elements that can be found in most post-war housing are balconies (Konstantinou, Knaack, 2011). These balconies are usually thermally connected to the construction, in the sense that the construction of the balcony is its own element that is then attached to the building itself. For this reason, the balcony may pose challenges for the thermal performance of the building and is then typically renovated as well in order to improve the thermal insulation of the apartment building. There are examples of balconies being removed for renovation and then replaced with a new construction with better thermal insulation. This is typically done because of the increased amount of material surrounding the balcony in order to properly insulate it (Guerra-Santin, Bosch, Budde, Konstantinou, et al., 2018). This component will be considered in this project because of the common place utilization of balconies in post-war housing. It must be addressed as the post war buildings move forward to nZEB goals.

Figure 38 | Facade Types of Post-War Housing Constructions in the Netherlands

MUWI Construction Description

From this list of construction systems, MUWI was selected for the proposal of a renovation in the sense that it includes aspects that are necessary for renovation in many post war housing buildings. In addition to being one of the most popular construction systems in the Netherlands from this era, the construction has a large amount of glazing that requires updating with current window standard sizing. The balcony in the MUWI construction is an addition that is usually found on the front and back side of the building orientation, this is also the long edge of the building (Priemus, Van Elk, 1971).

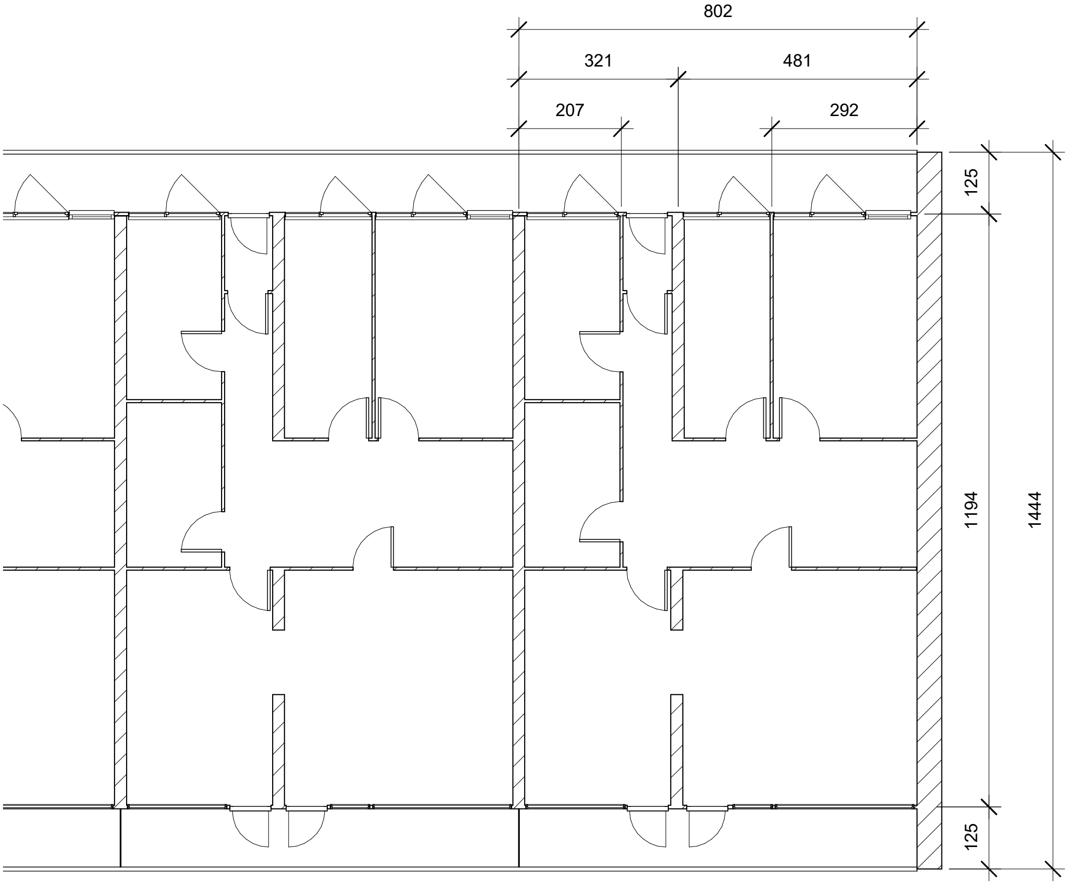


Figure 39 | Single Apartment MUWI (Priemus, Van Elk, 1971)

The construction of MUWI includes a cantilever balcony of approximately 1.25 meters. This is suitable in consideration of the standard hallways sizing requirements, which is at least 0.95 width for a single wheelchair. In a renovation, the goal is to increase or maintain the size of the balcony to accommodate for accessibility measures.

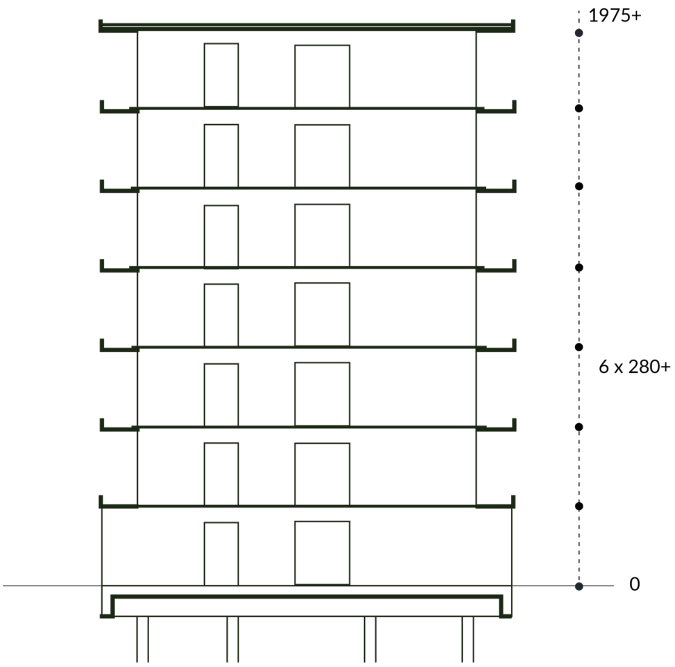


Figure 40 | Section (Sourced from Priemus, Van Elk, 1971)

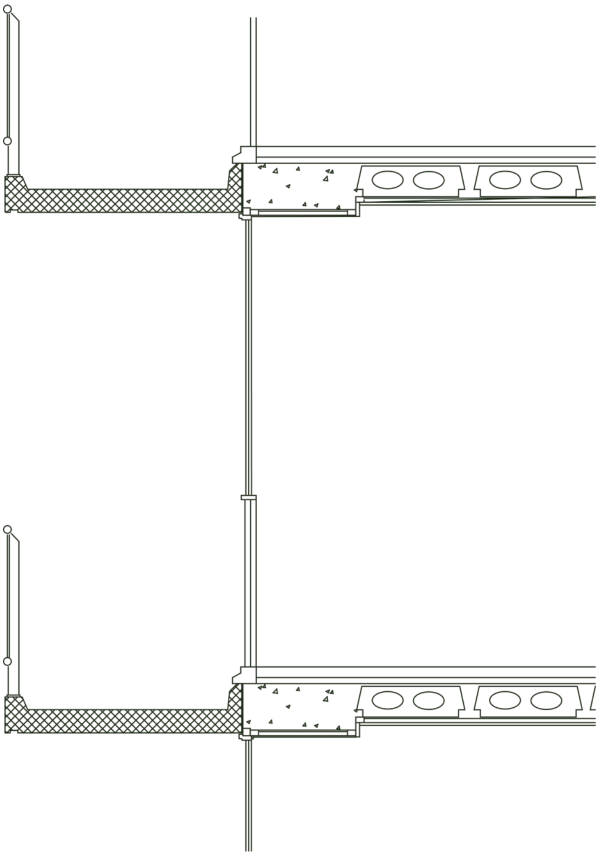
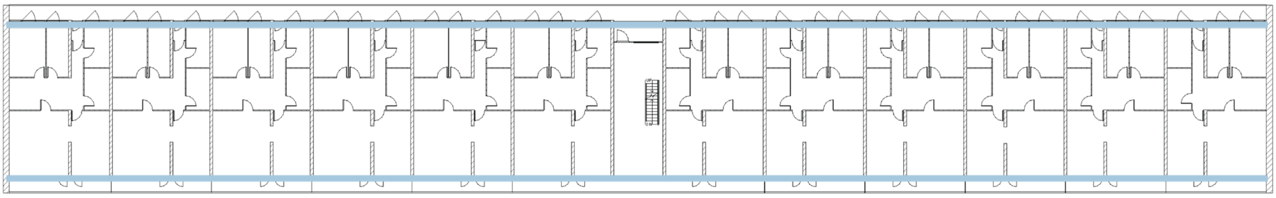


Figure 41 | Balcony Existing Detail (Sourced from Priemus, Van Elk, 1971)

Acknowledging that a large portion of the MUWI facade is glazed means that much of these windows will have to be replaced but also can be sized with a renovation panel to accommodate additional fixtures such as shading, double skin, and cavity insulation if the construction of the wall is improved. For this reason, it is suggested that the new panels also decrease the area of glazing for improved insulation and decreased heating and cooling demands. For this reason, a panel that is suggested may also include the decreased or maintain area of glazing for this construction.

There are however concerns of daylighting impact by reducing the glazing area. Since lighting is only accessed through the long edges of the building, usually oriented north and south, daylighting must be accounted for within the recommended limits. For this reason, proposed solutions maintains or can increase glazing of the direct façade or maintain the same surface area.

Glazing and Openings Facade



Full Cover Facade

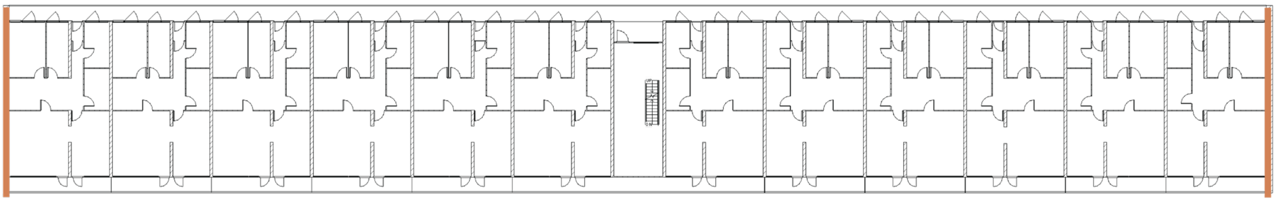


Figure 42 | Floor plan Highlighting Facade Type Glazing Facade and Full Cover Facade (Priemus, Van Elk, 1971)

Table 7 | MUWI Construction Statistics

	Single MUWI 1 Building	All MUWI Constructions in NL 37831 Buildings
Number of Floors	6	
Number of Apartment Per Floor	12	
Total Apartments	72	2723832
Average Family Size in Netherlands	2.14	2.14
Number of Residents Approximately	154	419688035

Table 8 | Areas and Dimensions of MUWI Construction

	Area of Single Facade (m2)	Number of Facades	Total Area (m2)
Full Cover Panels	63.936	2	127.872
Opening Panels	361.8	2	723.6

Renovation Data

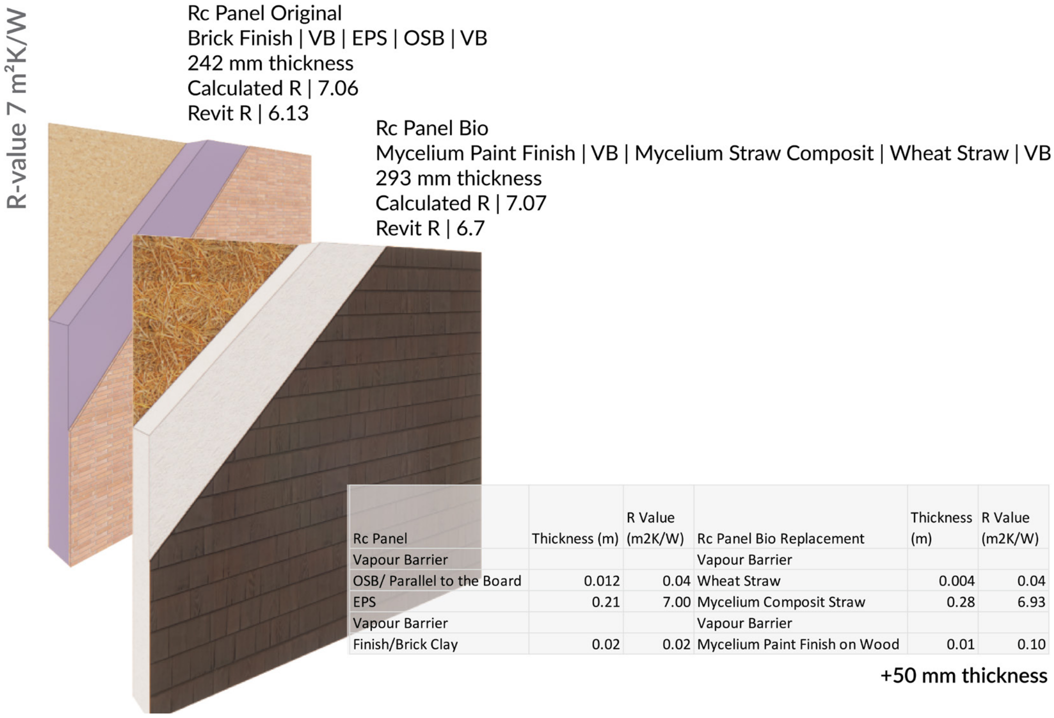
Validation of modular construction can come from the repetition of the same designed item in the same construction. In order to meet efficient means of construction for a large amount of dwellings utilizing the MUWI system, a panel construction should be configured and meets the requirements for MUWI construction. This means configuring the window sizing, doorway openings and accommodating for the structural strength of walls in the construction. Plans of MUWI are derived from “niet-traditionele woningbouwmethoden in nederland” for further understanding of the construction and how to integrate modular facades in the systematic construction of the building.

Since MUWI is one of the most popular dwelling systems in the Netherlands during the Post-War period, a modular approach would effectively acknowledge a portion of dwellings that are in need for renovations. Acknowledging the demand for mass production of a renovation solution, a panel for MUWI systems was selected for the design. For this research based design portion of the thesis, a design was created to meet the demands of the building industry in terms of renovation, nZEB goals, and the need for more biobased material use in the construction in hopes to reduce material pollution values.

Figure 43 | MUWI Construction Facade Revit Model

Bio-base Materials for Renovation

Utilizing the case study of a single Rc Panel, the replacement of traditional materials with bio-base materials was experimented and compared with existing panel product.



Rc Panel Original
Brick Finish | VB | EPS | OSB | VB
242 mm thickness
Calculated R | 7.06
Revit R | 6.13

Rc Panel Bio
Mycelium Paint Finish | VB | Mycelium Straw Composit | Wheat Straw | VB
293 mm thickness
Calculated R | 7.07
Revit R | 6.7

Rc Panel	Thickness (m)	R Value (m2K/W)	Rc Panel Bio Replacement	Thickness (m)	R Value (m2K/W)
Vapour Barrier			Vapour Barrier		
OSB/ Parallel to the Board	0.012	0.04	Wheat Straw	0.004	0.04
EPS	0.21	7.00	Mycelium Composit Straw	0.28	6.93
Vapour Barrier			Vapour Barrier		
Finish/Brick Clay	0.02	0.02	Mycelium Paint Finish on Wood	0.01	0.10

+50 mm thickness

Figure 44 | Rc Panel Bio-base Material Replacements Compared to Original Composition

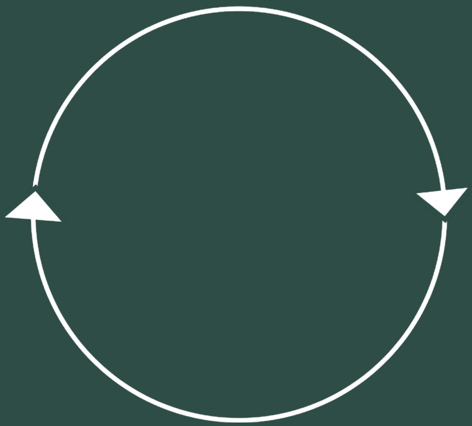
Table 9 | Rc Panel compared to biobased material replacement for insulation

Rc Panel	Function	Thickness (mm)	Thickness (m)	Thermal Conductivity (W/mK)	R Value (m2K/W)
Polysester/Polyethylene Lower Density	Vapor Barrier	0	0	0.417	0
OSB/ Parallel to the Board	Structure	12	0.012	0.300	0.04
EPS	Insulation	210	0.21	0.030	7.000
Polysester	Vapor Barrier	0	0	0.417	0
Finish/Brick Clay	Exterior Finish	20	0.02	0.500	0.04
Construction Values (Expected R value 7)		242	0.242		7.08

Table 10 | Rc Panel compared to biobased material replacement for insulation example bio-base material replacements

Rc Panel	Bio-base Material Replacement	R Value (m2K/W)	Direct Replacement Thickness (m)
Polysester/Polyethylene Lower Density	Polyester	0	0
OSB/ Parallel to the Board	WheatStraw Board	0.04	0.004
EPS	Mycelium Composite Straw	7.000	0.294
Polysester	Polyester	0	0
Finish/Brick Clay	Mycelium Paint Finish on Wood	0.0400	0.044
Construction Values (Expected R value 7)	Construction Values (Expected R value 7)	7.08	0.342

CIRCULAR DESIGN INTRODUCTION



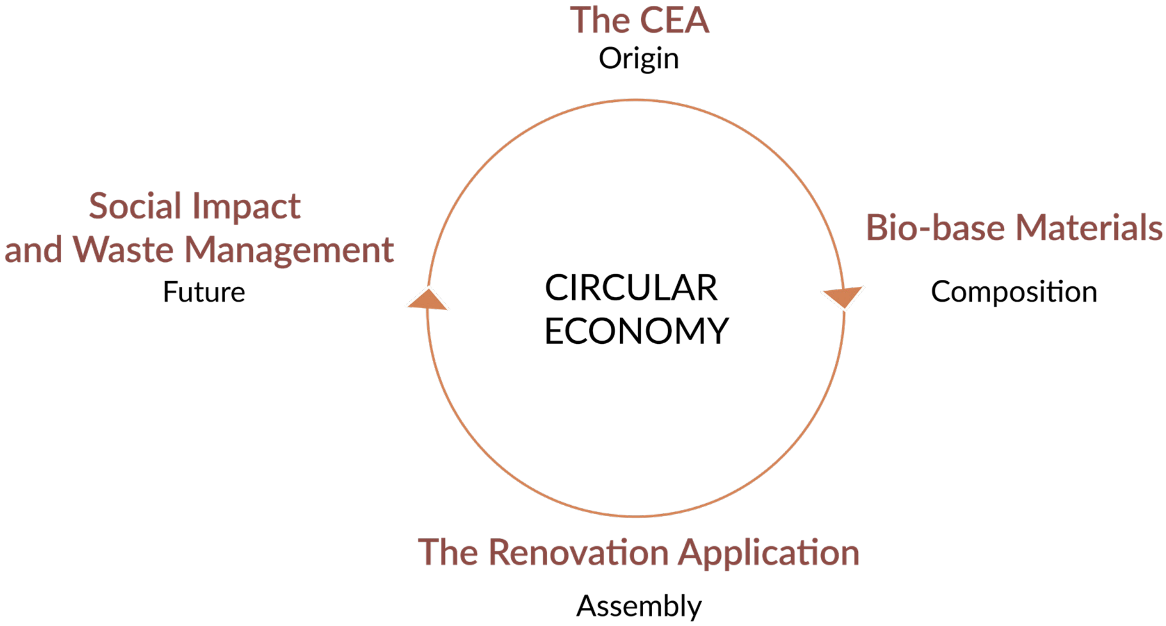


Figure 45 | Circular Design Approach Scheme

Circular product design approach includes Origin, Composition, Assembly, and Future application. By acknowledging each of the steps within this approach allows for the understanding the circular economy and how bio-based materials and CEA systems can be part of the bio-economy. The circular product design includes the fundamental aspects of resource consumption as well as waste. The design of this thesis includes three fundamental aspects which corresponds to the response to creating a more circular economy, each of which have a contribution factor of the Origin, composition, assembly, and future of a circular product as well as circular economy system.

WEF Nexus

The Water-Energy-Food, WEF, Nexus acknowledges the interdependencies and connections between the sourcing and consumption of basic humans needs. In simple terms, “water is needed to generate energy, energy is needed to supply water, energy is needed to produce food, food can be used to produce energy, water is needed to grow food, while food transports water, often using energy” (Stringer, Quinn, Le, et al., 2018).

WEF nexus provides an opportunity to see how the three sectors rely on each other for a complete supply chain and how reduction and reuse of resources can minimize the WEF nexus and promote circular economy (Del Borghi, Moreschi, Gallo, 2020). By following the WEF connections, projects and concepts are able to acknowledge factors and challenges in the built environment and society such as climate change, urbanization, regional and economy develop as well as infrastructure and facilities (Chang, Li, Yao, et al., 2016). In the Bonn 2011 Nexus conference, WEF was proposed as a solution for a green economy which acknowledges water resources, land use and food security and its connections with lifecycle stages. Within this thesis, land use and food security are the aspects of focus for a larger scale resilience framework, while the nexus is connects bio-base materials, renovation application, and CEA.

In the method of research, as outlined in the paper Resilience meets the water–energy–food nexus: mapping the research landscape (2021), follows the scope of which WEF nexus can be analyzed.

Scope of Nexus – Linked Systems, Approach
- Consideration of different scales for resolving interconnected challenges, embracing complexity and promoting management and innovation

Emphasis of Components – Water, Energy, Food, or Equal WEF
- Focus on the by-products of food thus oriented towards food efficiency and production as the means

Level of Integration – Assimilation, Cross-linking, Incorporation
- Looking at the nexus from the perspective of the built environment perspective and attempting the inclusion of other WEF components

Resilience Type – Specific, General
- Resilience as it related to a particular part of the whole system, control of bio-base materials and to relieve the environmental and agriculture shocks that may occur to the system

Disturbance Phase – Foresee, Cope, Recover
- To predict future scenarios and create an adaptive capacity that withstands the shocks to the system

Disturbance Source – External, Internal, Both
- Outside of the system disturbance to then create a resilience to such environmental and agriculture shocks

Scope of Resilience – ER, SES R, Transformation
- Extreme resilience through the transformation of the system to create a more stable landscape that is prepared for opportunity or creating conditions of opportunity for navigating the transformations over a large timescale of decades or centuries.

Thematic Domain – Infrastructure, Policy, Governance, Social Capital, Investment, Technology
- Focus on innovation and operational scale

Spatial Scale – Local, National, Regional, Global

Although WEF nexus is utilized as a tool to understand the larger scale of a project, it can also assist in estimating the global warming potentials and over use of resources similar to a LCA approach (Del Borghi, Moreschi, Gallo, 2020). By investigating more clearly the energy use within the Nexus, direct and indirect energy consumption is identified, such as the food system consumes resources for agriculture goods but the energy system required indirect energy for extraction and transportation of such goods (Li, Ma, 2020). Many of the challenges for agriculture that were outlined in the research portion are also verified by the WEF nexus, thus presenting further support for the use of CEA for bio-base material growth in the application of the built environment (Chang et al., 2016).

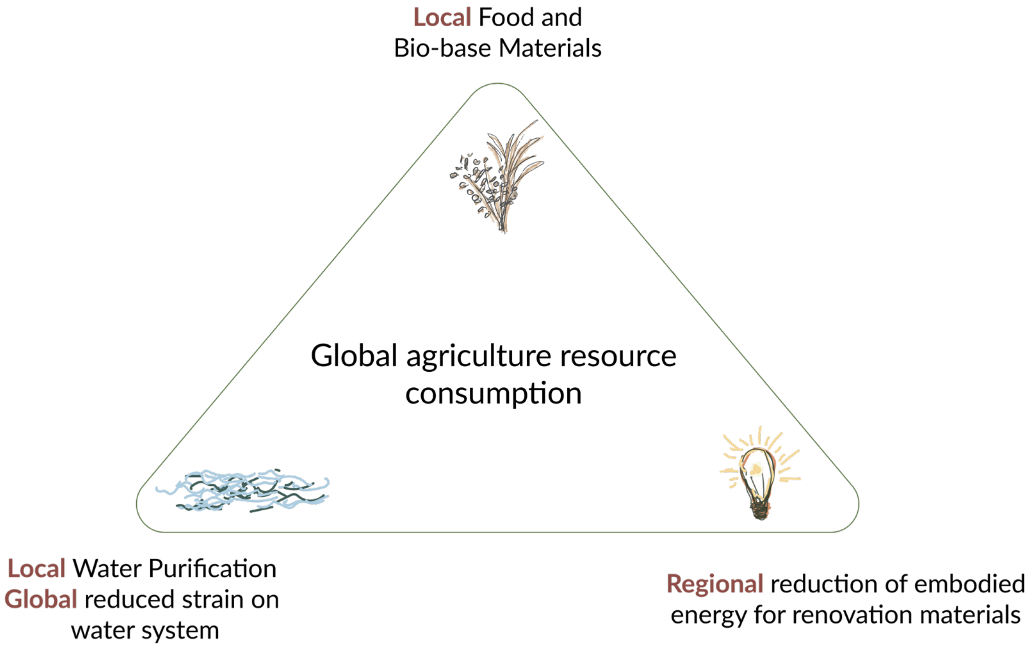


Figure 46 | WEF scale in Circular Design on Local, Regional, and Global Scale Impact on Agriculture Resource Use

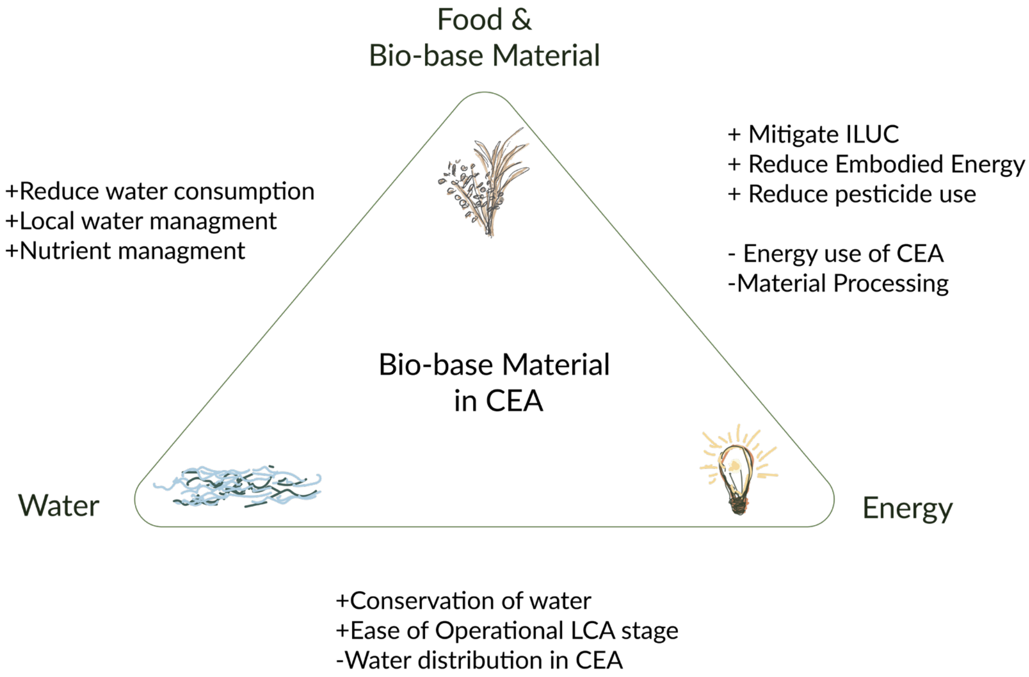


Figure 47 | WEF scale in Circular Design for Bio-base Materials growing in Vertical farm

Renovations

Within the renovation, a circular design apporach was investigated and applied through the application of the renovation panel. In this approach the panel is design to be demountable as well as able to be taken apart further into its material components due to the minimization of adhesives and utilization of adjustable mounting sytems. As building products are being innovated for renovation application, acknowledgement of the shearing layers makes the renovation flexible not only for the current renovation, as well as future renovation applications.

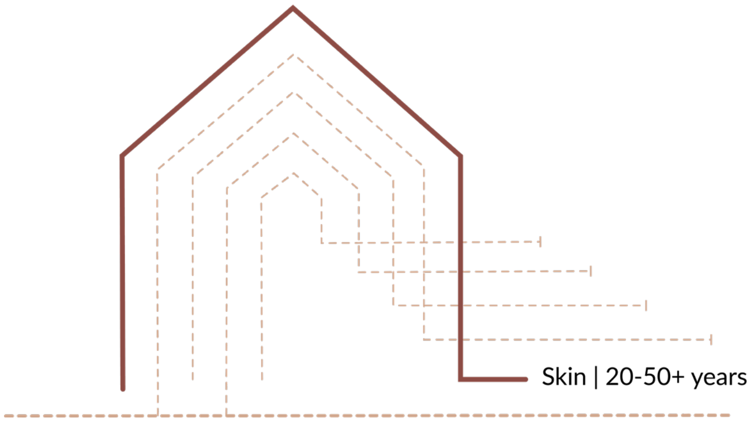


Figure 48 | Shearing Layer Skin Renovation

CEA

Acknowledging the criteria for bio-based materials, there are limitations of how biobased materials of the future are to be produced as the demand continues to increase. As outlined in the research, land management will be a challenge for bio based materials as ILUC will change the means and ways that harvestable land is utilized.

Bio-base Materials

In the form of materiality, bio-base innovations are described as a means of closing the resource loop through responsible cultivation, application, and biodegradability. Based on the investigation of bio-base materials, these products are described as materials that meet Cradle to Cradle Products criteria. In addition to meeting sustainability criteria as a material, bio-based materials have additional positive effects, such as improved air quality through not utilizing VOC, Volatile Organic Compounds, as well as improving indoor living comfort. In the circular economy framework of the Ellan MacArthur Foundation, outlines that just increased the use of biological resources does not guarantee a more sustainable society. For biobased materials to be part of the circular economy, the following foundation criteria are outlined by the Ellan MacArthur Foundation (2017).

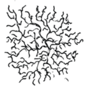
- Material origin from regenerative agricultural or forest land managed in a way that avoids negative externalities
- land management
- harvesting and further processes in material life cycles
- materials to be designed so they can re-enter the biosphere at the end of life

CIRCULAR DESIGN
DESIGN CONSIDERATIONS

BIO-BASE MATERIALS

Origin

Wheat
Barley
Rice
Rye
Dandelions
Mycelium Composites
Tree Saplings



With the understanding that the biobased materials that are applied in the renovation should be directly grown in a CEA environment, the CEA space in which the products are growing should be outlined and described further. Growth of these plants require different germination, growing, and cultivation timeframes which should be coordinated with the other plants in the CEA space. Plants were only selected based on the ability to be grown in a hydroponic system as well as meeting the maximum plant height and root depth requirements. In the understanding of the background of the bio-base materials it is important to understand that they are not grown or cultivated in the same form. Each of the plants also require additional attention to the planting density. In traditional formats, plant density is based on the crop rows and spacing in between. In mass production and growing of these plants, a more fodder system can be utilized, where plants are grown in large trays with high density. Fodder is commonly planted for livestock feed and can be defined as alfalfa, barley, and other cereal grains. With increased planting density, the yield of dry mass increases for efficiency (Kozai, Niu, Takagaki, 2019). In a CEA, the growth of plants is also increased with the air of supplemental lighting as well as the utilization of CO2 enrichment.

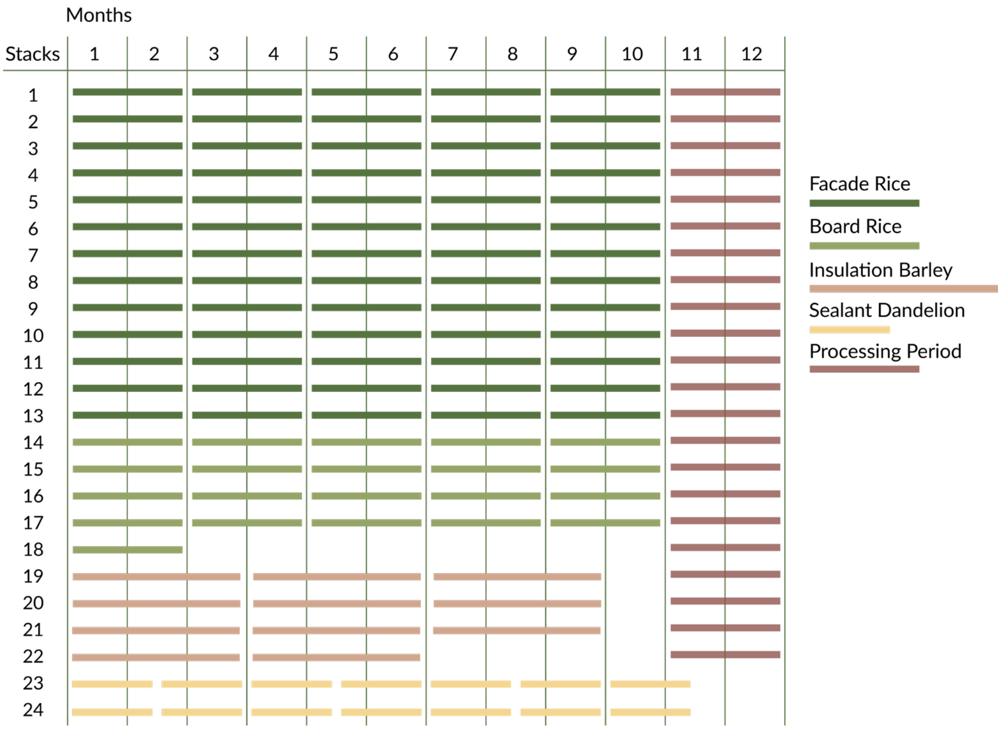
Processing for material application includes the need for a drying process or cleaning process which prepares the material for application or form fitting. Each plant, due to the differences in water content will require different drying periods which will coincide with the first step of composition of the material.

Plant Growing Phasing

From the design data that was calculated above, the CEA will have all year-round harvesting. Accounting for the rotation of plants based on growing phases, plants are placed in groups for harvesting periods and phases

Plants are specifically grouped together based on desired air temperature for growth as well as accounting for the amount of water needed and spacing ended between tiers.

Figure 49 | Phase Calendar for Plants and Harvesting



Composition

To meet the thermal performances required for renovations, thermal calculations were performed for the biobased materials selected for renovations that can be grown in a CEA format, as outlined in the research portion of this report. As mentioned in the panel renovation design, there are 4 aspects of the panel construction that can be replaced with biobased materials, the OSB board, Insulation, Cladding, and Finishes.

Insulation

Mycelium Composite Straw
Wheat-Barley Blend Straw
Barley Straw
Compressed Rice Husks
Bales Rice Husks

Board

Rice Husks
Flax Straw
Mycelium Composite Straw
Mycelium Composite Flax
Wheat Straw

Cladding

Compressed Barley Finish
Compressed and PFA Flax Finish
Mycelium Finish on Timber Slats
Rice Husks with mineral oil and Salt composite Finish

Waterproofing finishes

Dandelion Natural Rubber

Structure Material

Sawn Timber

Assembly

The use of bio-base materials directly in renovations can positively influence the living comfort indoors through moisture absorption and sound insulation, all the meanwhile reducing embodied energy during the production and end of life process. However, due to its materiality, bio-base materials require a specific type of construction compared to traditional construction types. In traditional types of construction, walls are designed to be air and water tight to reduce the build up of moisture and thermal bridging between the indoor and outdoor spaces. Bio-base materials have the advantage of being able accumulate up to 30% of the bio-base material mass in moisture content and then release it again (de Visser, van Wijk, van der Voort, 2015). In comparison with traditional building materials, such as PUR, are not able to accumulate moisture, leading to mould and material damage. For this reason, a vapour open construction is recommended. In this construction, traditional vapour barriers which are utilized to ensure airtight skin building layer is replaced with vapour open layers (Pujadas-Gispert, Alsailani, van Dijk, et al., 2020) which allows moisture to balance between the indoor and outdoor climate. This makes for a breathing effect in the material for excess moisture indoors to diffuse through the construction and outside. This breathing effect does not have any room ventilation properties, thus will still require active or passive ventilation techniques in the building.

It is recommended that vapour open insulation materials to be towards the outer layer while the inner side of the construction should be more damp-proof (de Visser, et al., 2015). This means there is a varying degree of water and moisture proofing. Concern for thermal losses are mitigated with the heat absorption and storage properties of the bio-base materials, reducing the need for strict air tightness of the building skin layer. Open construction techniques are still investigated but the constructions provide an opportunity to be environmentally friendly as well as provide a more natural thermal comfort control system (Dorsch et al., 2014).

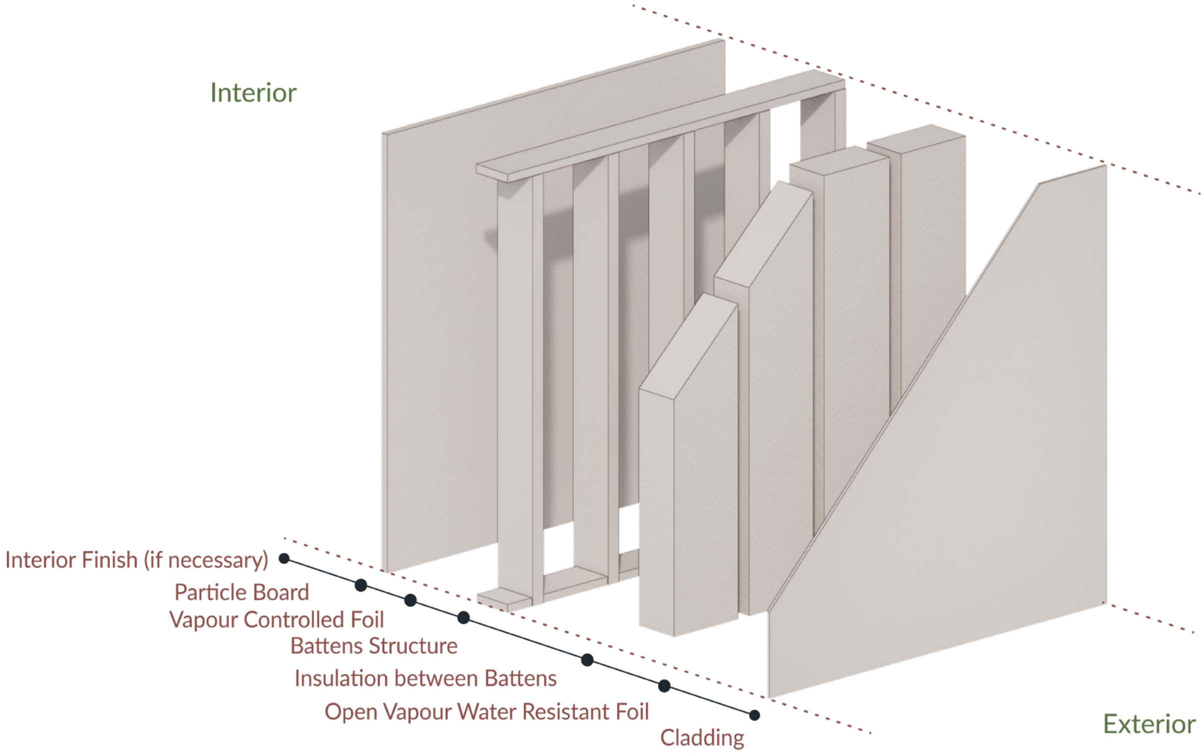


Figure 50 | Bio-base Material Open Construction Panel Composition

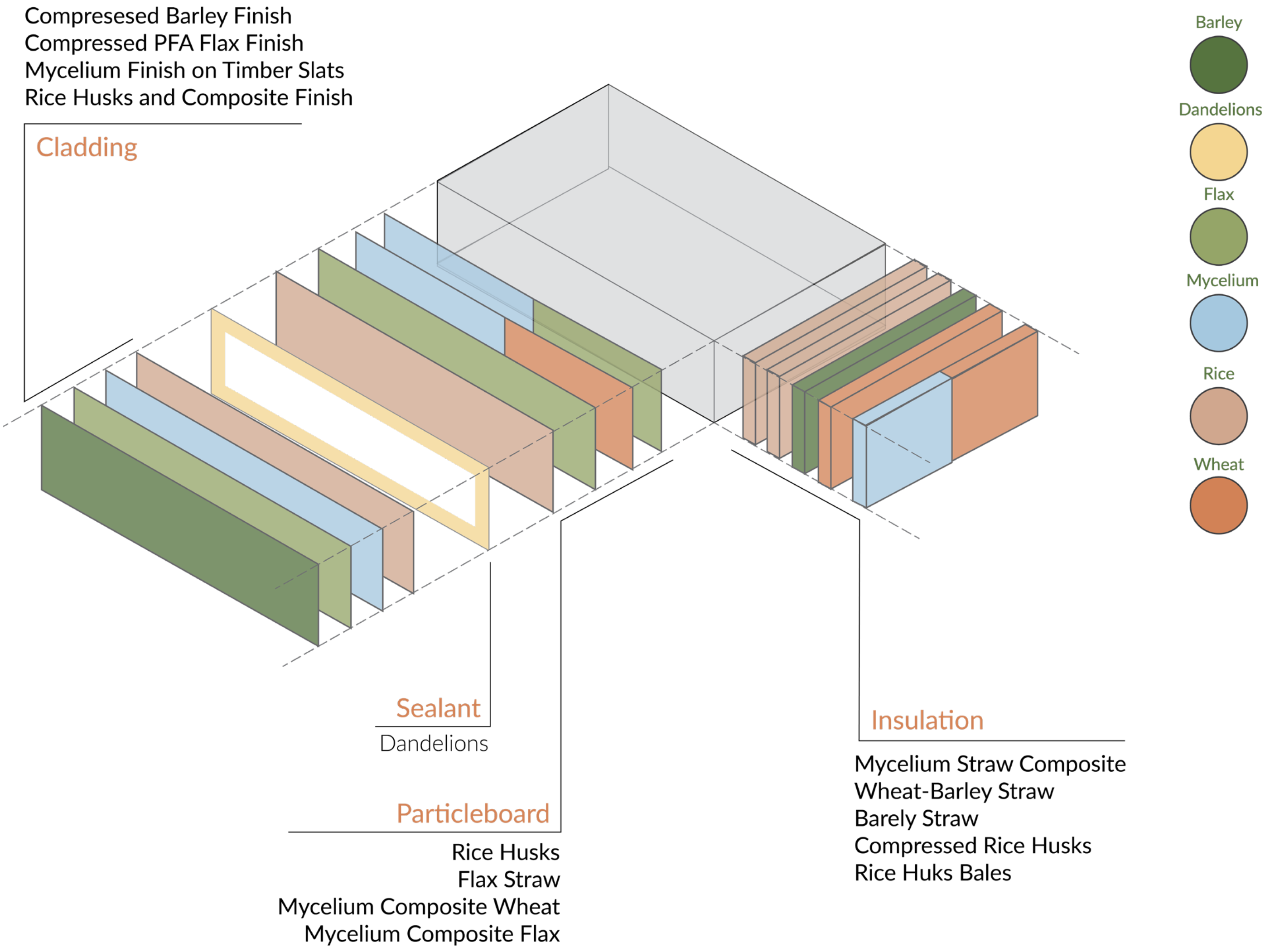


Figure 51 | Selected Bio-base materials and their potential applications in Skin Renovation

Future

In future renovation, panels must meet disassembly requirements due to material lifespans and limitations of materials. Utilizing the shearing layer assessment by Stewart brand, the layer of renovation has approximately a lifespan of 20-50 years. This is depending on the material type and its durability but in general it is aimed to meet these lifespans in order to prevent constant renovation of dwellings and to ensure that the building is utilizing materials and renovation efforts efficiently. Bio-based materials generally have a shorter lifespan compared to oil-based or more traditional materials utilized in the built environment. The need for replacement for bio-based materials generally occurs more quickly due to biodegradation of the material while it is in application.

Table 11 | Lifespan of array of Materials in Building Application

Common Construction Materials		Service Lifespan
Insulation	EPS	35-50
Insulation	PUR	50
Insulation	Mineral Wool	100+
Boards	OSB	30-60
Facade	Brick	100+
Facade	Aluminium Cladding	50-100
Sealants	Silicon	20
Sealants	PU	50
Bio-base Construction Materials		Service Lifespan
Insulation	Mycelium Composite	20
Insulation	Barley Straw	20
Insulation	Rice Husks	20
Boards	Mycelium Composite Straw	20
Boards	Rice Husks	20-30
Boards	Flax Straw	50-100
Boards	Wheat Straw	100
Facade	Timber Cladding with Myco Finish	60-80
Facade	Flax and PFA Finish	40
Sealants	Dandelion	Unknown
Sealants	Starch Adhesive	100+

The future stage of the materials after application and use is outlined based on the Lifecycle Assesment Framework. These phases can occur in a cascading effect but however have different environmental outcomes. In the end products will have to be disposed of but it is a question of how.

- Deconstruction and demolitions
- Transport to the product waste
- Preparation for reuse, recovery or recycling
- Disposal

There are however some limitations on the guaranteeing of end of life applications. As designers that investigate materials for their life cycle assessment, there is little guarantee that the material will follow through with the initially predicted EoL outcomes due to changing building components and the resources available (Hart, 2020). There is an overall consensus that the water flow of biobased materials is underdeveloped and unproven due to its relatively new application and innovation (Hafner, Ott, Winter, 2014). It is within this limitation that the most successful bio-based materials utilize a limited amount of additives and treatments in its processing.

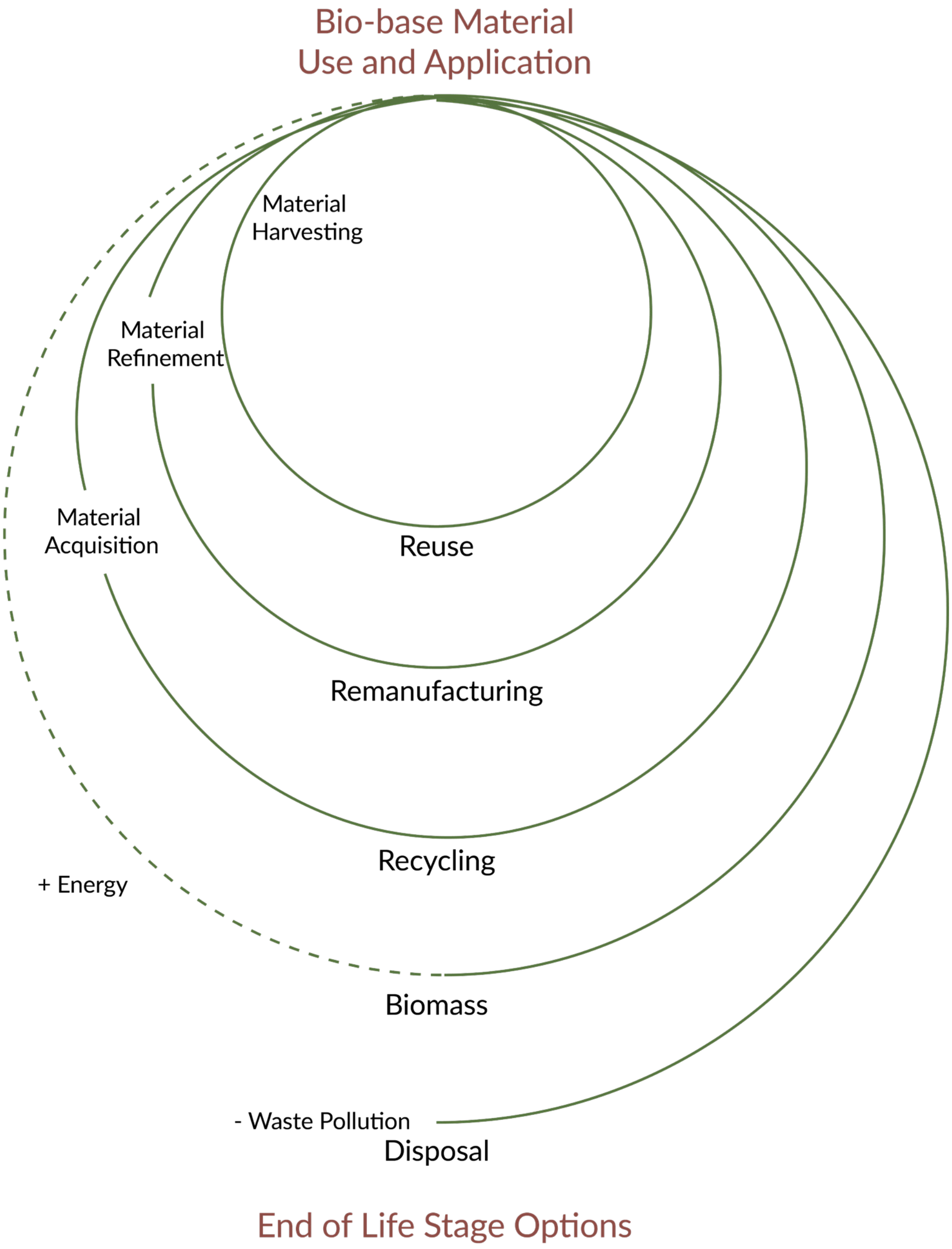


Figure 52 | Predicted cascading use at End of Life (EoL)

By-Products

In the process of growing bio-base Materials from agriculture crops, a by-product will be grains for food consumption. The priority of the CEA construction is to produce bio-base materials although many times it is merely seen as a by-product of food products. In this thesis, the approach for CEA construction is challenged. Acknowledging that the CEA is optimized for its bio-based materials rather than food production of a specific population size, the feeding population size from a single design CEA will not be related to a city but a smaller neighborhood population size.

Estimations of food consumption for wheat and rice are based on globalized average values for the average person in food secure locations. Since wheat and rice are major staples in diets, it is assumed that consumption in diverse neighbourhoods will meet these levels, even within the Netherlands (Samal, Babu, Mondal, 2021). The bio-base materials that are applied in renovations should reflect also the demands of the community not only in terms of demand for renovation, but also for the dietary needs while being culturally sensitive. Flax and Barely consumption was done in terms of EU dietary demands (Hermann, Hjorth, Christensen, Poulsen, 2011) due to the fact that these foods are more specialized within EU and are not considered to be staples currently.

Table 12 | Yield of Straw and Grain based on Harvest Grain Index

Bio-base Source	Yield from Field (kg/ha)	Straw harvest Yield (kg/ha)	Yield Grain/Food expected (kg/ha)	Harvest Grain Index (%)
Wheat	10200	6100	3200	31%
Flax	8750	4950	3800	43%
Barley	6400	5260	1760	28%
Rice	10000	7000	3000	30%
Dandelions				
Mycelium Composites				
Tree Saplings				

Equation 2 | Yield Grain and Straw Harvest based on Harvest Grain Index

$$Harvest\ Grain\ Index\ \ (\%) = \frac{Yield\ Grain\ Expected}{Total\ Yield\ from\ Field}$$

$$Harvest\ Grain\ Index\ \ (\%) = \frac{\left[\frac{kg}{ha}\right]}{\left[\frac{kg}{ha}\right]}$$

Table 13 | Food consumption levels

Bio-base Source	1000-grain Weight (g)	Factored Yield Grain/Food expected (kg/m2)	Factored Global Food Demand Per year per Capita (kg/person)
Wheat	43.3	0.16	66.9
Flax	4.62	0.19	0.438
Barley	40.9	0.088	1.8104
Rice	30	0.15	53.9
Dandelions			
Mycelium Composites			
Tree Saplings			

Mycelium that is produced for construction will not have mushroom outputs, thus will not be a source of nutrition avaliable the community. This is due to the characteristic of mycelium in the bio-base material application. Dark spots and burning appear in the material processing heating step if the mycelium is allowed to grow mushrooms on the substrate surface (Jones et al., 2020). This is not a desired appearance as well as may be a potential vulnerable location within the material if the mycelium hyphae, also known as its binding threads, are damaged. It is noted that even if the mycelium can be left to grow mushrooms not for bio-base materials but for mushroom cultivation, an alternative strain of mushrooms should be utilized, as the mycelium utilized for bio-base material application is genetically modified and selected for its mycelium binding strength.

CEA

Origin

The construction of the vertical farm is applied with the intention of growing bio-base materials but will have a longer lifespan past the desired renovations. Vertical farms have been placed in various constructions, as found in the research portion of the thesis. Construction varies from contained modular shipping containers, smaller scale commercial spaces, to large warehouse constructions. In this design, it will be also proposed that bio-base materials can be utilized in converting a warehouse space into a suitable construction for a CEA which utilizes artificial lighting.

It is concluded that the construction of a vertical farm will be in the adaptive reuse or construction of warehouse. This portion of the design is set out in order to show proof of concept that the CEA that is part of the renovation process can be a functional tool part of the urban landscape rather than interrupt the city in a temporary manner.

Table 14 | Table of CEA Requirements Arrangements

CEA Aspect	Design Criteria	Predicted Outcome
Vertical Stacking of plants	At least 6 meter vertical clearance for stacking	Construction with multiple floors or large ceiling space
Construction hosting the CEA	Affordable structure with ease of construction in urban settings	Adaptive reuse of existing warehouse construction for repurpose function
Indoor Environment Thermal Control	Well insulated and ventilated space for plant growth. At minimum R-value of 7	Insulation of the construction with bio-based materials if required
Artificial Lighting	Spacing between tiers are used to accommodate for lighting and maintenance of plants during growing periods	Lighting is approximately 5cm from max plant height and the lighting fixture is a height of 40 cm between each layer
Structural Strength of Layers	Vertical farm indoor structure will require structural integrity to carry plants and water systems	Design of the frame will not be in the framework of this design, timber frame is suggested for maintaining biobased materials but will require additional treatment in humid and wet indoor conditions
Height and Area	Values needed in order to determine the avaliable space for plants.	Height is assumed to be approximately 11.2 to match warehouse construction size of AeroFarms, NJ.
Water	Water distribution within the level of the CEA	Water system will not be part of the design of this project
Aisles	Between rows and stacks, clearance required for maintenance and circulation	Each stack will require aisles of 5 meters between
Layer Maximum Area	Requirement for maintenance and harvesting	30 meters span row by 2 meters width

Table 15 | CEA existing and application design demands

CEA Aspect	Existing Warehouse
Primary Construction Material	Metal construction with Concrete slab
Stories	Single Story Construction, Grand Hall Space
Existing Thermal Conductivity of construction	Concrete R-13,
Existing Thermal Conductivity of Facades	0, will require insulation R-7

Composition

Proximity of the site is based on the size of the population that the CEA is supporting. The design of the CEA includes the design criteria of the construction, as found in the background section. The construction of the CEA is predicted to be either in an existing warehouse structure or in a post war housing dwelling.

The following are the required additions that compose the space to be suitable CEA conditions. It is assumed that the CEA that is growing material for application is the same size as the CEA of application. Thus a CEA can be transitioned from growing renovation material to CEA construction panel to then food production. It is assumed that the CEA construction facade construction is developed as full cover panels that have similar structure as the panel developed specifically for MUWI construction.

Table 16 | Biobased materials required for CEA construction

	Single CEA
Insulation Area needed (m2)	8960
Insulation Assumed	Rice Bale
Thickness (m)	0.36
Volume of Material needed (m3)	3199
Material content needed (kg)	1209116

Assembly

Table 17 | Biobased materials required for CEA construction

Bio-base Source	Growing Height (cm)	CEA Tier Spacing (cm)	Number of CEA layers possible	Single Layer Output (kg)	Number of Harvests in a year
Wheat	100	140	7	31183.2	5
Flax	90	130	8	25304.4	4
Barley	60	100	10	26889.1	4
Rice	70	110	9	35784.0	6
Dandelions	45	85	12	214.7	7
Mycelium Composites	Board Thickness	Board Thickness + 40			6
Sapplings Nursury	100	140	7	66096	1

Assembly of the CEA not only includes the layout of the building but also the general assembly of the CEA in the context of the neighborhood.

Future

The future of the CEA for the growing of Bio-based materials is predicted and intended to be a permanent structure. Just as the plants selected have the primary function for bio-base materials, there is a secondary agriculture grain output, the CEA can transition to alternative plants that suit the local economy and community. A single CEA however can produce enough material for a local community as well as its neighboring cities.

RENOVATION PANEL

Assembly

Criteria

Mounting System
Panel Construction Interactions
Openings and glazing incoorporated
Panel Edges
Primarily comprised of Bio-base Materials

Assembly Aspects

1. Building Structure evaluation and potential anchor points for panel
2. Determine what kind of mounting system is being utilized and the aspects needed for panel anchoring, i.e. railings, framing
3. Identify existing structure limits for panel access to mounting, i.e. balconies, ceilings
4. Facade distribution of openings and outline equal distribution of panels while accommodating for one or two panel sizes/lengths that can be manufactured to maintain modular design
5. Determine the panel to panel interactions and interlinking
6. Accommodate for panel edges
7. Determine the integration of mounting system into the panel
8. Determine areas that will require additional attention after the placement of the panel for insulation and waterproofing purposes
9. Determine design for disassembly components and possibilities for End of Life

After evaluating the options for biobase materials, exterior panel options were evaluated utilizing the Renovation condition steps as suggested above. In this portion, the structure limitations and conditions are directly applied to the MUWI construction to understand the limitations and design decisions based on the restraints. These conditions are then analyzed for how they influence the design of the panel construction.

1 Building Structure evaluation and potential anchor points for panel

A MUWI structure consists of solid Concrete Masonry Unit (CMU) wall constructions at spans of 481 and 321 cm apart alternating. The main structure on the ends of the building is a CMU stack construction with a cavity and brick facade finish. The structure also includes balconies, which are embedded in the structure and cantilever from the structure approximately 125 cm. Panels will also span between one floor, which is approximately a height of 280cm in floor to floor elevation.

Design Consideration: When looking at the structure, renovation panels should be anchored into the structure of the existing building, thus if panels that are smaller than 481 are utilized, an additional substructure will be needed to reinforce the panel attachment. Panel cannot be anchored into the existing balcony construction and must be connected either to the structural wall elements or be additional strucutral construction. Additional consideration is needed for the balcony construction considering that it is a thermal bridge between the building and exterior, which may lead to additional losses in the insulation of the building.

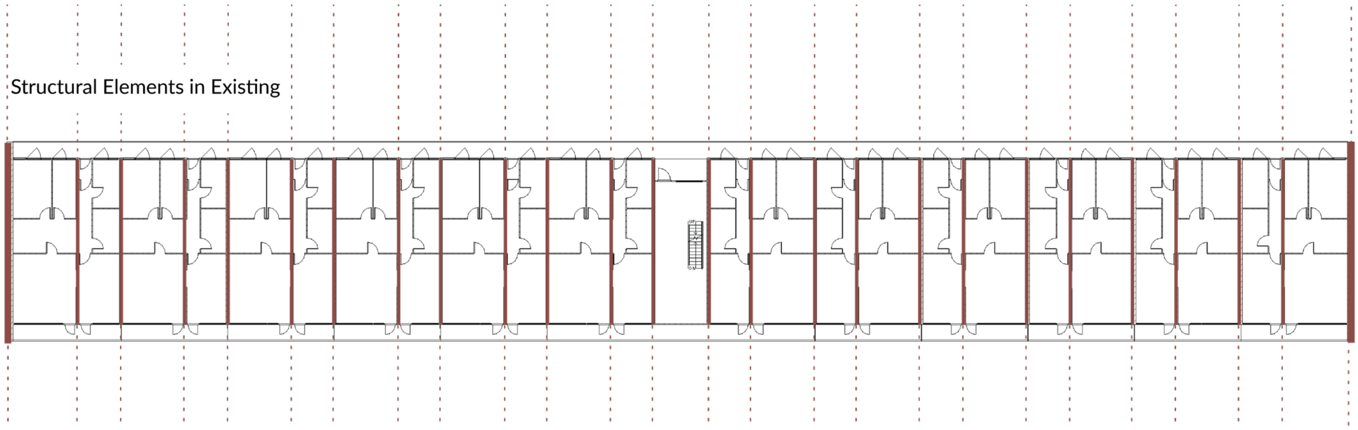


Figure 53 | MUWI Structural Elements along Glazed Facade

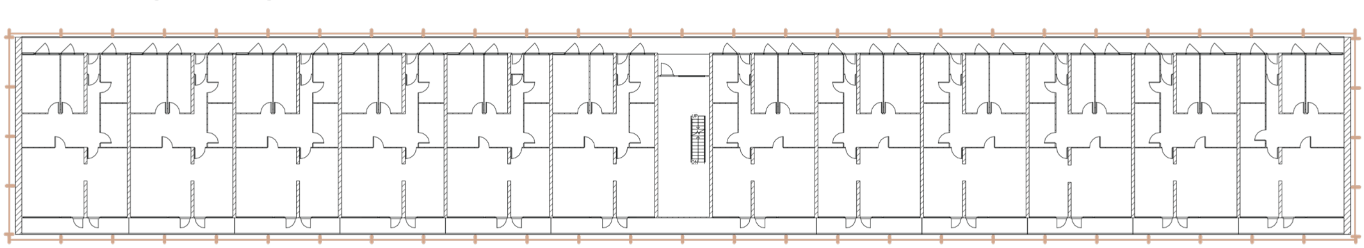


Figure 54 | Suggestion for utilizing timber framing external of frame, distributing construction mass

2 Determine what kind of mounting system is being utilized and the aspects needed for panel anchoring, i.e. railings, framing

Mounting system that is selected will be based on previous research and considerations of renovation case studies. Constructions that are considered include the use of panel framing and hanging systems. In addition, the goal is to reduce the number of thermal bridges into the building. These are defined as a component of a construction which has higher thermal conductivity than the surrounding insulation materials, thus creating a path from the outside or inside to transfer heat/cold.

Design Consideration: The mounting systems to be utilized must accommodate for large spans for the panel construction as well as not obstruct the large amount of openings in the facade. This means that a railing system cannot be utilized without additional structural elements to accommodate for secury mounting fixture.

3 Identify existing structure limits for panel access to mounting, i.e. balconies, ceilings

MUWI construction includes balconies in the facades with glazing. Since the glazing on these facades are also floor to ceiling glazing, the window frames directly lead into the balcony construction.

Design Consideration: Because of the balconies, there is obstructed access to the top and bottom part of the renovation panels. This will limit the ability to affix the panel to the existing construction. For this reason, fixing of the facade panels should happen either on the edges of the panel or should be done in a framing structure. Framing structure can be supported through the use of multiple smaller window areas to cover a large window area in the existing construction. In other renovation examples, the balconies have been removed and replaced in order to reduce the thermal bridge between the building and exterior. It can be recommended to do this in this renovation as a means of improving the energy efficiency of the building as well as replacing the balcony for a construction with a larger walking width as well as to accommodate for the integration of the facade panels.

Table 18 | Comparisons of why and why not renovating the glazed facades

Benefits of renovating full or more than half glazed Facades with modular panels	Limits of renovating full or more than half glazed facades with modular panels
Ease of construction and adaptability of glazing frame demands in new façade construction	Insulation Unit of glazing can be replaced in the existing construction
Improvement of window sills for thermal performance	Primarily glazed façade with large glass panels that are customized for the construction type
New window functions with ventilation or integrated sun shading can be utilized	Limited daylighting in apartment means same glazing area should be utilized to optimize lighting
Extended window sills	Structural framing for the panel may interrupt glazing area provided
Ease of construction	Transom windows limiting structural framing of renovation panel
Customizable building character through renovation of window openings and new façade framing around windows	

Although there are challenges in renovating the glazed facades with a biobased construction panel due to the balcony limitations and structure anchoring points, it is still recommended to made a renovation on these facades because of the leaking of openings as well as to improve the efficiency of the limited covered portions below and in between openings. For this reason, it is recommended to perform a renovation which integrates the use of a panel construction, as well as a panel/balcony construction.

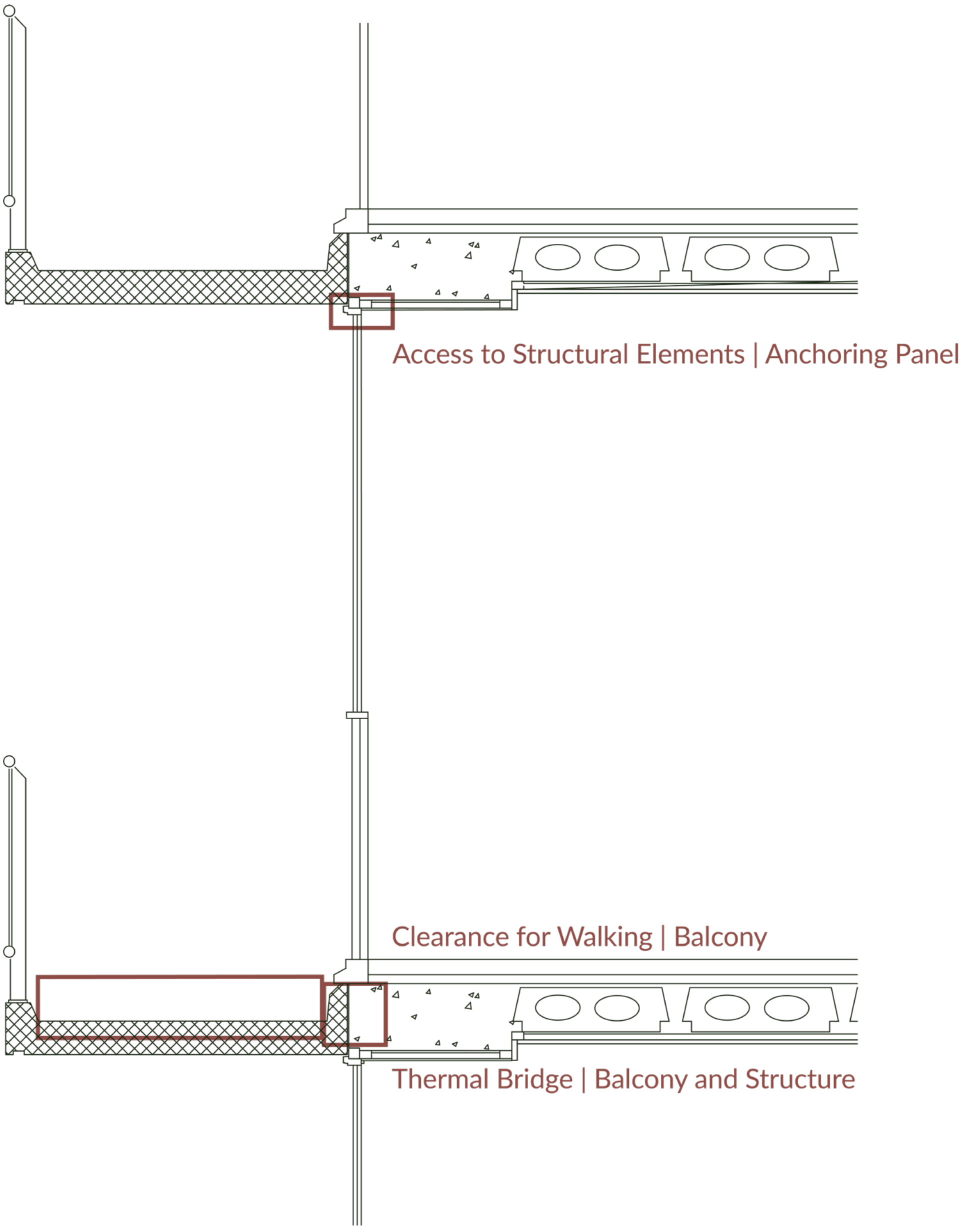


Figure 55 | Identify Challenge Points in the Existing MUWI Construction for the Application of Renovation Panel directly on Facade

Facade Panel and New Balcony

Insulation of construction through removal of existing balcony and replacement with extended timber or steel construction and new insulation on facades. Thermal bridge reduced but intensive construction.

- Construction | Intensive
- Feasibility | Low
- Cost | High
- Social Addition | High

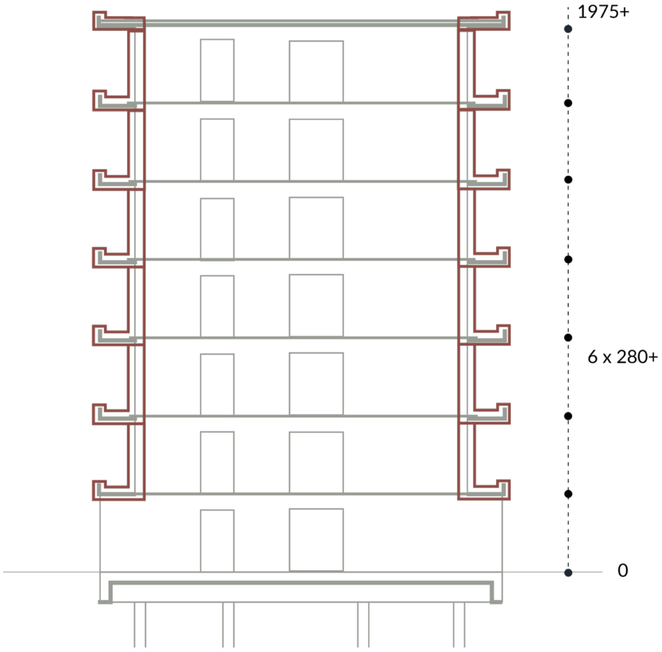


Figure 57 | Schematic Design of Wrap-around insulation for balcony and facade

Second Skin Facade Panel

Insulation of construction by enclosing thermal bridge and balcony for a second skin thermal buffer. Structural reinforcement needed.

- Construction | Medium
- Feasibility | High
- Cost | High
- Social Addition | High

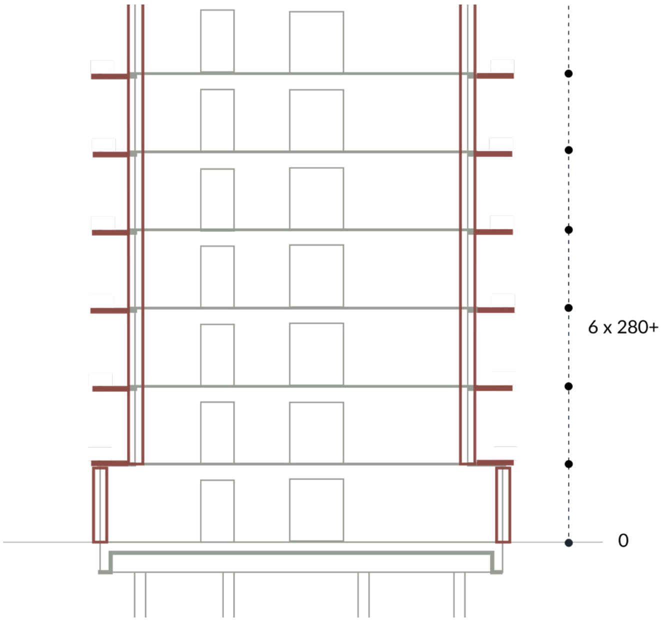


Figure 56 | Schematic Design of Facade Panel and New Balcony Construction

Facade Panel and Wrap-around Insulation

Insulation around balcony to reduce thermal bridge. Exessive building Material and reduction of balcony width.

- Construction | Medium
- Feasibility | High
- Cost | Medium
- Social Addition | Low

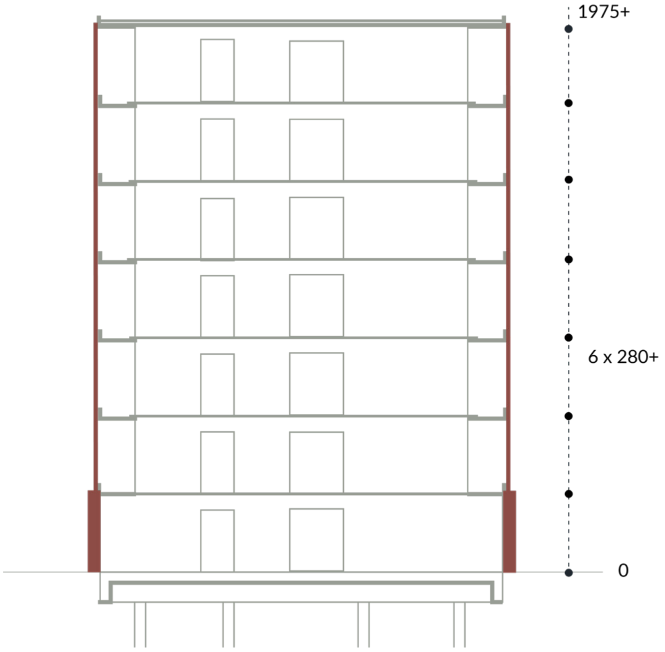


Figure 58 | Schematic Design of Second Skin Panel and structural reinforcement

4 Facade distribution of openings and outline equal distribution of panels while accommodating for one or two panel sizes/lengths that can be manufactured to maintain modular design

The facade types for MUWI include a brick facade as well glazed walls. Glazed walls also include doorways as well as a transom window over the doors and windows. These glazed facades are predominantly made from glass that require to be updated with new glazing that is also cost effective as well as provides ventilation in the interior spaces.

Design Consideration: The panels utilized on the brick facade will have ease of renovation in the sense that it will not impact the inhabitants, but the glazing facades will face the most challenge to accommodate for large openings that are in specific dimensions. It is recommended to use tilt and turn windows for the glazing replacement which will require additional window framing as well as may reduce daylighting due to frame. In the situation of the transom windows above the windows and doors, replacement or filling will be conducted in order to accommodate for the panel railing system as well as structure from the tilt and turn windows.

Figure 59 | Glazed Facade Apartment Extents for Private and Public Balcony

Table 19 | Summary of Modular Dimensions of Panels

Façade Replacement	Length (m)	Height (m)
Full Cover Facades	3.70	2.80
Glazed Facedes -Glazed Portion	3.70	1.90
Glazed Facedes -Bio-Base Material Portion	3.70	0.90

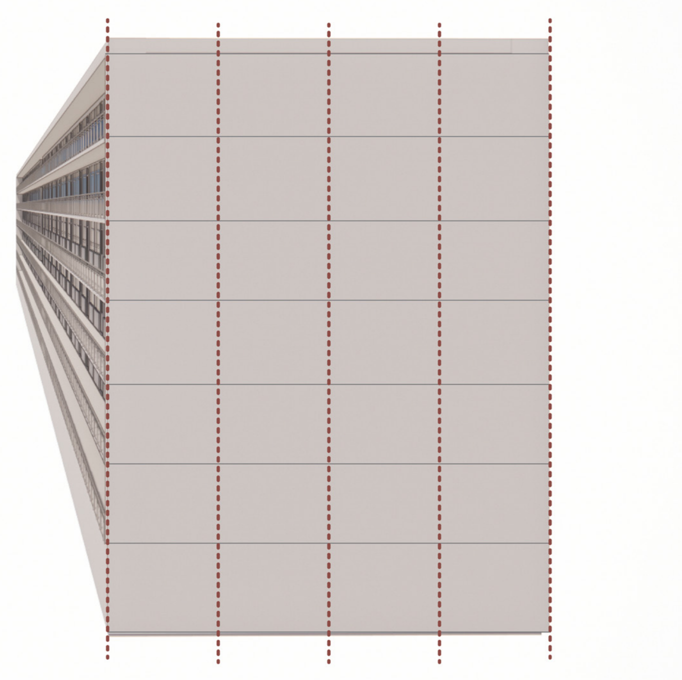


Figure 60 | Full Cover Facade Modular Distribution of Panels

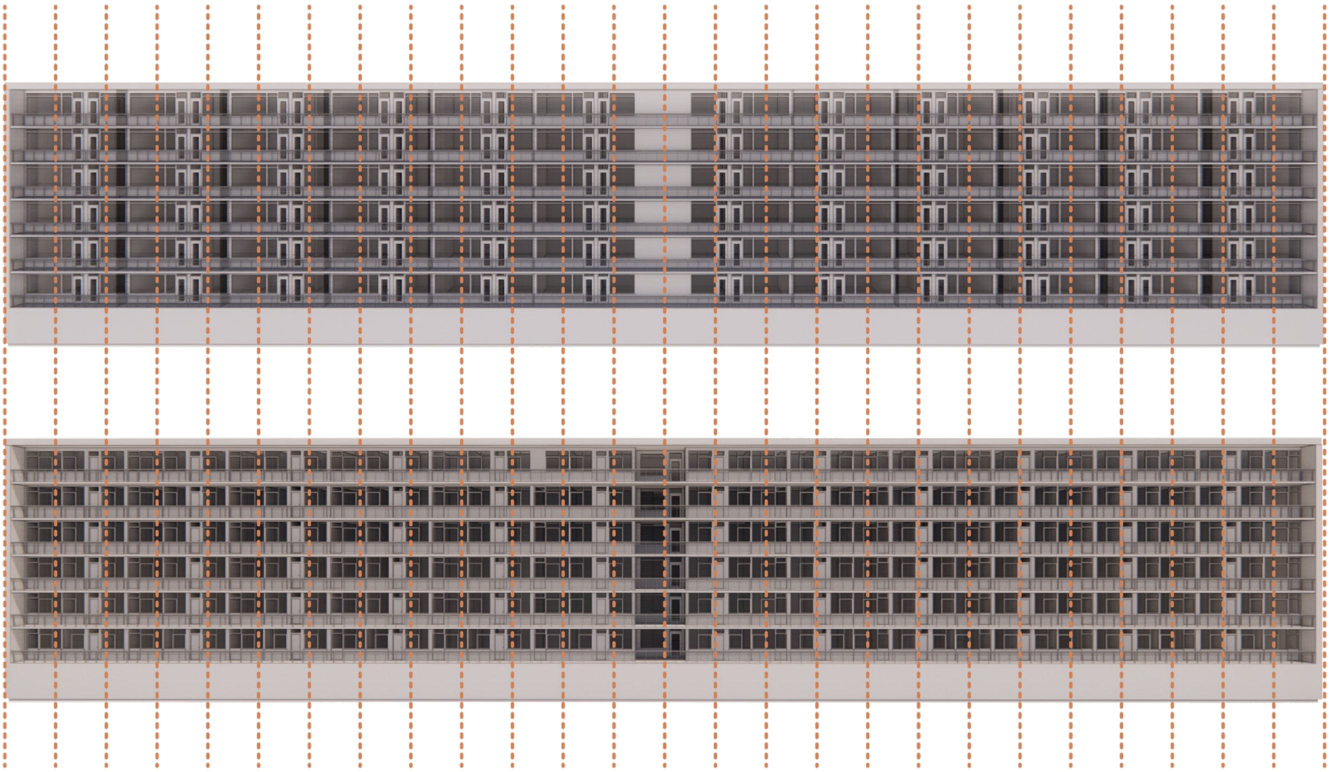
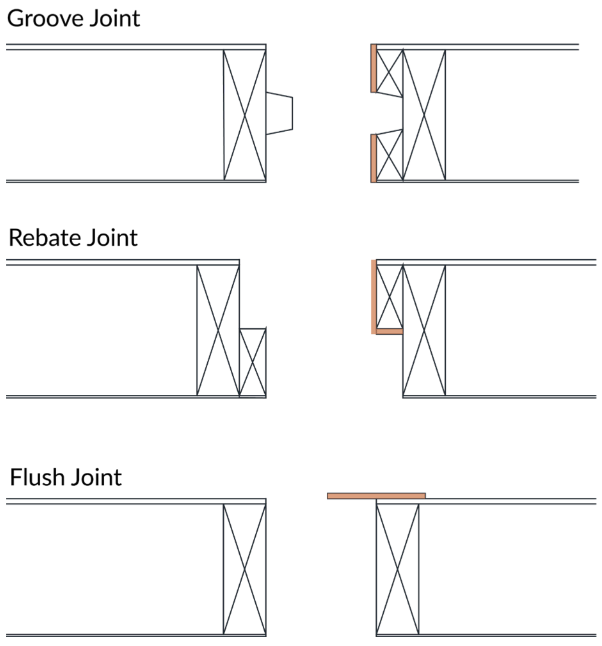


Figure 61 | Glazed Facade Modular Distribution of Panels

5 Determine the panel to panel interactions and interlinking

Between the panel interactions recommended are rebate joint, flush joint, or a groove joint. Each joint requires the use of waterproofing between panels in order to prevent water entering the construction. Renovation panel precedents has shown more examples of flush construction were panels are directly placed next to each other rather than interlocked. Interlocking has the potential of reducing water from entering the construction but limits the panel adjustments on the X and Y axis, parallel to the facade as well as leveling the panel off the existing facade.

Design Consideration: To accommodate the interlocking as well as the mounting system, a combination of a flush and rebate joint is determined as the most suitable. This allows for the use of hanging structure without creating a large cavity between the renovation panel and the existing structure.



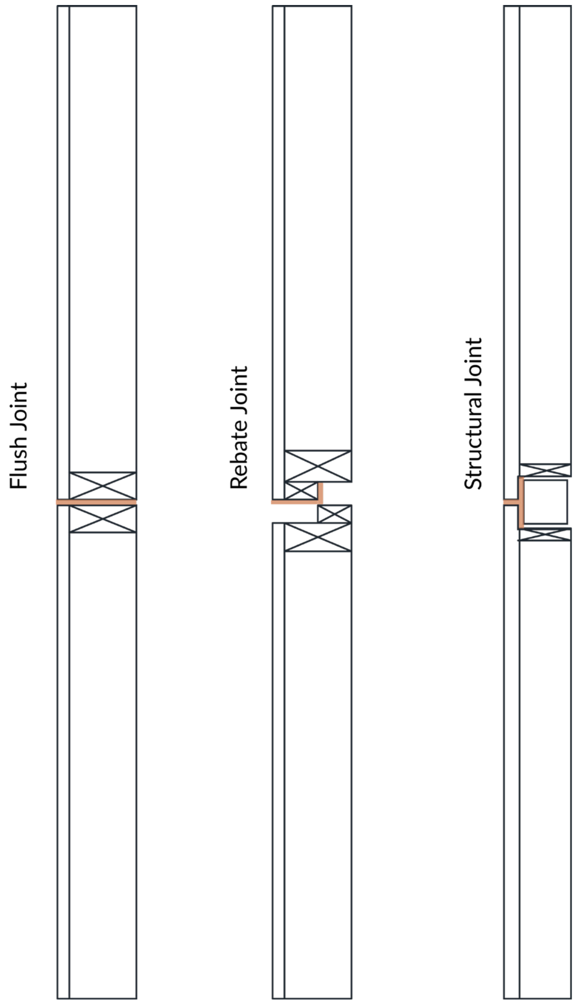


Figure 62 | Horizontal Panel to Panel Interlocking

Figure 63 | Vertical Panel to Panel Interlocking

6 Accommodate for panel edges

Panel edges are specifically for the ends of the panel which are exposed. Waterproofing is necessary for these ends as there is exposure to outside. Additionally, the full cover facade panels will require a larger corner edge which also accommodates the edges that are utilized for the balcony end walls. These wall ends will require insulating as they are also thermal bridges between the outside and inside. These corner edges also allow for flexibility of design which interlock with the glazed panels. Panel edges also include not only the parallel corners but also the horizontal corners found between the panel and panel or panel and balcony.

Design Consideration: The interlocking of panel edges must include the joint between the panel as well as maintain the thickness of insulation in order to properly insulate the construction. Additional considerations for the panel edges in MUWI construction includes the edge interaction between the panel and balcony. This edge can be sealed with the use of an additional construction that is placed after the fixing of the panel to the existing facade.

7 Determine the integration of mounting system into the panel

With the consideration that the renovation panel will require to be as close to the existing facade, reducing the cavity/spacing in between, an integrated mounting system would be an effective means of utilizing the panel volume effectively.

Design Consideration: The integration of a mounting system means that there are limits of what kind of mechanism can be applied. For this reason a hanging mounting system is considered as ideal for this situation. With the integration, The panel must accommodate for the mounting plate as well as screws.

8 Determine areas that will require additional attention after the placement of the panel for insulation and waterproofing purposes

As previously mentioned, waterproofing around the panel is necessary as well the waterproofing between the roof and the panel. Renovation case studies show the utilization of rubber finishes on the top as well as a roof extension for waterproofing and water collection. Renovation case studies showed the use of existing roof structure if possible.

Design Consideration: MUWI construction does not have an extended roof over the end full cover facades, thus will require the need of additional construction to accommodate the roofs. This construction will be added to the last panel on the top floor. Additional areas of attention are around the existing openings and the renovation panel. By considering the openings, window sills should extend into the existing face footprint to bridge the gap between the new facade and interior of the existing.

9 Determine design for disassembly components and possibilities for End of Life

This portion is discussed in the next stage of the circular economy phase which acknowledges the challenges and criteria needed to follow the best End of Life situation for the renovation panel product.

Future

The ease of sustainable disposal of the material, it is a limiting factor in its application. Thus, designing for removal is a vital part of the renovation panel but must be balanced with the need for an airtight application between panels.

Table 20 | Pro con list disassembly challenges and tactics

Disassembly Tactic	Explained	Design Challenge
Minimizing Components	Reducing the number of parts that are needed to take apart the component, simple construction of the panel as well as mounting system	To minimize the components for mounting the panel construction
Mechanical fixings such as screws minimized as well as adhesives	Reducing fixing that would damage material with holes or fracture once the fixing is removed, minimizing connections between the panel layers	Fixing the panel layers together with timber profiles when possible
Connections	Connections between the panel and existing façade should be secure but allows accessibility to remove Ability to remove the panel when it is needing replacement or updated material	Utilizing a mounting system that can be reused repeatedly without concerns of wear-and -tear of the connection
Design for Adaptability	Ability to utilize mounting components again for different functions and panels, flexibility to change integrated panel	Predicting the need for future designers in the MUWI construction. Assumptions that the balcony or façade openings may need to change in the future. Mounting system can be adapted for potential future uses with simple construction
Demountable	The ability to remove the panel with ease without demolishing any existing construction	Connection that allows for mounting system to be removed while mounted while not having to remove other panels in the construction

After the use of the renovation panel, many of the biobased materials in the composition of the panel can serve an additional function. It is however predicted that all materials will be then placed back into the soil for decomposition. In this stage, the sequestered CO2 of the raw material will then be placed back into the soil as long as it is not contaminated with additional finishes or coatings. The future of this panel is to have the possibility of disassembly. In the case of the panel construction with balcony, the panel is able to be removed without removal of the new balcony construction. This is for accessibility to the renovation panel as it is part of the skin shearing layer which requires replacement more often.

Composition

OUTSIDE

Cladding Finish
Open Vapour and Water Resistant Foil
Insulation between Timber Framing
Vapour controlled and Water Resistant Foil
Particleboard
Interior Finish (If Necessary)

INSIDE

Insulation

In this construction, direct replacements of materials were found based on the R values of the existing product. The product R Value is set at R-7, where the insulation layer had the most influence on the overall R value. It is clear that bio-based materials will overall require more material and thickness to replicate the same thermal insulation values as EPS or other oil based insulation materials. For this reason, in the most ideal situations, the biobase material with the lowest thermal conductivity should be utilized. However, this can be limited by the resources that are available, such as in this thesis which is limited by the CEA construction and hydroponic possibilities of the biobase material plants.

Table 21 | R value tables for expected nZEB and Bio-base Materials meeting requirements

Insulation Replacement	Expected Density (kg/m3)	Thermal Conductivity (W/mK)	Required Thickness (m), R-7	Mass of Material R-7 (kg)
Mycelium Composite Straw	94	0.04	0.28	22410.7
Wheat/Barley Straw (Perpendicular)	106.3	0.064	0.448	40549.1
Barley	78.3	0.04	0.28	18667.7
Rice Husks	378	0.08	0.56	180239.6
Rice Bale	200	0.051	0.357	60795.1

Facade Finishes

Bio-base cladding finishes have a standard sizing that can be assumed for the facade panel. These finishes are utilized more for aesthetic value rather than thermal value. Thickness were found based on bio-base material appraoches in research phase (Sandak, et al., 2019). The following are the standard thicknesses that are assumed for bio-based facade finishes:

Table 22 | Façade Finish and thicknesses

Façade Replacement	Façade Thickness Expected (mm)	Expected R Value (m2K/W)
Barley (PFA added)	15	0.25
Flax (PFA add)	10	0.117647059
Rice (Rice husks, mineral oil, rock salt add)	13	0.065326633
Mycelium Paint Finish (Wood Cladding add)	45	0.375

Particle Board

Bio-base cladding finishes have a standard sizing that can be assumed for the facade panel. These finishes are utilized more for aesthetic value rather than thermal value. The following are the standard thicknesses that are assumed for bio-based facade finishes:

Table 23 | Particle Board Characteristics

Structural Board	Min Density of Material (kg/m3)	Max Density of Material (kg/m3)	Min Thickness Approx. (mm)	Max Thickness Approx. (mm)
Flax	320	560	16	50
Rice	400	900	50	100
Mycelium Composite Wheat Straw	99	115	90	90
Mycelium Composite Flax Straw	192	200	90	90
Wheat Straw	750		20	
Barley	750		20	

Timber Framing

In between the insulation layers, a timber frame construction is utilized. Timber is commonly utilized to create framing for renovation panels and is utilized for creating ventilation behind the panel construction. This type of construction includes the use of batten constructions, which are generally 1.2-2.4 cm in thickness and are commonly spaced approximately 40cm to 60cm apart depending on the window openings as well as the structural expectations of the panel. In this construction, the battens spacing will be determined by the openings as well as the overall length of the panel construction. Additional reinforced timber framing is needed around openings, which also may interrupt the spacing. In these situations, battens are still needed surrounding the frame of the opening with the addition of a lintel structure to distribute the load around the openings.

Sealant Finishes

Sealant that is utilized in the panel construction are usually rubber, silicon, or poly based materials, which is resistant to water and weathering. This is to produce the interior layers of the panel while allowing the cladding exterior to be exposed to the elements. In ideal situations, sealants are airtight and provide additional thermal value to the construction and maintain their elastomer properties regardless of the weathering exposure. The construction of the panels will utilize the rubber of dandelions between panels as is possible to grow dandelions hydroponically, while potatoes, which are high in starch content needed for biobased elastomers, do not grow well in hydroponic systems.

Table 24 | Dandelion locations in the panel that are needed

	Total length of Renovation (m)	Thickness of panel (m)	Number of Between Panels
Natural Rubber	1174.2	0.2	792

Table 25 | Dandelion Rubber demand for whole building renovation

	Material Selection	Material Content needed for one Renovation (kg)	Area needed for Harvesting Demand (m2)
Natural Rubber	Dandelion Rubber	652	322

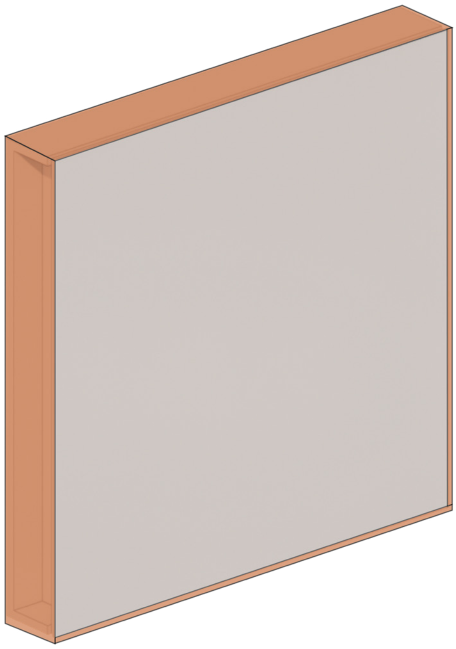


Figure 64 | Sealant Area Around the Full Cover Panel

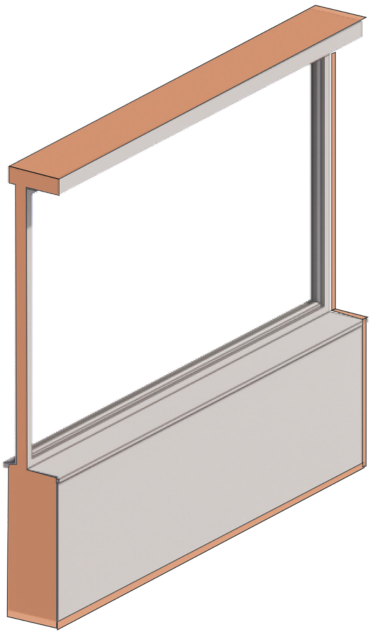


Figure 65 | Sealant Area Around Glazed Cover Panel

Processing

The processing of these biobased materials to be formed into the panel is the origin of the renovation. Each of the different material replacement categories have similar processing but precedents materials that are already applied in the industry are accounted for as well.

The plants that have been selected have a large array of applications based on additives and processing that the dry product goes under. It is recommended to see each of the products for their raw primary or blended product to calculate an estimate how much plant material is necessary for the construction materials. For this thesis, it is acknowledged that there are natural additives in many bio-base materials which improve the materials durability or flexible application, however, these are not included in the CEA growing environment and will only be accounted for in the processing portion.

Table 26 | R value tables for expected nZEB and Bio-base Materials meeting requirements

	Origin	Composition	Mycelium Growth	Heating	Pressing
Insulation Materials					
Mycelium Composite Straw	CEA	Mycelium, Wheat, Barley	Y	Y	Y
Wheat/Barley Straw (Perpendicular)	CEA	Wheat and Barley	N	N	Y
Barley Bale	CEA	Barley	N	N	Light
Rice Husks	CEA	Rice	N	N	Y
Rice Bale	CEA	Rice	N	N	Light
Board Materials					
Flax	CEA	Flax	N	Y	Y
Rice	CEA	Rice	N	Y	Y
Mycelium Composite Wheat Straw	CEA	Mycelium, Wheat	Y	Y	Y
Mycelium Composite Flax Straw	CEA	Mycelium, Flax	Y	Y	Y
Wheat Straw	CEA	Wheat	N	Y	Y
Barley	CEA	Barley	N	Y	Y
Façade Materials					
Barley	CEA	PFA	N	Y	Y
Flax	CEA	PFA	N	Y	Y
Rice	CEA	Mineral Oil, Rock Salt	N	Y	Y
Timber Slats	CEA and Plantation	Wood - Norway Spruce Scotch Pine	Outsourced	Outsourced	Outsourced
Mycelium Coating	Lab	Mycelium	Outsourced	Outsourced	Outsourced
Sealant Materials					
Dandelion Rubber	CEA and Lab	Dandelion Sap from Roots	N	Y	N

Mycelium Medium Growth

Within the renovation construction applications, mycelium is utilized as a binder for agriculture waste materials as well as a coating for timber facades. The binding of the mycelium is done through the mycelium hyphae, which is the network of fibres that usually travel though the soil for the mushrooms. The material growth of mycelium can be done directly inside the CEA. Cool and dark storage of the mycelium panels are proposed to be stack in shelf style, similar to the plant growth. This however can be done more densely, with approximately a max height of 6 meters for accessibility and 15cm between mycelium boards and 35cm between the proposed insulation panel.

The mycelium panels for the MUWI construction requires lengths either of 1.60 meters or 3.21 meters for the glazed facades. This is then rounded to 3.3 for clearance around the board for a total of 10 boards per tier and 30 tiers. This means approximately 300 boards of 1x3.5 can be manufactured the area of one tier per half year, and 600 boards for a whole year. This will cover the total required glazed area, which requires approximately 432 boards.
The full cover panels required for the renovation need panels that are 3.7 x 2.8 meters. Due to the sizing the tiers, two boards will be required to cover one panel, means they will be 1.85x 2.8 meters. Approximately 330 boards can be manufactured in half a year, covering the required 112 boards needed for the full cover panels. Together, the board panels that require mycelium processing are configured in one CEA Tier length. This however is limits the space for insulation material with mycelium to be developed simultaneously.

The mycelium that is utilized for the façade coating requires processing outside of the CEA environment. In this situation, the coating is processed and developed in an “outsourced” lab (Xyhlo, 2020).

Insulation materials that are made from mycelium must be sized to meet the desired spacing between battens within the panel. Batten spacing for glaze panels have been configured to approximately 50cm between. Insulation must be 1x.5 meters for the glazed facades and 2.8x .5 meters for full cover facades.

CIRCULAR DESIGN
DESIGN

Composition

Based on the criteria of the layers of a renovation panel, proposals were created for exterior panel renovation possibilities. These panels are designed utilizing the consideration for the highest R-value, 7, that are needed to meet the nZEB requirements. The material grown and timeframe which it will be grown in for the renovation. As mentioned previously, the glass is not part of the material calculation as it is assumed that a comparable biobased panel or traditional material panel will utilize the same amount of glazing for the renovation panel construction.

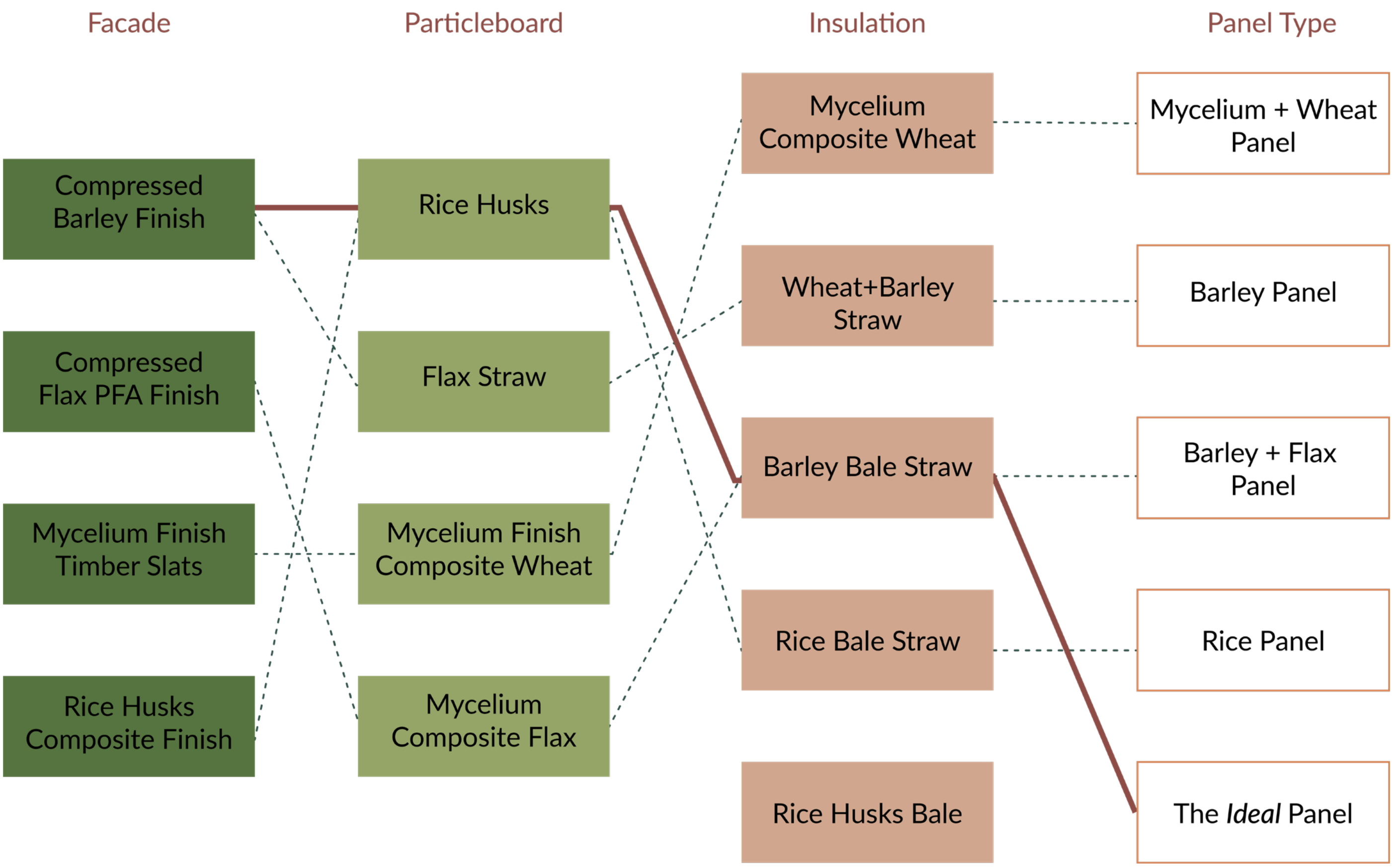


Figure 66 | Congrifuration Chart of Panels

Table 27 | Panel Configuration Examples

	Material Selection	Thickness (m)	R Value (m2K/W)	Material Content needed for one Renovation (kg)	Average Area for indoor Harvesting (m2)
Panel 1 Configuration					
Insulation	Mycelium Composite Straw	0.28	7	134464	44087
Board	Thin Mycelium Composite Wheat Straw	0.05		49198	16131
Façade Finish	Mycelium Paint Finish with timber cladding	0.045	0.375		
Total		0.375	7.375		60217
Panel 2 Configuration					
Insulation	Wheat/Barley Straw (Perpendicular)	0.525	7	243295	92508
Board	Barley	0.02		76632	29138
Façade Finish	Barley	0.015	0.1	8156301	3101255
Total		0.56	7.117647059		3222901
Panel 3 Configuration					
Insulation	Rice Bale	0.36	7	364771	104220
Board	Rice Board	0.06		280986	80282
Façade Finish	Rice	0.01	0.1	870005	248573
Total		0.43	7.07		433075
Panel 4 Configuration					
Insulation	Barley Bale	0.28	7	112006	42588
Board	Mycelium Composite Flax Straw	0.09		90120	36412
Façade Finish	Flax	0.02	0.117647059	2320015	937380
Total		0.39	7.12		1016380
Panel 5 Configuration					
Insulation	Barley Bale	0.28	7	112006.0328	42588
Board	Rice Board	0.06	0	280985.76	80282
Façade Finish	Rice	0.01	0.0653	870005.4801	248573
Total		0.35	7.07		371442

Compressed Barley Finish

Rice Husks Composite Finish

Compreseed Flax PFA Finish

Mycelium Finish Timber Slats

Figure 67 | Facade Finish Pallet

Mycelium Composite Wheat

Wheat and Barley Straw

Barley Bale Straw

Rice Bale Straw

Rice Husks Bale

Figure 68 | Insulation Finish Pallet

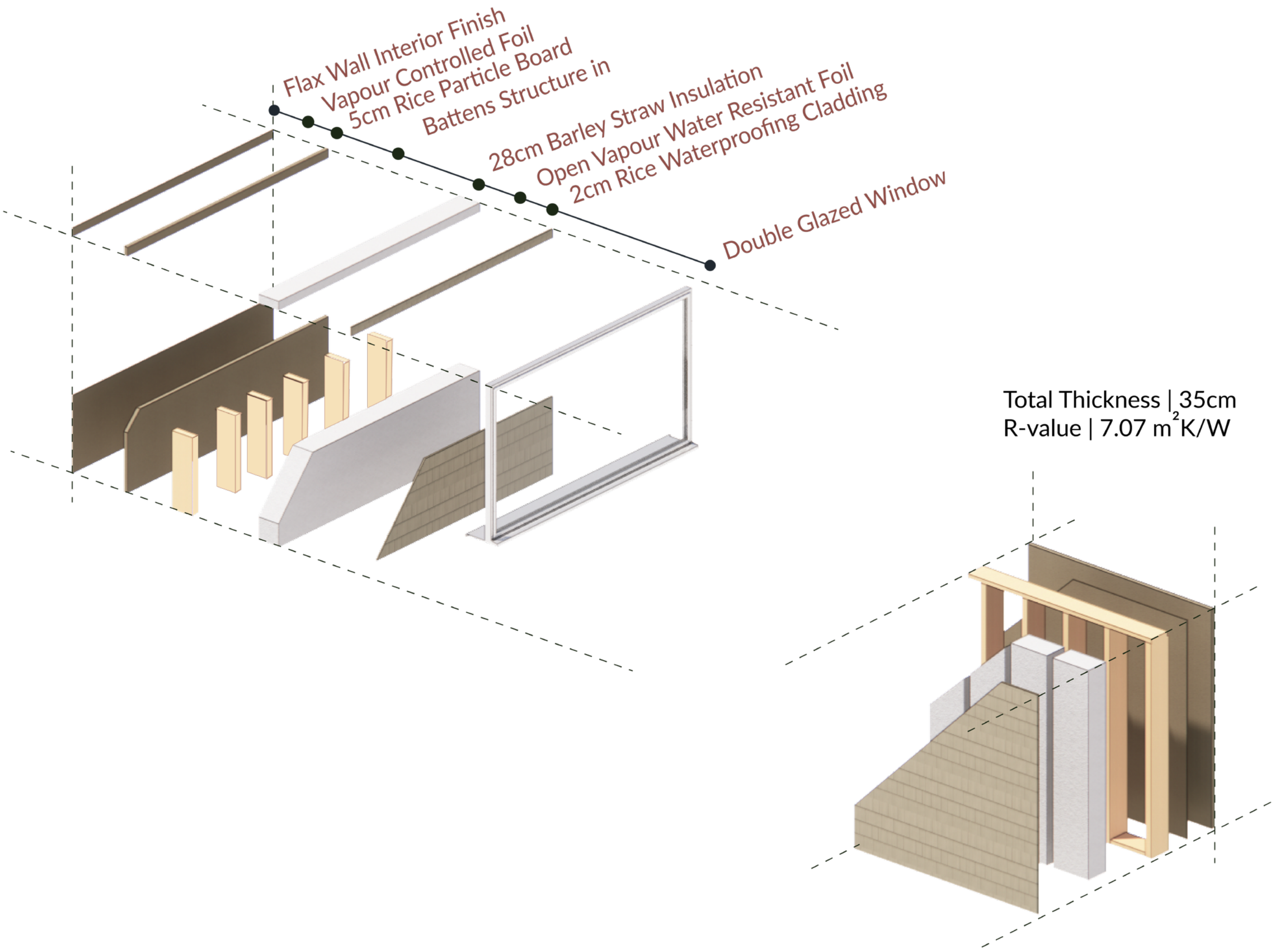


Figure 69 | Composition of Renovation Panel Construction

Table 28 | Vertical Farm Demands per panel and Material growth

Configuration	Material Content needed for one Renovation (kg)	# of Layers	# of Harvests	# of Stacks	Percent of Vertical Farm utilized
1	183663	164.5	31.6	6.508	27%
2	8476229	8805.7	2413	237	986%
3	1515762	1183.3	204.2	22.2	93%
4	2522140	2777.0	760.8	99.845	416%
5	1262997	1014.9	187.0	20.016	83%
Mycelium Composites		-	0.5	1	5%
Dandelion Rubber	652	85	11.6	1.0	4%
Tree Saplings		2.0	0.0143	1	5%

Table 29 | Compare Open Field Growing to Vertical Farm Configuration

Configuration	Field Area needed (m2)	Area Vertical Farm (m2)	Percent Compare
1	301086	2382	0.79%
2	16114503	86567	0.54%
3	2165374	8141	0.38%
4	5081898	36543	0.72%
5	1864707	7326	0.39%
Mycelium Composites			
Dandelion Rubber			
Tree Saplings			

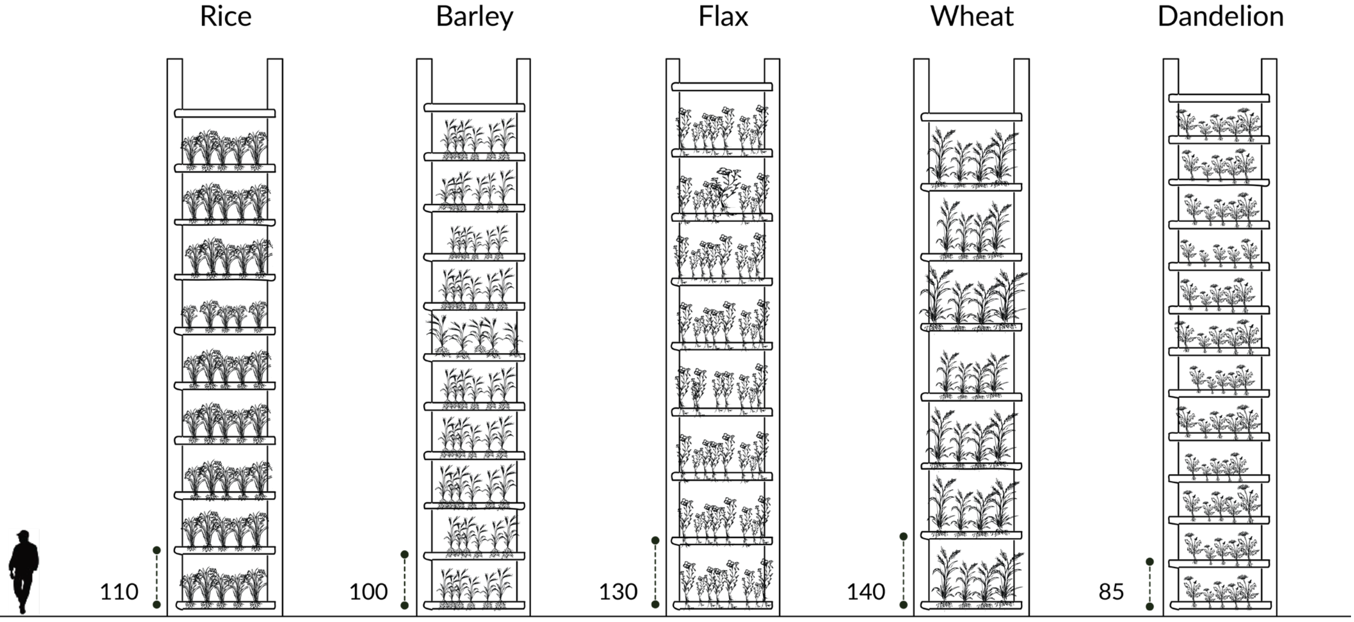


Figure 70 | Configuration of Vertical Farm to accomodate for Agriculture Bio-base Material Crops

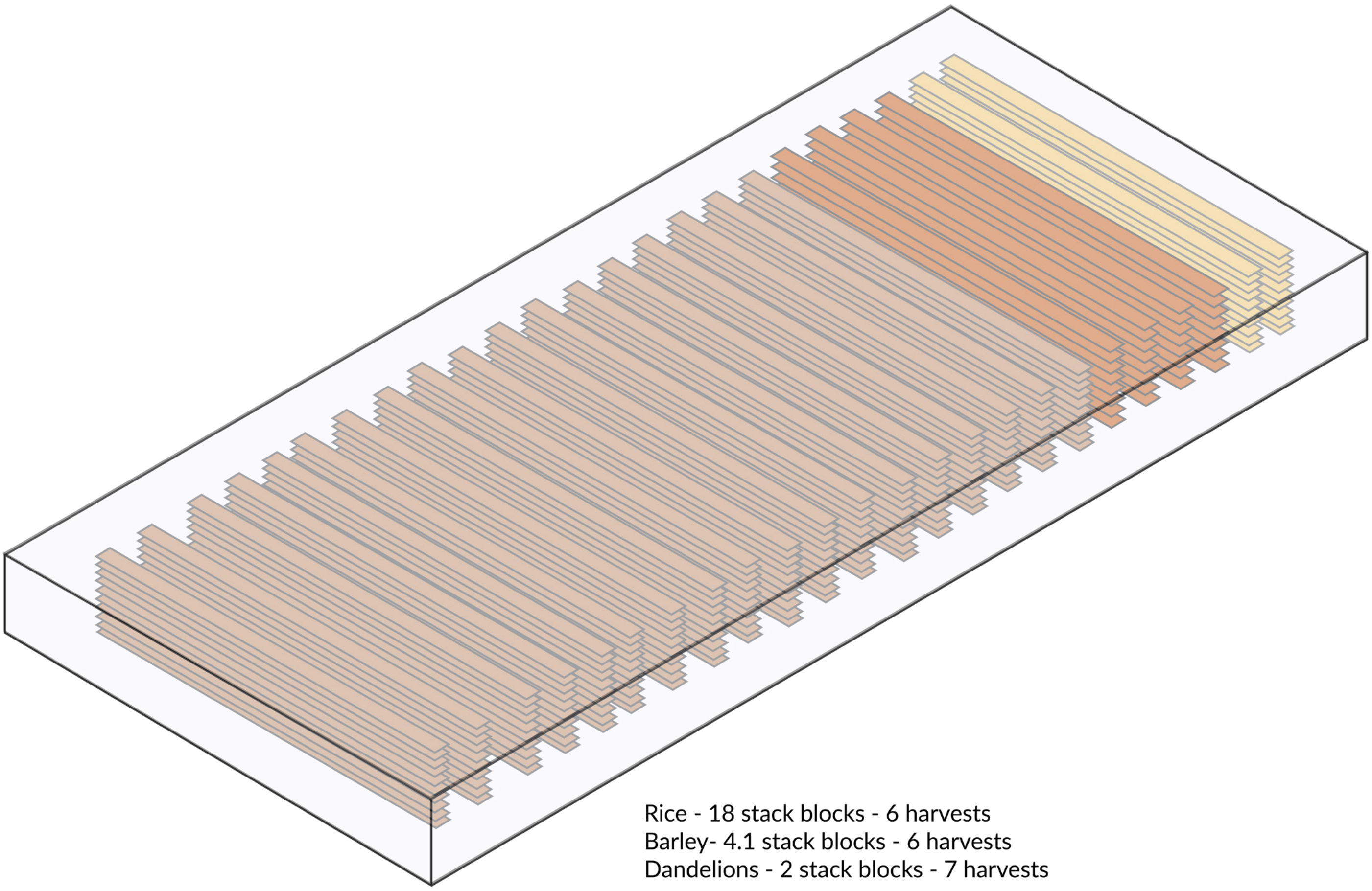
Acknowledging that panel 1, 4, and 5 are able to grow in less than one year, these are the most ideal panels for application in MUWI construction. However, considering the food demands of the area, panel 5 follows more closely to the dietary needs and context. For this reason, panel 5 with Barley Bale insulation, Rice Board and Rice Facade finish is the most ideal panel for application.

With the dimensions of 250x130 meters, the warehouse construction for bio-base material growing and collection is comparable to other warehouses found in the Netherlands. Within the construction, major corridors, 4 meters wide, and minor corridors, 3 meters wide, are designated surrounding the 24 total stacks of vertical farm.

The vertical farm accomodates for manufacturing time as two months and not all stacks are utilized during the entire year of material growth.

Table 30 | CEA for Panel 5 Figures

	Single Warehouse	CEA
Footprint (ha)	3.3	0.9
Footprint (m2)	32500.0	8784
Height (m)	11.2	-
Width (m)	250.0	3 Each Vertical Stack
Length (m)	130.0	122



Rice - 18 stack blocks - 6 harvests
Barley- 4.1 stack blocks - 6 harvests
Dandelions - 2 stack blocks - 7 harvests

Figure 71 | Configuration of Vertical Farm to for Renovating Single MUWI construction within a yea

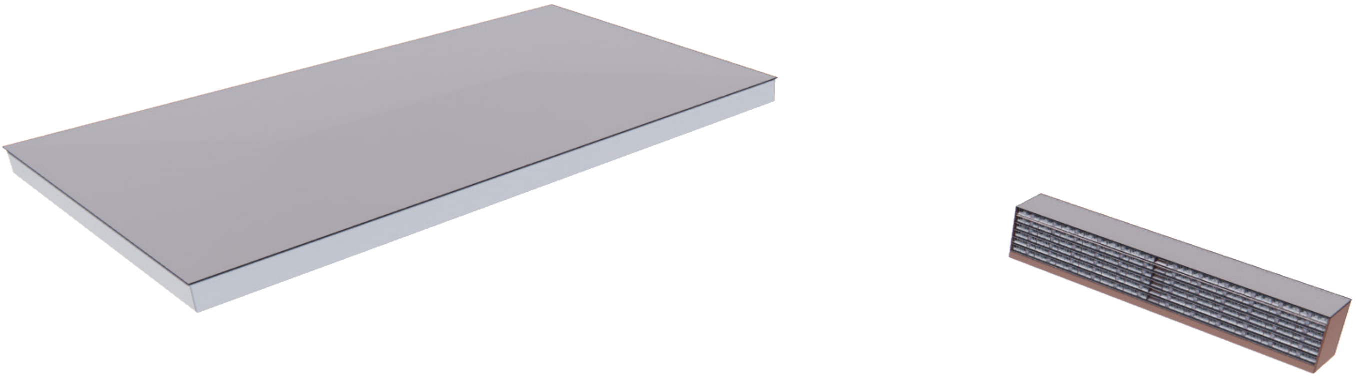


Figure 72 | Configuration of Vertical Farm relative to MUWI construction

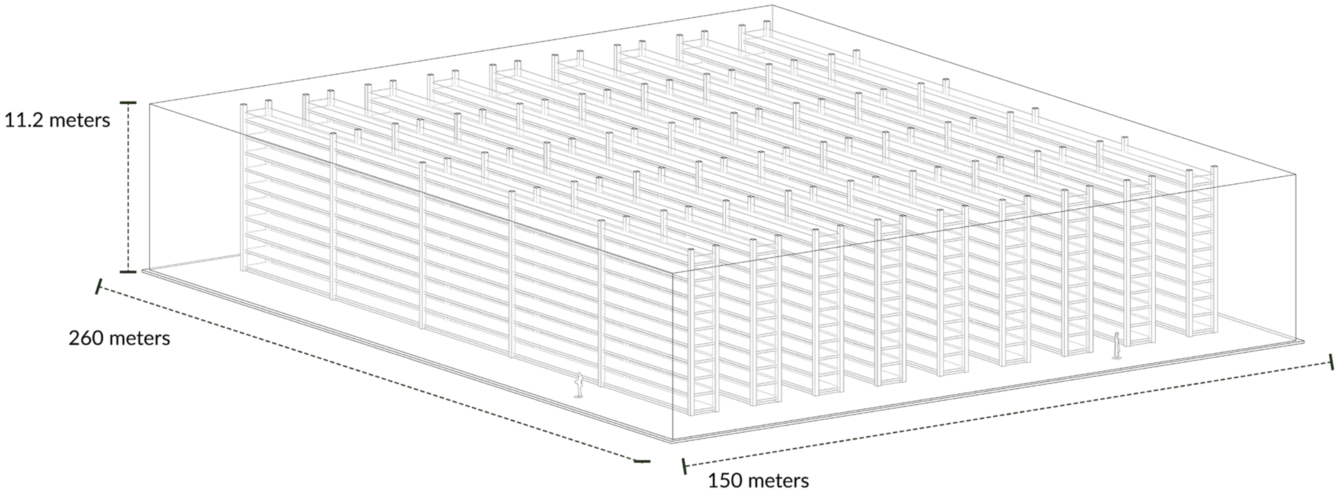


Figure 73 | Sizing of Vertical Farming Construction

Panel Spacing

After the consideration of the design constraints from above, the renovation panel design was done with the idea of a standard facade panel as well as a facade panel with the integration of a balcony integration. The facade panels are separated between full cover facade panel and openings facade panel. Each of these panels are different dimensions in order to accommodate for the building structure that MUWI construction system has standardized. Balcony construction is only recommended in order to reduce thermal bridges in the construction and to improve the efficiency of the construction, but is not required when completing a renovation. Removing the balconies would be considered to be a deep renovation rather than just an exterior renovation, thus is more intensive and requires the building to be unoccupied during renovation.

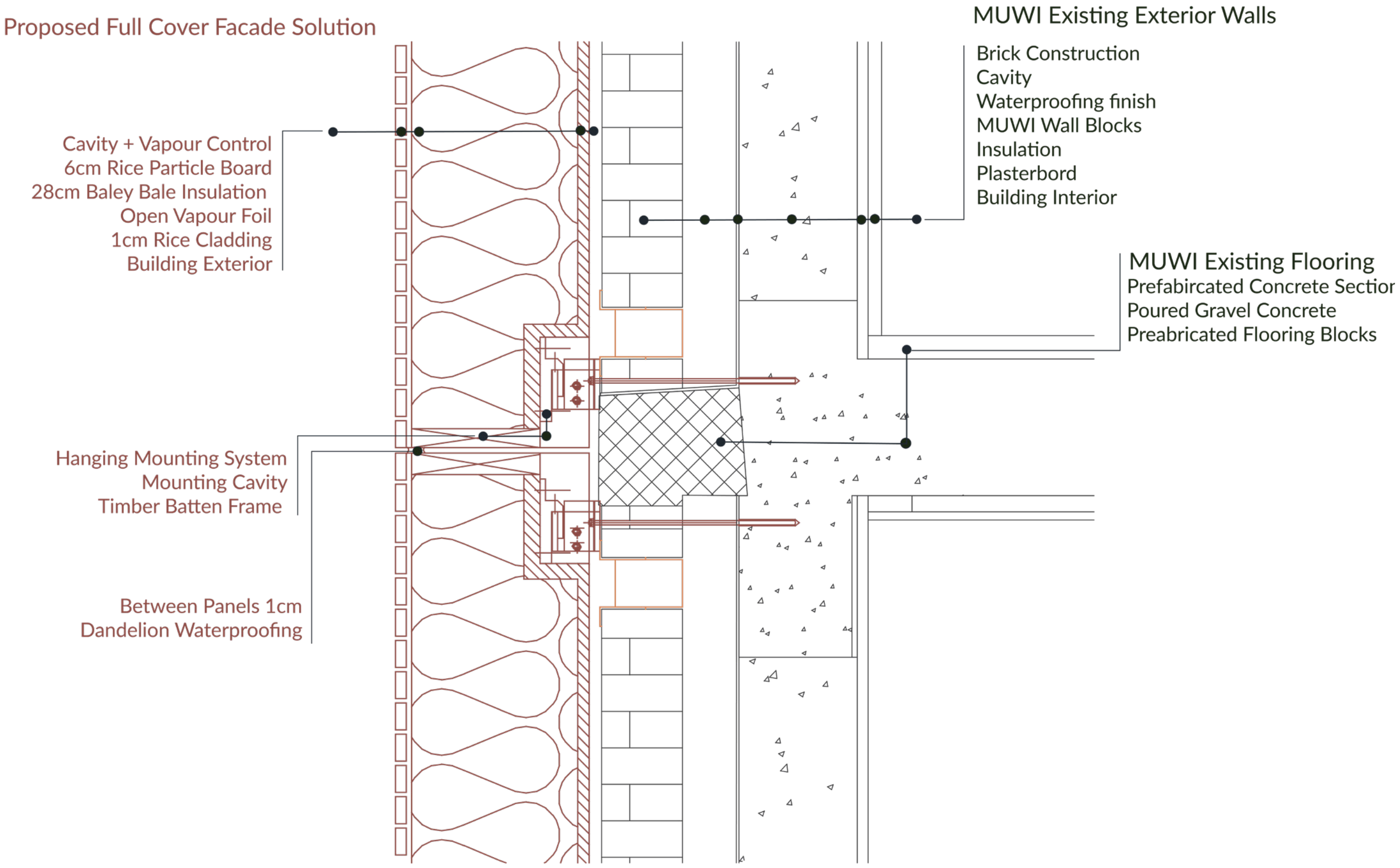


Figure 74 | Full Cover Detail

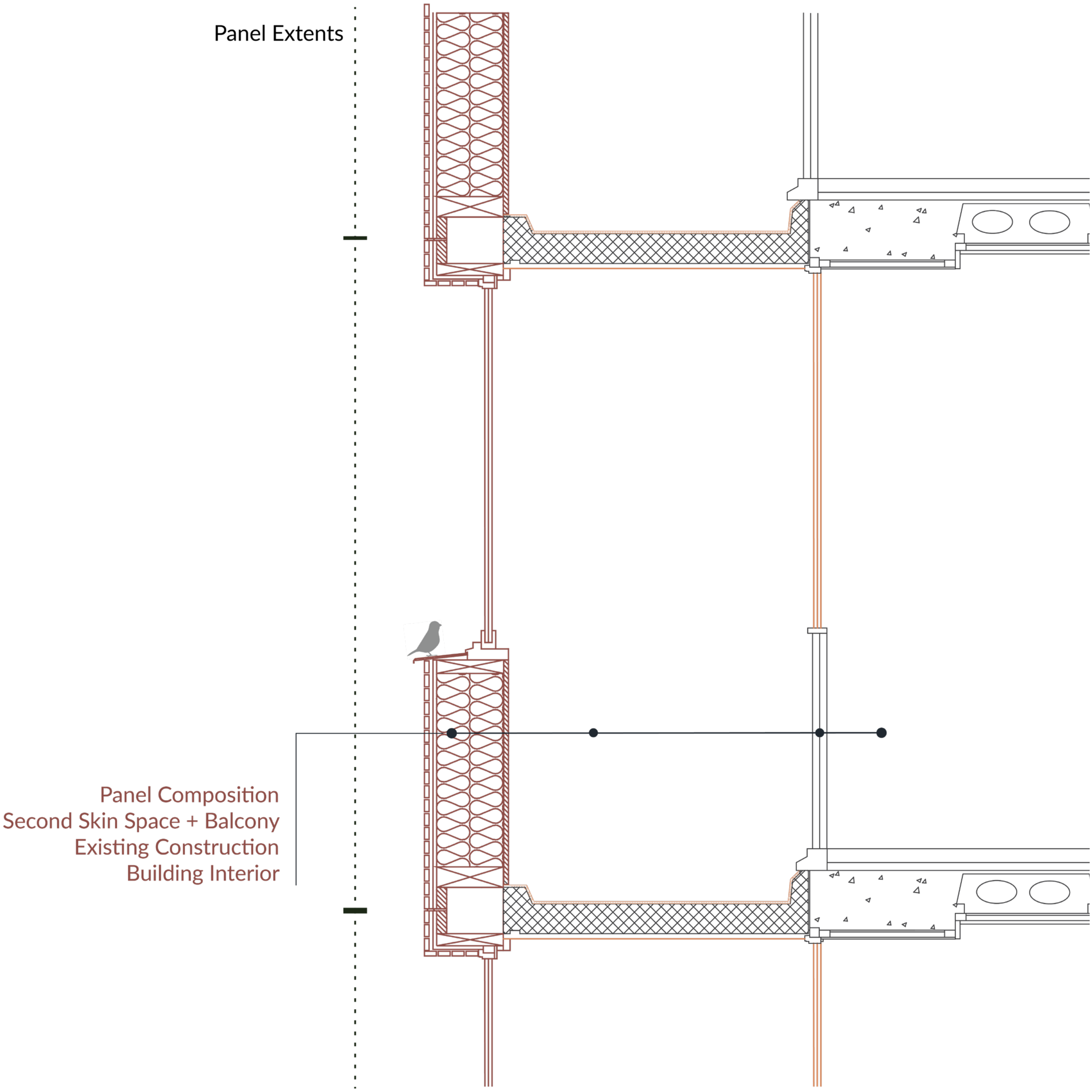


Figure 75 | Balcony and Second Skin Application Detail

Mounting

The mounting system of the panel is also based on the type of facade that is being renovated. The full cover renovation panels are hung to the load bearing walls of the MUWI construction while the opening façade panels will needed a substructure which is will span between the load bearing walls. Limitations of this hanging structure are found for the openings façade panels because of the restrictions of the in place balconies found in the construction.

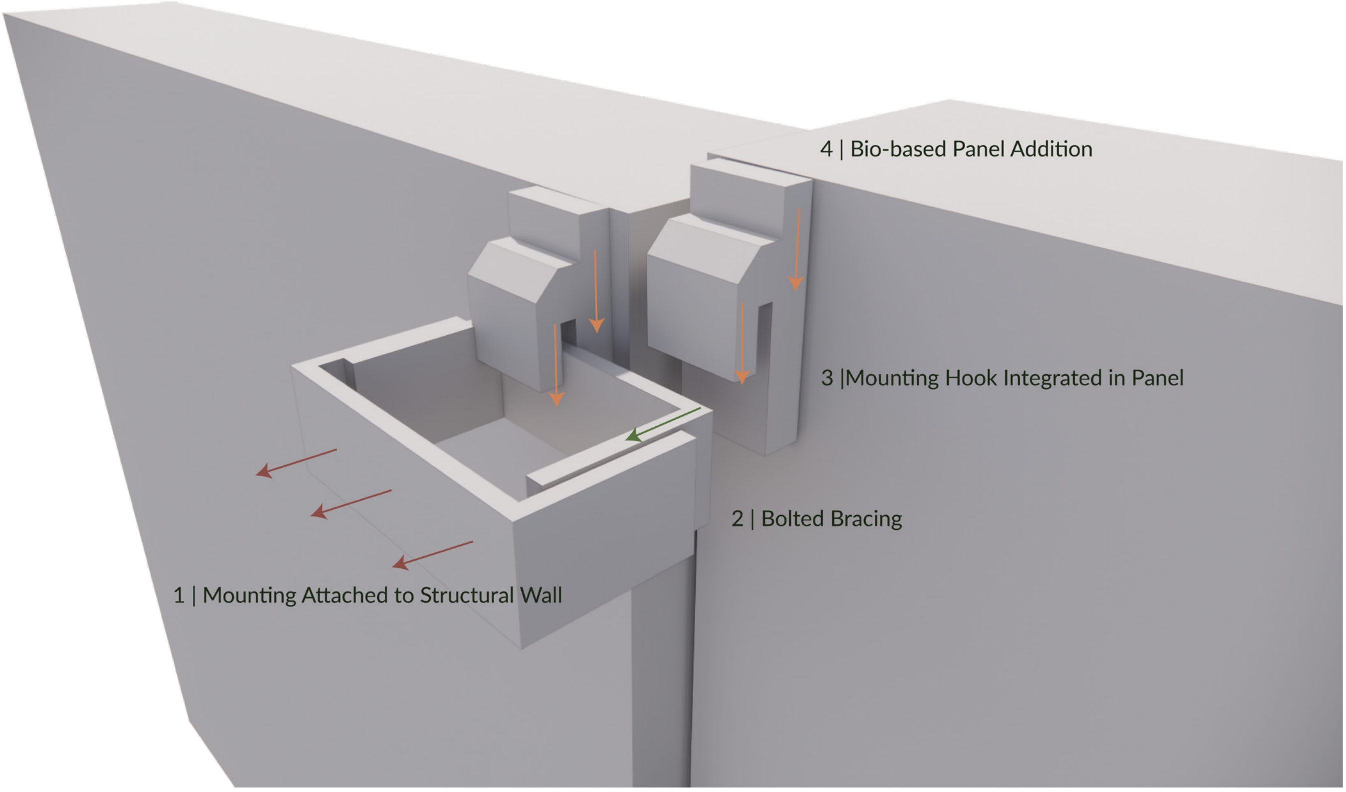


Figure 76 | Mounting System for Full Cover Panels

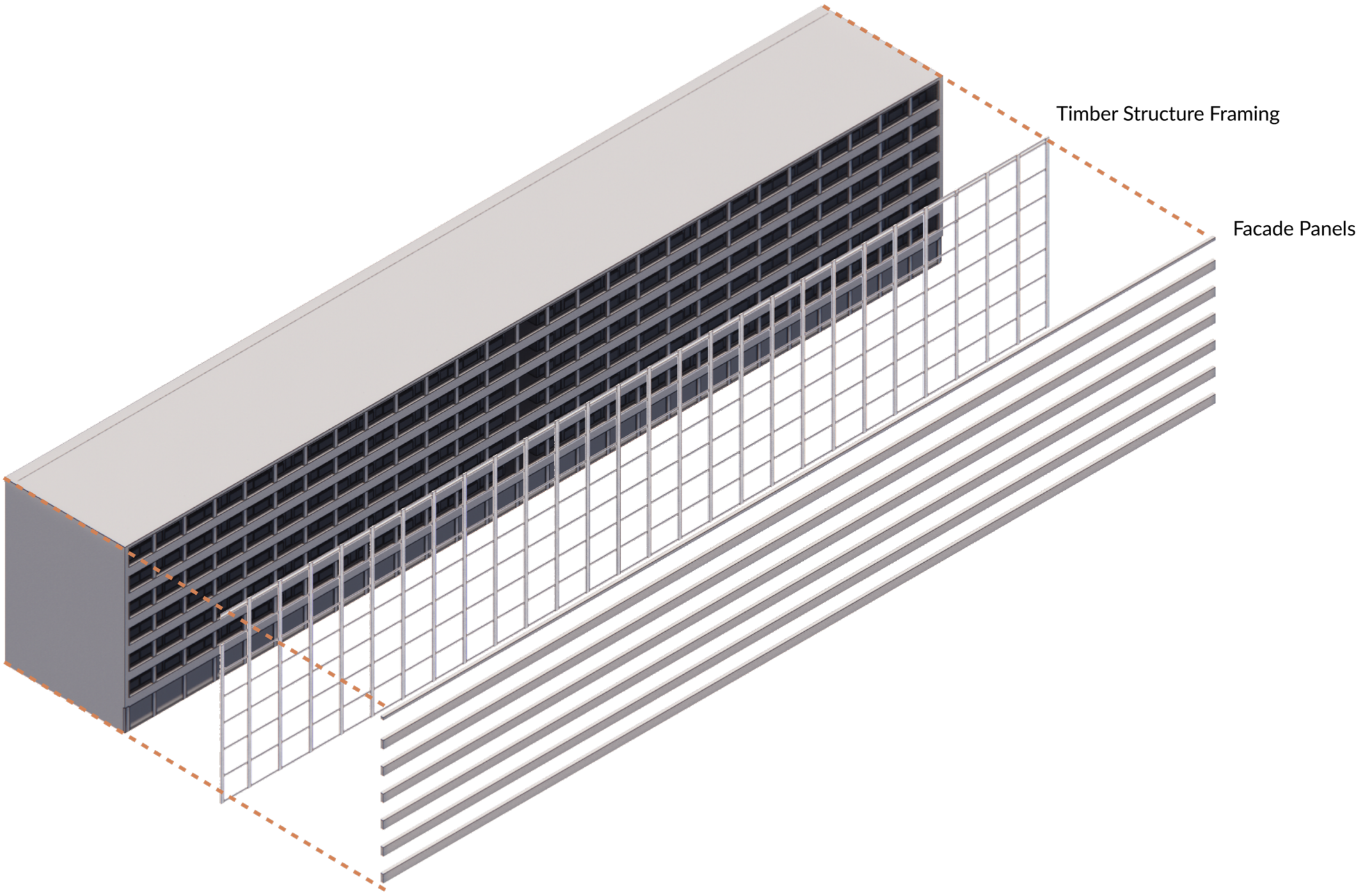


Figure 77 | Frame System on Facade

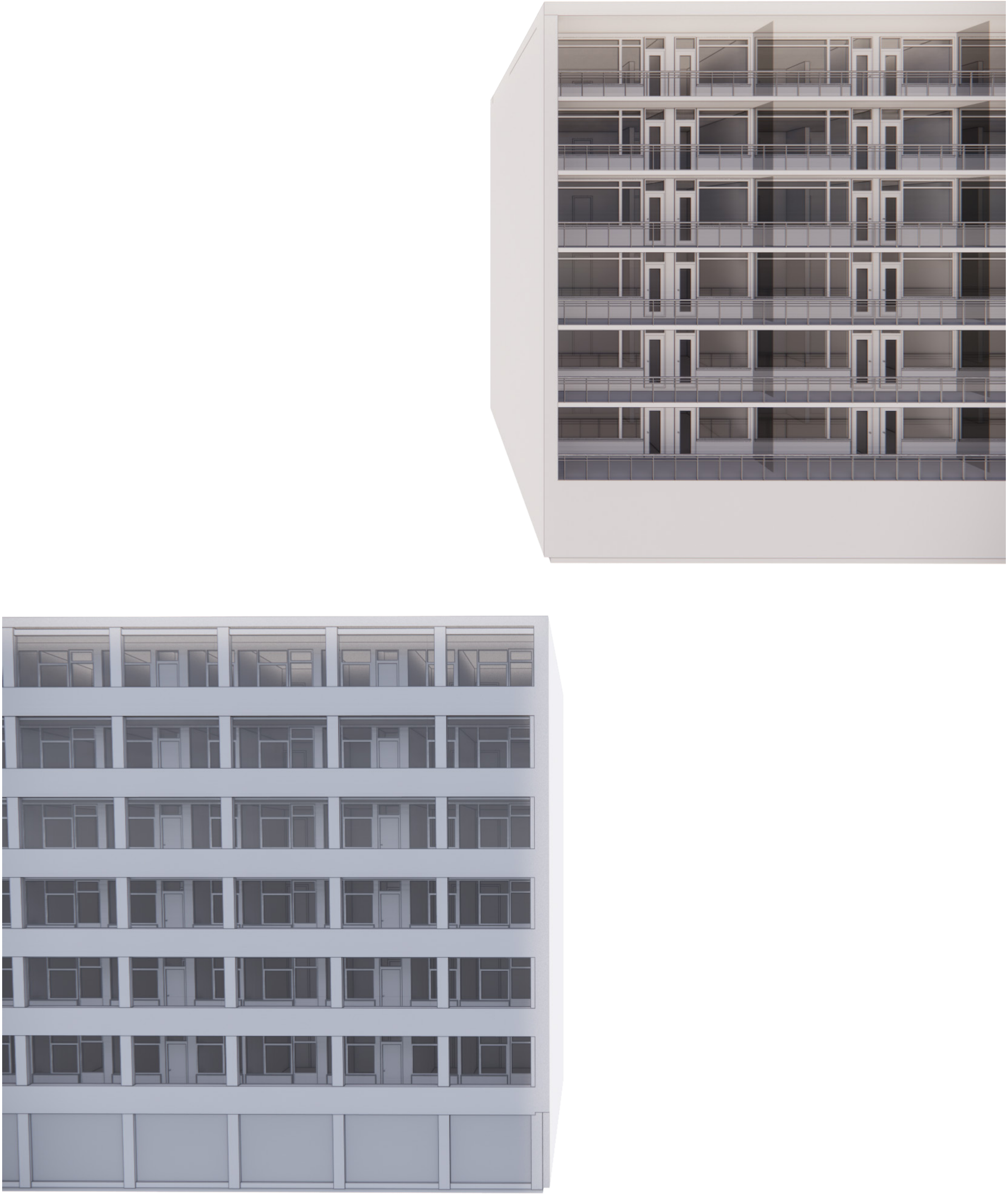


Figure 78 | MUWI Construction Before and After Addition Renovation

Figure 79 | MUWI Construction Before and After Interior Second Skin

Figure 80 | Barely, Flax, Rice, Mycelium and Timber Agriculture Bio-base Facade Comparisons and Options

Local Impact - Single Renovation

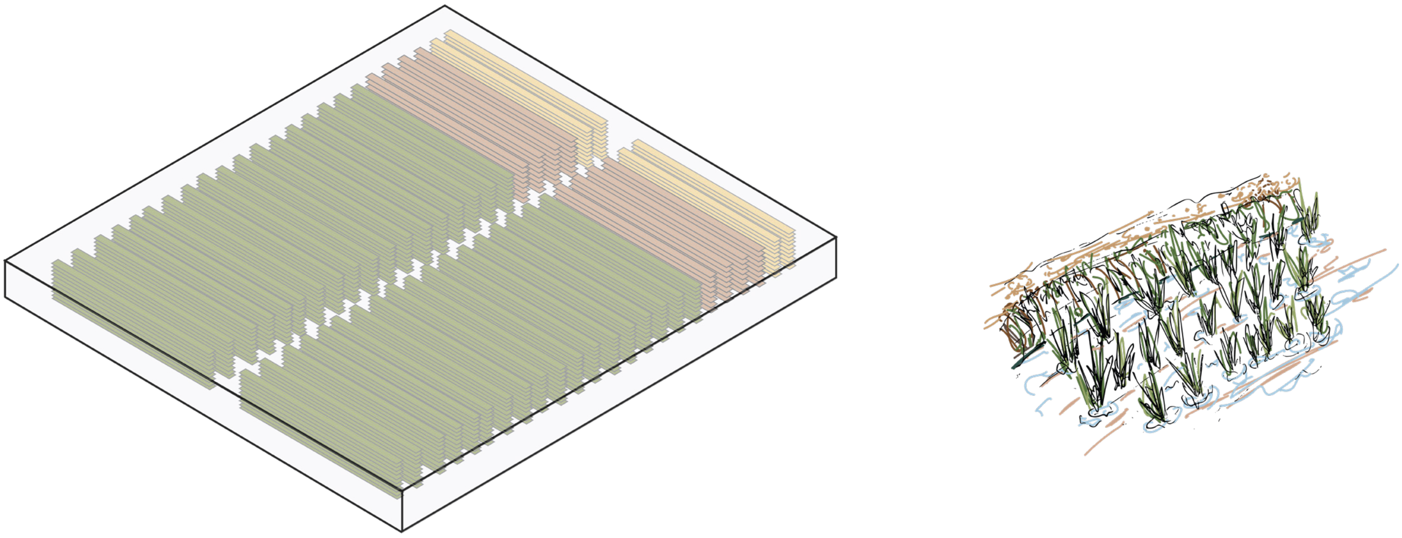
Noting that Configuration 1 will have less land demand due to the missing facade component, which comprises of the largest portion of material demand in the panels

Table 31 | Compare Open Field Growing to Vertical farm Configuration

Configuration	Single Renovation Output				Number of people fed in a year of single renovation			
Grain Output	Wheat	Flax	Barley	Rice	Wheat	Flax	Barley	Rice
1	10119				151			
2			283615				156659	
3				64961				1205
4		389517	3748			889307	2070	
5			7054	49328			3896	915

Table 32 | Single Renovation Compare Open Field Growing to Vertical farm Configuration

Confiruration	Compared field land (km2)	Compared field land for one renovation in one year (km2)	One Renovation in one Year (m2)	Compared field land for one renovation in one year (m2)
1	97	14	5333	13977677
2	1359	1	82749	994525
3	561	2	28650	2409774
4	766	2	62149	1763335
5	145	9	7816	9321857



1 CEA Construction | 0.03 km2

4.5 Futbol Fields

1 Open Field | 1.9 km2

260.5 Futbol Fields

Figure 81 | Scale of Land Use for Single MUWI Construction Renovation with Bio-base Materials

Regional Impact - All Renovation

Table 34 | MUWI Construction in the Netherlands

Number of MUWI constructions	37831
Years until 2050	28
Rate of Renovation per year (Dwelling/year)	1351

Table 33 | All Renovations Compare Open Field Growing to Vertical farm Configuration

Confiruration	Number of Vertical farm cosntructions Needed per Year	Dedicated Land to Vertical farm (m2)	Compared field land (ha)	Compared field land per year(km2)	Vertical farm land (km2)	Percent Difference between Vertical farm and Field
1	366	11906489	40680	406.8	11.9	2.93%
2	13315	432747637	2177242	21772.4	432.7	1.99%
3	1252	40697033	292565	2925.7	40.7	1.39%
4	5621	182678667	686619	6866.2	182.7	2.66%
5	1127	36621610	251942	2519.4	36.6	1.45%

Table 35 | Scale Amsterdam

Confiruration	Open Field # of Amsterdams	Vertical farm # of Amsterdam	Open Field # of Vodelpark	Open Field # of Vodelpark
1	1.9	0.05	866	25
2	99.3	1.97	46324	921
3	13.3	0.19	6225	87
4	31.3	0.83	14609	389
5	11.5	0.17	5360	78

Table 36 | Scale New York

Confiruration	Open Field # of Manhattan	Vertical farm # of Manhattan	Open Field # of Central Park	Vertical farm # of Central Park
1	4.68	0.14	119.3	3.5
2	250.26	4.97	6384.9	126.9
3	33.63	0.47	858.0	11.9
4	78.92	2.10	2013.5	53.6
5	28.96	0.42	738.8	10.7

Prioritizing panel configuration 5, the same material content grown in a Open Fields compared to the Vertical farm means that the area is reduce to 0.35% of the land that is demanded by open fields. By understanding the scale of which bio-base materials will have to be collected from traditional agriculture, further emphasizes that utilizing bio-base materials for construction through tradtiional means is highly laborus and will require higher level of centralization and standardization. By incorporating Vertical farm construction for bio-base materials allows the ease of localization and improve food accessibility.

When comparing the different panel construction to each other in relationship with the TU Delft campus for a single MUWI renovation, it can be seen that configuration panel 5, which is then applied in this proposal, utilises approximately half of Central Park, NYC for open feild cultivation. In comparison, a single footprint area of Met Museum building construction needs to be converted to a vertical farm producing rice, barley and dandelions.

In this example, found in figure 76, it can be visualized that if bio-base materials were to be sourced on a local scale, then taking a CEA approach will conserve valuable urban land. The dedication of land for future sustainable materials not only can transform the appearances of post-war housing in the Netherlands, but also has the potential of changing the methods and means of which we renovate with bio-base materials and cultivate with local WEF Nexus in mind.

Figure 82 | Scale of Land Use Relative to TU Delft for Single MUWI Construction Renovation with Bio-base Materials

To understand the scale of the required material collection that is needed for all the MUWI construction renovations with bio-based materials, relative scale is utilized. Following the approximately 1300 building renovations needed each year to renovate all of the MUWI constructions in the Netherlands by 2050, the space needed for open fields is more than 5 times more than the land needed for vertical farming. To place in perspective, the yellow highlighted is the land needed for open field cultivation while the orange highlighted area is the land needed for vertical farming, all relative to the New York City Tri-State area as well as the area around Amsterdam, and then compared to the size of Manhattan and inner city Amsterdam, respectively.

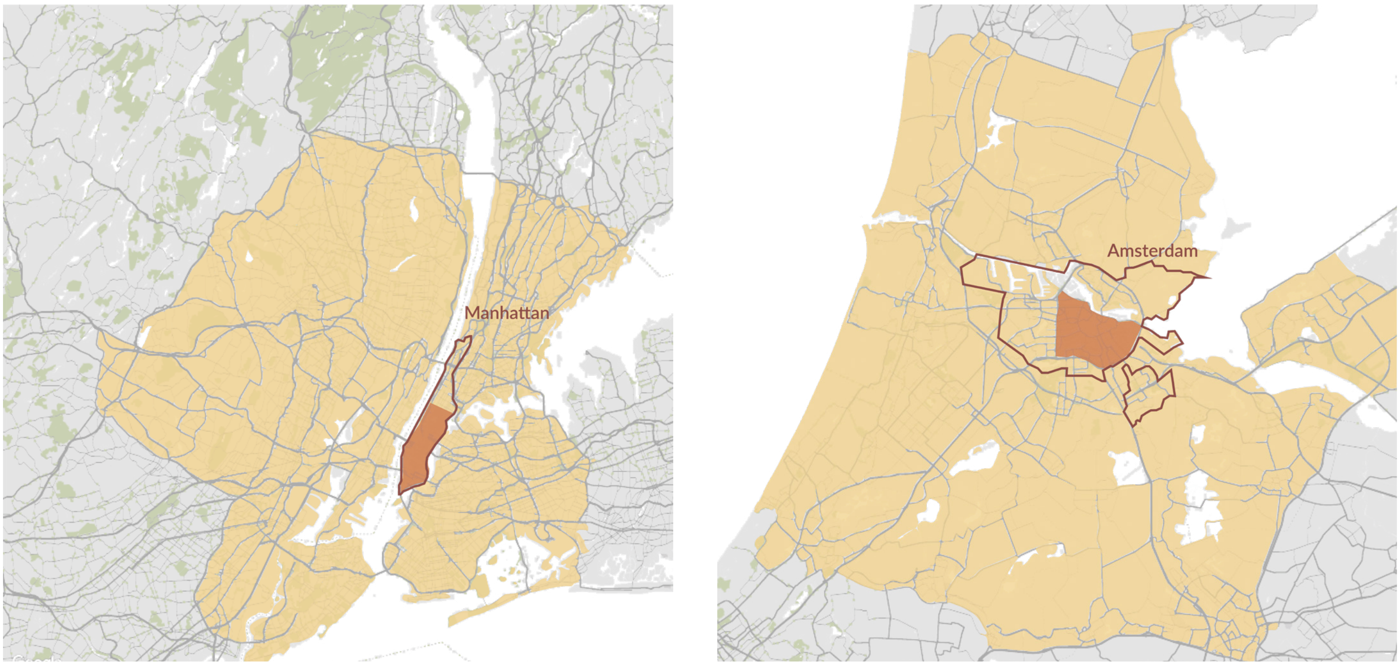


Figure 83 | MUWI Construction Requirements Open Field, yellow, and Vertical Farm construction, orange, every year assuming equal rate of renovation until 2050

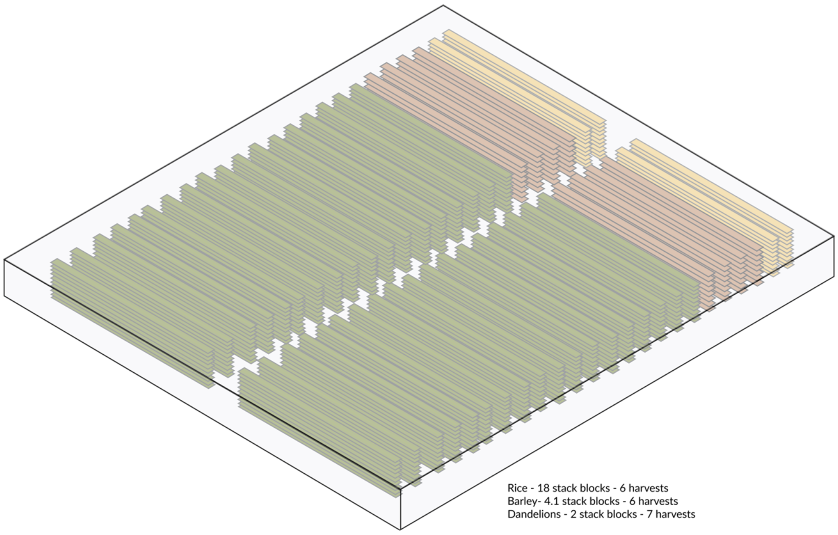
CIRCULAR DESIGN STORYLINE

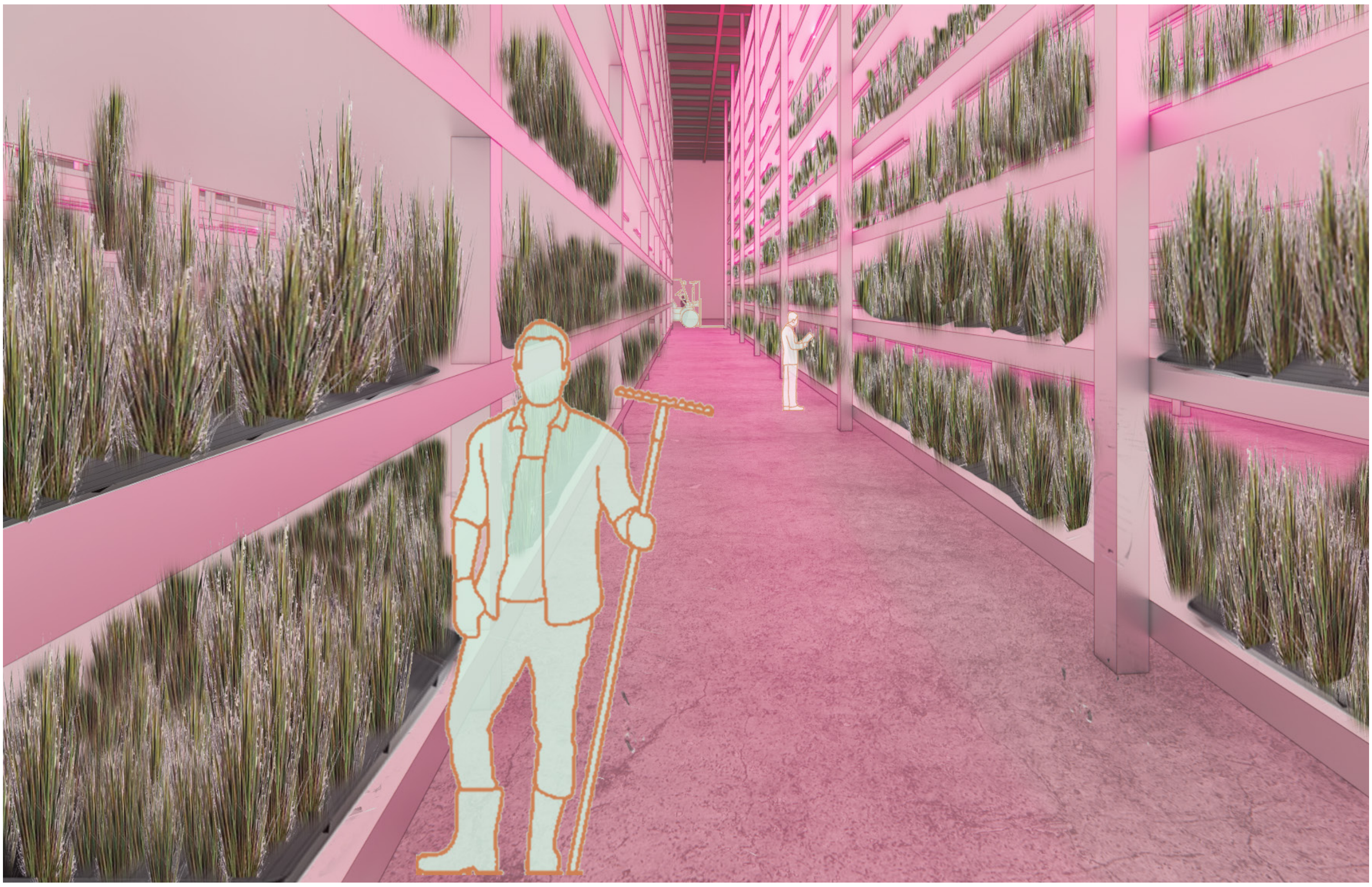
Origin

As MUWI constructions are commonly situated in shared Dutch neighbourhoods, it can be envisioned that a single neighbourhood with several MUWI constructions are in need of renovation due to the nZEB goals and the aims to reach improved energy efficiency through a panel renovation. In many cases, additional post-war housing construction types can be found and can be improved through similar exterior renovation strategies. Communities in this stage can acknowledge that the neighbourhood character is defined by brick and concrete constructions, making for a repetitive appearance. By acknowledging that the MUWI constructions are in need of renovation community members are able to set up a vertical farm for bio-base materials in close proximity for relative localized material growing and gathering.

Composition

After the construction and function of the vertical farm for bio-base materials in localized proximity from the location of MUWI renovations, agriculture plants can begin growing in the expected phase growing. This is with the acknowledgement that each agriculture plant demand specific growing periods in controlled indoor farming conditions. Through the improved automation of vertical farm cultivation, trays can be cultivated all at once and then separated between grain and straw. Straw material will then be dried for material processing in the vertical farm construction warehouse.



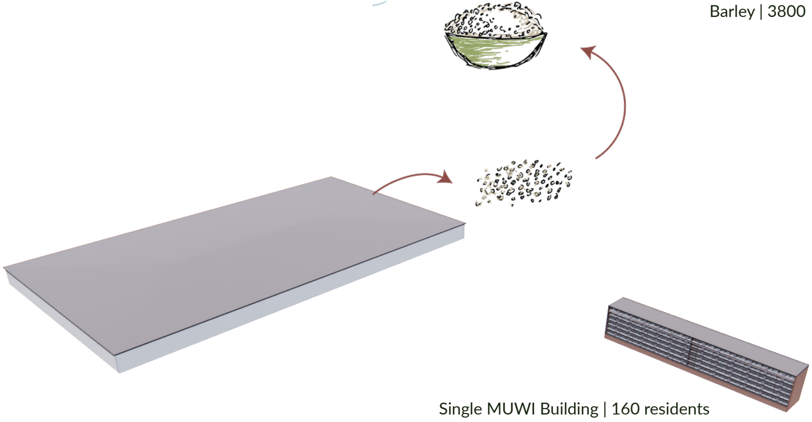


Assembly

After the material is collected and processed on-site of the vertical farm and then placed in panel construction, the panels can be transported to the site of renovation. Prior to panel placement, timbe framing construction is placed on the construction with additional structural reinforcement to carry the weight of the panels without placing any forces on the existing balcony construction. It must be ensured that the balconies do not carry any weight because they are cantilevered. Panels are mounted in place in the 370cm span timber frames with crane and construction workers. Panels placed on the full-cover facades can be placed through a mounting hanging system. Because of the ease of panel application, renovation is short-term and can be done in a step phasing.

Future

At the competition of the MUWI construction renovation, the neighbourhood has a changed exterior appearance which follows sustainable material applications for reducing material emissions set out by the UN Paris Agreements as well as the nZEB goals set by the EU. In this process, buildings are given a new type of characteristic and provide a new thermal buffer space in between the private residence and the exterior. Although the renovations are complete based on the specific plants grow in the vertical farm, the farm can be transformed to meet the requirements of the next building renovation. The vertical farm will continuously have grain by-product that is able to feed the local community as well can be transformed for changing crops uses and functions based on the innovation of bio-base material applications as well the improvement of vertical farming.



One Renovation in One Year
Rice | 49,000 kg
Barley | 7,000 kg
Rice | 915 people
Barley | 3800 people

Single MUWI Building | 160 residents

CONCLUSION AND REFLECTION

Conclusions

Hypothesis

MUWI post-war housing constructions are able meet thermal performance nZEB goals through panel renovations that are primarily assembled from responsibly sourced agriculture bio-based material grown in a localized CEA construction, which provides opportunity to foster resilience to land competition and environmental hazards while also acknowledging circular economy practices and the Water-Energy-Food Nexus.

-

This design has touched upon the many layers and scales at which bio-base material applications in renovations require as well as the introduction of a novel idea of utilizing CEA as a means of growing the bio-base materials.

Through the research and design it can be concluded that, in order to meet the bio-base material demands that are currently existing, large strides have to be completed in order to collect, manufacture and apply the bio-base materials made specifically from agricultural waste. When comparing the field size required for a set value of renovation material, the vertical farm utilizes a mere 1% of the open field required land. Further emphasis on the scale of which bio-base materials are required to be cultivated in order to shift to renewable materials and reduced embodied energy, shows that the integration of bio-base materials from fields into everyday construction requires further systematic planning than what is currently available.

The application of agricultural crops within a vertical farm is still an expanding field with technological advancements of improving the efficiency of vertical farm growth and harvesting as well as plant sciences developing selected breeding for bio-base materials. In this light, the project has touched upon a large scale interdisciplinary nexus between bio-base materials, vertical farming, and application in the built environment.

Through the utilization of vertical farming as tool for agriculture bio-base materials to become more resilient to land competition and environmental hazards, highlighted the interdependencies of the circular economy to the global and regional supply chain. By decentralizing the material collection process and placing the circular design approach for renovation panels within the localized community, creates an opportunity at which communities are able to create a resilient framework for implementing long term sustainable design practices through materiality. In such manner, bio-base materials have positive impact all the way from a single renovation panel for MUWI construction all the way to proposing systematic method of cultivating bio-base materials on a globalized scale.

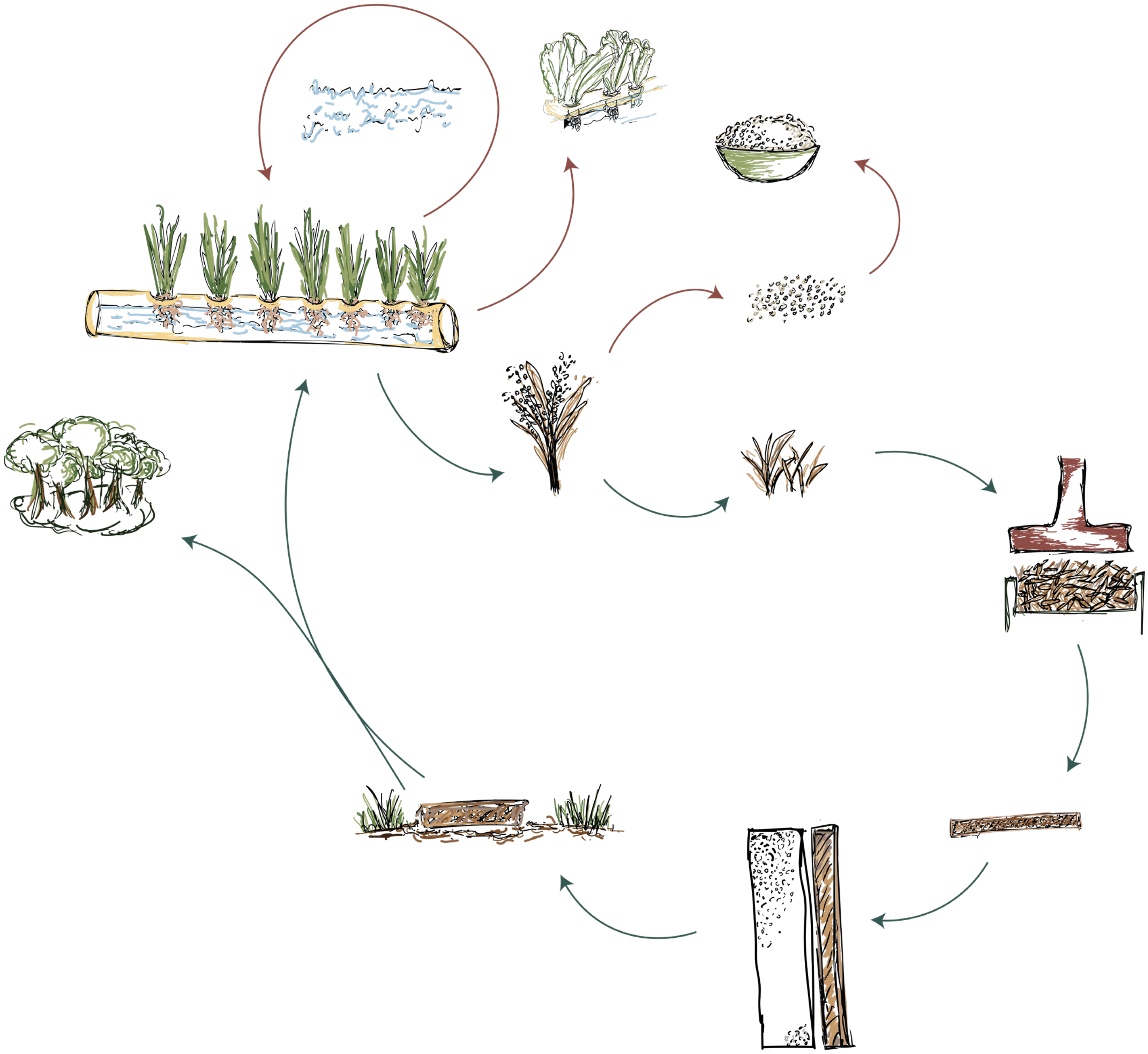


Figure 84 | Full Lifecyle of bio-base Materials harvested in CEA for building application

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APPENDIX

Appendix

Agriculture

Table 1 | Density of Farming Comparisons between open field, Greenhouse enclosure and Vertical Farming

Agriculture Type	Density of Growth (plants/hectare)	Average Plant Productivity (g/plant)	Produce Output (kg produce/hectare)
Open Field	11960	300	3530
Greenhouse Enclosure	25000	994	21868
Vertical Farm Enclosure	50000	450	42500

Sourced from (Balashova, Sirota, & Pinchuk, 2019) (Graamans, Baeza, Van Den Dobbelsteen, et al, 2018) (Clavreul, Butnar, Rubio, et al, 2017)

Table 2 | Water and Fertilizer Use and Conservation compared to Productivity of Various CEA practices and techniques

	Hydroponics					
	Media Soilless		Nutrient Solution			
	Open	Closed	Open	Closed	Aeroponics	Aquaponics
% Irrigation water Saving	80	85	85	90	95	80-85
% Fertilizer saving	55	80	68	85	85	85-99
% Productivity Increase	100	150	200	250	300	100-150
% Water Productivity	1000	1600	2000	3500	8000	1000-1600

Table 3 | Commonly utilized components and materiality for a vertical farm with Bio-base material replacement recommendation

Item	Function	Details	Materials	Potential Bio-Materials
Seedling Mat	Growing System	28x58x2.8 cm mat consisting of 300 cubes or cuboids, 2.3x2.3x2.8cm, with a small hole (7-10 mm in diameter, 5-10 mm in (depth). Painted black to prevent algae growth.	urethane	compressed coco coir or mycelium mat

Foamed Plastic Tray	Growing System	Dimensions 30cm by 60cm and 4cm high on the outer. Inner is 28cm by 58cm by 2.8cm	Polystyrene tray	Mycelium composite tray with bioplastic starch finish, bamboo
Culture Panel	Growing System	26 holes panels and placed in a hydroponic system with culture bed 1.4 cm thick, 29.8x59.6cm	Hard Board from Urethane	Mycelium composite, Rice husks, Kokoboard
Growing Medium	Growing System	Allows for drainage and can be placed in water for extended periods of time	rice hulls, woodchips, vermiculite, cellulose or and growing stones.	Bio-based materials already utilised
Holding Structure PFAL	Structure System	Structure needed for stacking 30cm VF	Stainless Steel	Timber or bamboo
Water Transport Pipes	Water System		PVC Plastic	Bio-plastic
Water Tank	Water System		Galvanised Steel	NA
Drainage Tank	Water System		Galvanised Steel	NA
Nutrient Solution Tank	Water System		Galvanised Steel	NA

Bio-base Materials

Table 4 | Initial Bio-base material selection List, characteristics and applications

Crop Name	Part of Plant	Raw material Utilised	Renovation Uses
Mycelium	Crop	Mycelium	3D printing, Insulation, Particleboards, Facades
Crop Residue	Byproduct	Leaves / Crop Residue, Agriculture Pulp	Flooring, Insulation, Particleboards
Rye	Byproduct	Rye Straw	Flooring, Particleboard

Soybeans	Crop	Soybean adhesive, Soybeans	Bio-polymer
Barley	Byproduct	Barley Straw	Flooring, Insulation, Particleboard
Wheat	Byproduct	Wheat Straw	Insulation, Particleboard
Rice	Byproduct	Rice Husks Ash, Rice Husks	Bricks, Facades, Flooring, Insulation, Particleboards, Wall Finish
Peanuts	Byproduct	Peanuts Husks, Peanut Shells	Flooring, Particleboard
Alfalfa	Crop	Alfalfa	Particleboard
Potatoes	Crop and Byproduct	Potato, Potato Peelings, Starch blends	3D printing, Bio-polymer, Flooring, Particleboard
Agave	Crop	Agave	Insulation, Bricks

Table 5 | Material comparison of various insulation types with the same R-value outcome

Type	Insulation Type	Thermal Conductivity	R value	Thickness (mm)
Rigid Foam	PUR	0.021	7.142857	150.0
Processed	Rockwool	0.03	7	210.0
Rigid Foam	EPS	0.03	7	210.0
Rigid Foam	PS	0.036	7	252.0
Bio-Base	Mycelium Composite Straw	0.04	7	280.0
Bio-Base	Barley	0.04	7	280.0
Processed	Fiberglass	0.04	7	280.0
Bio-Base	Crop Residue	0.041	7	287.0
Bio-Base	Hemp Wool	0.045	7	315.0
Bio-Base	Rice Bales	0.051	7	357.0
Bio-Base	Wheat	0.064	7	448.0
Bio-Base	Rice	0.086	7	602.0
Bio-Base	Mycelium	0.18	7	1260.0

Figure 6 | Particleboard Strength properties of various bio-base compositions

Raw material	Cellulose (%)	Modulus of Rupture (MPa)	Modulus of Elasticity(MPa)	Internal Bond Strength (MPa)	Tensile Strength		Density (kg/m3)
					2 h %	24 h %	

Tomato stalks / Crop Residues (16% PU; 35 kg/cm2) [1]	43.11	20.5	1123.9	0.91	10.6	18.1	950
Flax shives [1]	47.7	11.9	2250	0.24	n/a	35	650
Wheat [2]	n/d	20.6	1879	n/d	2.31	11.1	n/d
EU 312:2010 (General Use type P1)	n/d	10	n/d	0.24	n/d	n/d	n/d
EU 312:2010 (Furniture Use type P2)	n/d	11	1600	0.35	n/d	n/d	n/d
EU 312:2010 (Non-load bearing Under humid conditions P3)	n/d	14	950	0.45	8	14	n/d

1. Papadopoulou, Chrissafis, 2017
2. Rojas-Leon, A., Guzmán-Ortiz, F. A., Bolarín-Miró, A. M., Otazo-Sánchez, E

Table 7 | Bio-base Material Selection Existing Applications

Bio-base Source	Insulation (Approximate R-value)	Board	Facades	Sealants
Wheat	Organoid Technologies GmbH (0.045)	Greenfield- 95% wheat straw with nontoxic MDI	-	-
Flax		Board and additional paster/finishing	Nabasco 8010 – Flax and Barley, reeds, drinking water treatmenet waste, and biobased polyester resin	-
Barley	Organoid Technologies GmbH - Hay on a wood panel (0.052)	Organoid Technologies GmbH	Nabasco 8010 – Flax and Barley, reeds, drinking water treatmenet waste, and biobased polyester resin	-
Rice	Ricehouse - 100% rice husks (0.036)	ECOboard- MDI and rice husks Kokoboard - Raw straw materials, rice straw, adhesive Bioflexi- 80-90% of rice or renewable raw material	Sonite - Composit mixture-Tiles Resysta- 60% rice husks, 22% salt, 18% mineral oil Organoid Technologies GmbH	Rice grains for starch based adhesives

Dandelions	-	-	-	Taraxa - Rubber Sealant
Mycelium Composites	Greensulate (0.18) MYX (0.04)	Myco Board	Xyhlo - fungus and natural oil on timber, prolonging lifespan of the façade Krown.Bio Design	-

Table 8 | Processing Table for material types and applications with CO2 emissions approximate

			CO2 Footprint kg CO2 per kg material							
-	Material	Density (kg/m3)	Production (CO2 kg/ kg)	Water Use (L/kg)	Processing Type	Processing (CO2 kg/ kg)	Recycling (CO2 kg/ kg)	Combustion (CO2 kg/ kg)	Heat Recovery (MJ/kg)	Landfill
Insulation	Fiberglass	2550	3	90		X	X	X	X	O
Insulation	Mineral Wool	33	6.53	167	Grinding	1.71 per kg	X	X	X	O
Insulation	PUR	28	2.3	433	Moulding	1.59	X	2	21.2	O
Insulation	PS	1040	2.5	150	Moulding	1.24	1.43	3.3	39.9	O
Board	Particle Board	450	0.6	665	Coarse machine	0.05 per kg	X	1.73	19.7	O
Board	Dense Fibre Board	600	17.6	665	Coarse machine	0.5 per kg	X	1.73	19.7	O
Façade	Brick	1930	0.229	5.27	Grinding	0.727 per kg	O	X	X	O
Façade	Softwood	440	0.348	665	Coarse machine	0.0923	O	1.76	20.7	O
Sealant	Epoxy Matrix	1750	5.88	192	Filament Winding	0.206	X	0.968	12	O

Renovation

Table 7 | Outline of existing construction insulation values in the Netherlands, investigating the number of renovations and façade upgrades to follow the nZEB goals.

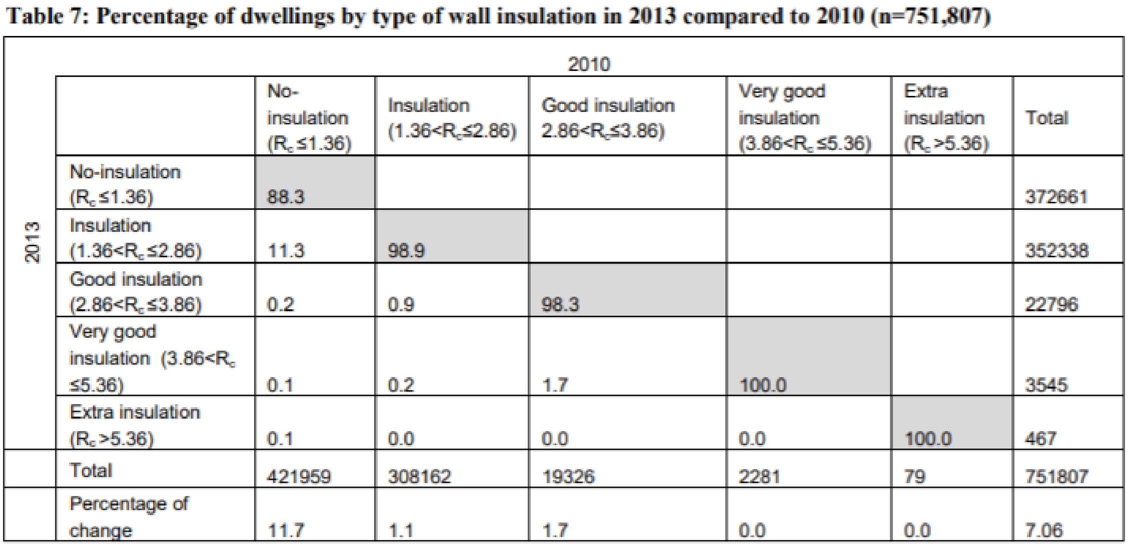

Table 7: Percentage of dwellings by type of wall insulation in 2013 compared to 2010 (n=751,807)

		2010					
		No-insulation (R_c ≤1.36)	Insulation (1.36<R_c≤2.86)	Good insulation 2.86<R_c≤3.86)	Very good insulation (3.86<R_c ≤5.36)	Extra insulation (R_c >5.36)	Total
2013	No-insulation (R_c ≤1.36)	88.3					372661
	Insulation (1.36<R_c ≤2.86)	11.3	98.9				352338
	Good insulation (2.86<R_c ≤3.86)	0.2	0.9	98.3			22796
	Very good insulation (3.86<R_c ≤5.36)	0.1	0.2	1.7	100.0		3545
	Extra insulation (R_c >5.36)	0.1	0.0	0.0	0.0	100.0	467
	Total	421959	308162	19326	2281	79	751807
	Percentage of change	11.7	1.1	1.7	0.0	0.0	7.06

(Sourced Filippidou, Nieboer, Visscher, 2016)

Table 8 | Post-War Housing Construction types in the Netherlands

Typology	Number of houses, in 2017	% in the Housing Stock
MUWI	37831	11.1%
RBM	32292	9.5%
Coegnet-groep	31378	9.2%
BMB	29369	8.6%
EBA-giet-bouw	19291	5.7%
Pronto	17836	5.2%
Rottinghuis	17000	5.0%
Kottelbeton	15394	4.5%
VAM	14000	4.1%
BBB - Z-65	13118	3.8%
Wilma II	12579	3.7%
Pe-Ge	12000	3.5%
Smit II	10000	2.9%
Airey	9975	2.9%
ERA	9810	2.9%
Elementum-Larsen & Nielsen	8574	2.5%
Vaneg	7000	2.1%
Bakker VB	5643	1.7%
Welschen	5602	1.6%
BG	5581	1.6%
Tramonta	4845	1.4%
EBO II	4586	1.3%
Schokbeton H-I	4000	1.2%
Simplex	3800	1.1%
Bitcon	2245	0.7%
Sanders	1883	0.6%

Bouwvliet	1616	0.5%
Huco	1042	0.3%
GBS	643	0.2%
Heykamp L	589	0.2%
Lisman	521	0.2%
PBG	481	0.1%
Breda	446	0.1%
TOTAL	340970	

Table 9 | Top Four Post war Housing Construction types in the Netherlands

System	% of Building Stock	Type of Construction	Parapet for window	Roof Type	Balcony	Primary Facade Types	Secondary Facade Type
MUWI	11	Stacked	no	Flat	yes, 1.25m cantilever	Full Glazing	Full Cover
RBM	7	Cast in Place	no	Flat	Yes, cantilever, both facades	Brick and Glazing Combination	Full Cover
Coignet-Groep	9	Heavy construction	Yes	Flat	Loggia and cantilever, single façade	Brick and Glazing Combination	Full Cover
BMB	8	Heavy construction	Yes	Flat	Loggia and cantilever, Single Façade	Brick and Glazing Combination	Full Cover

Table 10 | Construction and Insulation Values of existing constructions

Construction Type	Component	Notes	GIVEN R-value(m2 h C/ kcal)	GIVEN k-value (kcal/m2 h C)	U-value (W/m2K)	R-value (m2K/W)	Existing R-Values
MUWI	Exterior Façade	Construction Approval		1.400	1.628	0.614	0.614

MUWI	Floors			1.400	1.628	0.614	0.614
MUWI	Construction	Brick Construction		1.900	2.210	0.453	
RBM	Construction	Cavity Construction with Brick	0.5	2.000	2.326	0.430	
RBM	End Facades		0.9	1.111	1.292	0.774	0.774
RBM	Floors	Thickness of 11cm and 3cm finishing					
Coignet-Groep	End Facades	Cavity construction with 1.5cm Polystyrene	0.8	1.250	1.454	0.688	
Coignet-Groep	Outer walls	Sandwich pane with gravel concrete and 4cm polystyrene	1.5	0.667	0.775	1.290	1.29
Coignet-Groep	Floors	Without Finishing layers 18cm (alternatively 16cm)	0.25	4.000	4.652	0.215	
BMB	Outer walls	Medium-weight concrete thick, with PS Foam 1cm , 19.3 cm +Brickwork	1.05	0.952	1.108	0.903	0.903
BMB	Outer walls	Medium-weight concrete, gravel concrete outdoor cavity + 1cm PS Foam (Alternatively 1.5 PS or 1 PS with and without Brickwork)	1	1.000	1.163	0.860	0.86
BMB	Floors	Solid Concrete 10cm-14cm (Alternatively with cavity 17-18cm)	0.1	10.000	11.630	0.086	0.1
BMB	Outer walls Façade Construction	Sandwich panel 20cm, with cavity wall, 1.5cm PS foam	1.1	0.909	1.057	0.946	0.946

(Priemus, Van Elk, 1971)

Table 11 | Comparisons of all renovation case studies investigated

Project Name	Country	Typology	Complete Year	Primary Materials in Renovation	Type (Interior,	Method (Panels, Design)	Inhabited

					Exterior, Deep)		
Old Thread Storage Building	Spain	Low Rise	1940	Timber	Interior	Design	X
Rozemaai Housing	Belgium	High Rise	1970	Glass Balcony, Insulation	Deep	Design	x
Marco Pololaan	Netherlands	Mid Rise	1960	Timber	Example of each	Design	O
Urban Renewal	Netherlands	High Rise	1960	Glass Balcony, Insulation	Exterior	Design	O
The Horsten	Netherlands	Mid Rise	1970	Glass Balcony, Insulation	Exterior	Design	0
Camera Obscuradreef	Netherlands	High Rise	1965	Insulation, Timber	External	Design	0
Landlust	Netherlands	Mid Rise	1930	Insulation and Finishes	Interior	Design	0
Park Hill	UK	High Rise	1957	Bright Aluminium panels and large glazing sections	Deep	Design	X
Prinsessenflats	Netherlands	High Rise	1964	Balcony and roof insulation	Exterior	Design and Panels	X
BGDD	Netherlands	Low Rise	1970	Wood, Cellulose, Recycled Paper	Exterior	Design Standard	O
Le Lignon	Swiss	High Rise	1963	Standard, Insulation	Exterior	Design, Panel options	O
2ndSKIN Research	Netherlands	Mid Rise	1960	Insulation	Deep	Panel	O
Gap3 Skin	Austria	Mid Rise	1960	Timber and lamination surface	Exterior	Panels	O
PEER	Canada	Low Rise	1970	Stonewood , Fibrous insulation	Exterior	Panels	O
P2ENDURE	Italy	Mid Rise	1970	Mineral wool, gypsum Board	Exterior	Panels	O
RC Panels	Netherlands	Low Rise	1965	polyester, OSB, EPS and finishing layer	Exterior	Panels	O

Bertim	Norway	Low Rise	1980	Timber, OSB, Rockwool	Exterior	Panels	O
Woodside Multistory	UK	High Rise	1960	Standard, Insulation	Exterior	Panels	O
Dextall	USA	High Rise	1950	Mineral Wool, steel	Exterior	Panels	O

Table 12 | Comparisons of all Panel Case Studies and Breakdown of Panel Composition

Rc Panel	Function	Thickness (mm)	Thickness (m)	Thermal Conductivity (W/mK)	R Value (m2K/W)
Rc Panel					
Polysester/Polyethylene Lower Density	Vapor Barrier	0	0	0.417	0
OSB/ Parallel to the Board	Structure	12	0.012	0.300	0.04
EPS	Insulation	210	0.21	0.030	7.000
Polysester	Vapor Barrier	0	0	0.417	0
Finish/Brick Clay	Exterior Finish	20	0.02	0.500	0.04
Construction Values (Expected R value 7)		242	0.242		7.08

Bertim Panel Without Intergration	Function	Thickness	Thickness (m)	Thermal Conductivity (W/mK)	R Value (m2K/W)
Compressible Rockwool	Insulation	50	0.05	0.03	5.55556E-05
Polyester	Vapour Control	0	0	0.417	0
OSB	Structure	12	0.012	0.300	0.04
Rockwool (w/Batten 140x62mm)	Insulation	140	0.14	0.04	3.5
Waterproof Sheet	Vapour Control	0	0	0.417	0
Finish Brick	Exterior Finish	20	0.02	0.901	0.0222
Construction Values		222	0.222		3.562255556

Bertim Panel With Intergration	Function	Thickness (mm)	Thickness (m)	Thermal Conductivity (W/mK)	R Value (m2K/W)
Compressible Rockwool	Insulation	20	0.02	0.03	0.666666667
Compressible Rockwool	Vapour Control	20	0.02	0.03	0.666666667
CLT	Structure	75	0.075	0.380	0.19725

Rockwool Insulation (w batten 240x62mm)	Insulation	100	0.1	0.04	2.5
Vapour Control (in the Rockwool for pipes)	Vapour Control	10	0.01	0.417	0.024
Rockwool Insulation (w batten 240x62mm)	Insulation	100	0.1	0.04	2.5
Waterproof Sheet	Vapour Control	15	0.015	0.417	0.036
Finish Brick	Exterior Finish	20	0.02	0.901	0.0222
Construction Values		360	0.36		6.612783333

P2EDURE		Thickness (mm)	Thickness (m)	Thermal Conductivity (W/mK)	R Value (m2K/W)
Rockwool (not in panel)	Insulation	20	0.02	0.04	0.5
Battens (not in panel)	Substructure	15	0.015	0	
Gypsum Fiber Board	Substrcture	12.5	0.0125	0.2	0.0625
Vapour Barrier	Vapour Control	0	0	0.417	0
Rockwool (w batten 200x?mm)	Insulation	60	0.06	0.04	1.5
Vapour Barrier	Vapour Control	0	0	0.417	0
Fermacell Powerpanel HD	Finish	15	0.015	0.4	0.0375
Construction Values (Expected value R 2.03)		122.5	0.1225		2.1

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