

Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences



Graduation Plan: All tracks

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

| Personal information | |
|----------------------|------------------------------------|
| Name | Timothius Nicolaas Maria de Kanter |
| Student number | 5930812 |

| Studio | | |
|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| Name / Theme | Circular Products & Processes | |
| Main mentor | Olga Ioannou | Façade & Product Design |
| Second mentor | Martin Tenpierik | Climate Design |
| Argumentation of choice of the studio | In recent years, I have developed a growing interest in bio-based building materials due to their various advantages over conventional materials. Since detailing with these materials is different from conventional materials, I aim to acquire new technical knowledge on correctly detailing with bio-based materials through this research. By evaluating these details for moisture transport and thermal bridges, I seek to validate their effectiveness. My personal goal is to contribute to the design of sustainable buildings. | |

| Graduation project | |
|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Title of the graduation project | Bio-based reference façade wall details: Design and analysis of moisture transport and thermal bridges for Dutch residential top-up buildings |
| Goal | |
| Location: | The Netherlands |
| The posed problem, | The Dutch construction industry suffers from a lack of technical design knowledge in the field of bio-based structures. This knowledge gap is a significant barrier to achieving the Dutch government's stated goal of full circularity by 2050. The conservative nature of the construction industry hinders the implementation of new construction techniques, leading to reluctance among professionals to apply biobased materials and thus develop technical expertise. In addition, the limited knowledge about the building physics properties of biobased materials further hinders the implementation of bio-based building materials. |

| | |
|-------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>research questions and</p> | <p>Main question: 'How can bio-based façade wall reference details for residential top-up buildings be developed according to thermal and moisture regulation within the construction?'</p> <p>Sub questions: 'What are the advantages of using bio-based building materials instead of conventional building materials?' 'What makes bio-based building materials relevant to residential top-up buildings.' 'What properties of bio-based building materials are crucial for analysing thermal bridges and moisture in WUFI?' 'Which bio-based building materials can be used for bio-based façade wall details with a focus on analysing thermal bridges and moisture transport?' 'How can the selected bio-based materials be effectively applied to develop validated bio-based façade wall details?'</p> |
| <p>design assignment in which these result.</p> | <p>Research outcomes: The achieved results of this research encompass various aspects that contribute to the development and application of bio-based construction techniques. Arguments have been presented for the transition to bio-based construction and the value of bio-based materials for residential top-up buildings. Following the presentation of these arguments, the important building physics properties necessary for assessing thermal bridges and moisture transport through the construction using WUFI have been outlined. Subsequently, a selection of bio-based materials has been presented along with the corresponding products and how these products can be applied in façade walls. Additionally, bio-based products from various suppliers have been listed with the associated product properties. If these properties were not clear or available from the suppliers, a similar product from WUFI can be used to obtain the necessary properties. This is less accurate but helps to analyse the details.</p> <p>The expected results of this research include several aspects that contribute to the development and application of bio-based construction techniques. Firstly, design principles have been presented on how to detail with the various selected bio-based products. Secondly, a series of validated horizontal and vertical 1:5 façade wall details will be designed, specifically for bio-based residential top-up buildings. Additionally, the research provides an analysis of the behaviour of thermal bridges, moisture accumulation, and condensation formation in the developed bio-based façade wall details, obtained through simulations in WUFI.</p> |

| | |
|--|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| | <p>With this analysis, the details will be further optimized to prevent thermal bridges and ensure effective moisture transport, avoiding moisture accumulation and condensation in the developed details.</p> <p>Research outputs: Eventually, multiple horizontal and vertical 1:5 façade wall details will be developed and validated for thermal bridges and moisture transport using WUFI. These validated details will be presented as reference details that can serve as tools for designers and architects in the technical elaboration of bio-based residential top-up buildings. The details should be easily applicable in practice, which means the details will be drafted in accordance with the Dutch Building Decree. The results of the assessments on thermal bridges, moisture accumulation, and condensation formation will be presented clearly and comprehensively as an addition to the reference details. The overall outcome provides insight into the mentioned building physics performance of bio-based materials and the application in various configurations.</p> <p>Finally, all of the above results will be documented in a detailed report, listing the suppliers of the used materials along with the corresponding building physics properties. This facilitates the direct evaluation of the products by designers and increases awareness of bio-based suppliers. Visualisations, such such as 3D axonometric images, will be added to the report to better illustrate the applicability and performance of the details.</p> |
|--|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

[This should be formulated in such a way that the graduation project can answer these questions.
The definition of the problem has to be significant to a clearly defined area of research and design.]

Process

Method description

The method of this thesis is divided into two parts to answer the main research question: a literature review and the development of bio-based façade wall details tested with WUFI. The literature review combines various methodologies to gather the necessary knowledge for developing and analysing the reference façade wall details. In the second part, the reference details will be developed and tested for thermal bridges and moisture transport using WUFI. This involves applying research through design and conducting simulations.

Literature review:

For the sub-questions ‘‘What are the advantages of using bio-based building materials instead of conventional building materials?’ and ‘What makes bio-based building materials an ideal candidate to residential top-up buildings?’, a combination of Dutch policy documents and scientific literature has been consulted.

Dutch policy documents have been used to describe the ambitions regarding the use of bio-based building materials in the construction sector and the addition of extra homes to address the housing shortage in cities through top-ups. Subsequently, the scientific literature outlines the advantages of bio-based materials compared to conventional materials in the construction sector. The focus has been on material density, phase shift, temperature amplitude damping, prefabrication possibilities, and the reduction of disturbances for nearby residents. Additionally, the hygroscopic properties have been investigated, such as thermal conductivity, diffusivity, specific heat capacity, vapor permeability, and vapor diffusion resistance. Specific literature has been consulted for each property.

For the third sub-question, ‘What properties of bio-based building materials are crucial for analysing thermal bridges and moisture in WUFI?’, scientific literature has been reviewed along with consulting the WUFI database.

Scientific sources have been consulted that describe the thermal performance of thermal bridges in lightweight constructions and the consequences of thermal bridges for heat loss. Additionally, the impact of mold formation on thermal bridges and how correct detailing can influence thermal bridges have been investigated. Furthermore, the WUFI database has been consulted to obtain the necessary hygroscopic properties required for assessing thermal bridges and moisture transport. Important terms for the scientific literature in this context include Moisture Storage Function, Liquid Transport Coefficient, Water Vapour Diffusion Resistance Factor, Thermal Conductivity and Enthalpy.

The sub-question ‘Which bio-based building materials, available on the West European market, are most promising for bio-based façade wall details, with a focus on analysing thermal bridges and moisture transport?’ combines Dutch policy documents, the WUFI database, scientific literature, and material desk research.

Dutch policy documents have been consulted to select bio-based materials with which the Dutch construction sector already has some design and construction knowledge. For further material reduction, the WUFI database has been consulted. This is because many specific properties required for the analyses are often not yet known.

The selection of materials is included in the scientific literature, with explanations about the materials, products, and applications. Subsequently, material desk research was conducted to describe various suppliers along with product properties. Properties not shared by suppliers can be supplemented with values from the WUFI database.

For the final sub-question, 'What principles are essential to effectively detail with the selection of bio-based building materials?', the material and product selection was used to conduct a literature review. This review was specified to technical manuals and scientific literature that together provide guidelines on detailing with the specific materials.

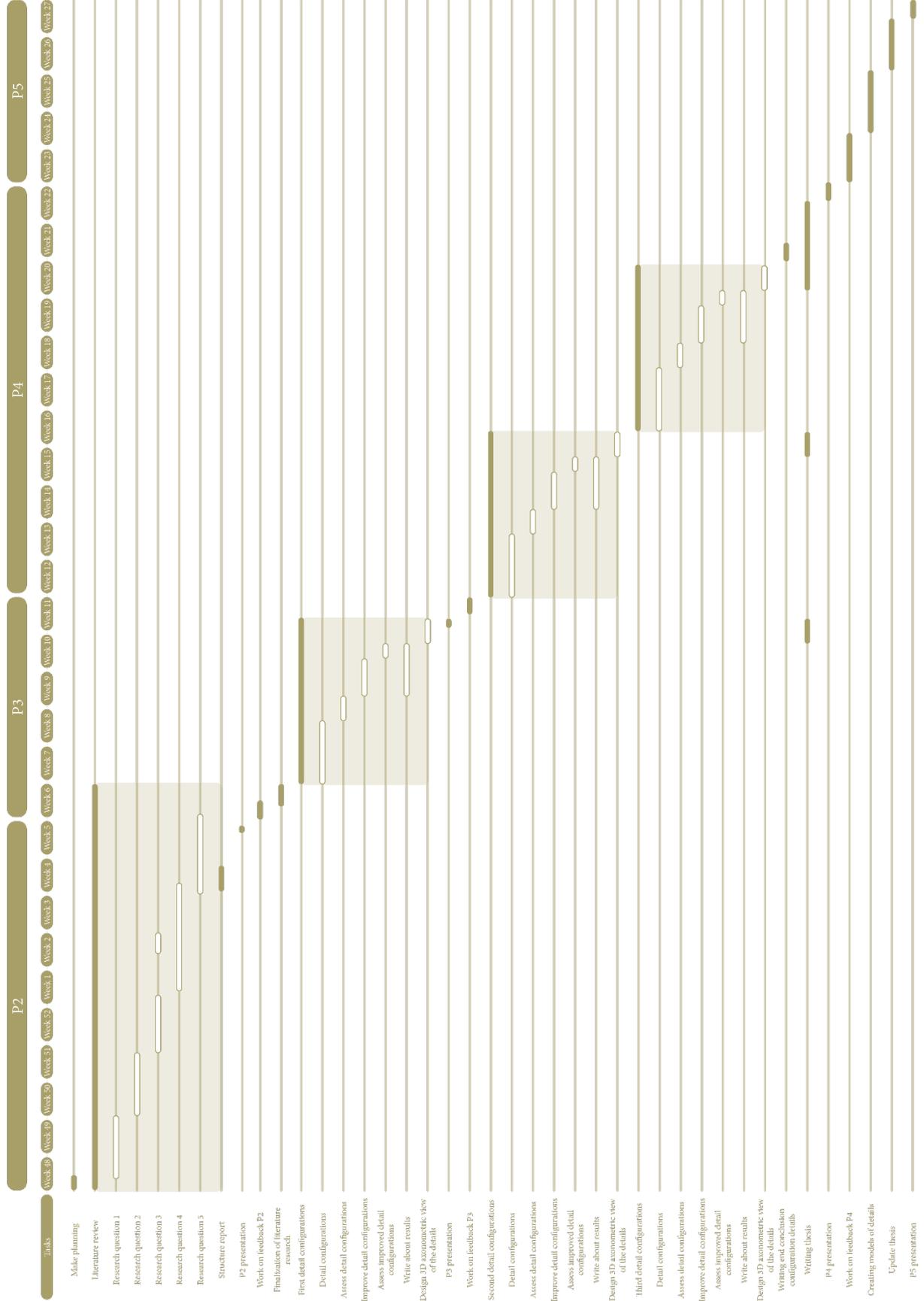
Development of bio-based façade wall details

Following the literature review, the technical details of the horizontal and vertical façade wall details will be developed and tested for thermal bridges and moisture transport after P2. During this phase different combinations of materials will be experimented to identify the most effective solution. If certain design detail challenges are not sufficiently understood, additional literature research will be conducted. This method aligns with the approach used during the literature review for the final sub-question.

The building physics research focuses on setting up and analysing simulations using WUFI software. Utilizing this software, the thermal bridges and moisture transport within the details will be analysed and evaluated. Through an iterative process, the details will be continuously adjusted and improved based on the simulation results. The iterative process consists of multiple cycles of design, simulation, and adjustment. It is expected that at least two iterations will be performed to achieve optimal details. By following this process, thermal bridges are prevented, and moisture and mold formation are excluded. Ultimately, the details will be validated based on the simulation outcomes. Multiple rounds will take place in which different configurations of details are drafted, tested, improved, and validated. Each round will be executed one after the other as also can be seen in the planning.

The obtained details and the corresponding simulation results will eventually be documented and published in the thesis. In this way, designers can benefit from the acquired knowledge and make the application in future projects possible.

Planning:



Literature and general practical references

Because the main part of the literature review is already completed, the most important sources will be listed first. Following this, the literature I intend to consult will be presented.

Reviewed literature

- Aghamohammadi, N., & Shahmohammadi, M. (2023). Towards sustainable development goals and role of bio-based building materials. *Bio-Based Materials and Waste for Energy Generation and Resource Management: Present and Emerging Waste Management Practices: Volume 5 of Advanced Zero Waste Tools*, 243–279. <https://doi.org/10.1016/B978-0-323-91149-8.00004-1>
- Alhawari, A., & Mukhopadhyaya, P. (2018). Thermal bridges in building envelopes – An overview of impacts and solutions. *International Review of Applied Sciences and Engineering*, 9(1), 31–40. <https://doi.org/10.1556/1848.2018.9.1.5>
- Arnoldusse, J., Endhoven, T., Kok, J., Groot, P., Blok, M., & Kamps, M. (2022). *Materiaalstromen in de bouw en infra*.
- Artés, J., Wadel, G., & Martí, N. (2017). Vertical Extension and Improving of Existing Buildings. *The Open Construction and Building Technology Journal*, 11(1), 83–94. <https://doi.org/10.2174/1874836801711010083>
- Arup. (2024). *Onderzoek NTA 8800*.
- Asdrubali, F., Baldinelli, G., & Bianchi, F. (2012). A quantitative methodology to evaluate thermal bridges in buildings. *Applied Energy*, 97, 365–373. <https://doi.org/10.1016/j.apenergy.2011.12.054>
- Ashour, T. (2007). *Equilibrium Moisture Content for Some Natural Insulating Materials*. <https://www.researchgate.net/publication/275464595>
- Asokan, R., Rathanasamy, R., Paramasivam, P., Chinnasamy, M., Pal, S. K., & Palaniappan, S. K. (2023). Hemp composite. *Green Sustainable Process for Chemical and Environmental Engineering and Science: Natural Materials Based Green Composites 1: Plant Fibers*, 89–112. <https://doi.org/10.1016/B978-0-323-95167-8.00007-7>
- Barbhuiya, S., & Bhusan Das, B. (2022). A comprehensive review on the use of hemp in concrete. *Construction and Building Materials*, 341, 127857. <https://doi.org/10.1016/J.CONBUILDMAT.2022.127857>
- Bardage, S. L. (2017). Performance of buildings. *Performance of Bio-Based Building Materials*, 335–383. <https://doi.org/10.1016/B978-0-08-100982-6.00006-9>
- Bekin, M. (2024, August 26). *What Are the Pros and Cons of Interior Timber Cladding*. Eco Choise.
- Benmahiddine, F., Cherif, R., Bennai, F., Belarbi, R., Tahakourt, A., & Abahri, K. (2020). Effect of flax shives content and size on the hygrothermal and mechanical properties of flax concrete. *Construction and Building Materials*, 262, 120077. <https://doi.org/10.1016/J.CONBUILDMAT.2020.120077>

- Bosch, S., Jansen, L., Aartsma, G., Schouten, N., Rohmer, M., van Hoof, S., van Munster, L., Spitsbaard, M., van den Broek, B., Schillemans, P., van Leeuwen, M., Hartmann, T., van Grinsven, J., & van Laar, D. (2023). *Woningbouw binnen planetaire grenzen*.
- Bourbia, S., Kazeoui, H., & Belarbi, R. (2023). A review on recent research on bio-based building materials and their applications. *Materials for Renewable and Sustainable Energy*, 12(2), 117–139. <https://doi.org/10.1007/s40243-023-00234-7>
- Bredenoord, J. (2024). Bamboo as a Sustainable Building Material for Innovative, Low-Cost Housing Construction. *Sustainability*, 16(6), 2347. <https://doi.org/10.3390/su16062347>
- Brischke, C., & Humar, M. (2017). Performance of the bio-based materials. *Performance of Bio-Based Building Materials*, 249–333. <https://doi.org/10.1016/B978-0-08-100982-6.00005-7>
- Brookes, A. J., Brookes, A. J., & Meijs, M. (2008). *Cladding of Buildings*. Taylor & Francis. <https://doi.org/10.4324/9780203099780>
- Budding-Polo Ballinas, M., Garcia Chavez, L., & Molenaar, R. (2023). *Synergies & trade-offs of Wageningen climate solutions in primary production systems: Urban case study biobased construction materials: contributing to a sustainable housing system in Europe and enhancing climate neutral and resilient cities*.
- Building Balance. (2023). *Advies Interdepartementaal Opschalingsplan Biobased Bouwen (IDOB) 2023 – 2030*. <https://www.centrumhout.nl/wp-content/uploads/2023/11/Advies-Interdepartementaal-Opschalingsplan-Biobased-Bouwen-IDOB-DEF.pdf>
- Cascione, V., Roberts, M., Allen, S., Dams, B., Maskell, D., Shea, A., Walker, P., & Emmitt, S. (2022). Integration of life cycle assessments (LCA) in circular bio-based wall panel design. *Journal of Cleaner Production*, 344, 130938. <https://doi.org/10.1016/J.JCLEPRO.2022.130938>
- Centraal Bureau voor de Statistiek. (n.d.). *Dossier Verstedelijking*. Retrieved January 18, 2025, from <https://www.cbs.nl/nl-nl/dossier/dossier-verstedelijking>
- Centraal Bureau voor de Statistiek. (2019, November 4). *Meeste afval en hergebruik materialen in bouwsector*. <https://www.cbs.nl/nl-nl/nieuws/2019/45/meeste-afval-en-hergebruik-materialen-in-bouwsector>
- Cobouw. (2024, April 30). *Zijn er genoeg grondstoffen voor de bouw van 900.000 woningen?* <https://www.cobouw.nl/304105/zijn-er-genoeg-grondstoffen-voor-de-bouw-van-900-000-woningen>
- College van Rijksadviseurs. (2023). *Inspiratieboek biobased en natuurinclusief bouwen*.
- College van Rijksbouwmeester en Rijksadviseurs. (2022, February 2). *Wat is biobased bouwen?* <https://www.collegevanrijksadviseurs.nl/projecten/nieuwe-bouwcultuur/voorbeeldprojecten/wat-is-biobased-bouwen#:~:text=Biobased%20bouwmaterialen%20zijn%20bouwmaterialen%20gemaakt,Deal%20Circulair%20en%20Conceptueel%20Bouwen>
- CORDIS. (2018, July 10). *Bio-based insulation materials facts & myths*. <https://cordis.europa.eu/article/id/123721-biobased-insulation-materials-facts-myths>

- Cosentino, L., Fernandes, J., & Mateus, R. (2023). A Review of Natural Bio-Based Insulation Materials. *Energies*, *16*(12), 4676. <https://doi.org/10.3390/en16124676>
- Cosentino, L., Fernandes, J., & Mateus, R. (2024). Fast-Growing Bio-Based Construction Materials as an Approach to Accelerate United Nations Sustainable Development Goals. *Applied Sciences*, *14*(11), 4850. <https://doi.org/10.3390/app14114850>
- Czerwinska, N. (2024). *Sustainable materials for improving Indoor Air Quality*. Università Politecnica Delle Marche.
- Dams, B., Maskell, D., Shea, A., Allen, S., Cascione, V., & Walker, P. (2023). Upscaling bio-based construction: challenges and opportunities. *Building Research & Information*, *51*(7), 764–782. <https://doi.org/10.1080/09613218.2023.2204414>
- dataholz. (2022a, May 10). *Wood-fibre insulation board*.
- dataholz. (2022b, October 5). *Light composite wood-based beams and columns*.
- De Kort, J., Gauvin, F., Loomans, M., & Brouwers, J. (2023). *Emission rates of bio-based building materials, a comparison between cork panels and reference building materials*.
- De Visser, C., Van Wijk, K., & Van der Voort, M. (2015). *Health, comfort, energy use and sustainability issues related to the use of biobased building materials*.
- Deshmukh, G. S. (2022). Advancement in hemp fibre polymer composites: a comprehensive review. *Journal of Polymer Engineering*, *42*(7), 575–598. <https://doi.org/10.1515/polyeng-2022-0033>
- Fantucci, S., Isaia, F., Serra, V., & Dutto, M. (2017). Insulating coat to prevent mold growth in thermal bridges. *Energy Procedia*, *134*, 414–422. <https://doi.org/10.1016/j.egypro.2017.09.591>
- Farrokhirad, E., Gao, Y., Pitts, A., & Chen, G. (2024). A Systematic Review on the Risk of Overheating in Passive Houses. *Buildings*, *14*(8), 2501. <https://doi.org/10.3390/buildings14082501>
- Fedorik, F., Zach, J., Lehto, M., Kymäläinen, H. R., Kuisma, R., Jallinoja, M., Illikainen, K., & Alitalo, S. (2021). Hygrothermal properties of advanced bio-based insulation materials. *Energy and Buildings*, *253*, 111528. <https://doi.org/10.1016/J.ENBUILD.2021.111528>
- Fischer, H., & Korjenic, A. (2023). Hygrothermal Performance of Bio-Based Exterior Wall Constructions and Their Resilience under Air Leakage and Moisture Load. *Buildings*, *13*(10), 2650. <https://doi.org/10.3390/buildings13102650>
- Geuting, E., Wevers, J., Thomasia, M., & Dul, A. (2023). *De potentie van splitsen en optoppen*.
- Gil, L. (2014). *Materials for Construction and Civil Engineering*. Springer.
- Göswein, V., Arehart, J., Phan-huy, C., Pomponi, F., & Habert, G. (2022). Barriers and opportunities of fast-growing biobased material use in buildings. *Buildings and Cities*, *3*(1), 745–755. <https://doi.org/10.5334/bc.254>
- Grabner, M., Nemestothy, S., & Wächter, E. (2022). Wooden Roofing: Split Shingles versus Sawn Boards. *International Journal of Wood Culture*, *2*(1–3), 19–37. <https://doi.org/10.1163/27723194-bja10002>

- Greve, M., & Koning, M. (2024). *Meer woningen door verbouw -Potentie en belemmeringen bij optoppen, splitsen en transformeren.*
- Groene Bouwmaterialen. (n.d.). *Faseverschuiving & biobased isolatie*. Retrieved January 18, 2025, from https://www.groenebouwmaterialen.nl/biobased-bouwen/faseverschuiving/?srsId=AfmBOorxGyrDtdkQ3fPKN4bm8AnAKusHcEilCQATGXzn6aXTfdq906r_
- Grow2Build. (n.d.). *BOUWEN MET VLAS EN HENNEP*. www.nibe.org
- Hamrouni, I., Jalili, H., Ouahbi, T., Taibi, S., Jamei, M., & Mabrouk, A. (2024). Thermal properties of a raw earth-flax fibers building material. *Construction and Building Materials*, *423*, 135828. <https://doi.org/10.1016/J.CONBUILDMAT.2024.135828>
- Hanenburg, A. (2022). *Biobased Bouwen met Kurk*.
- Hung Anh, L. D., & Pásztor, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. *Journal of Building Engineering*, *44*, 102604. <https://doi.org/10.1016/J.JOBE.2021.102604>
- Ingeli, R., Podhorec, J., & Čekon, M. (2016). Thermal Bridges Impact on Energy Need for Heating in Low Energy Wooden House. *Applied Mechanics and Materials*, *820*, 139–145. <https://doi.org/10.4028/www.scientific.net/AMM.820.139>
- Ivanovic-Sekularac, J., Šekularac, N., & Tovarovic, J. C. (2016). *Wood as element of façade cladding in modern architecture*. <https://www.researchgate.net/publication/294647271>
- Johra, H. (2021). *Thermal properties of building materials - Review and database*. <https://doi.org/10.54337/aau456230861>
- Jones, D. (2017). Introduction to the performance of bio-based building materials. *Performance of Bio-Based Building Materials*, 1–19. <https://doi.org/10.1016/B978-0-08-100982-6.00001-X>
- Julistiono, E. K., Oldfield, P., & Cardelicchio, L. (2023). Up on the roof: a review of design, construction, and technology trends in vertical extensions. *Architectural Science Review*, *67*(1), 63–77. <https://doi.org/10.1080/00038628.2023.2240289>
- Kain, G., Idam, F., Federspiel, F., Réh, R., & Krišťák, L. (2020). Suitability of Wooden Shingles for Ventilated Roofs: An Evaluation of Ventilation Efficiency. *Applied Sciences*, *10*(18), 6499. <https://doi.org/10.3390/app10186499>
- Kaminski, S., Lawrence, A., & Trujillo, D. (2016). Structural use of bamboo. Part 1: Introduction to bamboo. *The Structural Engineer*, *94*(8), 40–43. <https://doi.org/10.56330/PNSC8891>
- Klijn, W., Spaan, R., & Eickmeier, C. (2017). *BOUWEN MET STRO Stro als ecologisch isolatiemateriaal*.
- Knapic, S., Oliveira, V., Machado, J. S., & Pereira, H. (2016). Cork as a building material: a review. *European Journal of Wood and Wood Products*, *74*(6), 775–791. <https://doi.org/10.1007/s00107-016-1076-4>

- KNMI. (n.d.). *Vochtigheid*. Retrieved January 18, 2025, from <https://www.knmi.nl/kennis-en-datacentrum/uitleg/vochtigheid#:~:text=De%20relatieve%20vochtigheid%20geeft%20aan,De%20lucht%20is%20dan%20verzadigd>
- Koh, C. H. (Alex), & Kraniotis, D. (2020). A review of material properties and performance of straw bale as building material. *Construction and Building Materials*, 259, 120385. <https://doi.org/10.1016/J.CONBUILDMAT.2020.120385>
- Koppenhol, L., Hertzberger, B., Müller, T., & El Ayadi, Y. (2024). *Technische richtlijnen en overwegingen bij het optoppen*.
- Koppenhol, L., Müller, T., & El Ayadi, Y. (2024). *Optoppen: de constructie en fundering, uitdagingen en oplossingen voor duurzame stadsontwikkeling*.
- Kuczyński, T., & Staszczuk, A. (2020). Experimental study of the influence of thermal mass on thermal comfort and cooling energy demand in residential buildings. *Energy*, 195, 116984. <https://doi.org/10.1016/J.ENERGY.2020.116984>
- Kuhlmann, T., Heisma, R., & Rohmer, M. (2023). *Routekaarten voor een duurzame bouw*. www.metabolic.nl
- Künzel, H. (1995). *Simultaneous heat and moisture transport in building components : one- and two-dimensional calculation using simple parameters* [Fraunhofer Institute]. https://www.researchgate.net/publication/41124856_Simultaneous_heat_and_moisture_transport_in_building_components_One-_and_two-dimensional_calculation_using_simple_parameters
- Lafond, C., & Blanchet, P. (2020). Technical Performance Overview of Bio-Based Insulation Materials Compared to Expanded Polystyrene. *Buildings*, 10(5), 81. <https://doi.org/10.3390/buildings10050081>
- Lawrence, M., Shea, A., Walker, P., & De Wilde, P. (2013). Hygrothermal performance of bio-based insulation materials. *Proceedings of the Institution of Civil Engineers - Construction Materials*, 166(4), 257–263. <https://doi.org/10.1680/coma.12.00031>
- Le, D. L., Salomone, R., & Nguyen, Q. T. (2023). Circular bio-based building materials: A literature review of case studies and sustainability assessment methods. *Building and Environment*, 244, 110774. <https://doi.org/10.1016/J.BUILDENV.2023.110774>
- Li, Y., & Xu, P. (2006). Thermal Mass Design in Buildings – Heavy or Light? *International Journal of Ventilation*, 5(1), 143–150. <https://doi.org/10.1080/14733315.2006.11683731>
- Liu, H., & Zhao, X. (2022). Thermal Conductivity Analysis of High Porosity Structures with Open and Closed Pores. *International Journal of Heat and Mass Transfer*, 183, 122089. <https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2021.122089>
- Lu, Z., Hauschild, M., Ottosen, L. M., Ambaye, T. G., Zerbino, P., Aloini, D., & Lima, A. T. (2024). Climate mitigation potential of biobased insulation materials: A comprehensive review and categorization. *Journal of Cleaner Production*, 470, 143356. <https://doi.org/10.1016/J.JCLEPRO.2024.143356>
- Lyons, A. (2006). Timber and timber products. *Materials for Architects and Builders*, 96–148. <https://doi.org/10.1016/B978-075066940-5/50031-9>

- Majer, S., Wurster, S., Moosmann, D., Ladu, L., Sumfleth, B., & Thrän, D. (2018). Gaps and Research Demand for Sustainability Certification and Standardisation in a Sustainable Bio-Based Economy in the EU. *Sustainability*, 10(7), 2455. <https://doi.org/10.3390/su10072455>
- Maskell, D., Da Silva, C. F., Mower, K., Rana, C., Dengel, A., Ball, R. J., Ansell, M. P., Walker, P., & Shea, A. (2015). Properties of bio-based insulation materials and their potential impact on indoor air quality. *First International Conference on Bio-Based Building Materials*. https://www.researchgate.net/publication/279196144_PROPERTYES_OF_BIO-BASED_INSULATION_MATERIALS_AND_THEIR_POTENTIAL_IMPACT_ON_INDOOR_AIR_QUALITY
- Miles, J., & Krug, D. (2013). *OFFSITE CONSTRUCTION: Sustainability Characteristics*. https://www.buildoffsite.com/content/uploads/2015/03/BoS_offsiteconstruction_1307091.pdf
- Minister van Binnenlandse Zaken en Koninkrijksrelaties, S. van I. en W. M. voor K. en E. M. van E. Z. en K. (2023). *Nationale Aanpak Biobased Bouwen Van boerenland tot bouw materiaal*.
- Ministerie van Binnenlandse Zaken. (2022, February 25). *Pablo van der Lugt: De noodzaak van een nieuwe, biobased bouw cultuur*. <https://www.collegevanrijksadviseurs.nl/projecten/nieuwe-bouwcultuur/aan-het-woord/pablo-van-der-lugt>
- Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2024a). *Landelijke aanpak Optoppen*. www.volkshuisvestingnederland.nl/optoppen
- Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2024b, May 31). *Wat is de landelijke aanpak optoppen*. <https://www.volkshuisvestingnederland.nl/onderwerpen/optoppen/wat-is-de-landelijke-aanpak-optoppen>
- Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, Ministerie van Infrastructuur en Waterstaat, Ministerie van Landbouw, N. en V., & Ministerie van Economische Zaken en Klimaat. (2023). *Nationale aanpak biobased bouwen: Van boerenland tot bouw materiaal*.
- Ministerie van Economische Zaken. (2016). *Energieagenda - Naar een CO₂-arme energievoorziening*. <https://www.rijksoverheid.nl/documenten/rapporten/2016/12/07/ea>
- Ministerie van Infrastructuur en Waterstaat. (2023a, May 4). *Omslag naar circulaire economie versnellen*. <https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/omslag-naar-circulaire-economie-versnellen>
- Ministerie van Infrastructuur en Waterstaat. (2023b, October 24). *Noodzaak van circulaire economie*. Circulaire Economie | Rijksoverheid.NL.
- Ministerie van Volkshuisvesting en Ruimtelijke Ordening. (2024, September 13). *Kabinet pakt woningnood aan: sneller, slimmer en met minder regels bouwen*. <https://www.rijksoverheid.nl/actueel/nieuws/2024/09/13/kabinet-pakt-woningnood-aan-snel-slimmer-en-met-minder-regels-bouwen>
- MNEXT. (n.d.-a). *Stro als biobased bouw materiaal*. MNEXT. Retrieved January 22, 2025, from <https://www.mnext.nl/wiki/stro-als-biobased-bouw-materiaal/>
- MNEXT. (n.d.-b). *Vlas*.

- Novogradac, M. (2024). Affordable Housing Developers Facing Increased Development Challenges. *Journal of Tax Credits*, 15(5).
- Nunes, L. (2017). Nonwood bio-based materials. *Performance of Bio-Based Building Materials*, 97–186. <https://doi.org/10.1016/B978-0-08-100982-6.00003-3>
- O'Brien, L., Li, L., Friess, W., Snow, J., Herzog, B., & O'Neill, S. (2025). Review of bio-based wood fiber insulation for building envelopes: Characteristics and performance assessment. *Energy and Buildings*, 328, 115114. <https://doi.org/10.1016/J.ENBUILD.2024.115114>
- OECD. (2018, October 22). *Raw materials use to double by 2060 with severe environmental consequences*. Organisation for Economic Co-Operation and Development (OECD). <https://www.oecd.org/en/about/news/announcements/2018/10/raw-materials-use-to-double-by-2060-with-severe-environmental-consequences.html#:~:text=severe%20environmental%20consequences-,Raw%20materials%20use%20to%20double%20by%202060%20with%20severe%20environmental,to%20a%20new%20OECD%20report>
- Orsini, F., & Marrone, P. (2019). Approaches for a low-carbon production of building materials: A review. *Journal of Cleaner Production*, 241, 118380. <https://doi.org/10.1016/J.JCLEPRO.2019.118380>
- Owczarek, M., Owczarek, S., Baryłka, A., & Grzebielec, A. (2021). Measurement Method of Thermal Diffusivity of the Building Wall for Summer and Winter Seasons in Poland. *Energies*, 14(13), 3836. <https://doi.org/10.3390/en14133836>
- Palumbo, M., Lacasta, A. M., Holcroft, N., Shea, A., & Walker, P. (2016). Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials. *Construction and Building Materials*, 124, 269–275. <https://doi.org/10.1016/J.CONBUILDMAT.2016.07.106>
- Pittau, F., Krause, F., Lumia, G., & Habert, G. (2018). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, 129, 117–129. <https://doi.org/10.1016/J.BUILDENV.2017.12.006>
- Planbureau voor de Leefomgeving. (2022, July 6). *Prognose: in 2035 vooral meer inwoners in en om grotere gemeenten*. <https://www.pbl.nl/actueel/nieuws/prognose-in-2035-vooral-meer-inwoners-in-en-om-grotere-gemeenten>
- Popescu, C. M. (2017). Wood as bio-based building material. *Performance of Bio-Based Building Materials*, 21–96. <https://doi.org/10.1016/B978-0-08-100982-6.00002-1>
- Pramreiter, M., Nenning, T., Malzl, L., & Konnerth, J. (2023). A plea for the efficient use of wood in construction. *Nature Reviews Materials*, 8(4), 217–218. <https://doi.org/10.1038/s41578-023-00534-4>
- Rabbat, C., Awad, S., Villot, A., Rollet, D., & Andrès, Y. (2022). Sustainability of biomass-based insulation materials in buildings: Current status in France, end-of-life projections and energy recovery potentials. *Renewable and Sustainable Energy Reviews*, 156, 111962. <https://doi.org/10.1016/J.RSER.2021.111962>

- Raja, P., Murugan, V., Ravichandran, S., Behera, L., Mensah, R. A., Mani, S., Kasi, A., Balasubramanian, K. B. N., Sas, G., Vahabi, H., & Das, O. (2023). A Review of Sustainable Bio-Based Insulation Materials for Energy-Efficient Buildings. *Macromolecular Materials and Engineering*, 308(10). <https://doi.org/10.1002/mame.202300086>
- Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P. F., & Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, 68, 333–359. <https://doi.org/10.1016/J.RSER.2016.09.107>
- Reilly, A., & Kinnane, O. (2017). The impact of thermal mass on building energy consumption. *Applied Energy*, 198, 108–121. <https://doi.org/10.1016/J.APENERGY.2017.04.024>
- Rijksdienst voor Ondernemend Nederland. (2024). *Sectorstudie: Duurzame gebouwen en openbare ruimte*.
- Rutte Groep. (2021, November 1). *Circulair beton*. Circulariteit in de bouw. <https://themasites.pbl.nl/o/circulariteit-in-de-bouw/rutte-groep/>
- Šadauskienė, J., Ramanauskas, J., Šeduikytė, L., Daukšys, M., & Vasylius, A. (2015). A Simplified Methodology for Evaluating the Impact of Point Thermal Bridges on the High-Energy Performance of a Passive House. *Sustainability*, 7(12), 16687–16702. <https://doi.org/10.3390/su71215840>
- Sandak, A., Sandak, J., Brzezicki, M., & Kutnar, A. (2019). *Bio-based Building Skin*. Springer Singapore. https://doi.org/https://doi.org/10.1007/978-981-13-3747-5_2
- Schik, W., Meijer, K., Verkerk, D., Paardekooper, D., Grim, L., & Peek, T. (2022). *De urgente belofte van biobased bouwen*.
- Schmidt, S., & Hartwig, K. (2006). *Welcome to WUFI (4.1.)*. WUFI. https://wufi.de/download/WUFI41_help_e.pdf
- Schulte, M., Lewandowski, I., Pude, R., & Wagner, M. (2021). Comparative life cycle assessment of bio-based insulation materials: Environmental and economic performances. *GCB Bioenergy*, 13(6), 979–998. <https://doi.org/10.1111/gcbb.12825>
- Sharma, B., Gatóo, A., Bock, M., & Ramage, M. (2015). Engineered bamboo for structural applications. *Construction and Building Materials*, 81, 66–73. <https://doi.org/10.1016/J.CONBUILDMAT.2015.01.077>
- Sijm, J. (2024). *Verkenning van toekomstige ontwikkelingen en uitdagingen voor een klimaatneutraal elektriciteitssysteem in Nederland, 2030-2050*. www.tno.nl
- Sun, X., He, M., & Li, Z. (2020). Novel engineered wood and bamboo composites for structural applications: State-of-art of manufacturing technology and mechanical performance evaluation. *Construction and Building Materials*, 249, 118751. <https://doi.org/10.1016/J.CONBUILDMAT.2020.118751>
- Suttie, E., Hill, C., Sandin, G., Kutnar, A., Ganne-Chédeville, C., Lowres, F., & Dias, A. C. (2017). Environmental assessment of bio-based building materials. *Performance of Bio-Based Building Materials*, 547–591. <https://doi.org/10.1016/B978-0-08-100982-6.00009-4>

- Sutton, A., Black, D., & Walker, P. (2011). *Straw bale - An introduction to low-impact building materials*. BRE Publications.
- Taher, A., & Brouwers, H. J. H. (2023). Sorption isotherm measurements for porous materials: A new hygroscopic method. *Construction and Building Materials*, 379, 131166. <https://doi.org/10.1016/J.CONBUILDMAT.2023.131166>
- The Wit, M. H. (2008). *Heat and Moisture in Building Envelopes*.
- Thoemen, H., Irle, M., & Sernek, M. (2010). *Wood-based Panels - An Introduction for Specialists*. Brunel University Press.
- TNO. (n.d.). *Bio-based building materials market in development*. Retrieved January 18, 2025, from <https://www.tno.nl/en/sustainable/circular-industrial-construction/bio-based-building-materials-market/>
- van Dam, J., & van den Oever, M. (2019). *Catalogus biobased bouwmaterialen 2019 : Het groene en circulaire bouwen*. <https://doi.org/10.18174/461687>
- Van der Lugt, P. (2021). *Houtbouwmythes ontkracht het onderscheid tussen fabels en feiten*. www.ams-institute.org
- Van der Schuit, J., Van Hoorn, A., Sorel, N., & Rood, T. (2023). *Kenmerken, voorraad en materiaalketens van de bouw*. https://www.pbl.nl/uploads/default/downloads/pbl-2023_kenmerken-voorraad-en-materiaalketens-van-de-bouw_4853_.pdf
- Van der Velde, O., & Van Leeuwen, M. (2019). *Potentie van biobased materialen in de bouw*.
- Van Hooft, T. (2023, September 16). *Waarom raakt het stroomnet in Nederland enorm overbelast? energie kennis*. <https://energie-kennis.nl/waarom-raakt-het-stroomnet-overbelast/>
- Vermeulen, M., Van der Waal, J., Van Woerden, B., & Voorter, L. (2020). *Ruimte voor Biobased Bouwen*.
- Vinha, J., & Käkelä. Pasi. (1999). *Water vapour transmission in wall structures due to diffusion and convection*.
- Walker, R., & Pavía, S. (2014). Moisture transfer and thermal properties of hemp–lime concretes. *Construction and Building Materials*, 64, 270–276. <https://doi.org/10.1016/J.CONBUILDMAT.2014.04.081>
- Wang, J. S., Demartino, C., Xiao, Y., & Li, Y. Y. (2018). Thermal insulation performance of bamboo- and wood-based shear walls in light-frame buildings. *Energy and Buildings*, 168, 167–179. <https://doi.org/10.1016/J.ENBUILD.2018.03.017>
- Weterings, M., Van den Bogaard, J., Duijm, F., Van den Elsen, G., & Lops, S. (2005). *GGD Richtlijn Gezonde Woningbouw*. <https://www.rivm.nl/sites/default/files/2018-11/Richtlijn%20Gezonde%20Woningbouw%20%282005%29.pdf>
- Woolley, T. (2013). Low Impact Building: Housing Using Renewable Materials. In *Low Impact Building: Housing Using Renewable Materials*. Wiley. <https://doi.org/10.1002/9781118524169.advert2>

- Worch, A. (2004). The Behaviour of Vapour Transfer on Building Material Surfaces: The Vapour Transfer Resistance. *Journal of Thermal Envelope and Building Science*, 28(2), 187–200.
<https://doi.org/10.1177/1097196304044398>
- WUFI. (n.d.-a). *Details: Heat Conductivity Moisture Dependent*.
- WUFI. (n.d.-b). *Details: Liquid Transport Coefficients*. Retrieved January 20, 2025, from <https://www.wufi-wiki.com/mediawiki/index.php/Details:LiquidTransportCoefficients>
- WUFI. (n.d.-c). *Details: Moisture Storage Function*.
- WUFI. (n.d.-d). *Details: Water Vapor Diffusion*. Retrieved January 20, 2025, from <https://www.wufi-wiki.com/mediawiki/index.php/Details:WaterVaporDiffusion>
- Xue, Y., Fan, Y., Chen, S., Wang, Z., Gao, W., Sun, Z., & Ge, J. (2023). Heat and moisture transfer in wall-to-floor thermal bridges and its influence on thermal performance. *Energy and Buildings*, 279, 112642.
<https://doi.org/10.1016/j.enbuild.2022.112642>
- Yadav, M., & Agarwal, M. (2021). Biobased building materials for sustainable future: An overview. *Materials Today: Proceedings*, 43, 2895–2902. <https://doi.org/10.1016/J.MATPR.2021.01.165>
- Zondag, H. (2010). *De ontwikkeling van thermochemische warmteopslag*. www.tue.nl/taverne

Literature I intend to consult

- Ashour, T., & Wu, W. (n.d.). Using barley straw as building material. *Barley: Production, Cultivation And Uses*.
https://www.researchgate.net/publication/287478964_Using_barley_straw_as_building_material#ullTextFileContent
- Brookes, A. J., Brookes, A. J., & Meijs, M. (2008). Cladding of Buildings. In *Taylor & Francis eBooks*.
<https://doi.org/10.4324/9780203099780>
- Hill, C., Kymäläinen, M., & Rautkari, L. (2022). Review of the use of solid wood as an external cladding material in the built environment. *Journal Of Materials Science*, 57(20), 9031–9076.
<https://doi.org/10.1007/s10853-022-07211-x>
- Keena, N., Raugei, M., Lokko, M., Etman, M. A., Achnani, V., Reck, B. K., & Dyson, A. (2022). A Life-Cycle Approach to Investigate the Potential of Novel Biobased Construction Materials toward a Circular Built Environment. *Energies*, 15(19), 7239. <https://doi.org/10.3390/en15197239>
- Koh, C. H., & Kraniotis, D. (2020). A review of material properties and performance of straw bale as building material. *Construction And Building Materials*, 259, 120385.
<https://doi.org/10.1016/j.conbuildmat.2020.120385>
- Minke, G. (n.d.). *Building with Bamboo*. Birkhäuser.

Pittau, F., Krause, F., Lumia, G., & Habert, G. (2017). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building And Environment*, 129, 117–129. <https://doi.org/10.1016/j.buildenv.2017.12.006>

Stanwix, W., & Sparrow, A. (2014). *The Hempcrete Book - Designing and building with hemp-lime* (1st edition). Bloomsbury Publishing.

Reflection

1. What is the relation between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS)?

This graduation project focuses on the development of biobased reference façade wall details, which are analysed for thermal bridging and moisture transport performance by running WUFI simulations. The subject aligns with the Building Technology (BT) master track within the MSc Architecture, Urbanism, and Building Sciences (AUBS) program, which emphasizes innovation and sustainable construction solutions, integrating technical, architectural, and environmental considerations.

The BT track's focus on sustainable building materials and advanced building physics is strengthened by this project, which investigates how biobased materials can serve as a viable alternative to conventional materials. This research, through the developed and tested details, makes a valuable contribution to advancing sustainable construction practices and promoting environmentally friendly solutions in architecture and building engineering.

2. What is the relevance of your graduation work in the larger social, professional and scientific framework.

The problem statement shows that the application of bio-based materials in construction projects is hindered by limited technical design knowledge and the need to apply new construction techniques. This research is relevant because it indicates that the limited Research & Development capacities of construction companies and poor knowledge exchange from academia to industry result in limited knowledge about the technical elaboration of designs with bio-based materials. This research develops façade wall reference details that are publicly available for use in various designs of residential top-up buildings. This contributes to the expansion of technical design knowledge, resulting in a broader application of bio-based materials in designs. Currently, designers do not know how to design buildings with bio-based materials, which hinders the application of these materials. Additionally, the research provides a solid foundation for further studies within academia. The used methodology in this research can be used to develop and analyse more bio-based materials using WUFI. Furthermore, it can serve as a starting point for developing details for floors and roofs. Finally, it can act as a starting point for elaborating other building physics elements, such as fire safety, acoustics, or structural aspects. The focus on sustainable and environmentally friendly building materials also supports academic goals related to sustainability. The research contributes to scientific efforts to achieve a sustainable world.

Regarding the social relevance, the research addresses reducing CO2 emissions, combating material scarcity, and reducing construction waste. This supports the transition to a more sustainable construction sector and helps reduce the

construction industry's impact on the environment. Promoting bio-based materials supports the principles of a circular economy. Bio-based materials can offer benefits for the health and safety of residents, such as improved air quality and the reduction of harmful substances. This improves the living environment and contributes to people's well-being. Thus, the research not only partially addresses the housing shortage in the Netherlands but also provides healthy housing. By ensuring that no thermal bridges occur, more energy-efficient buildings are created as well.