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	Tamara Lalyko
Student number	6075797

Studio		
Name / Theme	Building Technology Graduation Studio	
Main mentor	Simona Bianchi	Structural Design & Mechanics
Second mentor	Alessandra Luna Navarro	Façade & Product Design
Argumentation of choice of the studio	The topic of Integrated Multi-Hazard Resilience of Facades and the two fields of structural design and façade design were chosen out of personal interest and aim to contribute to academic research, as I strongly believe in the relevance of the topic. Further, I seek to expand my knowledge and gain more expertise in new domains such as probabilistic risk assessment.	

Graduation project	
Title of the graduation project	Retrofitting for Heat Resilience: A Dutch case study integrating overheating mitigation into cost-benefit analysis
Goal	
Location:	Netherlands
The posed problem,	There is lacking application of quantitative resilience assessment to analyze cost-effectiveness and inform decision-making of envelope systems. As a result, building stakeholders lack clear understanding of losses to expect from their building's vulnerability during the investment time span.
research questions and	**Main question** How can thermal resilience be integrated in cost-benefit analysis to inform decision-making of envelope retrofitting scenarios? **Sub-questions**

	- How can thermal resilience be measured and indicated considering interest of building stakeholders? - What are mitigation measures and parameters at envelope scale to reduce risk of overheating? - How does heat vulnerability relate to objectives, requirements and processes for renovation in the Netherlands? - Which cost-benefit analysis methods are useful for retrofitting scenarios? - How can the uncertainty of weather extremes be assessed in cost-benefit? - How can impact from thermal hazard be integrated into cost modelling? - How can risks for long-term hazard loss be outlined in cost-benefit giving insights into resilience? - How can resilience assessment with cost-benefit inform decision-making for envelope retrofitting?
design assignment in which these result.	Development of an adapted cost-benefit analysis for envelope retrofitting, which integrates the impact of performance variability from thermal hazard in cost-benefit analysis to better inform decision-making

Full Problem Statement:

With the increasing frequency and strength of heat hazards in the Netherlands, buildings face a growing risk of overheating, endangering occupant health and comfort while raising energy costs for cooling. Thermally vulnerable buildings are especially affected, and the purpose of energy renovations could be undermined by additional cooling energy implying greenhouse gas emissions.

Integrating passive mitigation strategies in retrofitting presents a crucial strategy to prevent overheating before resorting to active cooling. However, current renovation efforts prioritize energy efficiency for winter conditions, often neglecting overheating. This oversight is further reinforced by the lack of regulatory incentives and by thermal performance assessment considering typical meteorological years without including variability from temperature extremes.

To address this issue, existing studies have developed methods to quantify functional, economic, and ecological losses using simulations of documented heat extremes or future climate scenarios. However, these approaches struggle to

estimate expected losses over a specific time period due to uncertainties in climate development and event frequency. As a result, building stakeholders lack clear understanding of losses to expect from their building's vulnerability over an investment and use case period.
Existing research lacks application of quantitative resilience assessment to analyze cost-benefit and inform the selection of renovation alternatives. In practice, financial feasibility and cost-effectiveness are essential factors in decision-making since the worth of investments can only be determined by relating cost and efforts to expected benefits or downsides. Investigating resilience in cost-benefit analysis could improve renovation practice by revealing mitigation potential and long term cost for measures and further help to identify co-benefits in scenarios like energy retrofitting.

Full Objective:
The study will propose a framework for cost-benefit analysis (CBA) of renovation measures at the envelope scale. Adopting a common CBA method, the aim is to integrate the impact of performance variability due to thermal hazard, either in the form of cost or comprehensive specific functional loss.
For the framework design, existing methods for thermal resilience assessment will be reviewed and implemented, taking into account probability, vulnerability, and exposure to thermal hazards. The framework's goal is to inform in-practice decision-making on resilience and financial feasibility. Heat resilience will consequently be assessed in terms of value to the project's stakeholders. Non-expert stakeholders, like owners or occupants, are the ones directly affected by renovation projects. Therefore, the understanding of how stakeholders are impacted by decisions made in renovation planning should be supported.
The focus of the study lies on economic viability and monetary benefits from retrofitting instead of selecting renovation measures purely based on effectiveness. As a result, a main challenge of the study will be estimating hazard losses and probability over the project period and integrating functional loss as cost into the cost-benefit. Furthermore, overheating mitigation needs to be integrated into energy renovation practice to avoid counteracting outcomes.
The cost-benefit analysis will be tested in an exemplary case study of a common residential archetype, that could be subject to retrofitting. The benefits of different envelope renovation packages will be explored, and their impact on the building's thermal resilience will be assessed. The case study aims to prove the method's applicability in a renovation scenario and indicate how thermal hazards impact cost-benefit and review how this could inform non-experts,
The overall goal of this study is to gain insights on heat resilience from a cost-benefit and long-term impact point of view. The research should contribute to the Western European perspective on overheating mitigation in milder climates, where it is not yet standard practice and appropriate adaptation measures needs to be explored. Ultimately, the study seeks to enhance the thermal resilience of buildings by supporting decision-making for cost-effective envelope systems in renovation scenarios.

Process

Method description

The thesis develops a method for analyzing the cost-benefit of envelope renovations while integrating thermal resilience as a key factor. The research combines qualitative and quantitative methods using a literature review, probabilistic risk assessment, and performance simulation. Part of the research is also design-based, with literature references being used to propose renovation measures. The methodology follows a structured five-phase process, culminating in applying the proposed framework.

Literature Study

A state-of-the-art literature review using Scopus and public information from national institutes establishes foundational knowledge on heat resilience, renovation strategies, and early-stage decision-making. The first chapter outlines heat waves as a hazard, focusing on their impacting properties, the Dutch building stock's vulnerability, and the envelope systems' role in thermal performance. Further, the study identifies resilience metrics, hazard loss assessment methods, and passive mitigation strategies. Another chapter focuses on renovation practices to understand current retrofitting strategies, policies, processes, and benefits for stakeholders. Conclusions are then drawn on how thermal resilience relates to renovation interest. Finally, cost-benefit analysis methods are reviewed to find the most suitable for envelope retrofitting and risk assessment.

Framework Design & Implementation

Building on literature insights and case study requirements, the framework consists of two core components: 1.) Thermal Resilience Assessment, 2.) Cost-Benefit Analysis. The first part includes selecting a method for resilience loss quantification considering decision-maker interest and a metric that serves as a comparison index later in the case study. The second part of the framework design treats the integration of resilience in cost-benefit decision-making. The method mainly focuses on thermal performance but also considers other criteria in the renovation of value to decision-makers depending on the renovation scenario of the case study. The development addresses the main challenge of assessing the uncertainty of weather extremes over a specific time period in cost-modeling. Retrofit costs are estimated using sources such as RVO's 'kostenkentallen,' and the framework is implemented digitally to analyze trade-offs between different retrofit strategies.

Study Preparation

The case study is developed in parallel with the framework to ensure alignment. The chosen case study is a unit of a residential apartment block in Rotterdam from 1950, representing an older generation of porched houses with low energy performance. Considering regulatory requirements, the decision-maker perspective is defined, and thermal renovation objectives are set. Further, the energy model and other necessary data will be prepared and gathered. Three renovation packages (light to deep intervention) are designed, balancing mitigation potential, cost intensity, and feasibility. If necessary, individual measures are tested beforehand. If necessary, their thermal performance is tested singularly, or their cost-intensity will be reviewed beforehand.

Case Study
The case study will exemplify the proposed framework's application in a specific renovation scenario. The aim is to showcase how heat vulnerability of envelope systems influences cost-effectiveness investigating the previously developed renovation packages. At first, the base case, assuming no renovation, is assessed in terms of running cost, e.g. energy or maintenance, and thermal resilience. Then, the renovation packages will be evaluated by first doing an annual energy and thermal comfort simulations using mild, typical and extreme weather files. The performance results are then translated into monetary value and thermal resilience is quantified as a qualitative indicator. The variable annual capital costs of the baseline and retrofit are compared to assess savings or losses. Further, lifespan, involved costs, and effort, e.g., construction time, are estimated. Finally, the data is brought together in the cost-benefit analysis.

Evaluation of Results
The final phase evaluates the outcome of the case study. The analysis focuses on identifying the method's strengths and limitations. The quantified resilience index reflects how resilience becomes visible. The feasibility of integrating the framework into real renovation processes can also be questioned. Finally, suggestions for further exploration and for integrating additional resilience metrics and broader application scenarios are provided.

Literature and general practical references

The thesis work will review literature from several types of knowledge domains. This includes statistical data and field surveys on climate hazards, vulnerability of the built environment and renovation, official statutes and reports published by national institutions, as well as state-of-the-art research on resilience of building envelopes and multi-criteria decision making. The following is a list of all papers collected on the outlined topics.

Literature on Heat Hazard and Resilience:

A Digital Design Tool for Floods and Heatwaves Resilient Facade System. (2024).

Advies eis vermindering risico overhitting nieuwbouwwoningen in Omgevingsregeling. (n.d.). ministerie van Binnenlandse Zaken en Koninkrijksrelaties.

Baglivo, C., Congedo, P. M., & Malatesta, N. A. (2023). Building envelope resilience to climate change under Italian energy policies. Journal of Cleaner Production, 411, 137345. https://doi.org/10.1016/j.jclepro.2023.137345

Bianchi, S. (2023). Integrating resilience in the multi-hazard sustainable design of buildings. Disaster Prevention and Resilience, 2(3). https://doi.org/10.20517/dpr.2023.16

Climate ADAPT. (n.d.). Health Heatwave (High Temperature and Humidity), 1971-2099. Climate ADAPT - European Union. Retrieved January 20, 2025, from https://climate-adapt.eea.europa.eu/en/metadata/indicators/health-heatwave-high-temperature-and-humidity-1971-2099

Copernicus Europe. (2024, May 22). Heat stress: What is it and how is it measured? Copernicus Europe. https://climate.copernicus.eu/heat-stress-what-it-and-how-it-measured

Hamdy, M., Carlucci, S., Hoes, P.-J., & Hensen, J. L. M. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. Building and Environment, 122, 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031

Hamdy, M., & Hensen, J. (2015). Assessment of overheating risk in dwellings. Healthy Buildings Europe 2015.

Hummel, M., Büchele, R., Müller, A., Aichinger, E., Steinbach, J., Kranzl, L., Toleikyte, A., & Forthuber, S. (2021). The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe. Energy and Buildings, 231, 110454. https://doi.org/10.1016/j.enbuild.2020.110454

Kim, K. (2023). Resilience-based Facade Design Framwework.

Kim, K., Luna-Navarro, A., Ciurlanti, J., & Bianchi, S. (2024). A multi-criteria decision support framework for designing seismic and thermal resilient facades. Architecture, Structures and Construction, 4(2), 195–210. https://doi.org/10.1007/s44150-024-00116-0

Lassandro, P., & Di Turi, S. (2017). Façade retrofitting: From energy efficiency to climate change mitigation. Energy Procedia, 140, 182–193. https://doi.org/10.1016/j.egypro.2017.11.134

Mirzabeigi, S., Homaei, S., Razkenari, M., & Hamdy, M. (2023). The Impact of Building Retrofitting on Thermal Resilience Against Power Failure: A Case of Air-Conditioned House. In L. L. Wang, H. Ge, Z. J. Zhai, D. Qi, M. Ouf, C. Sun, & D. Wang (Eds.), Proceedings of the 5th International Conference on Building Energy

and Environment (pp. 2609–2619). Springer Nature. https://doi.org/10.1007/978-981-19-9822-5_279
Nahlik, M. J., Chester, M. V., Pincetl, S. S., Eisenman, D., Sivaraman, D., & English, P. (2017). Building Thermal Performance, Extreme Heat, and Climate Change. Journal of Infrastructure Systems, 23(3), 04016043. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000349
Paneru, S., Xu, X., Wang, J., Chi, G., & Hu, Y. (2024). Assessing building thermal resilience in response to heatwaves through integrating a social vulnerability lens. Journal of Building Engineering, 98, 111219. https://doi.org/10.1016/j.jobe.2024.111219
Rahif, R., Amaripadath, D., & Attia, S. (2022). Review on Overheating Evaluation Methods in National Building Codes in Western Europe. Clima 2022.
Ramakrishnan, S., Wang, X., Sanjayan, J., & Wilson, J. (2017). Thermal performance of buildings integrated with phase change materials to reduce heat stress risks during extreme heatwave events. Applied Energy, 194, 410–421. https://doi.org/10.1016/j.apenergy.2016.04.084
Sheng, M., Reiner, M., Sun, K., & Hong, T. (2023). Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages. Building and Environment, 230, 110001. https://doi.org/10.1016/j.buildenv.2023.110001
Shrotria, S. (2024). Enhancing Building Facade Resilience through Machine Learning.
Statistics Netherlands. (2019, August 16). More deaths during recent heat wave [Webpagina]. Statistics Netherlands. https://www.cbs.nl/en-gb/news/2019/32/more-deaths-during-recent-heat-wave
Sun, S., Kensek, K., Noble, D., & Schiler, M. (2016). A method of probabilistic risk assessment for energy performance and cost using building energy simulation. Energy and Buildings, 110, 1–12. https://doi.org/10.1016/j.enbuild.2015.09.070
Tzoutzidis, N. (n.d.). Quantification of thermal resilience in buildings.
van Dorland, R., Beersma, J., Bessembinder, J., Bloemendaal, N., Drijfhout, S., Groenland, R., Haarsma, R., Homan, C., Keizer, I., Krikken, F., van Meijgaard, E., Meirink, J. F., Overbeek, B., Reerink, T., Selten, F., Severijns, C., Siegmund, P., Sterl, A., de Valk, C., … Schreur, B. W. (n.d.). KNMI National Climate Scenarios 2023 for the Netherlands.
Vos, J. (n.d.). Praktijkboek Besluit bouwwerken leefomgeving (Bbl).
Wahi, P. (2020). Robustness of Building Envelope—Investigating robust design solutions for energy efficient educational buildings.
Wüest, T., & Luible, A. (2017). Increased thermal induced climatic load in insulated glass units. Journal of Facade Design and Engineering, 4(3–4), 91–113. https://doi.org/10.3233/FDE-161146

Literature on Cost Benefit Studies:

Araújo, C., Almeida, M., Bragança, L., & Barbosa, J. A. (2016). Cost–benefit analysis method for building solutions. Applied Energy, 173, 124–133. https://doi.org/10.1016/j.apenergy.2016.04.005
Belaïd, F., Ranjbar, Z., & Massié, C. (2021). Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector. Energy Policy, 150, 112122. https://doi.org/10.1016/j.enpol.2020.112122

Bragolusi, P., & D'Alpaos, C. (2022). The valuation of buildings energy retrofitting: A multiple-criteria approach to reconcile cost-benefit trade-offs and energy savings. Applied Energy, 310, 118431. https://doi.org/10.1016/j.apenergy.2021.118431

Dodoo, A., Gustavsson, L., & Tettey, U. Y. A. (2017). Final energy savings and cost-effectiveness of deep energy renovation of a multi-storey residential building. Energy, 135, 563–576. https://doi.org/10.1016/j.energy.2017.06.123

Ellram, L. (1995). Total Cost of Ownership: An Analysis Approach for Purchasing. International Journal of Physical Distribution & Logistics Management, 25, 4–23. https://doi.org/10.1108/09600039510099928

Galvin, R. (2023). How prebound effects compromise the market premium for energy efficiency in German house sales. Building Research & Information, 51(5), 501–517. https://doi.org/10.1080/09613218.2023.2176284

Galvin, R. (2024). The economic losses of energy-efficiency renovation of Germany's older dwellings: The size of the problem and the financial challenge it presents. Energy Policy, 184, 113905. https://doi.org/10.1016/j.enpol.2023.113905

Groh, A., Kuhlwein, H., & Bienert, S. (2022). Does energy retrofitting pay off? An analysis of German multifamily building data. IOP Conference Series: Earth and Environmental Science, 1078, 012116. https://doi.org/10.1088/1755-1315/1078/1/012116

Guardigli, L., Bragadin, M. A., Della Fornace, F., Mazzoli, C., & Prati, D. (2018). Energy retrofit alternatives and cost-optimal analysis for large public housing stocks. Energy and Buildings, 166, 48–59. https://doi.org/10.1016/j.enbuild.2018.02.003

Guazzi, G., Bellazzi, A., Meroni, I., & Magrini, A. (2017). Refurbishment design through cost-optimal methodology: The case study of a social housing in the northern Italy. International Journal of Heat and Technology, 35(Special Issue 1), S336–S344. Scopus. https://doi.org/10.18280/ijht.35Sp0146

Hu, M. (2019). Cost-Effective Options for the Renovation of an Existing Education Building toward the Nearly Net-Zero Energy Goal—Life-Cycle Cost Analysis. Sustainability, 11(8), Article 8. https://doi.org/10.3390/su11082444

Hyyrynen, M., Ollikainen, M., Käyhkö, J., Suomi, J., Lintunen, J., Käyhkö, J., Mäkelä, A., Groundstroem, F. M., & Juhola, S. (2025). Cooling is a cost-efficient way to adapt to heatwaves even in high-latitude cities. Climatic Change, 178(5). Scopus. https://doi.org/10.1007/s10584-025-03913-8

Johnstone, I. M. (2004). Development of a model to estimate the benefit-cost ratio performance of housing. Construction Management and Economics, 22(6), 607–617. https://doi.org/10.1080/0144619042000202825

Konstantinou, T., De Jonge, T., Oorschot, L., El Messlaki, S., Van Oel, C., & Asselbergs, T. (2019). The relation of energy efficiency upgrades and cost of living, investigated in two cases of multi-residential buildings in the Netherlands. Smart and Sustainable Built Environment, 9(4), 615–633. https://doi.org/10.1108/SASBE-04-2019-0044

Liu, Y., Xue, S., Guo, X., Zhang, B., Sun, X., Zhang, Q., Wang, Y., & Dong, Y. (2023). Towards the goal of zero-carbon building retrofitting with variant application degrees of low-carbon technologies: Mitigation potential and cost-benefit analysis for a kindergarten in Beijing. Journal of Cleaner Production, 393, 136316. https://doi.org/10.1016/j.jclepro.2023.136316
Mayer, Z., Volk, R., & Schultmann, F. (2022). Analysis of financial benefits for energy retrofits of owner-occupied single-family houses in Germany. Building and Environment, 211. Scopus. https://doi.org/10.1016/j.buildenv.2021.108722
Mikulić, D., Bakarić, I. R., & Slijepčević, S. (2016). The economic impact of energy saving retrofits of residential and public buildings in Croatia. Energy Policy, 96, 630–644. https://doi.org/10.1016/j.enpol.2016.06.040
Preciado-Pérez, O. A., & Fotios, S. (2017). Comprehensive cost-benefit analysis of energy efficiency in social housing. Case study: Northwest Mexico. Energy and Buildings, 152, 279–289. https://doi.org/10.1016/j.enbuild.2017.07.014
Sharbaf, S. A., & Schneider-Marin, P. (2025). Cost-benefit analysis of sustainable upgrades in existing buildings: A critical review. Energy and Buildings, 328, 115142. https://doi.org/10.1016/j.enbuild.2024.115142
Wahi, P. (2025). Preparing Dutch Homes for Energy Transition. https://repository.tudelft.nl/record/uuid:668e0b07-00f6-442e-ad71-8181afca3834
Zheng, D., Yu, L., Wang, L., & Tao, J. (2019). A screening methodology for building multiple energy retrofit measures package considering economic and risk aspects. Journal of Cleaner Production, 208, 1587–1602. https://doi.org/10.1016/j.jclepro.2018.10.196
Zhuang, C., Choudhary, R., & Mavrogianni, A. (2023). Uncertainty-based optimal energy retrofit methodology for building heat electrification with enhanced energy flexibility and climate adaptability. Applied Energy, 341, 121111. https://doi.org/10.1016/j.apenergy.2023.121111
Zhuang, C., Gao, Y., Zhao, Y., Levinson, R., Heiselberg, P., Wang, Z., & Guo, R. (2021). Potential benefits and optimization of cool-coated office buildings: A case study in Chongqing, China. Energy, 226. Scopus. https://doi.org/10.1016/j.energy.2021.120373

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)?

In building technology, the department's four chairs focus their research on advancing climate design, sustainable structures, facade systems, products, and digital technologies for the built environment. The chosen topic, 'Low-Carbon Resilient Building Envelopes,' is part of the structural design chair's studio theme, 'Sustainable Structures.' The topic belongs to research efforts focusing on climate hazard resilience in construction design and links to the façade and product design field. The thesis aims to investigate a subset of the topic: thermal resilience in cost-benefit analysis for envelope retrofitting. The work incorporates knowledge from multiple fields, including facade design, building physics, and building management. Since most fields were part of my master's education program, I use and try to expand my knowledge by learning from my mentor's ongoing research. As building management was not part of my education, I will lean on the expertise of the management in the built environment department. My project's goal is to connect these fields of expertise to deliver a comprehensive approach to the design practice of construction.

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

The impact of thermal hazards is increasing globally due to global warming. Under these circumstances, interest from expert and non-expert stakeholders in the topic of resilience and climate adaptation is growing increasingly. Moreover, academic research investigating resilience in construction is advancing. Research has examined mitigation via passive and active renovation strategies. However, there is still a lack of practical application of both thermal resilience assessment and heat mitigation measures in renovation. A missing key is cost-benefit analysis, where the integration of the impact of performance variability from thermal hazard is still lacking. My project aims to provide knowledge to enhance standard practice towards future-proof decision-making.