D16.3. Virtual intervention modelling

MULTICARE

Funded by
the European Union

D16.3 Virtual intervention

Dissemination Level:	Public
Lead Partner:	AMS
Due date:	31-03-2025
Actual submission date:	25-03-2025

PUBLISHED IN THE FRAMEWORK OF

MULTICARE (Horizon Europe grant 101123467)

AUTHORS

Evdokia Stavridou, OMRT
Hamidreza Shahriari, OMRT
Divyae Mittal, OMRT
Kyra Koning, AMS Institute
Zhikai Peng, AMS Institute
Anna Silva, AMS Institute
Anastasios Kokkos, AMS Institute

REVISION AND HISTORY CHART

VERSION	DATE	EDITORS	COMMENT
V0.1	06 Jan 2024	Evdokia Stavridou, Kyra Koning, Zhikai Peng	First draft
V0.2	21 Jan 2024	Evdokia Stavridou	Second draft
V1.0	17 Feb 2024	Evdokia Stavridou, Zhikai Peng, Anna Silva	Review
V1.1	11 Mar 2025	Simona Bianchi, Anna Maria Koniari	Review
V2	25 Mar 2025	Evdokia Stavridou, Zhikai Peng, Anna Silva, Anastasios Kokkos	Final version

DISCLAIMER

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Executive Summary

Table of contents

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

List of Tables

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

LIST OF FIGURES

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

GLOSSARY

ACRONYM	FULL NAME
BENG	Bijna Energie Neutrale Gebouwen
BVO	Bruto-vloeroppervlakte (gross floor area GFA) [m²]
clo	Clothing insulation unit, measure of thermal resistance due to clothing
DF	Daylight Factor [%]
IOH	Indoor Operating Hours
LTA	Light transmittance average [-]
g	Solar energy transmittance of glazing [-]
GO / GBO	Gebruiksoppervlakte (usable/net floor area UFA) [m²]
GTO	Gewogen temperatuuroverschrijdingsuren (weighted temperature hours)
HR	High performance/efficiency double glazing with a special coating applied inside the cavity (=space between glass plates)
HS	Heat stress / Heat wave
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
Qv	Infiltration rate [m³/s per m² façade]
Rc	Thermal resistance [m²K/W]
SH	Space Heating
U/Ug	Thermal transmittance [W/m²K]
WP	Work package
WWR	Window to wall ratio

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

1. Introduction

1.1. MULTICARE project

The built environment is ill-prepared for more frequent and increasingly intense climate-related extreme events. The current building stock is particularly vulnerable because it has limited or no capacity to adapt and recover from extreme events thereby leading to building failures that cause severe socio-economic losses and adversely affecting the health and wellbeing of people. Recent scientific and technological advances in the construction industry provide timely solutions for improving the resilience for specific single hazards (e.g. flood hazard or seismic hazard), but they are often not cost effective, rarely eco-friendly and nearly never address the multiple hazards present in many locations. This is hardly surprising because there is neither a clearly defined framework for quantifying the whole-life socio-economic-environmental impacts of extreme natural events nor tools for assessing the holistic climate resilience of buildings. Consequently, it is currently very challenging to develop/select optimal solutions for real-world multi-hazard scenarios.

MULTICARE will address this challenge directly by developing new multi-criteria decision-support frameworks and providing plug & play technological and digital solutions for improving the resilience of the built environment in a cost-effective, reliable and sustainable manner. The technological solutions consist of multi-functional low-carbon resilient technologies embedded in modular and prefabricated construction for the next generation of high performance and smart buildings, characterized by enhanced safety, energy efficiency, environmental-sustainability, improved quality of life, circularity, and scalability for a broad range of natural events and end-user. The plug & play technologies will be applied to either new multi-story buildings or existing structures by means of low-invasive external interventions. The digital solutions consist of a suite of multi-disciplinary digital services and tools for performing multi-hazard resilience assessment, design, operation and management across multiple scales (material, component, building, neighborhood/city). The new digital tools will enable stakeholders to make informed decisions in the selection of materials/solutions, including for heritage buildings, and support resilient supply chains. The effectiveness of the MULTICARE solutions will be demonstrated through large-scale pilots (3 buildings, 4 neighborhoods/district) in three different European countries carefully selected for their diverse local environmental, social and economic conditions (Italy, Netherlands, Romania). Banks and institutional investors will be engaged to better understand the financial risk reduction value of resilience and update existing and future “green finance” mechanisms that will help to leverage the project results. A user-center, inclusive and participatory approach will be consistently implemented throughout the project to engage citizens and extend the durability of MULTICARE impact.

To achieve these ambitious goals, MULTICARE brings together a unique interdisciplinary Consortium of 21 partners from 6 different EU countries with strong R&D and practical expertise, who are either established leaders in their sector or agile SMEs in emerging fields. Altogether the Consortium members span across the whole technical and value chain required for developing and implementing solutions in terms of design, digitization, manufacturing, construction and monitoring of resilient and sustainable buildings. The

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Consortium also includes partners with experience in social sciences, user engagement, and training to ensure the success and widespread application of new technologies in local communities. The Consortium will also support clustering activities with other relevant research projects to share knowledge and raise public awareness of building resilience. An international outreach and cooperation strategy will also be implemented to tackle the project challenges.

Table 1. Consortium

Number	**Role**	**Short Name**	**Legal Name**	**Country**
1	CO	TU Delft	TECHNISCHE UNIVERSITEIT DELFT	NL
2	BEN	PFE	PRIEDEMANN FASSADENBERATUNG GMBH	DE
3	BEN	IES R&D	IES R&D	IE
4	BEN	INCDFP	INSTITUTUL NATIONAL DE CERCETARE-DEZVOLTARE PENTRU FIZICA PAMANTULUI	RO
5	BEN	UNIROMA1	UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA	IT
6	BEN	XLD	X-LAM DOLOMITI SRL	IT
7	BEN	STRESS	SVILUPPO TECNOLOGIE E RICERCA PER L'EDILIZIA SISMICAMENTE SICURA ED ECOSOSTENIBILE SCARL	IT
7.1	AE	UNINA	UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II	IT
8	BEN	AMS Institute	STICHTING AMSTERDAM INSTITUTE FORADVANCED METROPOLITAN SOLUTIONS(AMS)	NL
9	BEN	PMB	MUNICIPIUL BUCURESTI	RO
10	BEN	ASM	ASM - CENTRUM BADAN I ANALIZ RYNKUSPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA	PL
11	BEN	RoGBC	ASOCIATIA ROMANIA GREEN BUILDING COUNCIL	RO
12	BEN	RINA-C	RINA CONSULTING SPA	IT
13	BEN	UTBV	UNIVERSITATEA TRANSILVANIA DIN BRASOV	RO
14	BEN	ACER	AGENZIA CAMPANA PER L EDILIZIA RESIDENZIALE	IT
15	BEN	Boom	BOOM BUILDS B.V.	NL
16	BEN	OMRT	OMRT BV	NL
17	BEN	ROTHO BLAAS SRL	ROTHO BLAAS SRL	IT
18	BEN	ARUP	ARUP BV	NL
19	BEN	Tecuci	MUNICIPIUL TECUCI	RO
20	BEN	Hölscher	DIPL.-ING. HÖLSCHER GMBH & CO.KG	DE

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

1.2. WP 16.3 Virtual intervention modelling for new built & renovation

The objective of WP 16.3 consists of the selection of a façade system and defining an urban intervention that optimizes energy efficiency, embodied carbon, climate resilience and circularity for buildings in Amsterdam, by using a parametric multi-criteria assessment.

Using the design handbook derived from WP 5-6 as a starting point, representative façade systems and materials were incorporated it the multi-criteria approach covering a wide range of new-built scenarios that are representative of the Dutch context and its specific characteristics. A similar parametric model is built, this time assessing renovation cases in the Amsterdam historical centre, carefully adapted to the climatic conditions and improvement properties of the renovated façades.

1.3. Deliverables

This deliverable provides the creation of 27 multi-criteria workflows (archetypes) covering a complete list of any renovation case in the city of Amsterdam.

Additionally, it results in the creation of virtual intervention modelling, more specifically, in one parametric model dedicated to new built constructions (located in Cruquiuseiland area) and a second one assessing renovation cases of typical residential units (Amsterdam historic centre). The visual configurator defines in a comprehensive, interactive and engaging manner all the possible scenarios investigated and simulated for the intervention design. Through the use of the configurator, the impact of different renovation strategies is determined with regards to the buildings' energy, internal comfort, sustainability and resilience aspects.

1.4. Connection to other MULTICARE deliverables

WP16 is directly linked to WP17 in the MULTICARE project, which tests the feasibility of the MULTICARE solutions developed by WP4, WP5, WP6, WP7, and WP8 in real-world contexts in Amsterdam.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

2. Virtual interventions for new builds

2.1 Multi-criteria parametric framework

The multi-criteria assessment of newly constructed buildings in Amsterdam commences with the identification of key parameters influencing the performance of building façades. Subsequently, an extensive set of values for each parameter is developed, representing façade systems that range from compliance with the minimum standards of the Dutch Building Decree (Bouwbesluit 2012) (BBL, 2023) to advanced and more sophisticated configurations meeting the latest industry standards. Particular attention is devoted to aligning these values with the material library previously established in WP5. The detailed characteristics and properties of both the transparent and non-transparent façade elements considered are overviewed in Table 2., whereas Table 3 provides the complete outline of the façade parameters identified in this specific multi-criteria assessment.

Table 2. Outline of the façade (non)-transparent properties incorporated

Façade Properties

Opaque Components				
	Min Bouwbesluit	Improved Insulation Scenario	Approximate Passive House	
Primary layer (Wall)	Timber	Timber	Timber	
Bracket type	Steel Bracket	Steel Bracket	Steel Bracket	
Secondary layer (Insulation)	Polyurethane (PU)	Cellulose	Rock wool	
Thermal membrane	Polypropylene (PP)	PVC (Polyvinyl Chloride)	EPDM	
Third layer (Cladding)	Wooden Based Board	Wooden Based Board	Wooden Based Board	
Transparent Components				
Name	Thickness [cm]	U[W/m²K]	g [-]	LTA [-]
Double high solar gain low-e	25.93	1.68	0.69	0.74
Double low-e (air) - deflected	21.45	1.61	0.36	0.68
Triple Clear	42.55	1.84	0.62	0.70
Triple low-e (argon)-deflected	42.51	0.70	0.30	0.51

Regarding the non-transparent/opaque façade configurations and their properties selected to be incorporated in the multi-criteria analysis, typical constructions with timber wall as their primary layer were evaluated. The selection of timber as basic layer of the façade constructions incorporated originates from the design principles adopted by the Amsterdam Demonstrator, the new-built construction located in Cruquiuseiland area. The façade typologies considered as well as their respective components and properties derived from an extensive library built by HOELSCHER GMBH & CO.KG. Although the extended information shared is based on approximated values originating from various sources of the market, it provides rough yet extremely valuable estimates of façade calculations, specifically intended for preliminary design purposes.

As far as the glazing options are concerned, the typologies above were selected as representatives of typical glazing scenarios. In more detail,

- "Double high solar gain low-e" resembles a basic double-glazing case
- "Double low-e (air) - deflected " stands for a better performing double-glazing that also functions as an active cooling measurement
- "Triple Clear" covers the standard triple glazing typologies
- "Triple low-e (argon)-deflected" reflects an advanced triple glazed option, simultaneously serving an active cooling solution

Table 3. Overview of façade parameters incorporated in the new built assessment

New Built Assessment

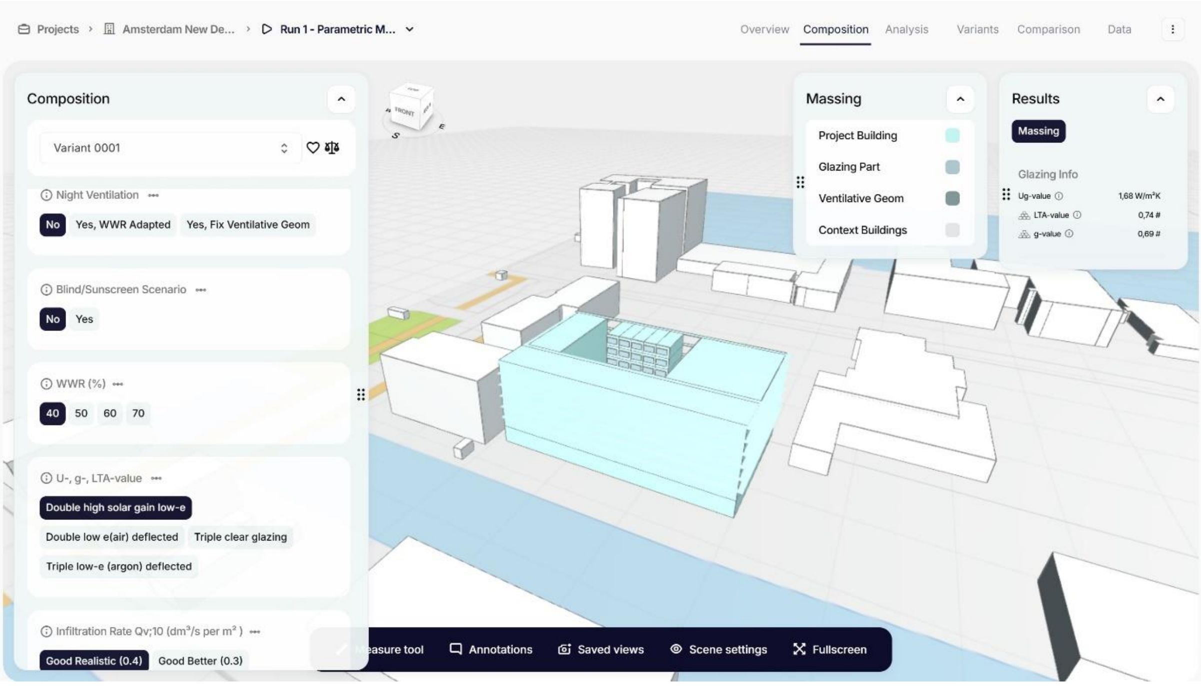
Night Ventilation	No / Yes		
Sunscreens / Blinds	No / Yes, external black blinds mechanically controlled, fixed to WWR / Yes, external black blinds mechanically controlled, proportional to WWR		
Window-Wall-Ratio (WWR)	0.4 / 0.5 / 0.6 / 0.7		
(Façade) Opaque Components			
Infiltration Rate (Qv)	0.60 / 0.40 / 0.30 / 0.20		
Thermal Transmittance (U), Door	1.65 / 1.40 / 1.20		
Thermal Resistance (Rc [m^2K/W])	Floor	Façade	Roof
	3.70	4.95	6.30
	4.70	5.40	6.30
	6.00	5.77	8.00
Façade Transparent Components			
4 Glazing Typologies	U[W/m^2K]	g[-]	LTA [-]
	1.68	0.69	0.74
	1.61	0.36	0.68
	1.84	0.62	0.70
	0.70	0.30	0.51

The aforementioned values collectively, also referred to as "variables", comprise the respective parametric framework which is eventually translated into a tangible and

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

interactive model hosted in the interactive dashboard of OMRT, the "hub" (Figure 1). This 3D model provides the user with the possibility to both qualitatively and quantitatively explore the impact of each variable separately as well as in combination with others over the façade performance while taking into consideration the specific climatic conditions of the Amsterdam region. In more detail, the performance of the different façade systems is evaluated by addressing various aspects, including energy and daylight performance, climate resilience as well as the indoor comfort provided to the building occupants.



Variant 0001

Night Ventilation: **No** | Yes, WWR Adapted | Yes, Fix Ventilative Geom

Blind/Sunscreen Scenario: **No** | Yes

WWR (%): **40** | 50 | 60 | 70

U-, g-, LTA-value: **Double high solar gain low-e** | Double low e(air) deflected | Triple clear glazing | Triple low-e (argon) deflected

Infiltration Rate Qv;10 (dm³/s per m²): **Good Realistic (0.4)** | Good Better (0.3)

Massing: Project Building | Glazing Part | Ventilative Geom | Context Buildings

Glazing Info

Ug-value	1,68 W/m²K
LTA-value	0,74 #
g-value	0,69 #

Figure 1. Aspect of the interactive dashboard hosted in the OMRT / hub

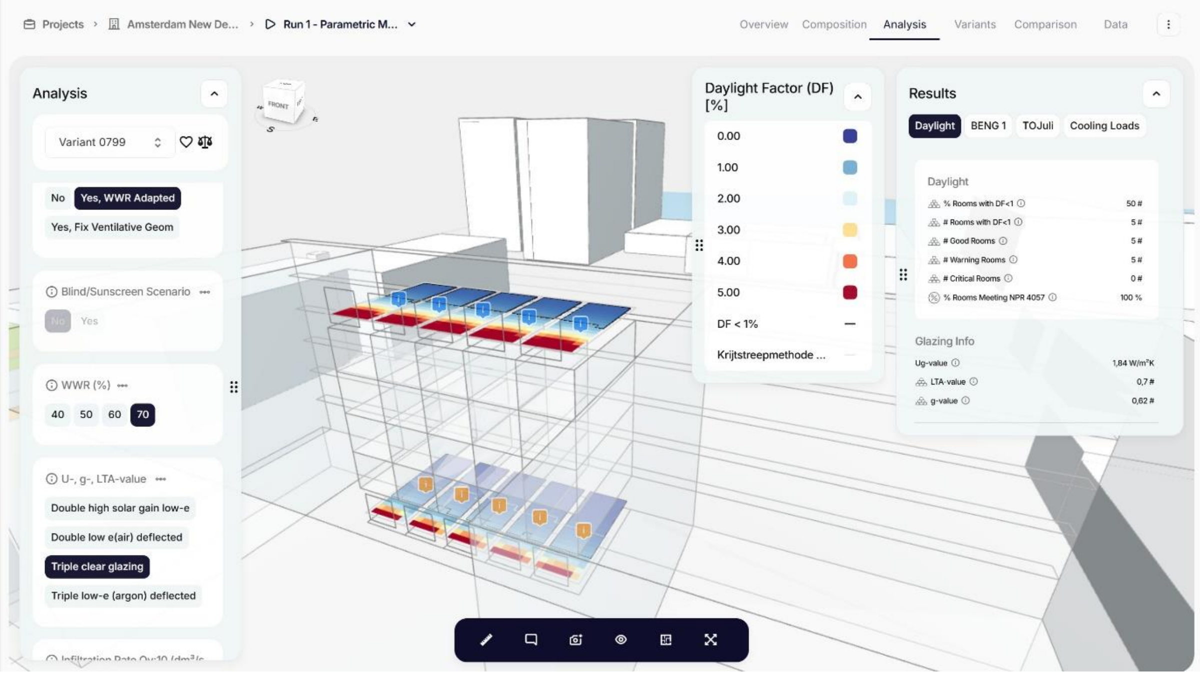
The user can choose different façade configurations by selecting between the options available for each variable category. The 3D model in the middle is instantly updated and so are the respective outputs presented to the right.

2.2 Analyses performed

While aiming for the main objective of this multicriteria assessment, namely the selection of a façade configuration that optimally combines various climate resilience factors, a set of typically representative analyses was decided to be assessed. Those analyses, briefly mentioned in the current section, form the selection criteria upon which the wide list of façade characteristics, and configurations as a whole, are evaluated within the context of the Amsterdam area and climatic conditions.

Daylight Factor (DF) assessment

Daylight analysis evaluates the quantity, distribution, and quality of natural daylight within a building under standard overcast sky conditions (Figure 2). Specifically, the daylight factor (DF) is calculated as the percentage ratio of indoor illuminance to outdoor illuminance, in accordance with NEN 17037 (NEN, 2022) and NPR 4057 (NEN, 2022). To ensure adequate access to natural light for health and indoor comfort, at least 50% of the floor area in a living space must meet the requirement, which for residential applications is defined as DF > 1%.



Variant 0799

No | **Yes, WWR Adapted** | Yes, Fix Ventilative Geom

Blind/Sunscreen Scenario: **No** | Yes

WWR (%): 40 | 50 | 60 | **70**

U-, g-, LTA-value: Double high solar gain low-e | Double low e(air) deflected | **Triple clear glazing** | Triple low-e (argon) deflected

Daylight

% Rooms with DF<1	50 #
# Rooms with DF<1	5 #
# Good Rooms	5 #
# Warning Rooms	5 #
# Critical Rooms	0 #
% Rooms Meeting NPR 4057	100 %

Glazing Info

Ug-value	1,84 W/m²K
LTA-value	0,7 #
g-value	0,62 #

Figure 2. Daylight Factor analysis

It indicates the share of outdoor light coming inside the housing unit based on a diffuse sky

It measures the amount of daylight penetrating a room through its openings and evaluates how effectively it is distributed over it.

The Daylight Factor (DF) analysis implemented by OMRT integrates the Krijtstreepmethode, offering deeper insights into compliance with NEN 17037 (NEN, 2022) and the Bouwbesluit 2012 (BBL, 2023), particularly valuable during the early design phases. By incorporating the Krijtstreepmethode, even when the 50% daylight rule for living spaces is not directly satisfied, critical information regarding the feasibility of achieving compliance is provided. Specifically, housing units that directly meet the daylight requirements according to NPR 4057 (NEN, 2022) are indicated by a blue annotation. For units that fall short, the Krijtstreepmethode is applied to assess whether compliance can be achieved through minor design adjustments. The units for which this approach ensures compliance are marked with orange annotations. On the contrary, units unlikely to meet the daylight requirements during the daylight calculation performed at later design stages, are labeled with a red annotation, signaling the need for significant design changes.

Therefore, the incorporation of Daylight Factor analysis with the Krijtstreepmethode ensures a comprehensive evaluation that considers both regulatory compliance and occupant comfort.

Energy, BENG 1 indication

The energy analysis tool provides critical insights over the influence of various façade characteristics that guide design choices, helping to reduce energy demand, to integrate renewable energy sources and to align with national sustainability objectives (Figure 3). In

Funded by the European Union

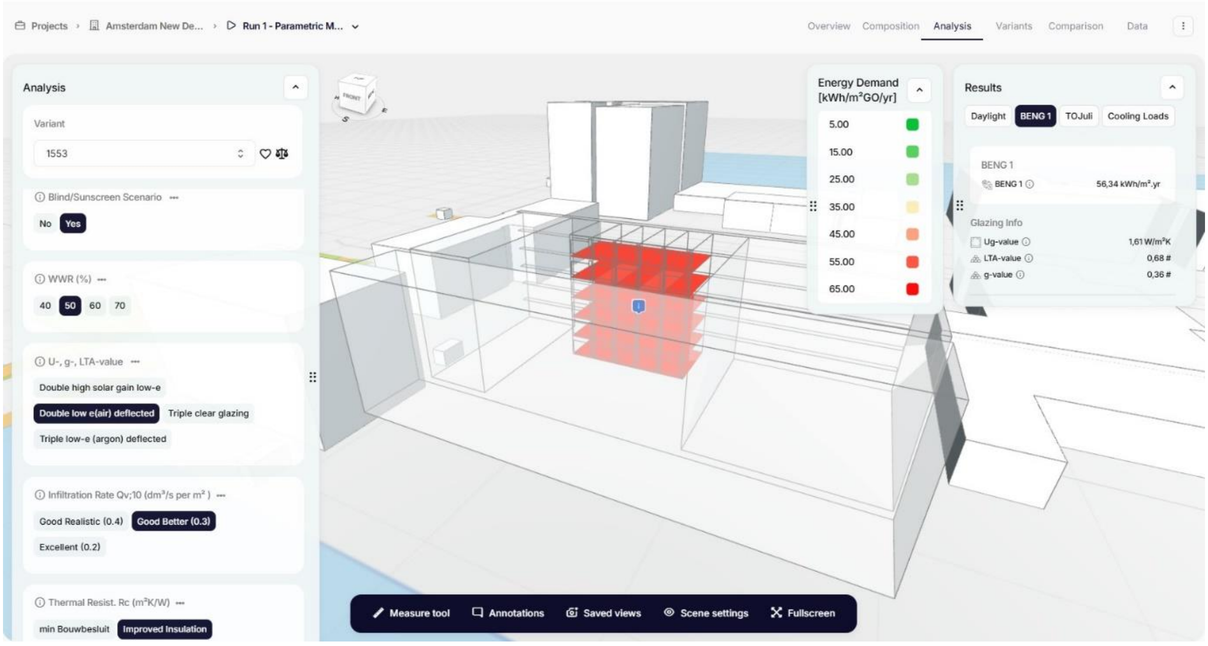
This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

this way, a preliminary assessment of the building's energy requirements is provided already during early design stages, facilitating the fine-tuning of design aspects and the identification of areas for improvement.

For this reason, key parameters that considerably influence the energy performance of a building are considered. To name a few, the insulation and airtightness of the building envelope, the building geometry and its orientation in relation to shading and natural ventilative options, the different glazing typologies and its subsequent characteristics e.g.

- the thermal transmittance (Ug) coefficient of glass quantifying the amount of energy a building loses through a window element,
- the total solar energy transmittance value (g-value) that represents the amount of energy penetrating the pane and thus delivering an energy gain for the building's interior,
- the light transmission factor (LTA) of a window indicating the proportion of visible light that passes through the pane.

Via the coupling of the energy analysis with Uniec3, the widely used software tool in the Netherlands designed for calculating the energy performance of buildings, the energy analysis performed recreates in a trustworthy, yet indicative, manner the alignment with the Dutch BENG (Bijna Energie Neutrale Gebouwen) standards (RVO, 2017). The BENG standards are based on NTA 8800 (NEN, 2024), prescribe nearly energy-neutral buildings in the Dutch context and have been mandatory for new constructions since January 1, 2021. Therefore, BENG 1 [kWh/m²/year] indicator is determined according to Uniec3 providing valuable insight in the annual total energy required by the residential building in order for it to satisfy its heating and cooling needs.



Variant: 1553

Blind/Sunscreen Scenario: No [✓ Yes]

WWR (%): 40 [✓ 50] 60 70

U-, g-, LTA-value: Double high solar gain low-e [✓ Double low e(air) deflected] Triple clear glazing Triple low-e (argon) deflected

Infiltration Rate Qv;10 (dm³/s per m²): Good Realistic (0.4) [✓ Good Better (0.3)] Excellent (0.2)

Thermal Resist. Rc (m²K/W): min Bouwbesluit [✓ Improved Insulation]

BENG 1

BENG 1: 56,34 kWh/m².yr

Glazing Info

Ug-value: 1,61 W/m²K

LTA-value: 0,68 #

g-value: 0,36 #

Figure 3. The BENG 1 building-level indicator

It provides insight into the total energy required for heating & cooling in residential buildings.

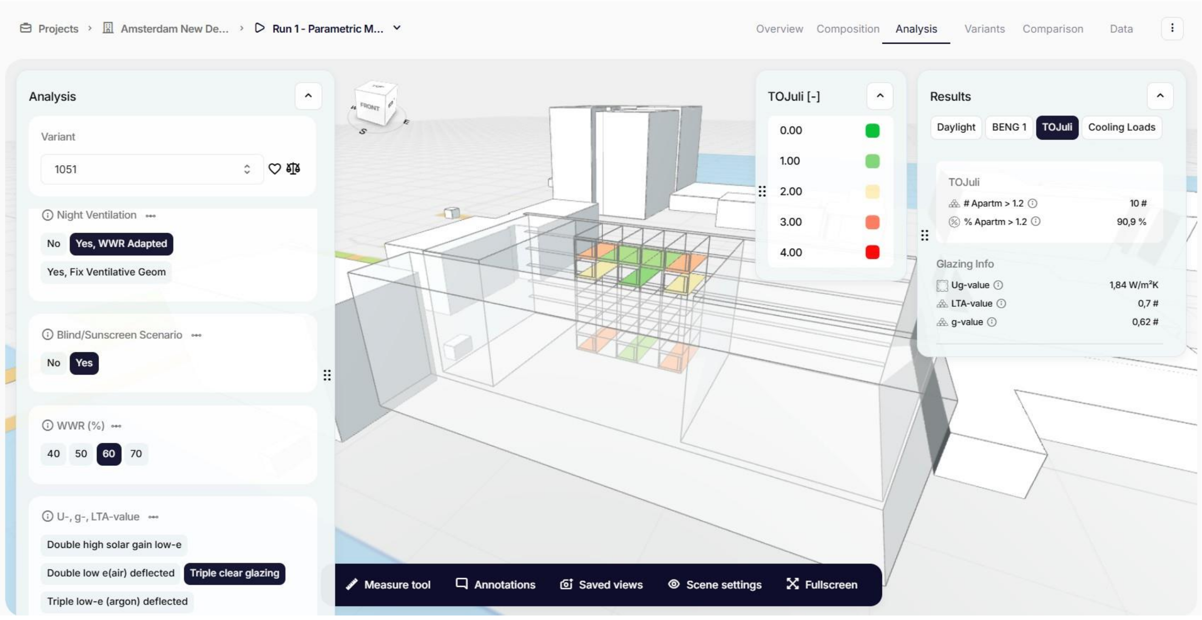
Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Indoor Comfort, TOjuli [-]

In addition, the thermal comfort indicator TOjuli [-] is assessed, efficiently describing the probability of a residential unit to overheat during summer months according to NTA 8800 (NEN, 2024) (Figure 4). In practice, the indicator is determined globally per orientation through the division of the heat surplus calculated for July by the heat resistance of the specific façade. The acronym TOjuli stands for "Temperatuur Overschrijding in juli", which practically translates to "Temperature Exceedance in July". It is a unitless factor that represents how efficiently a building can maintain interior comfort during the summer months by eliminating excessive heating overload in the living areas. The TOjuli calculation performed also originates from the coupling that OMRT has set up with Uniec3 software.

The importance of maintaining comfort interior conditions is highlighted by the ever-increasing risk of overheating even in the Dutch context, where summers tend to be warmer and last longer, resulting in rather uncomfortable conditions in the interior of buildings traditionally designed and constructed for cooler climatic conditions. The upper permitted TOjuli value is 1.2 [-] and applies in the Netherlands as a boundary for all housing units since 2024. Even for the cases where active cooling is applied, TOjuli calculation is still required to ensure that the cooling capacity provided suffices.



Variant: 1051

Night Ventilation: No | **Yes, WWR Adapted** | Yes, Fix Ventilative Geom

Blind/Sunscreen Scenario: No | **Yes**

WWR (%): 40 | 50 | **60** | 70

U-, g-, LTA-value: Double high solar gain low-e | Double low e(air) deflected | **Triple clear glazing** | Triple low-e (argon) deflected

TOJuli [-]	
0.00	🟩
1.00	🟩
2.00	🟨
3.00	🟧
4.00	🟥

TOJuli

# Apartm > 1.2	10 #
% Apartm > 1.2	90,9 %

Glazing Info

Ug-value	1,84 W/m²K
LTA-value	0,7 #
g-value	0,62 #

Figure 4. Overview of TOjuli analysis tab as seen on the "hub".

The legend facilitates the evaluation of the indoor comfort performance achieved. TOjuli is a building level indicator assessing the chance of overheating. When TOjuli ≤ 2 [-], the requirement is directly met. Typical parameters that affect the TOjuli calculation are shading implementation, summer night ventilation, infiltration values, internal heat production, clo values and metabolism rate.

The TOjuli boundary of 1.2 [-] statistically relates to the 450-hour requirement set for residential units as indicated by the GTO analysis. For the cases where the TOjuli ≤ 2 [-] requirement is not met, the internal comfort of the unit analyzed is still acceptable provided the GTO requirement is satisfied. Therefore, the GTO dynamic calculation is suggested to be performed.

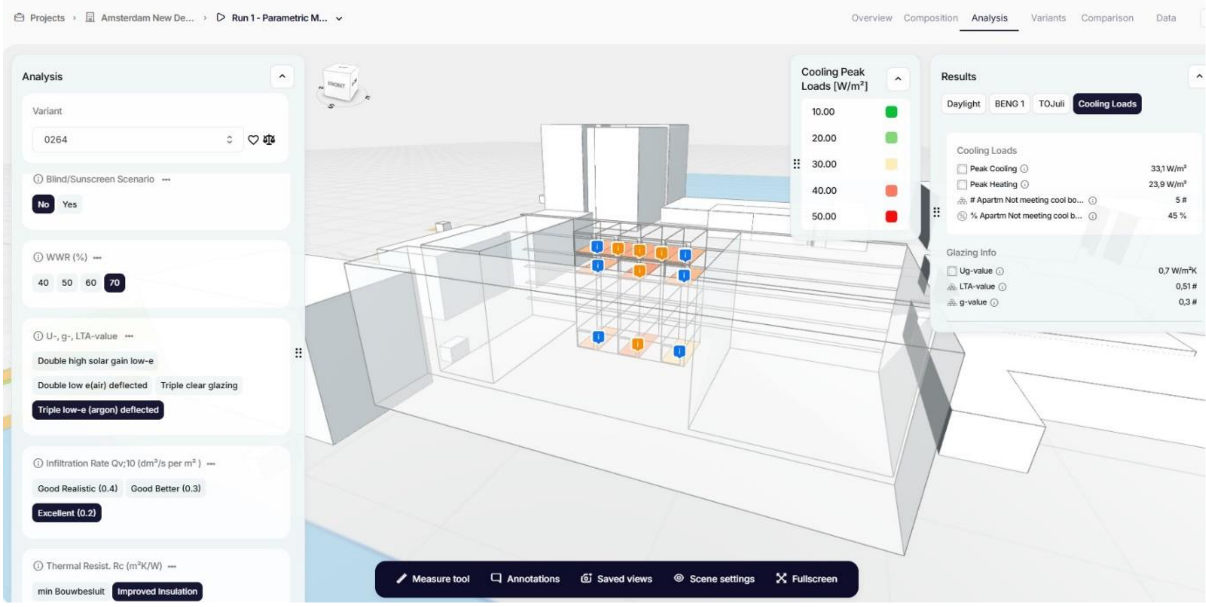
Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Cooling Loads

The Cooling Loads analysis is also conducted aiming to provide insight into originally the feasibility and further the performance of different cooling approaches (Figure 5). More specifically, the cooling capacity required for each residential unit is evaluated by assessing the respective Peak Cooling loads. The latter proves a useful indicator of not only the type but also the characteristics of the most appropriate cooling option, such as air conditioners, heat pumps, etc. In this way, the feasibility of typical cooling systems is indicated, floor cooling for the case of the Amsterdam demonstrator with a capacity of 35 W/m² considered as the feasibility threshold of typical systems available on the market.

Cooling Loads calculation, apart from preventing the over- or under-sizing of cooling systems that would eventually result in inefficiencies associated with misaligned systems, provides a thorough understanding of the different design parameters that considerably influence the cooling capacity of building units. Representative examples of such parameters are overhangs, window-to-wall ratios (WWRs), glazing types, ventilation solutions, building infiltration and insulation properties. The previous is particularly important in well-insulated buildings, where the typically advanced heat retention often leads to excessive indoor temperature and subsequent increased cooling needs during the warmer months of the year.



Analysis

Variant: 0264

Blind/Sunscreen Scenario: No | Yes

WWR (%): 40 | 50 | 60 | 70

U-, g-, LTA-value: Double high solar gain low-e | Double low e(air) deflected | Triple clear glazing | Triple low-e (argon) deflected

Infiltration Rate Qv;10 (dm³/s per m²): Good Realistic (0.4) | Good Better (0.3) | Excellent (0.2)

Thermal Resist. Rc (m²K/W): min Bouwbesluit | Improved Insulation

Cooling Peak Loads [W/m²]

10.00	🟩
20.00	🟩
30.00	🟨
40.00	🟥
50.00	🟥

Results

Daylight | BENG 1 | TOJuli | Cooling Loads

Cooling Loads

☐ Peak Cooling	33,1 W/m²
☐ Peak Heating	23,9 W/m²
# Apartm Not meeting cool bo...	5 #
% Apartm Not meeting cool b...	45 %

Glazing Info

☐ Ug-value	0,7 W/m²K
LTA-value	0,51 #
g-value	0,3 #

Figure 5. Cooling loads analysis visualisation as part of the multi-criteria analysis

Cooling Loads calculations are crucial in the building context, ensuring energy efficiency, evaluating potential cooling systems and their feasibility, verifying compliance with regulatory thresholds, and maintaining indoor comfort in response to rising summer temperatures and sustainability goals.

The comparative study of the analyses mentioned above plays a crucial role in the design of high-performance buildings through optimizing the natural lighting and indoor comfort while minimizing, to the extent possible, their energy use and overall environmental impact.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

The upcoming section provides insight into the way the actual multi-criteria approach is realized and, additionally, how it is facilitated by the 3D interactive tool. Therefore, representative cases of quantitative assessments are provided, indicating optimal façade interventions.

2.3 Multi-criteria assessment

Following the parametric framework creation of the multi-criteria assessment primarily aiming to explore various façade configurations and their influence on the overall performance of typical new constructions by conducting daylight, energy, interior comfort and sustainability analyses, the actual evaluation of the interrelation between the inputs and respective outputs takes place.

The previous is realized using a dual approach, partially via the interactive 3D model and additionally through the "Variant" tab of the hub platform where the evaluation of different façade configurations is enhanced in a more quantitate manner. The combination of the two approaches ensures a balanced and comprehensive evaluation.

The exploration of the multi-criteria assessment via the use of the 3D interactive model setup in hub is most probably rather straightforward to comprehend. By varying over the different design options incorporated the user gains valuable insights on their associated impact This is realized initially by studying for each study performed the colored meshes accompanied by their explanatory legends as well as by diving into the representative metrics shown in the outputs section and assessing their fluctuation in response to the input selection.

Moving on to the variant analysis tab, it not only provides a visual overview of the complete list of input parameters and calculated outputs but also allows for evaluating their interrelation and influence on the various optimization objectives. The respective graph is demonstrated in Figure 6 below.

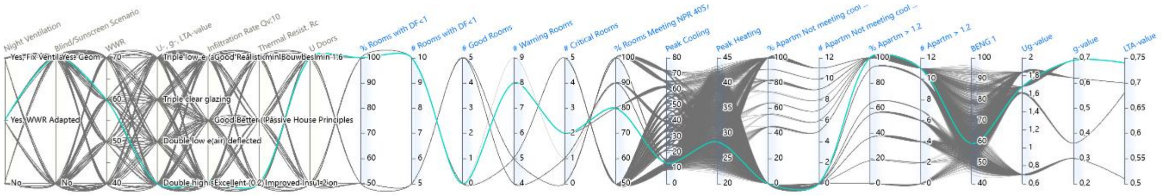


Figure 6. The variant graph as seen on the hub platform

This visualization provides an overview of the Parametric Multi-criteria Assessment followed and consists of the complete list of input parameters marked in grey color to the left and of the outputs in blue to the right. When a certain design option is selected, the respective input and output parameters are colored in cyan enhancing the information readability.

This variant interactive chart is highly useful in the decision making of multi-disciplinary workflows where usually a set of parameters performs best in one objective (daylight performance for example) but causes implications in others (e.g. energy efficiency). There, the interrelations between critical parameters are explored and substantiated discussions over the inevitable trade-offs are initiated.

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

By prioritizing the necessity and impact of the different objectives of multi-criteria assessments and by applying the respective filters, the extended input combinations are narrowed down to those aligning best with the project's priorities and KPI's.

An example of the previous is presented in Figure 7. The first image depicts the complete list of options tested, 1728 combinations in total, accompanied by the respective outputs. By filtering the performance indicators that are considered optimal per analysis, the objectives that result in the most favorable parameters combination are prioritized. Based on the performances considered as optimal, namely the elimination of critical apartments in terms of daylight, the minimization of BENG 1 values and Peak Heating Demand, the available design options that meet those requirements are limited from 1728 to only 24.

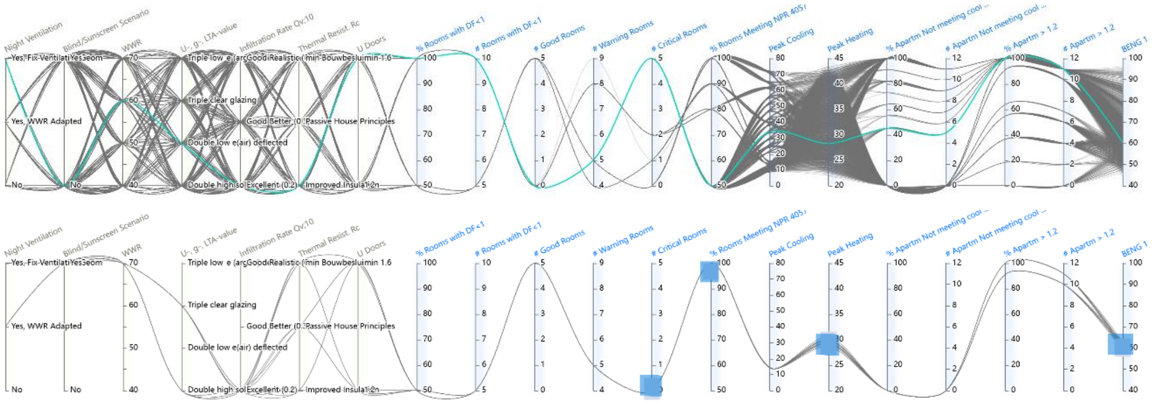


Figure 7. The multi-criteria results after resetting of performance boundaries

The graph above depicts the situation prior to the setup of performance boundaries whereas the one below this after their determination The boundaries themselves are colored in blue. By assessing the objectives defining some design options as better performing compared to others, the input combinations are drastically reduced, highlighting the most appropriate design options.

The selection of those 24 options will be updated in case the user sets different boundary conditions, both from the output perspective, as demonstrated above, and the input aspect. The latter is explained in cases where for various reasons certain input options are preferred, e.g. the WWR < 0.7 [-]. In this case, the better performing 24 combinations concluded above do not meet this requirement, therefore certain trade-offs in the output boundary conditions previously set are required in order for the better performing and feasible -according to the boundaries already made- solutions to be indicated.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

3. Virtual interventions for renovations

3.1 From baseline assessment to virtual interventions

The same Grasshopper base model presented in Deliverable 16.1 is utilized to compute the impact of the interventions. The renovation interventions values are based on the Dutch standard that are state in the "Voorbeeldwoningen 2022 | bestaande bouw" report (RVO, 2023).

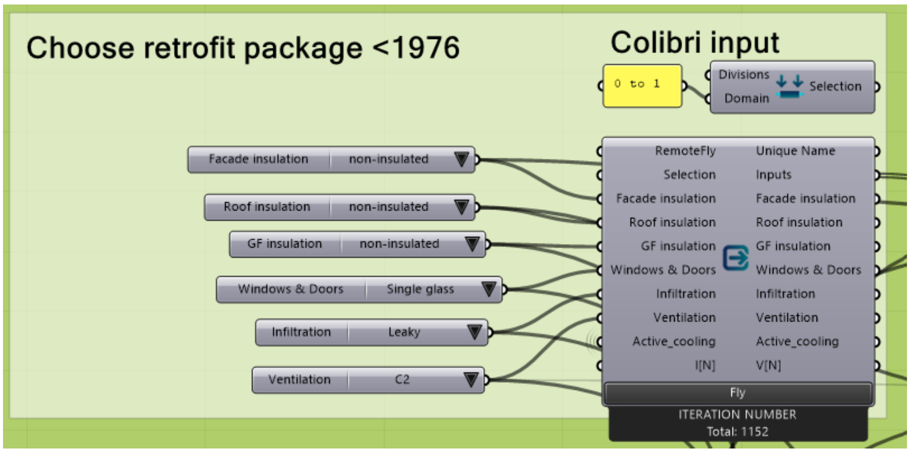
Each category of construction year has a distinct insulation value that will serve as the baseline for calculating the interventions. The starting point for each build year category can be seen in Table 4 and Figure 8 below:

Table 4. Baseline assessment building characteristics per construction year category

Baseline assessment	Construction year category		
	<1975	1976-1995	>1996
Façade Rc-value	Rc = 0.35	Rc = 1.30	Rc = 2.50
Roof Rc-value	Rc = 0.35	Rc = 1.30	Rc = 2.50
Ground floors Rc-value	Rc = 0.15	Rc = 0.52	Rc = 2.50
Window & glass doors U-value	Single pane glass	Double pane glass	Double pane glass
Ventilation type	Natural	Natural	Natural
Infiltration rate	0.0007	0.0007	0.0007
Active cooling	No	No	No

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.



Choose retrofit package <1976

Facade insulation: non-insulated
Roof insulation: non-insulated
GF insulation: non-insulated
Windows & Doors: Single glass
Infiltration: Leaky
Ventilation: C2

Colibri input

0 to 1

ITERATION NUMBER
Total: 1152

Figure 8. Intervention options for the renovation of historical buildings Grasshopper.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Intervention measurements

A wide range of intervention measurements is incorporated in this multi-criteria assessment. Those are divided into sub-categories, namely Insulative scenarios referring to façade roof and ground floor structures, Windows and Doors intervention, Infiltration as well as Ventilation, and are briefly outlined below.

Starting from the Insulative measurements and more specifically the façade intervention approach, two insulative options that would be possible to implement in historical buildings are proposed. Those suggest the reinforcement of the existing insulation by introducing 5 cm or 7.5 cm of additional insulation. While considering generic insulation values (EPS) it brings the façade to the following Rc-values. A similar approach is adapted for the insulative upgrade of the rest of the non-transparent elements of a building envelope, the roof and ground floor. Especially for the case of the roof, an additional insulative scenario is introduced, exploring the impact of an even larger insulative reinforcement, this of 12.5 cm. The aforementioned interventions measurements are summarized in Table 5.

Table 5. Insulative scenarios as intervention strategies of building renovations

Insulative scenarios	Construction year category		
	<1975	1976-1995	>1996
Façade intervention	Rc [m²K/W]	Rc [m²K/W]	Rc [m²K/W]
5 cm insulation	2.0	3.0	4.0
7.5 cm insulation	2.8	3.8	-
Roof intervention	Rc [m²K/W]	Rc [m²K/W]	Rc [m²K/W]
5 cm insulation	2.0	3.0	4.0
7.5 cm insulation	3.0	3.8	-
12.5 cm insulation	4.5	-	-
Ground floor intervention	Rc [m²K/W]	Rc [m²K/W]	Rc [m²K/W]
5 cm insulation	1.8	2.0	2.5
7.5 cm insulation	2.5	2.8	3.0

Within the insulative sub-category, the focus is on retrofitting the building envelope to enhance thermal resistance. The façade intervention approach outlines two feasible options for historical buildings—adding either 5 cm or 7.5 cm of insulation—to reinforce the existing insulation. By using generic insulation materials (EPS), these interventions achieve improved Rc-values that vary according to the construction year of the building. A similar methodology is applied to the roof and ground floor elements. In particular, the roof intervention introduces an additional scenario that explores the impact of an even larger reinforcement of 12.5 cm, providing a broader range of solutions to meet varying energy efficiency requirements. These scenarios are detailed in Table 5, which categorizes the

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

insulation strategies by construction period (<1975, 1976–1995, >1996) and presents the corresponding Rc-values for each intervention.

Beyond the insulative measures, the assessment also considers interventions in windows and doors, infiltration, and ventilation. An extended list of window and door materials typically encountered in the existing building stock of the Dutch region has been taken into consideration. Table 6 presents an overview of those materials and their respective thermal transmittance properties (U-values).

Table 6. Window and Doors' properties considered as intervention measurements

Windows & Doors intervention

	U-value [W/m²K]
Single glazing	5.8
Double glazing	2.8
HR-glazing	1.1
Triple or vacuum glazing	0.6

Infiltration

A standard infiltrating rate of 0.0007 $m^3/s/per\ m^2$ façade is used for all the baseline archetypes. The renovation measures improving the infiltration rate of each building is achieved through gap sealing, which is applicable to all the archetypes, regardless of their construction year category. This results in a new infiltration rate of 0.0004 $m^3/s/per\ m^2$ façade.

Ventilation

Three types of ventilation are considered for the intervention modelling, namely: Natural ventilation which is basically achieved through the opening of windows, doors and small gaps in the façade, C2 mechanical ventilation with natural air supply and mechanical exhaust with occupancy schedule, and finally D1 HRV 50% ventilation, that resembles ventilation with a 50% heat recovery system.

3.2 Combine virtual interventions into an interactive parametric model

Following the creation of the detailed visual interventions covering a complete list of renovation cases in the historic centre of Amsterdam, the development of a parametric workflow combining as many of those innervations possibly took place. The previous approach aims in the development of an interactive tool that not only provides a comprehensive overview of the renovation approaches implemented for the representative case of dwellings but also combines the originally independent approaches into a centralized one. The latter further expands the possibilities of evaluating the renovation parameters while enhancing the informed decision-making in the field of renovations based on various aspects of the buildings' performance including circularity, energy demand, indoor comfort, and heat wave assessment.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

In order for the aforementioned combination of multiple workflow interventions into a centralized one to occur, some modifications of the original concepts were needed. The main alteration refers to the creation of renovation packages options that practically consist of some, previously individual, renovation parameters.

In more details, the original renovation parameters concerning the opaque elements of the façade constructions were grouped into one input parameter, the "Opaque renovation scenario", with the following options:

- Existing Scenario
- Renovation Package 1
- Renovation Package 2

By selecting each of the options above, specific values for the Infiltration Intensity of the façade, as well as the insulation thickness for the Floor, Façade & Roof are attributed. By combining the modifications related to the façade's opaque part, it became feasible to combine the three different workflows referring to dwelling typologies, each one representative of different construction period (<1975, 1976-1995, >1995), as showcased in Table 7.

Table 7. Parametric framework of the virtual intervention renovation

Categories	Options selected
Function	**Dwelling /** Mixed Use / Utilities / Horeca
Compactness Ratio / Topology	Apartment / Row / Corner
Window-Wall-Ratio (WWR)	0.4 / 0.5 / 0.6 / 0.7
Opaque Component Scenarios	
Infiltration Rate	Leaky / Crack Sealing
Insulation Thickness: Floor	Non-Insulated / 5 cm
Façade	Non-Insulated / 5 cm / 7.5 cm*
Roof	Non-Insulated / 5 cm / 7.5 cm* / 12 cm *
Glazing Typology	Single* / Double / HR / Triple
Ventilation	Natural / C2 / D1 HRV 50%
Active Cooling	No / Yes
Insulation Material	Cellulose / Rockwool / EPS
Construction Period	<1975 / 1976 - 1995 / >1995

In this way, the originally extremely large amount of variable parameters (26.876.856) occurring after combining the dwelling workflows for all the construction periods studied was drastically reduced to 1.458 variables, resulting in a parametric model that is definitely easier to assess and comprehend.

A similar approach can be followed for the rest of the typologies (archetypes) of Mixed Use, Utilities and Horeca. For it to be achieved, proper handling of the workflow is required while

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

translating them into parametric multi-criteria models able to fine tune an extended list of parameter and intervention approaches.

3.3 Incorporating resilience factors in intervention modelling

Building renovations present an invaluable opportunity to enhance the resilience of existing structures. More specifically, resilience in the context of building design typically refers to a building's ability to adapt to and withstand various environmental challenges, such as climate change, extreme weather events, and energy demands, while ensuring the safety and comfort of its occupants.

To effectively integrate resilience into the building renovations, several critical analyses are undertaken to evaluate and improve performance across multiple factors. The Energy demand assessment, the Indoor Comfort Analysis, combined with the Heat Wave evaluation and the CO2 Embodied Carbon calculation are the resilience parameters incorporated into the intervention assessment of renovation projects located in the historic centre of Amsterdam area. Each of these analyses uses specific weather files, which originate from previous stages of the research process, to simulate future climate conditions and provide a robust understanding of how the building might perform under various scenarios.

In more detail, the indoor comfort evaluation takes place in August, the month that is often considered as the warmest one of the year and is based on the weather data sources originating from the NEN 5060:2018+A1:2021 (NEN, 2021) standard with 1% exceedance probability. The previous selection is expected to reflect anticipated future climate conditions, ensuring that the building can provide consistent comfort even during extreme weather events.

As for the energy performance assessment, this is calculated for the entire course of the year, accounting equally cooling and heating demands by incorporating seasonal extremes and climate variability. The weather file used to calculate the intervention modelling is the file “KNMI_2022_schiphol”, this is a morphed weather file created by Hamidreza Shahriari and Zhikai Peng. The standard .epw file for Amsterdam (location Schiphol) is morphed with data from a local weather station in the city center so that the urban heat island is better incorporated in the calculations. This morphing method is further elaborated in deliverable 16.1.

Finally, when the Heat Wave Assessment is concerned, the weather file used refers back to 2019 and was produced during previous work packages WP16.1 delivered by AMS and OMRT. This weather file was created according to the general recommendations, indicating that for the cases of Heat Wave, they should derive from past years and projected heat wave data enabling the modelling of the building's response. In this way, appropriate interventions can be derived, such as insulation improvement, shading device installation or cooling systems upgrade, enhancing the structure's overall resilience.

By integrating these resilience assessments into the renovation process, existing buildings can be transformed into more sustainable, comfortable, and adaptable structures that are better equipped to handle the challenges of a changing climate.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

4. Preliminary findings

4.1 Findings for new builds

The following section details the observational findings resulting from the evaluation of the parametric model designed for the Amsterdam Demonstrator. These observations, pertaining to the demonstration case located in Cruquiuseiland, Amsterdam, are categorized by the respective analyses performed. This organization is intended to facilitate a comprehensive review of the evaluation outcomes.

Daylight

Due to the geometrical configuration of the building analyzed, including housing units located on the ground floor surrounding by relatively high neighboring structures that belong to the analysis plot and subsequently block the daylight receiving of the units in question, meeting the daylight norm is rather challenging. However, useful conclusions can still be drawn by comparing the relative performance of each of the available options.

When observing the impact of the different glazing typologies, even when WWR=70%, the Triple low-e (argon) deflected glazing results in more critical performance compared to the rest of the options. To slightly elaborate on that, not even the apartments of the highest floors directly meet the NPR4057 norm; they can only potentially do so through the Krijtstreepmethode, whereas the ones of the lower floor are critical, therefore a change of the design is encouraged. On the other hand, the rest of the glazing options perform better, with the upper floor apartments directly meeting the boundary condition and the lower ones possibly through adequate design modifications.

The most drastically influencing parameter with regard to the building's daylight performance is undoubtedly the WWRs. As expected, the larger ratio over transparent to opaque surface the easier for the housing unit to comply with the NPR4057 requirement of DF> 1[%]. More specifically, the amount of critical rooms is completely eliminated only through the implementation of the larger WWR option, this of 70%.

BENG 1

For the construction design analyzed, the BENG 1 boundary can be further increased by 5 kWh/m^2 GO/year since light timber construction is applied as construction material. Due to the typically advanced insulative and airtightness properties of timber, the heating demand is significantly reduced, facilitating the compliance with the BENG 1 threshold of heating demand. However, the cooling demand threshold of the construction is typically challenging to be met as a result of the material's low thermal mass. Therefore, proper design, close selection of the façade system materials and of the integration of passive cooling strategies is crucial for managing overheating risks and ensuring compliance with the BENG 1 criterion.

In addition, the implementation of night ventilation significantly impacts BENG 1 value, in some cases even up to 10-12%. However, the impact of night ventilation on the overall energy demand of the building is highly dependent on other aspects such as the WWR, blind scenario, infiltration rates etc.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

TOjuli

When moving to the overheating assessment, the following observation regarding the two options of ventilative devices is made. Between the adaptive to WWR ventilative geometry or the Fixed large geometry, the latter results in reduced TOjuli values, which is crucial especially for the cases of smaller WWR (40-50%). There, the large ventilative devices when combined with well-performing glazing types, namely the low-e ones, result in TOjuli values ≤ 2 [-], therefore no further testing is needed in order for the thermal comfort requirements to be satisfied.

TOjuli is mainly affected by the WWR, night ventilation, blind scenarios & glazing typology. With the implementation of night ventilation, blinds, better-performing glazing (like Double low e (air) deflected & Triple low-e (argon) deflected) & a relatively low WWR (40-50%) TOjuli can be directly met.

While comparing the relative performance of the housing units tested, it is observed that the calculated overheating performance is increased (by 15-20% on average) in the apartments located on the upper floor compared to this of the intermediate ones.

Additionally, the possibility of overheating as assessed by TOjuli also appears increased in the corner apartments as opposed to the intermediate ones. The previous could have been easily substantiated in case in the losing surface of the corner apartments, that is increased compared to this of the intermediate units, increased heat gains would occur practically through openings. This is not the case in the examined residential units though since the typologies are mostly identical. Therefore, the increased differences mentioned previously most probably originates from a limitation of the TOjuli calculation itself. This overheating assessment is defined based on the façade surface per orientation, with the most critical result being the leading one. Subsequently, there are some cases where inaccuracies regarding the overheating risk calculated by TOjuli occur. For those cases, a more detailed overheating analysis is recommended, like the GTO (Gewogen Temperatuur Overschrijding) method, also introduced by NTA 8800 (NEN, 2024). In this method, the hours when the actual or calculated Predicted Mean Vote (PMV) exceeds the value of +0.5 are weighted proportional to the Predicted Percentage Dissatisfied (PPD).

Cooling Loads

Regarding the cooling loads assessment, the 35 W/m² threshold is mainly met when sunscreens/blinds are incorporated in the building design. Particularly for the increased WWRs options (70%) where larger transparent areas apply, the blinds application is crucial for the threshold to be met.

The other variable parameter that significantly impacts the cooling loads calculation is the glazing type. It is observed that the design options including Double and Triple low-e glazing with reduced solar energy transmittance (g-values < 0.4 [-]) considerably decrease the peak cooling loads calculated. Especially when combined with the relatively smaller WWRs (50 & 60%), they can even satisfy the 35 W/m² threshold even without the implementation of sunscreens/blinds. On the contrary, the remaining glazing options result in significantly increased cooling loads, therefore the shading implementation is imperative.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Overall, the building envelope design is observed to affect the cooling loads calculation more than ventilation and infiltration do. The previous is substantiated by the fact that the envelope dictates the building's baseline heat gains and losses, which is significant and rather consistent across the year. However, for buildings with substantial air leakage or in climates with high humidity, ventilation and infiltration typically play a major role. Subsequently, while aiming for the optimal energy efficiency of building structures, both factors should be addressed comprehensively.

4.2 Findings for renovations

Selection of renovation scenarios

Two boundaries were set to significantly reduce the number of viable package options, limiting the levels of acceptable Indoor Occupant Hours (IOH) and total Space Heating (SH) demand for Long-Term. For IOH, a maximum of 300 hours was determined, based on the GIW-ISSO guidelines; while a threshold of 50 kWh/m²/year was set for SH to meet the BENG standards for apartments and flats.

As illustrated in the accompanying figure, out of 1.152 potential scenarios, only 216 (highlighted in green) meet these criteria. The graphs provided exemplify renovation scenarios for a historic row house built prior to 1975. To further narrow down the scenarios, an additional criterion can be implemented: ensuring that the top floor achieves a minimum SH demand of 80 kWh/m²/year. Applying this limitation would refine the possibilities, leaving the renovation project with only 17 potential combinations of renovation measures, as depicted in the graph in Figure 9.

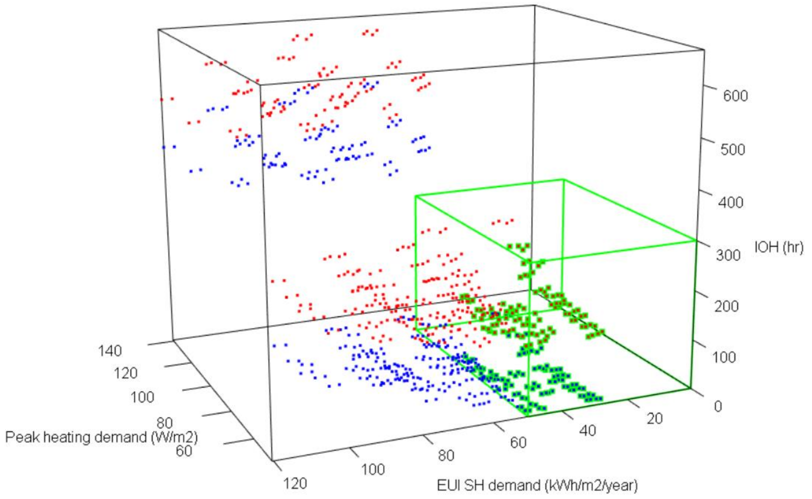


Figure 9. Selected renovation scenarios with acceptable IOH & SH demand

Renovation measures and their impact on SH and IOH

Every renovation will have impact on either SH, IOH or both. The following results can be derived from analyzing the renovation measures of all the archetypes:

Insulating the façade will reduce space heating; however, it increases the risk of internal overheating creation a trade-off with this measure. This is not the case for roof insulation, this measure will lead to a reduction in both space heating demand and internal overheating, particularly benefiting the top floor where these issues are most pronounced. Insulating the ground floor will reduce space heating demand; however, its impact on internal overheating is minimal. Retrofitting the glazing will result in decreased space heating demand and reduced internal overheating. Implementing infiltration measures, e.g. gap sealing, will lower space heating demand but could slightly increase internal overheating. Switching over to a mechanical ventilation system compared to natural ventilation is necessary when buildings are renovated and better insulation, the trade-off is that the C2 system (natural fresh air supply and mechanical exhaust) has a slight increase in heating demand, whereas the D1 HRV system decreases heating demand without significantly impacting internal overheating. Lastly, active cooling can help mitigate internal overheating; however, its effectiveness may be limited without prior retrofitting to address existing issues.

Combination of renovation measures

Adding insulation to the roof, along with renovating windows and glass doors, effectively reduces space heating demand and lowers internal operating hours (IOH). These measures complement one another and can be regarded as a beneficial retrofitting combination. While floor insulation lowers space heating demand, it does not impact IOH, making this intervention another worthwhile option. Infiltration retrofits are necessary renovation measures for all scenarios aimed at reducing space heating, although they may increase IOH. Therefore, it is essential to consider this trade-off, ensuring that infiltration measures are always paired with renovations that reduce IOH, such as improving glazing and roof insulation.

Active cooling in renovations

Results for the operative temperature simulations for three active cooling interventions (Figure 10) indicate that active cooling is not always required during renovations to achieve a desirable level of Indoor Operating Hours (IOH). However, when considering both IOH and Guidelines for Thermal Optimization (GTO) hours, a significant difference becomes evident. While the IOH may fall below the maximum threshold of 300 hours for existing buildings, the GTO hours exceed the 450-hour limit established for renovated existing dwellings, and even surpass the maximum of 900 hours designated for unrenovated existing dwellings. These temperature peaks can pose risks to vulnerable populations, and in such cases, the implementation of active cooling may be necessary to mitigate these extremes. This example illustrates a specific scenario, but it serves as an important consideration regarding potential limitations during extreme weather events.

Funded by
the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

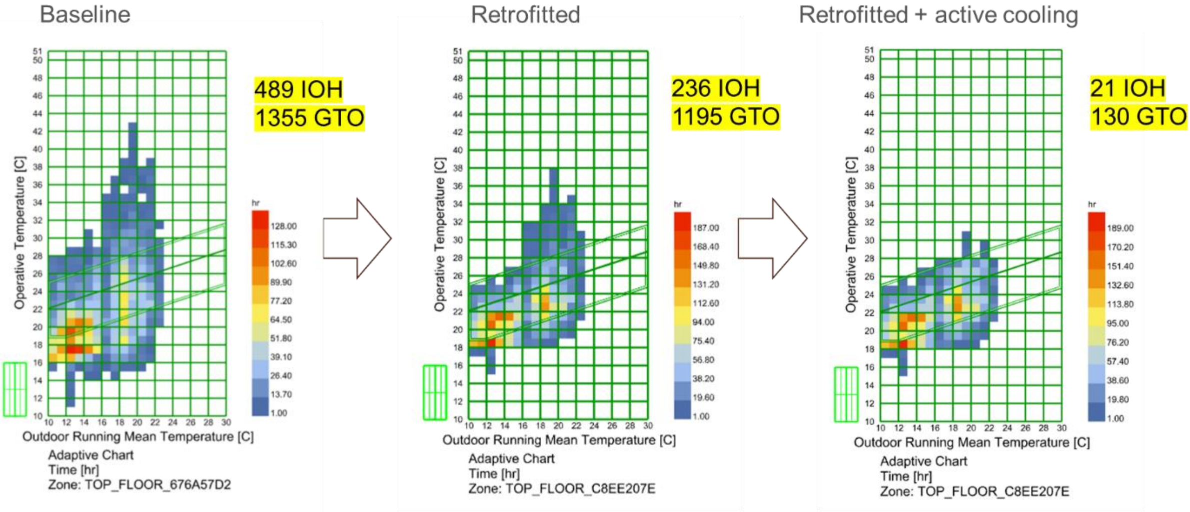


Figure 10. Operative temperature simulations for three active cooling interventions.

Energy performance

The analysis of energy performance reveals a significant discrepancy between cooling and heating consumption. Despite cooling systems being set to operate continuously throughout the year, cooling demand remains substantially low, when compared to the respective heating consumption. This calculation, performed over the full annual cycle, underscores the dominance of heating demand in the overall energy balance of the examined buildings.

A comparison of cooling demand estimates obtained from the standard energy calculation and the Heatwave Analysis highlights important methodological considerations. While both approaches provide valuable insights, a direct comparison is not feasible due to differences in the calculation period. The complete energy assessment accounts for the entire year, while the Heatwave Analysis focuses only on the short period between July 21–27, 2019. This discrepancy must be considered when interpreting the results and assessing their implications for building performance under extreme weather conditions.

The influence of building typology on energy performance is evident when comparing row houses to corner dwellings. As expected, corner buildings exhibit higher energy demand due to their larger external surface area, which increases heat exchange with the surrounding environment. This results in greater thermal losses during winter and higher cooling demand during summer, making these structures more sensitive to variations in insulation and façade design.

Heat Stress analysis

The heat stress analysis further confirms the impact of building topology on indoor thermal conditions. Corner dwellings experience a higher frequency of heat stress occurrences compared to row houses, particularly when the Heat Stress (HS) weather file is used. However, this trend is less pronounced when the alternative NEN5060 weather file is applied. Additionally, the average duration of heat stress periods in corner houses is shorter than in row houses, with the difference between typologies becoming more evident under

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

the HS weather conditions. A similar trend is observed for the longest recorded heat stress period, where the disparity between building types is amplified when the HS weather file is used.

The effect of opaque façade renovation on heat stress resilience presents a complex outcome. In the renovated scenarios, both the longest heat stress durations and the highest frequency of average heat stress periods are observed compared to the unrenovated baseline. Conversely, although the intensity of heat stress phenomena is lower in the existing (unrenovated) buildings, these events occur more frequently than in the renovated cases. This finding suggests that while renovations improve thermal buffering capacity, they may also lead to prolonged heat retention under extreme conditions, which requires careful consideration in the design process.

Indoor comfort

Regarding indoor comfort, the impact of opaque façade renovations emerges as a critical consideration. The renovation packages appear to increase the probability of indoor discomfort, as indicated by a higher number of GTO hours compared to the unrenovated baseline. This counterintuitive outcome raises the question of whether the implemented renovation measures are fully optimized for maintaining indoor comfort under various climatic conditions. Further investigation is needed to determine whether adjustments in insulation strategies, ventilation, or shading solutions could mitigate this unintended effect.

The analysis of window typologies further clarifies the relationship between glazing performance and indoor thermal comfort. Among the tested configurations, high-performance (HR) glazing demonstrates the most favorable impact, resulting in the lowest number of GTO hours and improving overall comfort conditions. In contrast, the results for existing double-glazing and triple-glazing options indicate a comparable effect on comfort, suggesting that the additional insulation provided by triple glazing does not significantly alter indoor conditions relative to standard double glazing.

Circularity assessment

Figure 11 displays the circularity KPIs, per insulation type and thickness. These results led to the following assessments:

- Embodied carbon had a more prominent impact on material flows than end of life. This indicates that materials should not only be adequately discarded, but also sourced.
- The greatest operational energy flow variation compared to the baseline was observed in heating demand. This energy source has a lower carbon intensity than electricity.
- Thicker materials had a higher carbon footprint but lower carbon payback times due to their energy benefits during building operation.
- EPS had higher embodied carbon and end of life emissions. However, it also led to more significant operational energy benefits.

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

- Cellulose had similar embodied carbon levels regardless of its thickness. This suggests that the origin of its emissions is not the raw material itself, but rather in the other steps of the "Product Stage". As a consequence, using thicker insulation does not have a relevant impact on circularity but can significantly improve building energy performance – making it mostly a single-criteria decision.
- Despite not having the highest material flows values, using Rock Wool is not recommended due to its low improvements on operational energy performance.

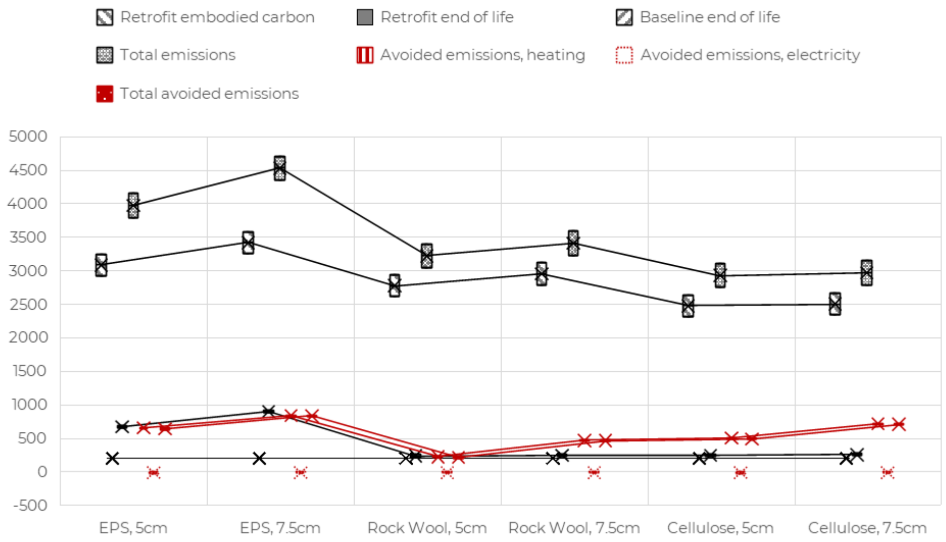
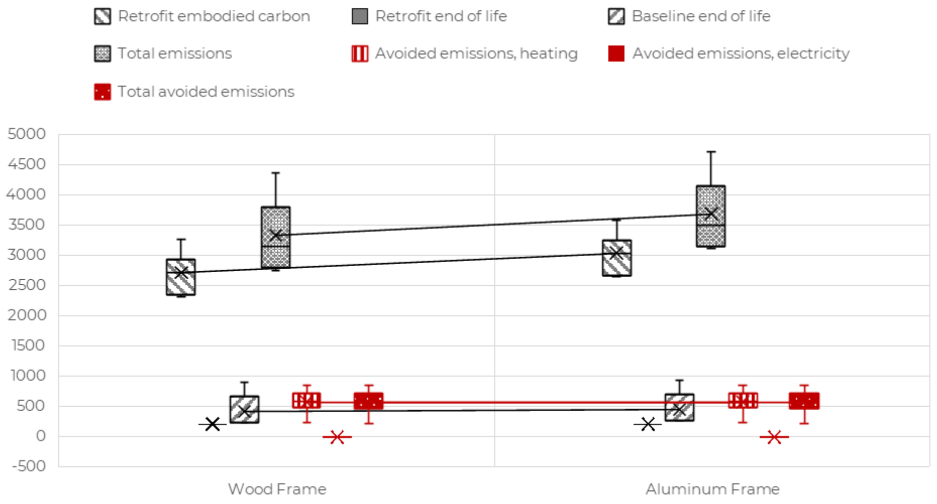


Figure 11. Material and operational energy flows, per insulation type and thickness.

Additionally, choosing a wood window frame instead of an aluminum one resulted in a reduction of embodied carbon ranging from 9.8% to 13.75%, as can be seen in Figure 12. This project decision does not influence energy performance nor thermal comfort.



Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Figure 12. Material and operational energy flows, per wood frame type.

Given enough time, the operational energy flow benefits can outweigh the embodied carbon from the material flows. One example can be seen in the graph below, which represents the net intervention emissions through the years of row houses from 1975, with aluminum window-frame and 7.5cm insulation thickness. In this case, the cross-over point between operational benefits and material flows occurs by year 13 (Figure 13). However, this scenario takes into consideration very specific premises: a constant carbon intensity through time for the energy sources; the transition of the overall Dutch energy matrix and potential on-site clean energy generation is not considered; it is assumed that no further maintenance is needed of either material.

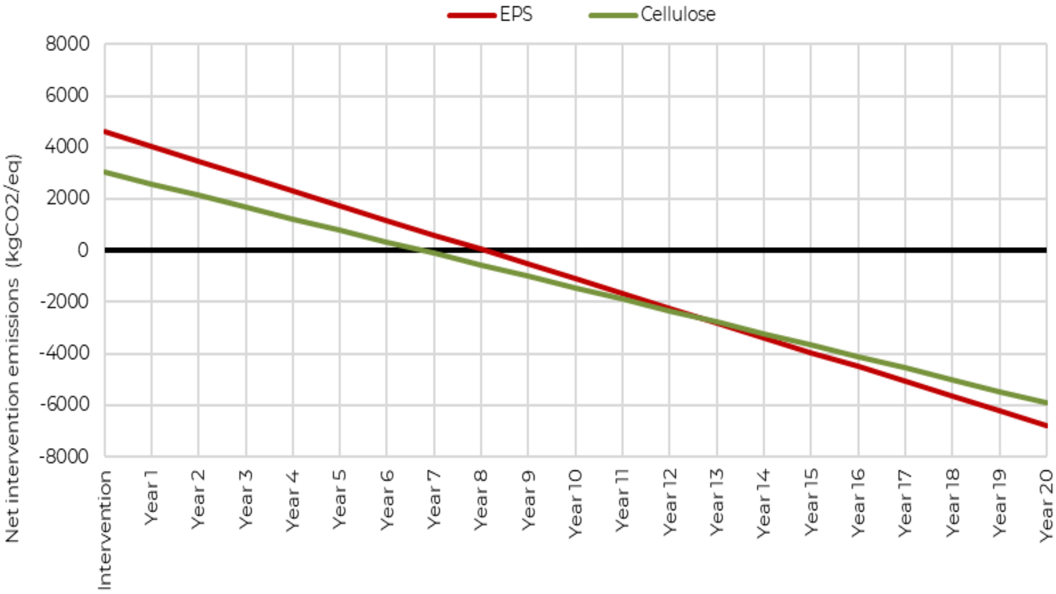


Figure 13. Net intervention emissions per year for EPS and Celullose.

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

5. Summary

5.1 Takeaways from WP16.3

As already discussed, the integration multi-performance building indicators, such as energy, indoor comfort and sustainability aspects into a multi-criteria analysis is essential for achieving a comprehensive understanding of how structures perform under various conditions, including standard as well as extreme ones. This approach enables a holistic evaluation, facilitating not only the assessment of overall structure efficiency but also the identification of optimal renovation strategies to enhance performance.

A key advantage of such analyses is their ability to serve as a validation mechanism for the input parameters selected during the setup of the assessment. When multiple performance criteria are examined simultaneously, inconsistencies or counter-intuitive results may emerge, signaling potential inaccuracies in the initial assumptions. By systematically reviewing these findings, researchers and practitioners can refine input data, improve the reliability of simulations, and enhance the realism of the results.

For instance, if an analysis produces an unexpected relationship between energy consumption and indoor thermal comfort—one that contradicts established physical principles—this discrepancy provides an opportunity to revisit and improve the initial dataset. This iterative process strengthens the validity of the study and ensures that final outcomes align more closely with the realistic building behavior.

Furthermore, the development of interactive models based on multi-criteria analysis represents a valuable tool for designing and renovating resilient structures. These models allow for dynamic scenario testing, enabling decision-makers to explore various configurations and select solutions that balance energy efficiency, occupant well-being, and environmental impact. By leveraging such comprehensive assessments, the built environment can be optimized to meet both present and future challenges in a scientifically robust manner.

5.2 Reflections from WP 16.3

To further enhance the accuracy and applicability of the current or similar to this multi-criteria analyses, several key areas of improvement can be explored, ideally during the future WP of the MultiCare project.

Impact of Different Weather Files

A deeper investigation into the influence of various weather files on energy performance, indoor comfort, and heatwave resilience should be conducted. This includes analyzing not only different climate datasets but also evaluating how the duration of the analysis period affects the results.

Future Resilience and Climate Projections

To ensure the model remains relevant under changing climate conditions, it is essential to integrate weather files that project future climate scenarios, such as those referring to the

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

typical years of 2030 and 2050. This will allow for more informed decision-making regarding the long-term resilience of buildings.

Influence of Additional Internal Mass

The presence of internal mass, such as furniture and internal doors, affects energy performance, indoor comfort, and heatwave resilience. Future studies should systematically assess how these factors influence the overall thermal behavior of buildings and incorporate them into simulations for improved accuracy.

Optimizing the Balance Between Thermal Mass and Insulation

A closer examination of the interplay between thermal mass and insulation thickness should be conducted. This includes analyzing variants with lightweight and heavyweight structures to determine the optimal insulation thickness for each case—particularly when using the same insulating material. Such research would ensure that insulation strategies are tailored to specific structural configurations, maximizing both energy efficiency and occupant comfort.

By integrating these enhancements into future multi-criteria models, the accuracy and predictive capability of building performance analyses can be significantly improved, leading to more resilient and sustainable design solutions.

Funded by
the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

6. References

BBL. (2023). Bouwbesluit *2012.* BBL. Retrieved from https://www.bblonline.nl/docs/wet/bb2012?q=bouwbesluit

GIW-ISSO (2008). Ontwerp en montageadviezen nieuwbouw eengezinswoningen en appartementen.

NEN. (2021). *Hygrothermal performance of buildings – Climatic reference values for building physical calculations and design of technical building services and installations (NEN 5060:2018+A1:2021).* NEN. https://www.nen.nl/en/nen-5060-2018-a1-2021-nl-280196

NEN. (2022). *Daylight in buildings (NEN-EN 17037:2018+A1:2022).* NEN. Retrieved from https://www.nen.nl/en/nen-en-17037-2018-a1-2022-en-279877

NEN. (2022). *Daglicht in gebouwen - Toelichting op NEN-EN 17037 (NPR 4057:2022 NL).* NEN. Retrieved from https://www.nen.nl/npr-4057-2022-nl-291670

NEN. (2024). *Energy performance of buildings - Determination method (NTA 8800:2024 NL).* NEN. Retrieved from https://www.nen.nl/nta-8800-2024-nl-291670

RVO. (2017). *Energieprestatie indicatoren - BENG.* Rijksdienst voor Ondernemend Nederland (RVO). Retrieved from https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/beng/indicatoren

RVO. (2023). *Voorbeeldwoningen 2022 bestaande bouw.* Rijksdienst voor Ondernemend Nederland. Retrieved from https://www.rvo.nl/sites/default/files/2023-01/brochure-voorbeeldwoningen-bestaande-bouw-2022.pdf

Funded by the European Union

This project has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101123467 MultiCare). Views and opinions expressed are however those of author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.