
TU Delft

P5

Vera Koster / 01 July 2024

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Decision Support

for

LT-Renovations

Development of a decision support framework & tool to enable low-temperature heating in multi-family buildings

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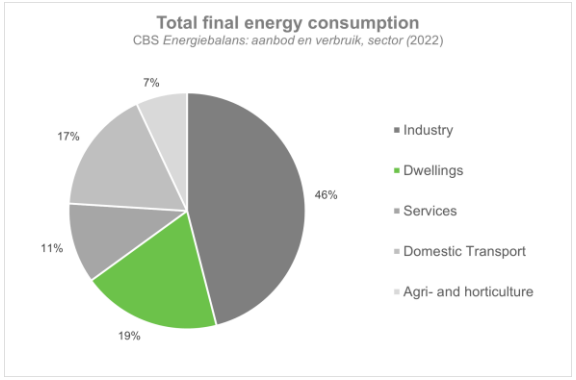
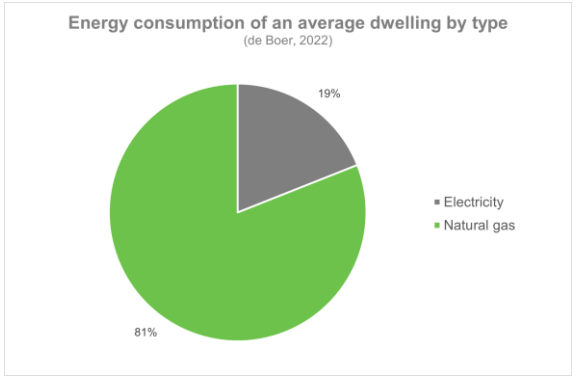
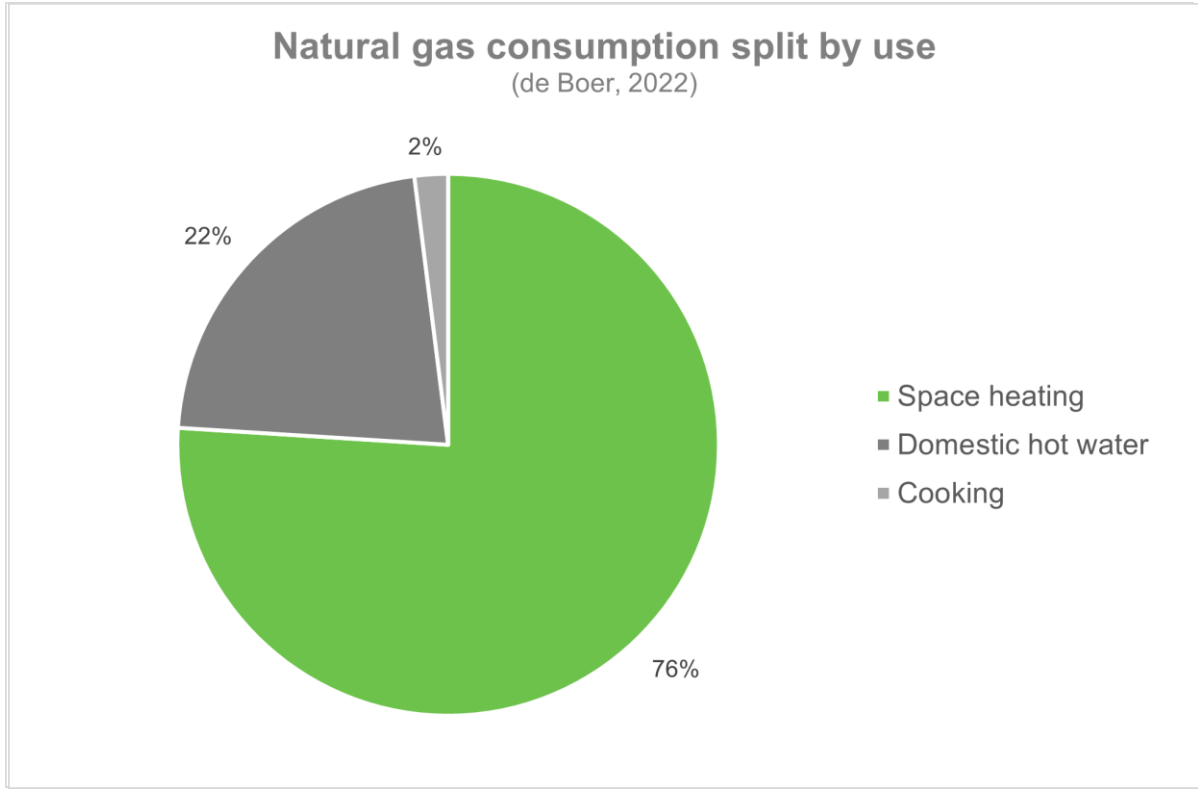
Introduction

Introduction







Introduction

Dinsdag 12 september 2023, 18:00

Experts: adviesbureaus nemen taak ambtenaren over bij energietransitie

INTERVIEW ENERGIETRANSITIE

'Als we de klimaatdoelen willen halen, zijn nu dappere keuzes nodig'

NOS Nieuws • Maandag 20 mei, 10:33

Warmtenet goedkoper dan warmtepomp, maar niet voor de burger

Donderdag 30 november 2023, 23:25

Netbeheerder vreest voor vertraging energietransitie bij rechts kabinet

NOS Nieuws • Donderdag 25 april, 11:44 • Aangepast donderdag 25 april, 13:08

Provincie Utrecht grijpt terug naar gas vanwege overvol stroomnet

ruimte en milieu / partnerbijdrage

Energietransitie in gebouwde omgeving moet anders

Vattenfall en Eneco leggen geen warmtenetten aan als overheid de baas wordt

Energiegiganten Vattenfall en Eneco steken geen cent in nieuwe warmtenetten als klimaatminister Jetten besluit dat de overheid de zeggenschap erover krijgt.

Ton Voermans 20-10-22, 14:59

Opinie: 'De energietransitie dreigt te falen als we ons focussen op de korte termijn'

NOS Nieuws • Vrijdag 12 april, 17:52 • Aangepast vrijdag 12 april, 18:03

Honderden miljoenen extra aan subsidie voor warmtenetten

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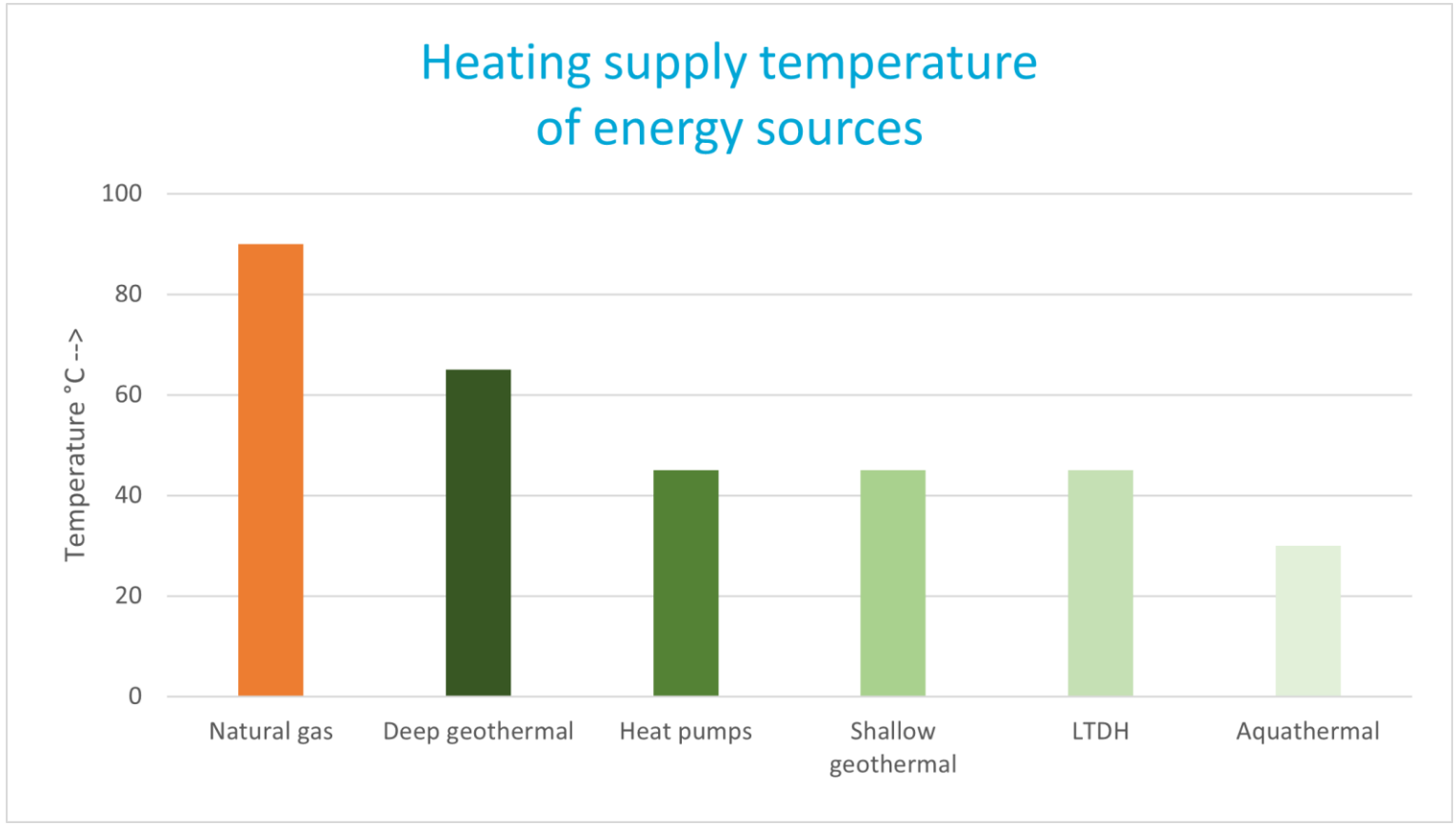
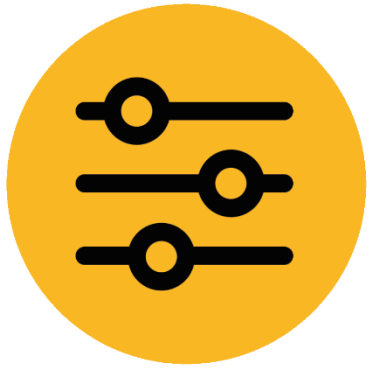
Introduction - LTH

High Temperature	=	75-90 °C
Medium Temperature	=	55-75 °C
Low Temperature	**=**	**30-55 °C**
Ultra Low Temperature	=	<30 °C



Problem Statement



MULTIPLE SCENARIOS

CONFLICTING INTERESTS

UNCLEAR DECISION-MAKING PROCESS

It is unclear how to select a renovation concept that enables low-temperature heating due to the varying effects of the renovation scenarios, multiple stakeholders with conflicting interests and the absence of a clear decision-making process.

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“ How can the **decision-making process** of **selecting an energy renovation concept** be **supported** that aims to make existing residential buildings compatible with **low-temperature heating**? ”

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Agenda

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Low-Temperature Heating (LTH)

Literature Research

Stationary Heat Balance

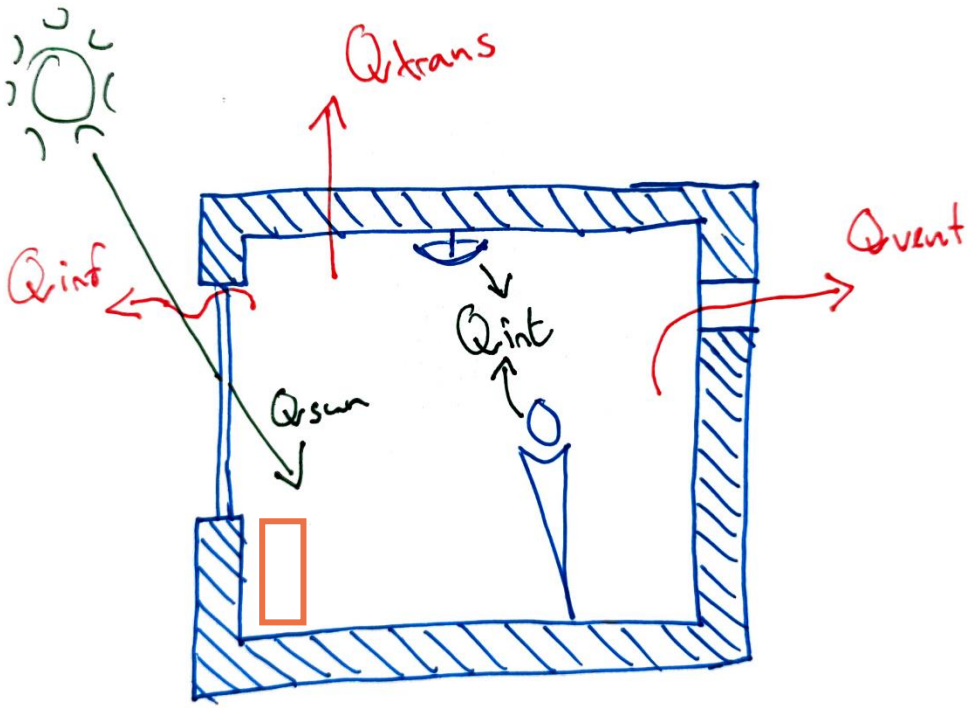
1) $$Q_{demand} = Q_{trans} + Q_{inf} + Q_{vent} - Q_{int} - Q_{sun}$$

2.1) $$Q_{capacity\ radiator} = k\ A\ \theta_m$$

$k = heat\ transfer\ coefficient\ [\frac{W}{m^2 K}]$
$A = surface\ area\ [m^2]$
θ_m = *mean temperature difference between the heat emitting surfaces and the ambient air [K]*

2.2) $$\theta_m = \frac{T_{supply} - T_{return}}{\ln((T_{supply} - T_{indoor})/(T_{return} - T_{indoor}))}$$

3) $$Q_{capacity\ radiator} \geq Q_{demand}$$



Winter situation

LT-Ready

1) $Q_{demand} = Q_{trans} + Q_{inf} + Q_{vent} - Q_{int} - Q_{sun}$

2.1) $Q_{capacity\ radiator} = k\ A\ \theta_m$

$k = heat\ transfer\ coefficient\ [\frac{W}{m^2K}]$
$A = surface\ area\ [m^2]$
θ_m = *mean temperature difference between the heat emitting surfaces and the ambient air [K]*

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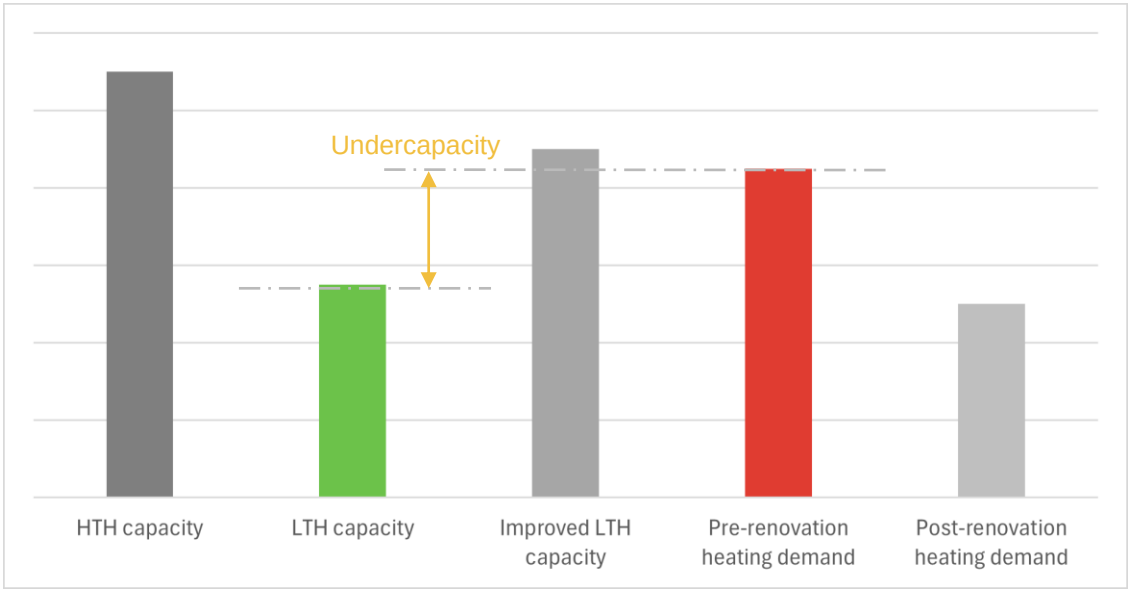

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LT-Ready

1) $Q_{demand} = Q_{trans} + Q_{inf} + Q_{vent} - Q_{int} - Q_{sun}$

2.1) $Q_{capacity\ radiator} = k\ A\ \theta_m$

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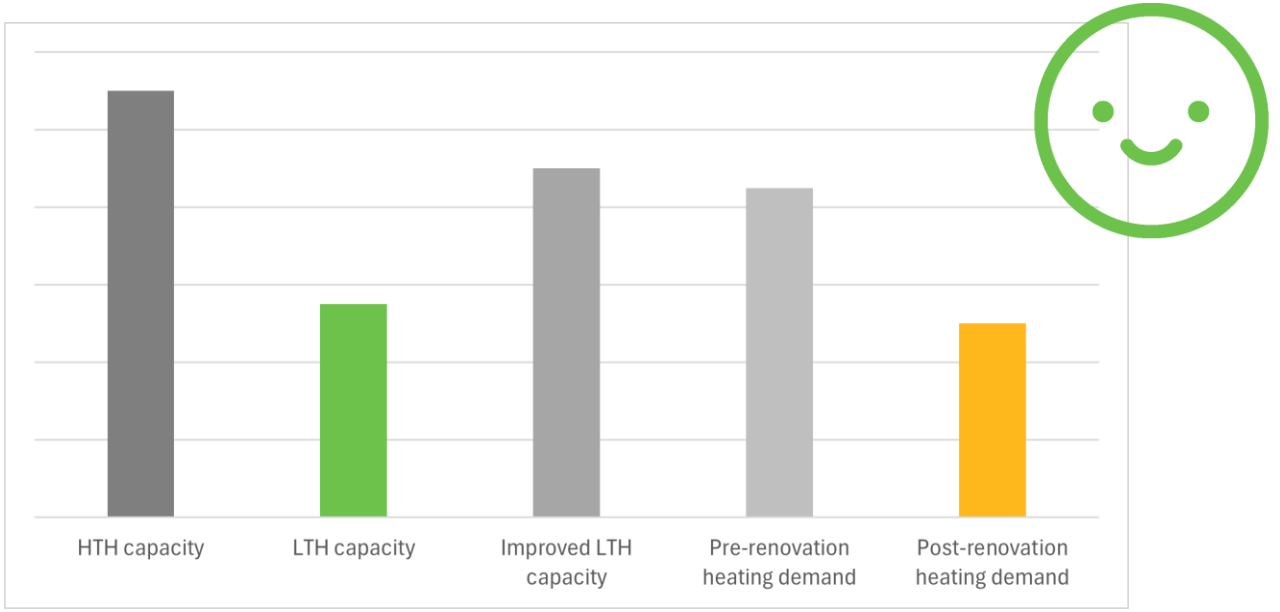

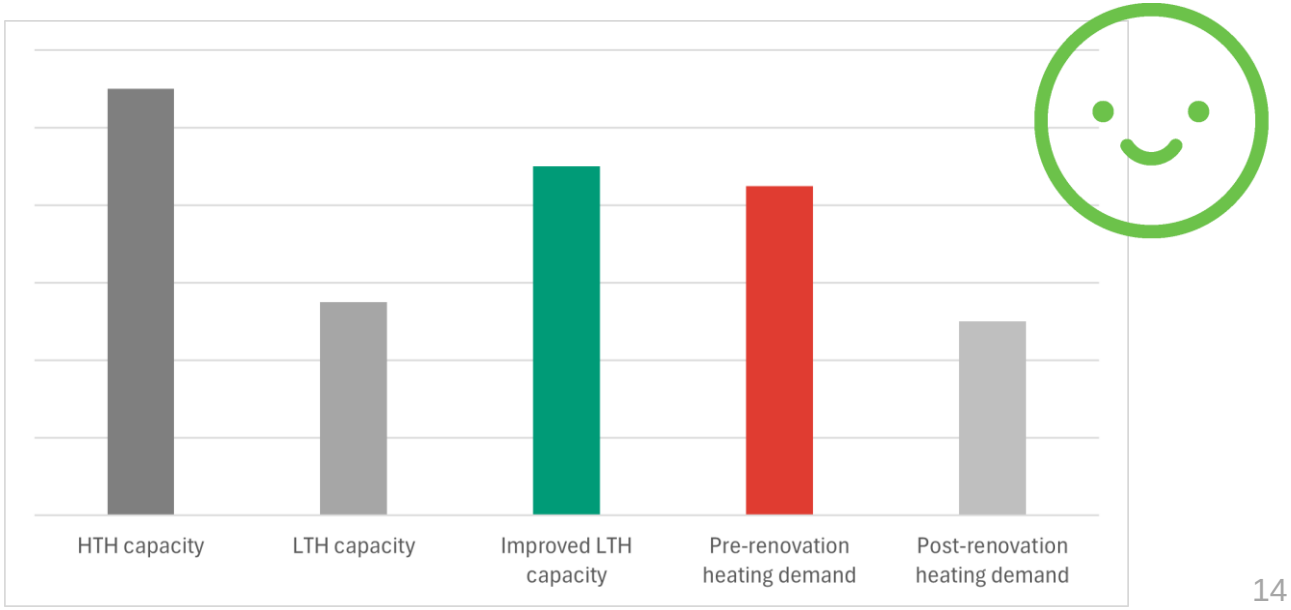

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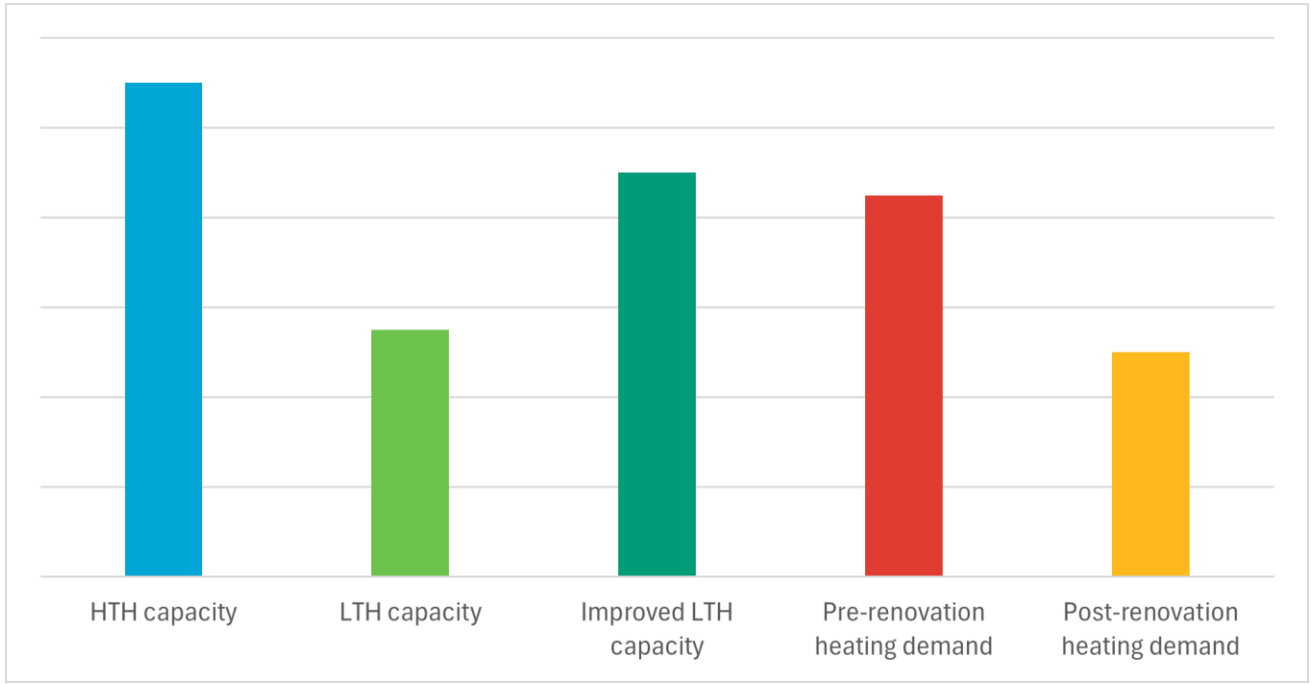
LT-Ready

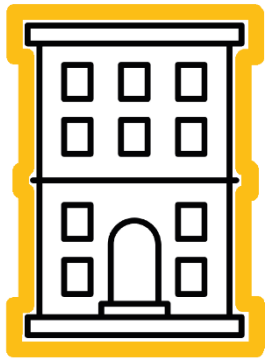
Definition

LT supply = 30-55 °C

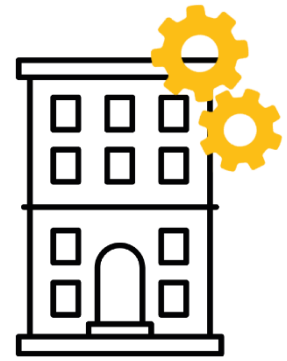
1. $Q_{capacity\_LT} \geq Q_{demand}$
2. $Q_{demand\_LT} \leq Q_{demand\_orignal}$
3. Thermal $comfort_{LT} \geq$ Thermal $comfort_{original}$



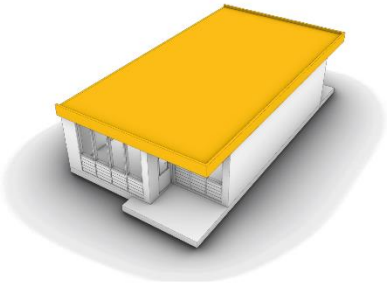
Renovation Measures



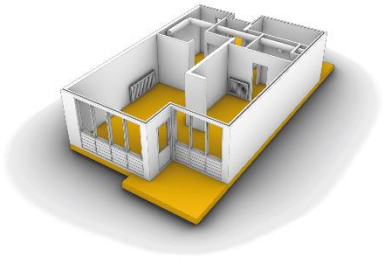
Building Envelope



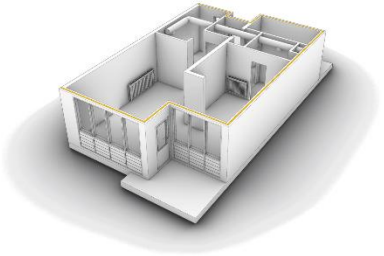
Building Installations



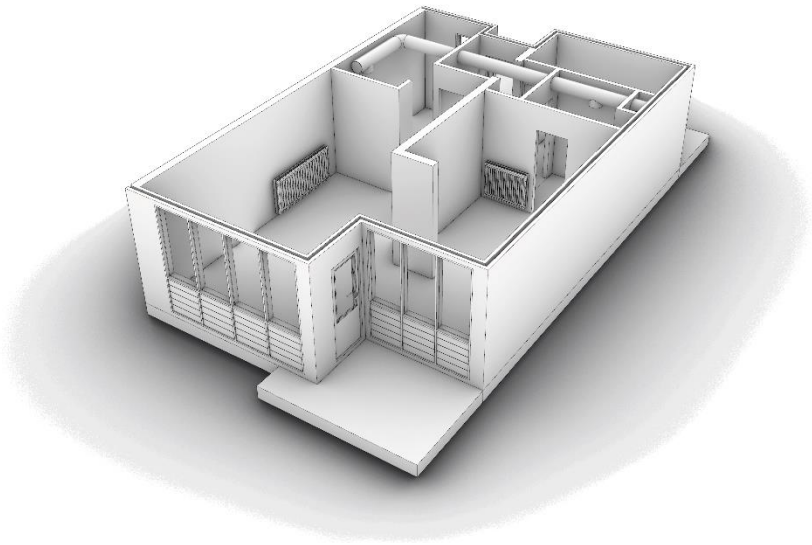
Roof Insulation

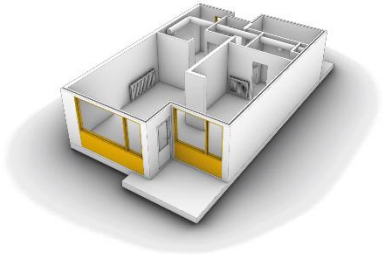


Floor Insulation

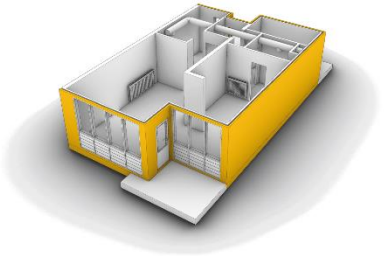


Cavity Insulation

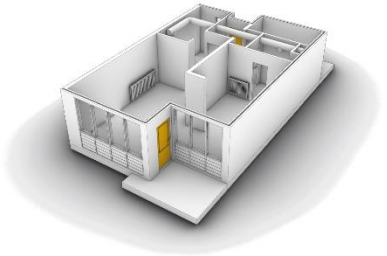




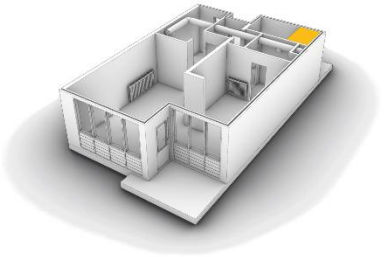
Window Insulation



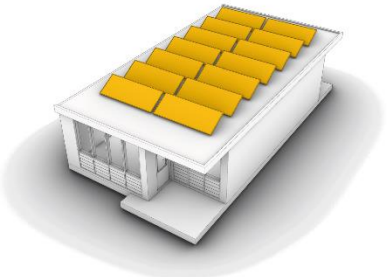
Wall Insulation



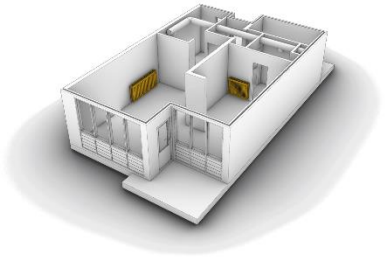
Door Insulation



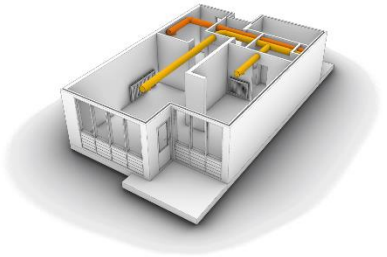
Heat Pump



PV(T)

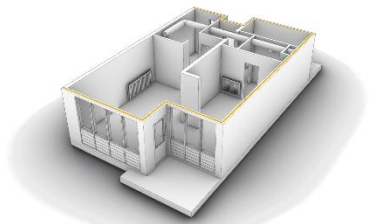


Radiators

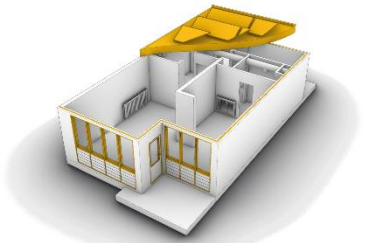


Ventilation System

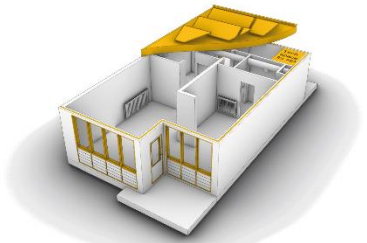
Renovation Scenarios



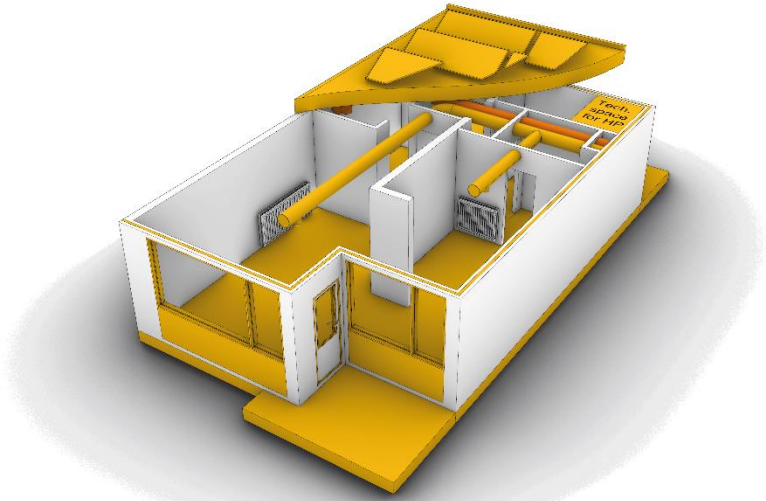
A1 - Cavity
HR Boiler



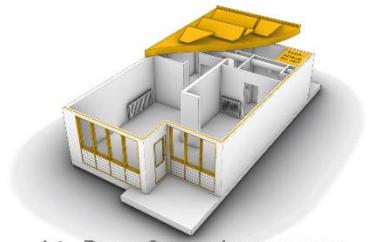
A2 - Roof, Cavity, Airtightness
HR Boiler, PV Panels



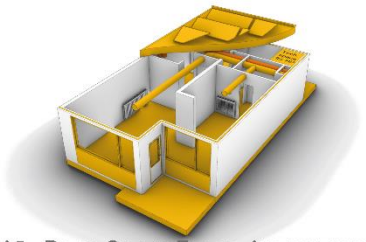
A3 - Roof, Cavity, Airtightness
Heat Pump, PV Panels



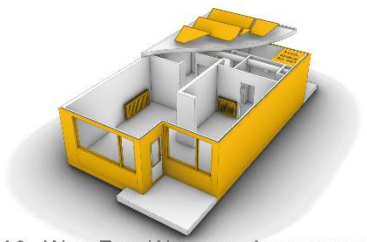
A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PV Panels, Ventilation D2



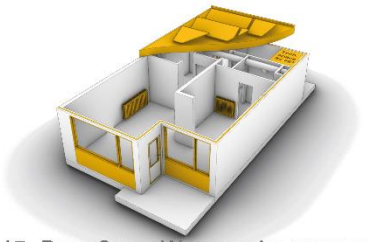
A4 - Roof, Cavity, Airtightness
Heat Pump, PVT Panels



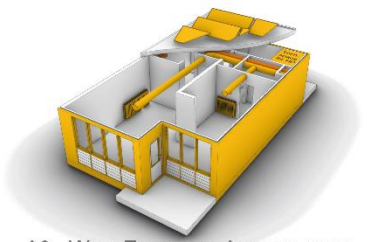
A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PVT Panels, Ventilation D2



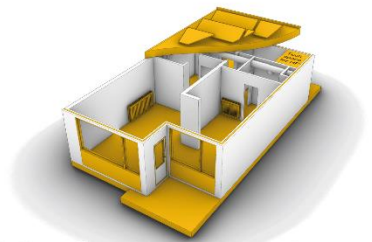
A6 - Wall Ext., Windows, Airtightness
Heat Pump, PVT Panels, Radiators



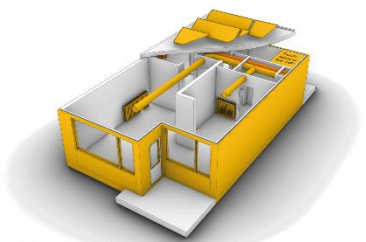
A7 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



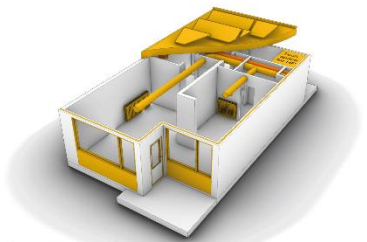
A8 - Wall Exterior, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



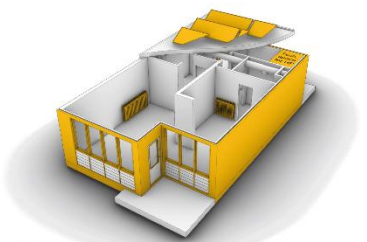
A9 - Roof, Cavity, Floor, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



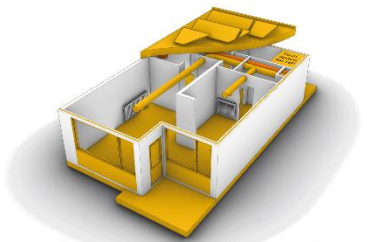
A10 - Wall Ext., Windows, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



A11 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



A12 - Wall Exterior, Airtightness
Heat Pump, PVT, Radiators



A13 - Roof, Cavity, Floor, Door, Window, Airtightness
Heat Pump, PVT Panels, Ventilation D2

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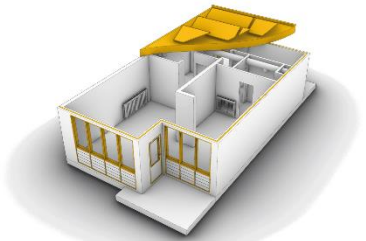
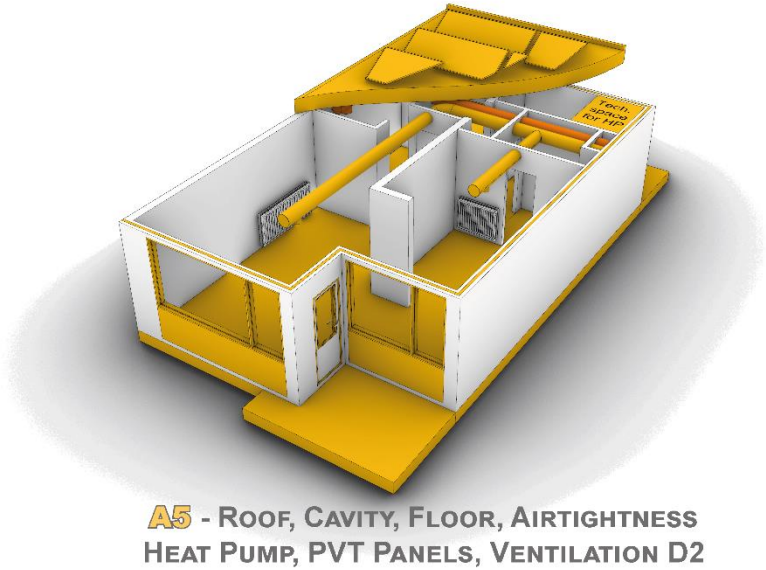
Filter Scenarios

HR Boiler

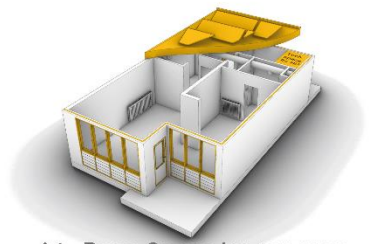


A2 - Roof, Cavity, Airtightness
HR Boiler, PV Panels

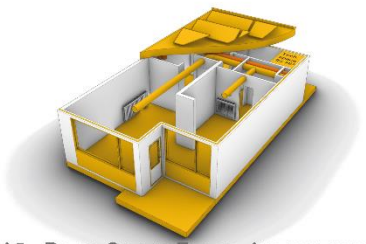
A3 - Roo[illegible]ghtness
Heat Pump, PV Panels



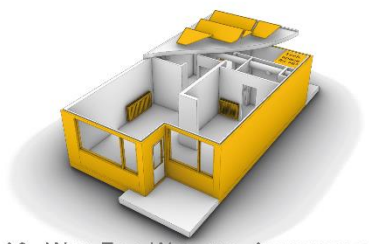
A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PVT Panels, Ventilation D2



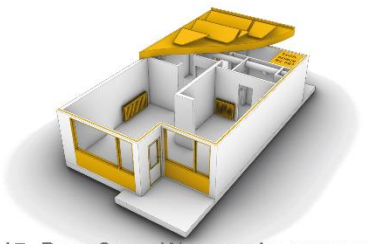
A4 - Roof, Cavity, Airtightness
Heat Pump, PVT Panels



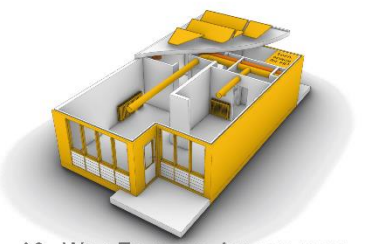
A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PVT Panels, Ventilation D2



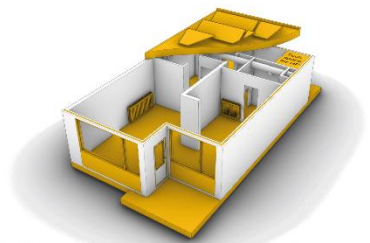
A6 - Wall Ext., Windows, Airtightness
Heat Pump, PVT Panels, Radiators



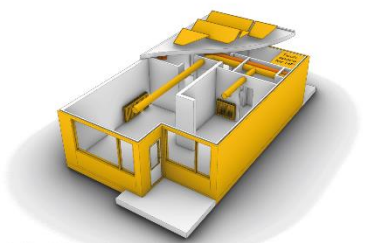
A7 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



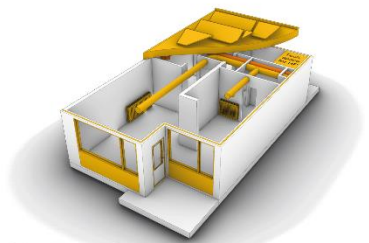
A8 - Wall Exterior, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



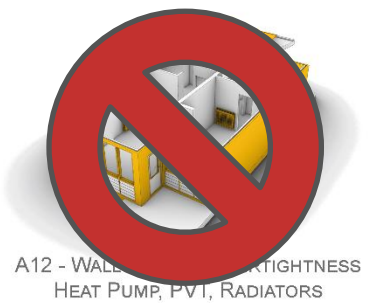
A9 - Roof, Cavity, Floor, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



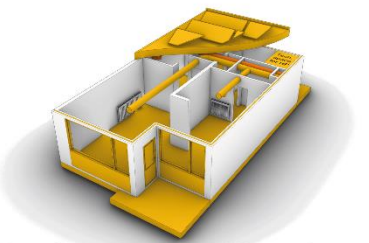
A10 - Wall Ext., Windows, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



A11 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



A12 - Wall [illegible]rtightness
Heat Pump, PVT, Radiators



A13 - Roof, Cavity, Floor, Door, Window, Airtightness
Heat Pump, PVT Panels, Ventilation D2

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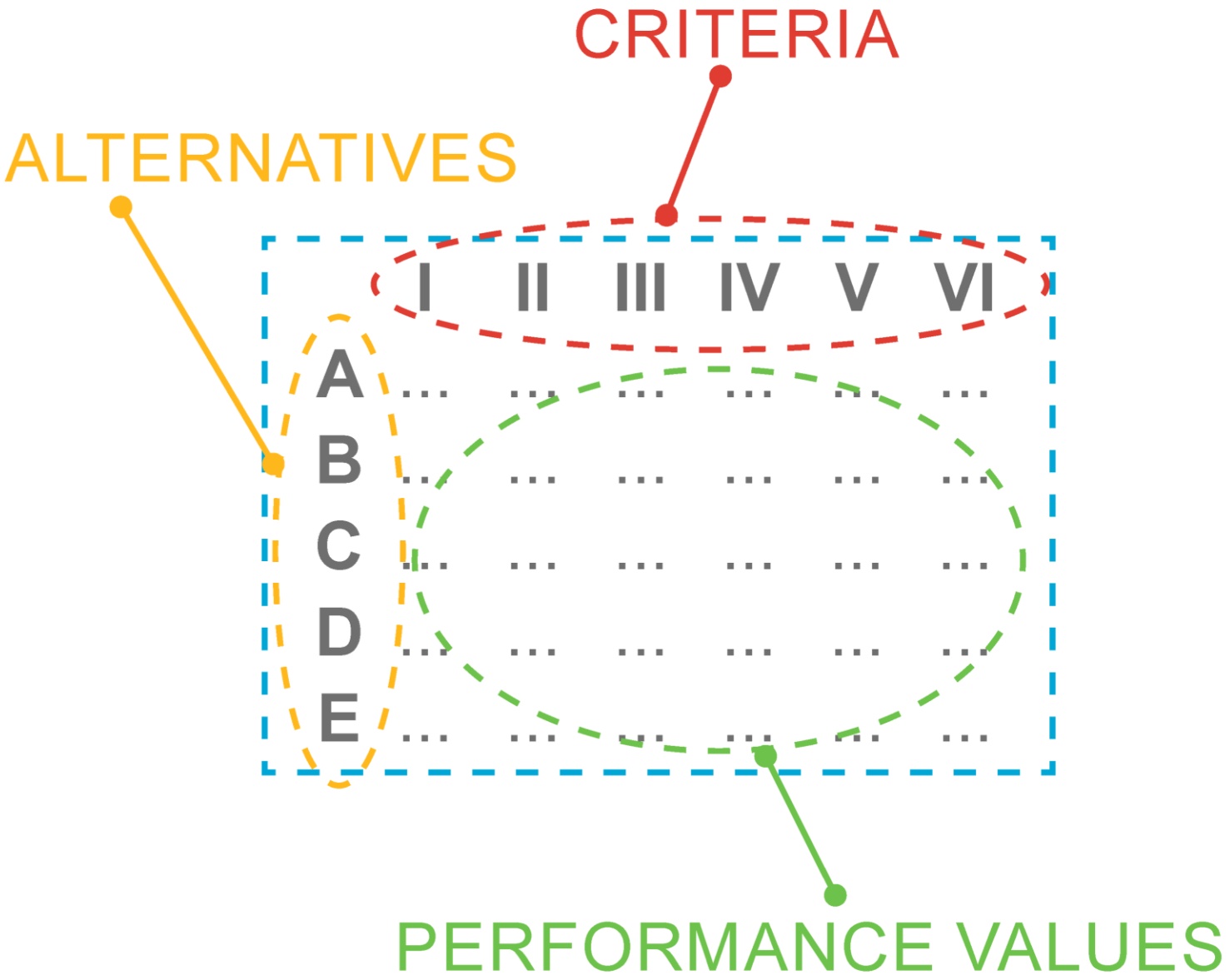
Decision Support

Literature Research

Decision-Making

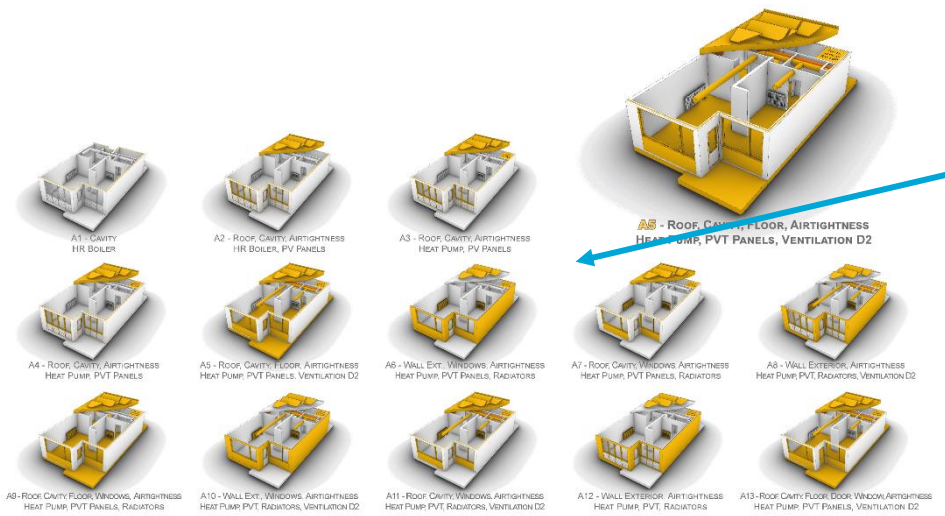
What do you need to know to make a decision?

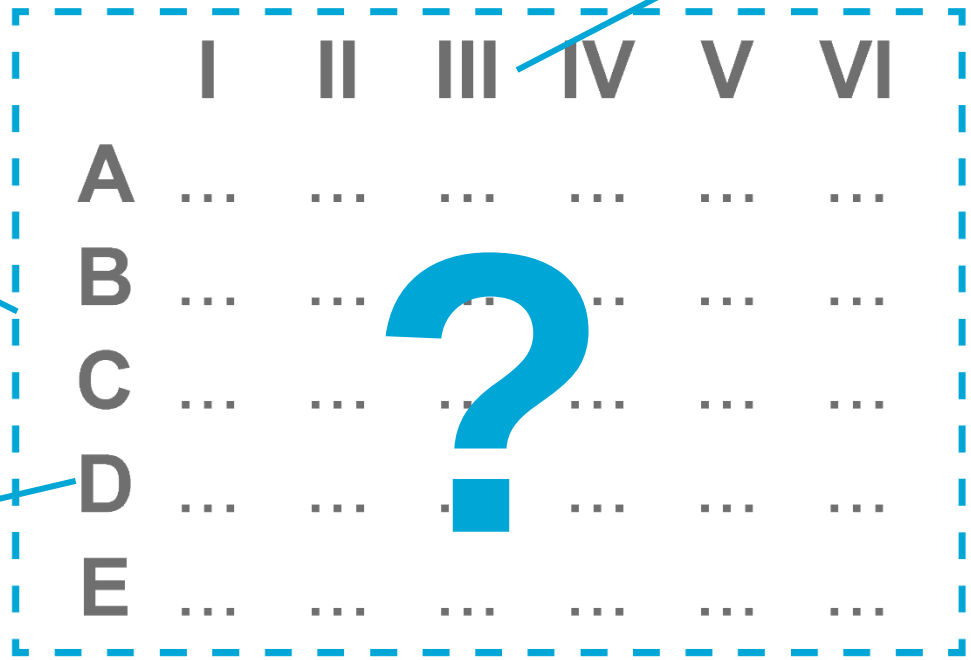
1. Problem
2. Aim
3. Options
4. Performance



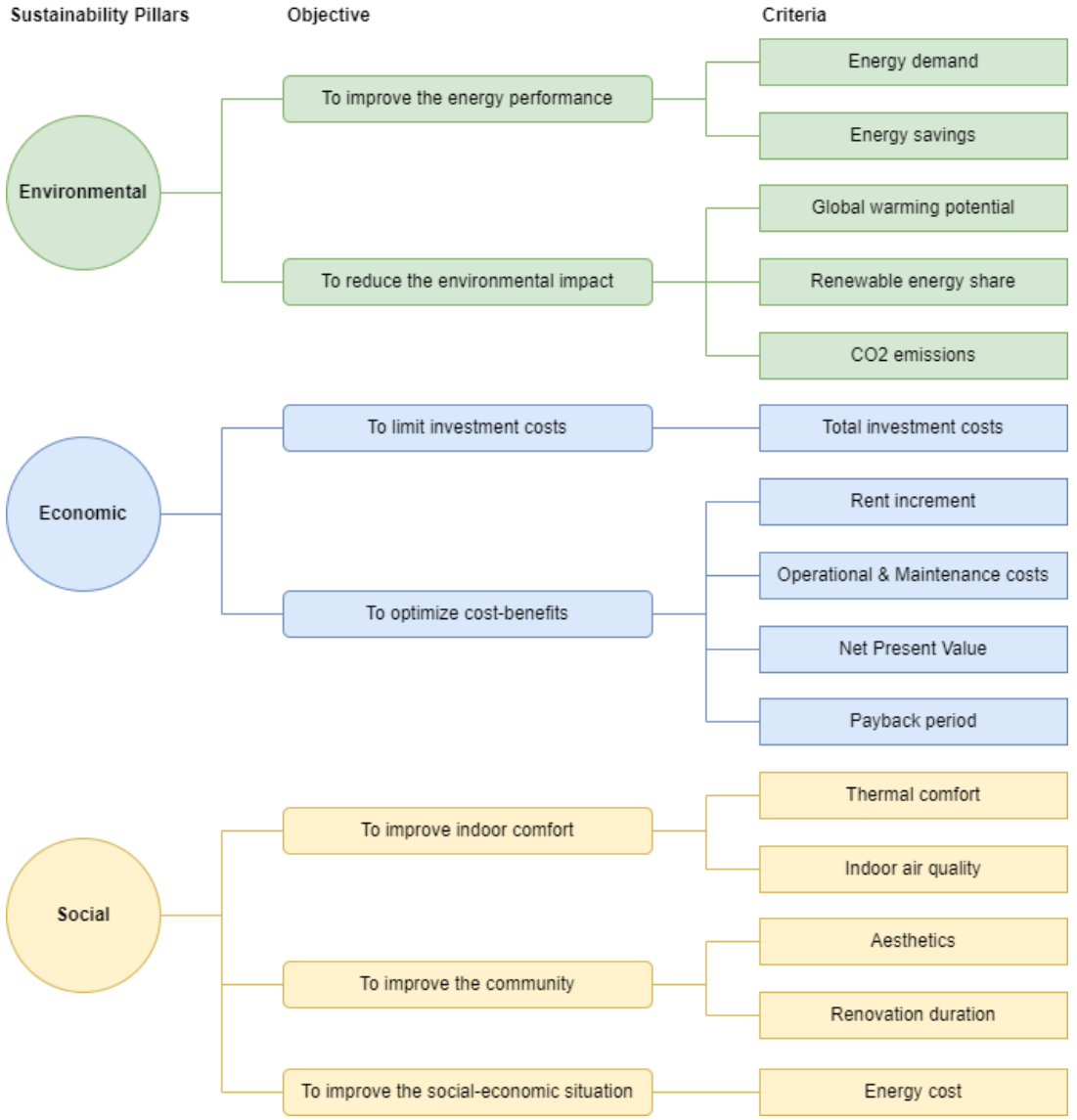
Decision-Making

Problem = Dwelling is not LT-Ready



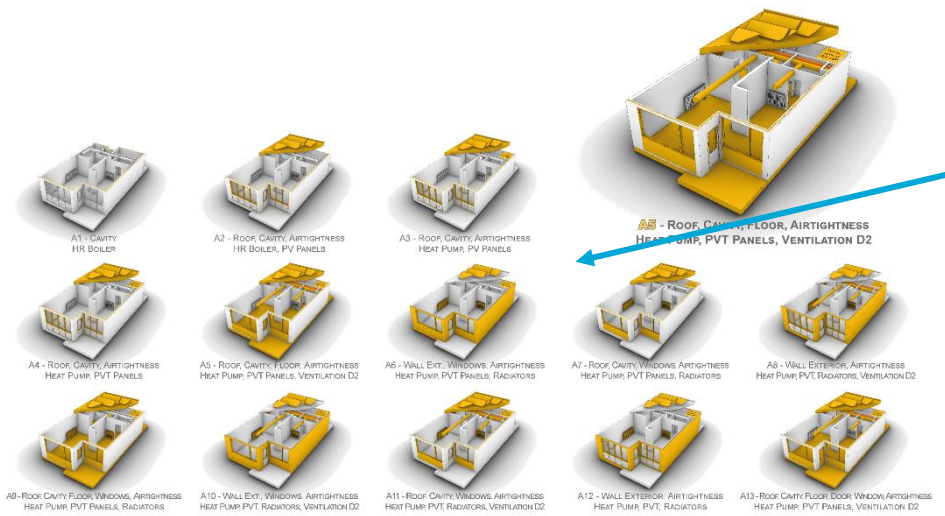


Decision Parameters – Objectives & Criteria



Decision-Making

Problem = Dwelling is not LT-Ready



	I	II	III	IV	V	VI
A	…	…	…	…	…	…
B	…	…	?	…	…	…
C	…	…	…	…	…	…
D	…	…	…	…	…	…
E	…	…	…	…	…	…

Criteria

- Energy demand
- Energy savings
- Global warming potential
- Renewable energy share
- CO2 emissions
- Total investment costs
- Rent increment
- Operational & Maintenance costs
- Net Present Value
- Payback period
- Thermal comfort
- Indoor air quality
- Aesthetics
- Renovation duration
- Energy cost

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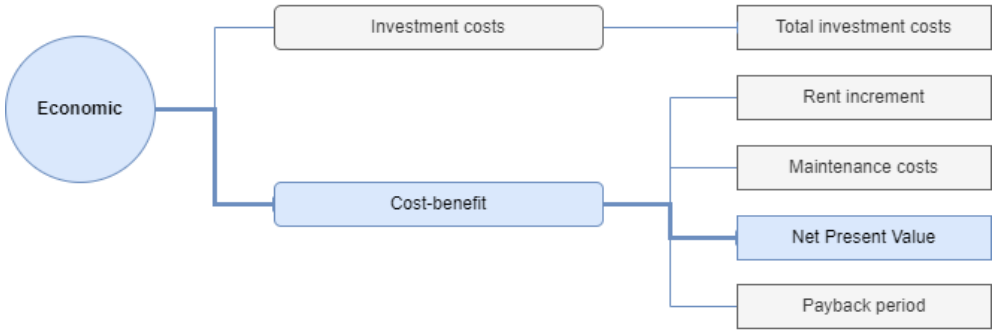
Quantification

1. Determine how to assess the criterion
2. Determine the data requirements to complete assessment
3. Determine method of calculation for the assessment



$$NPV(\tau)_{scenario} = \sum_{i=1}^{n} NPV(\tau)_{measure,\,n}$$

$$NPV(\tau)_{measure} = -I_0 + \sum_{i=1}^{\tau} \left(\frac{CF,i}{(1+d)^i} \right)$$

τ = calculation period
I_0 = investment cost of renovation measure [€]
CF,i = net cash flow of year i per measure [€]
d = discount rate [%]

Decision-Making

	I	II	III	IV	V	VI
A	…	…	…	…	…	…
B	…	…	…	…	…	…
C	…	…	…	…	…	…
D	…	…	…	…	…	…
E	…	…	…	…	…	…

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
A1	114	256.000	89
A2	182	182.000	113
A3	121	226.000	96

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Multi-Criteria Decision-Making | TOPSIS

1) $$r_{ij} = \frac{x_{ij}}{\left(\sqrt{\sum x^2{}_{ij}}\right)}$$

Decision Matrix

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
A1	114	256.000	89
A2	182	182.000	113
A3	121	226.000	96

Normalized Decision Matrix

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
A1	0,46	0,66	0,51
A2	0,74	0,47	0,65
A3	0,49	0,58	0,56

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Multi-Criteria Decision-Making | TOPSIS

2) $v_{ij} = w_j r_{ij}$

Normalized Decision Matrix

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
A1	0,46	0,66	0,51
A2	0,74	0,47	0,65
A3	0,49	0,58	0,56

Weighted Normalized Decision Matrix

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
	33,33%	33,33%	33,33%
A1	0,15	0,22	0,17
A2	0,24	0,16	0,22
A3	0,16	0,19	0,18

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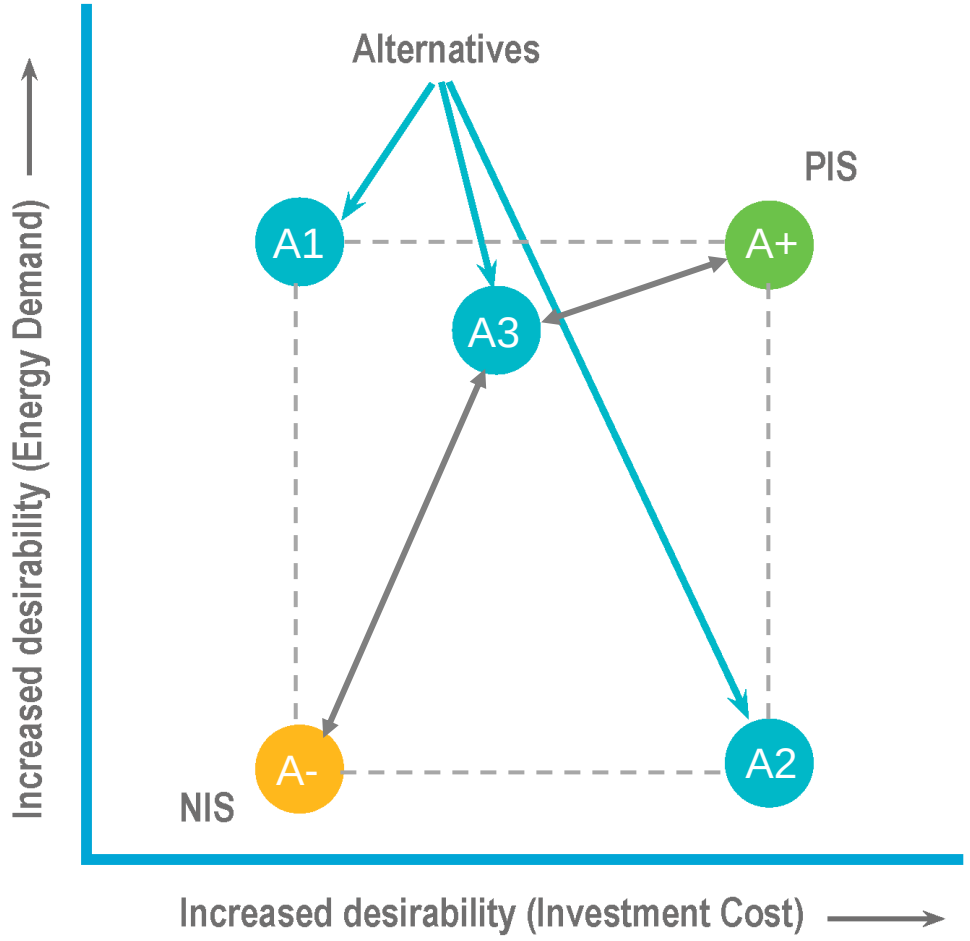
Multi-Criteria Decision-Making | TOPSIS



3)

Positive Ideal Solution (PIS) $A^* = \{v_{1*}, v_{2*}, \dots, v_{n*}\}$

Negative Ideal Solution (NIS) $A^- = \{v_{1-}, v_{2-}, \dots, v_{n-}\}$

4)

Separation measure PIS $S_{i*} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_{i*})^2} \; for \; i = 1, 2, 3, \dots, m$

Separation measure NIS $S_{i-} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_{i-})^2} \; for \; i = 1, 2, 3, \dots, m$

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]	Si +	Si -
A1	0,15	0,22	0,17	0,063	0,102
A2	0,24	0,16	0,22	0,102	0,063
A3	0,16	0,19	0,18	0,041	0,092

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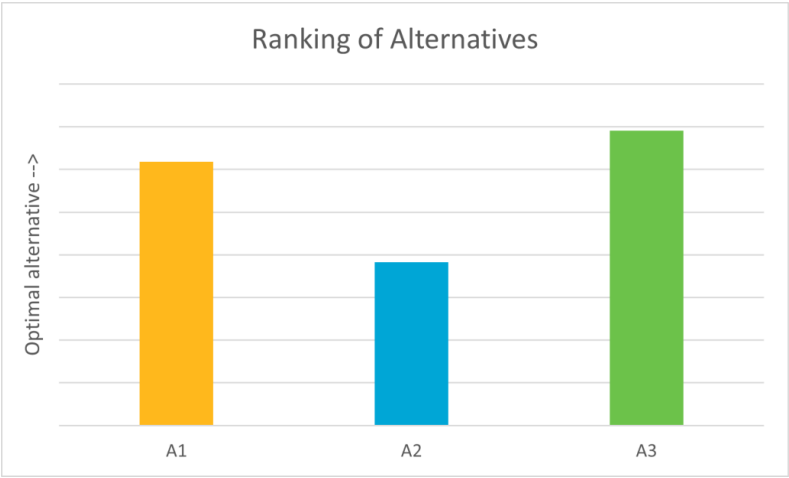
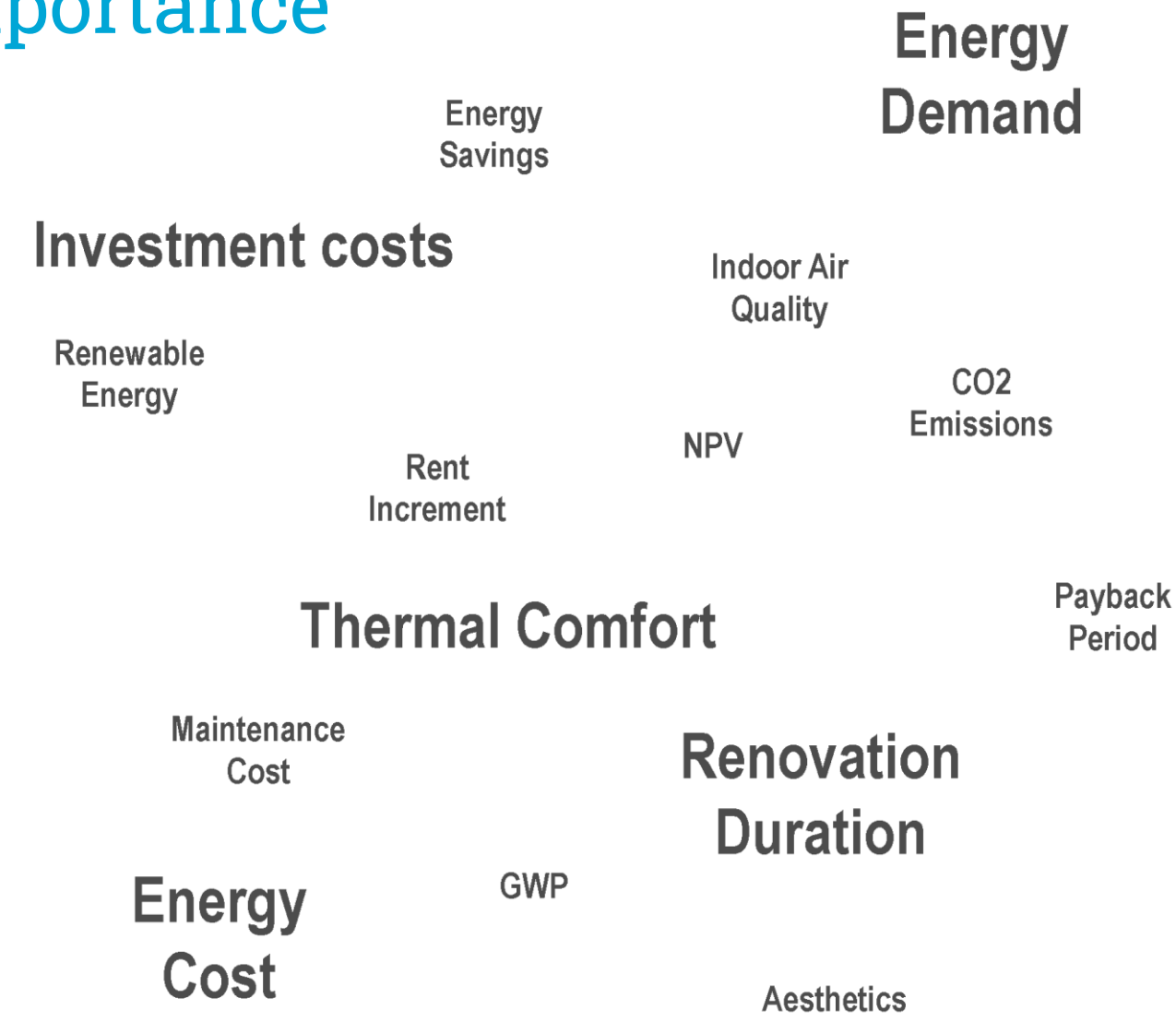
Multi-Criteria Decision-Making | TOPSIS

5) $$CC_i = \frac{S_i^*}{(S_i^* + S_i^-)} \quad , 0 < CC_i < 1$$

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]	Si +	Si -	CCi	RANK
A1	0,15	0,22	0,17	0,063	0,102	0,618	2
A2	0,24	0,16	0,22	0,102	0,063	0,382	3
A3	0,16	0,19	0,18	0,041	0,092	0,691	1



Relative Importance



Stakeholders

Decision-maker

- Social housing corporation
- Private owner

Authorizers

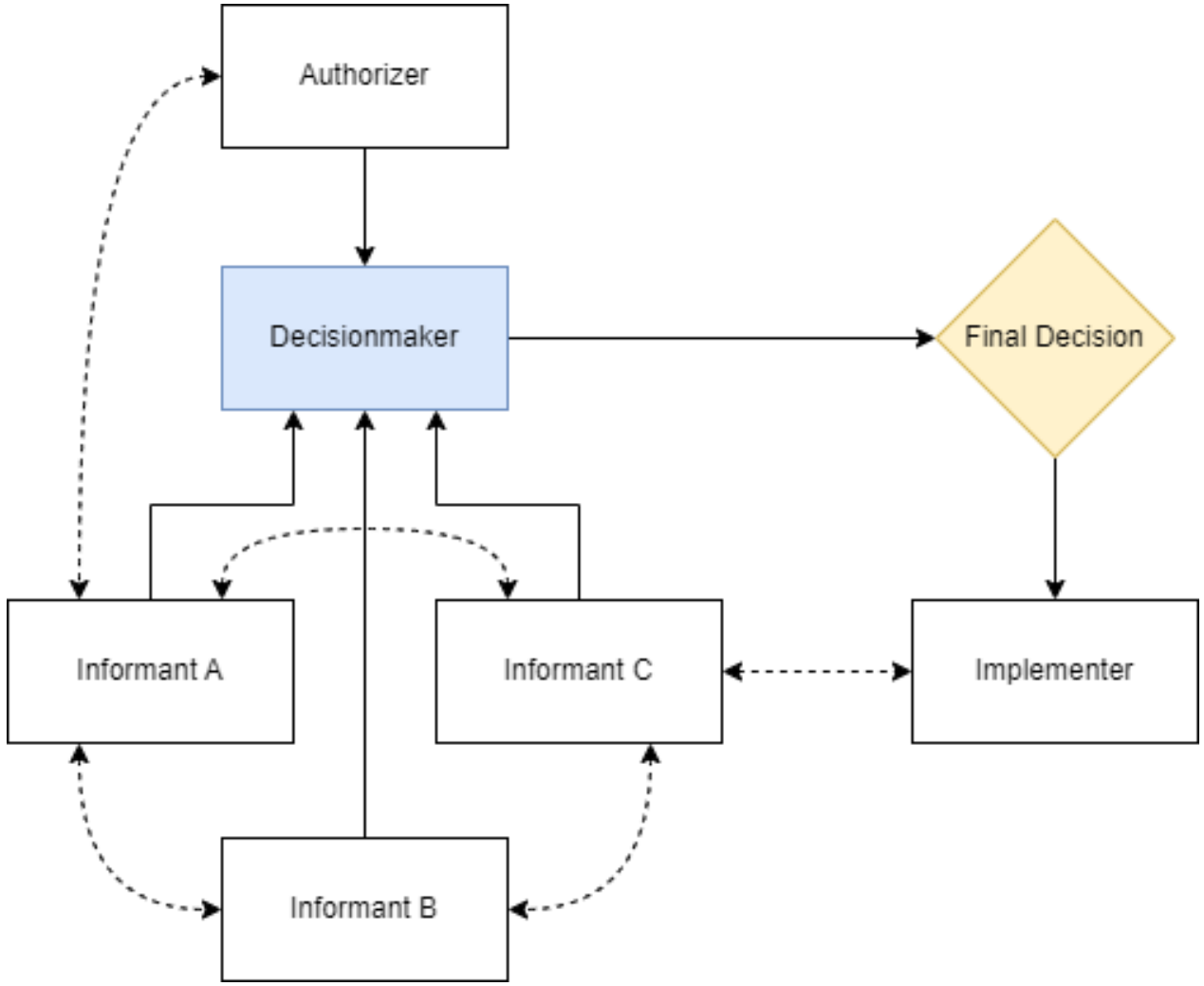
- Municipality
- Tenant

Informant

- Project manager
- Community representative
- Tenant
- Experts

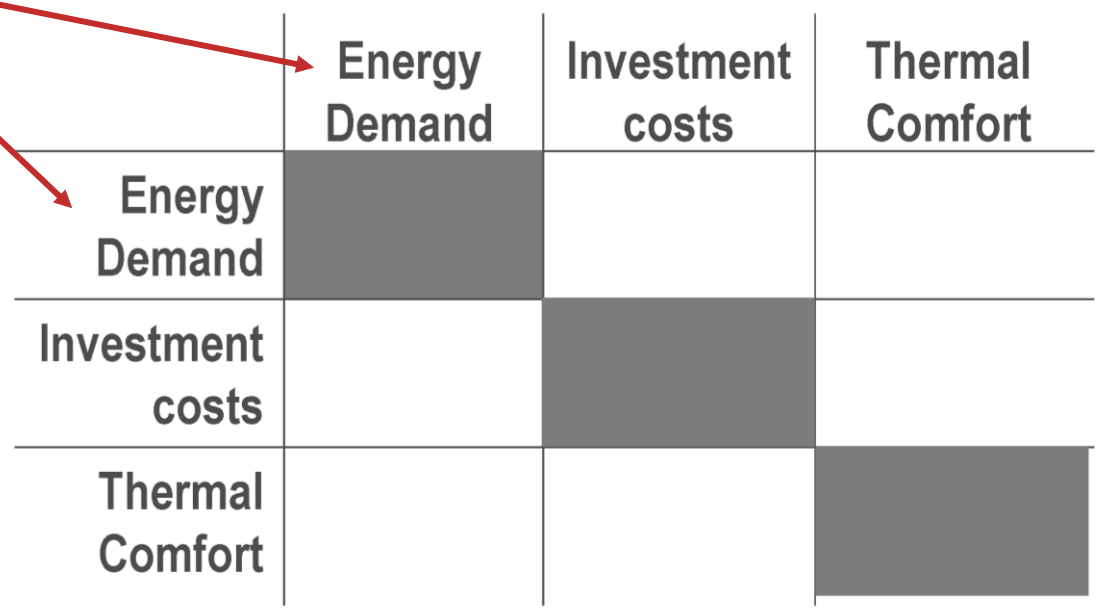
Implementers

- Net operator
- Contractor
- Supplier



Pairwise Comparison

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
A1	114	256.000	89
A2	182	182.000	113
A3	121	226.000	96



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Pairwise Comparison

	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme	
Energy Demand	9	7	5	3	1	3	5	7	9	Investment costs
Energy Demand	9	7	5	3	1	3	5	7	9	Thermal Comfort
Investment costs	9	7	5	3	1	3	5	7	9	Thermal Comfort

Pairwise Comparison

	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme	
Energy Demand	9	7	5	3	1	3	5	7	9	Investment costs
Energy Demand	9	7	5	3	1	3	5	7	9	Thermal Comfort
Investment costs	9	7	5	3	1	3	5	7	9	Thermal Comfort

$$w_k = \frac{1}{n} \cdot \sum_{j=1}^{n} \left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \right)$$

	Energy Demand	Investment costs	Thermal Comfort	
Energy Demand	1	1/3	1	18,7%
Investment costs	3	1	5	65,5%
Thermal Comfort	1	1/5	1	15,8%

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TOPSIS Relative Weighted Matrix

$$v_{ij} = w_j r_{ij}$$

Equal Weighted Normalized Decision Matrix

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
	33,33%	33,33%	33,33%
A1	0,15	0,22	0,17
A2	0,24	0,16	0,22
A3	0,16	0,19	0,18

Relative Weighted Normalized Decision Matrix

	Energy Demand [kWh/m²]	Investment Cost [€]	Thermal Comfort [h too cold]
	18,7%	**65,5%**	**15,8%**
A1	0,09	0,43	0,08
A2	0,14	0,31	0,10
A3	0,09	0,38	0,09

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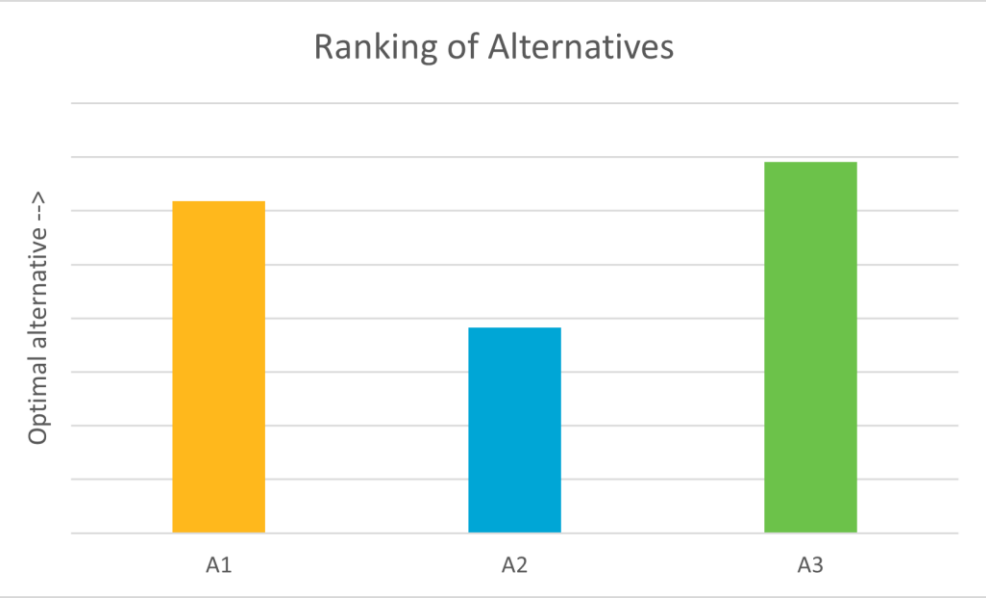
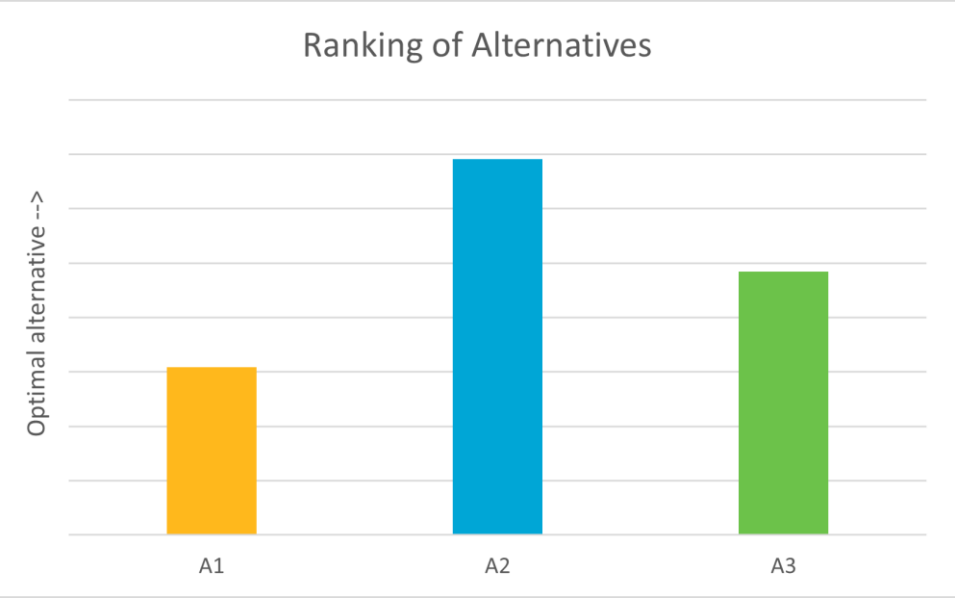
New Ranking

Equal Weights

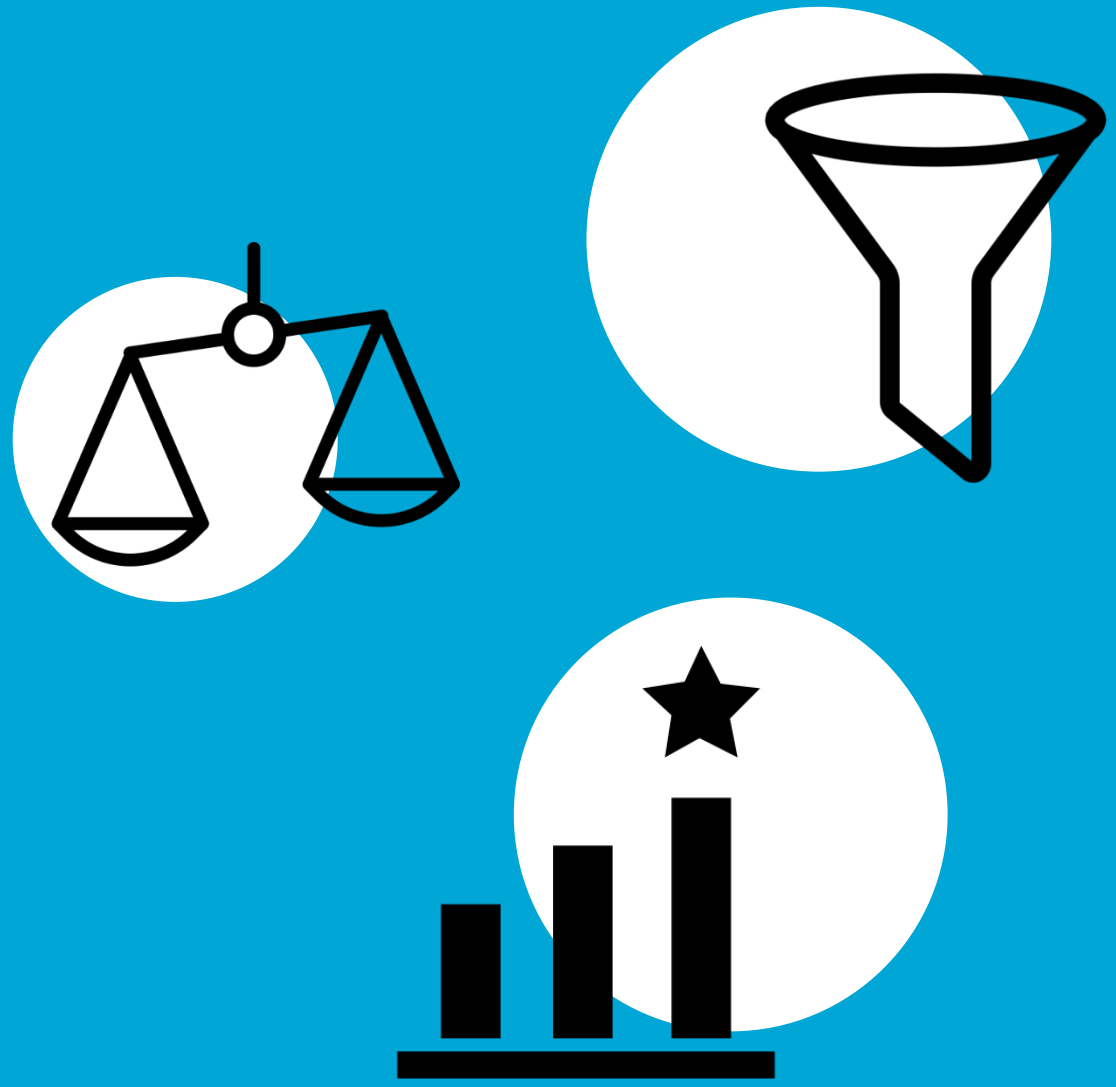


Pairwise Comparison Weights



Framework & Tool

Development



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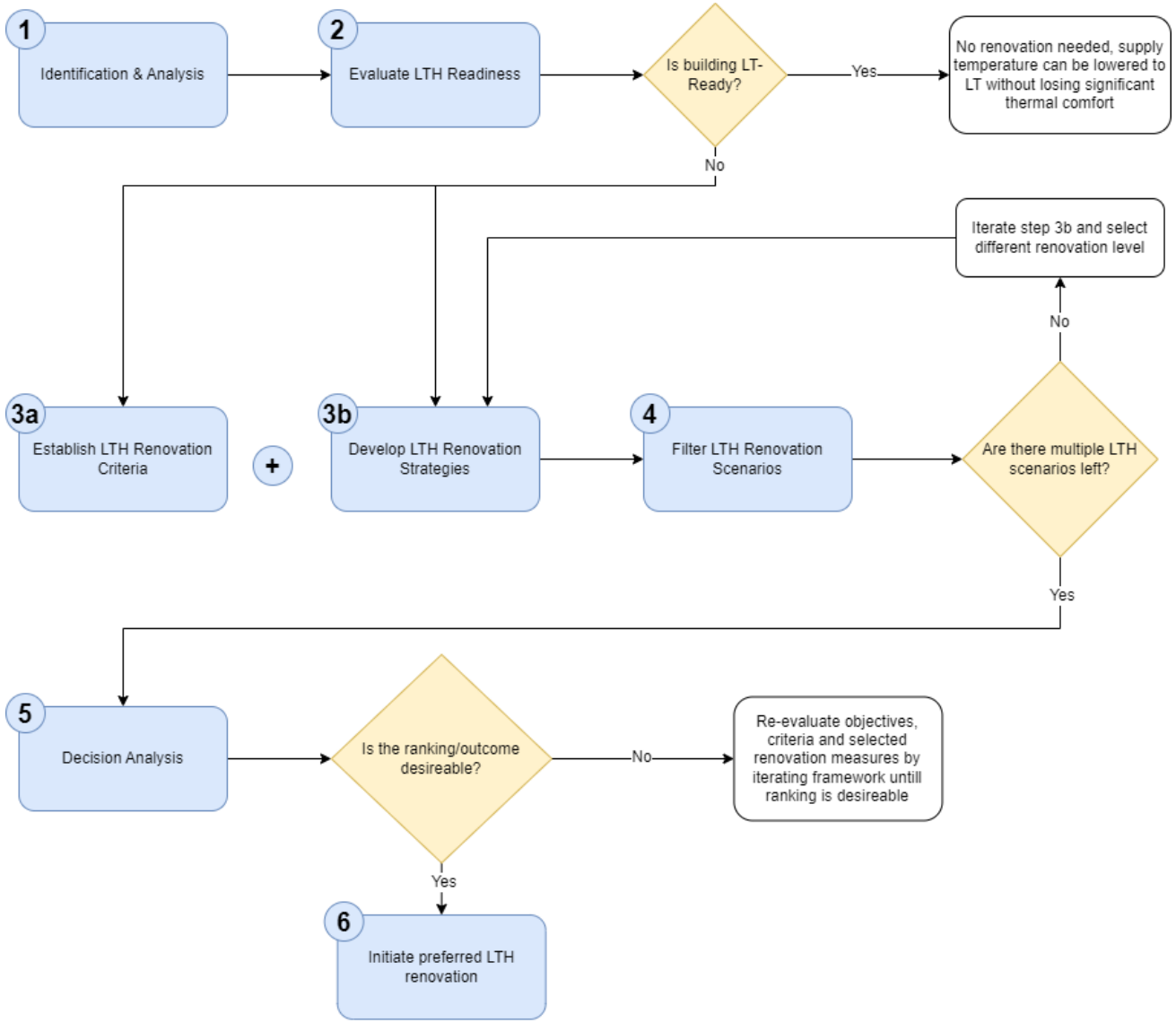
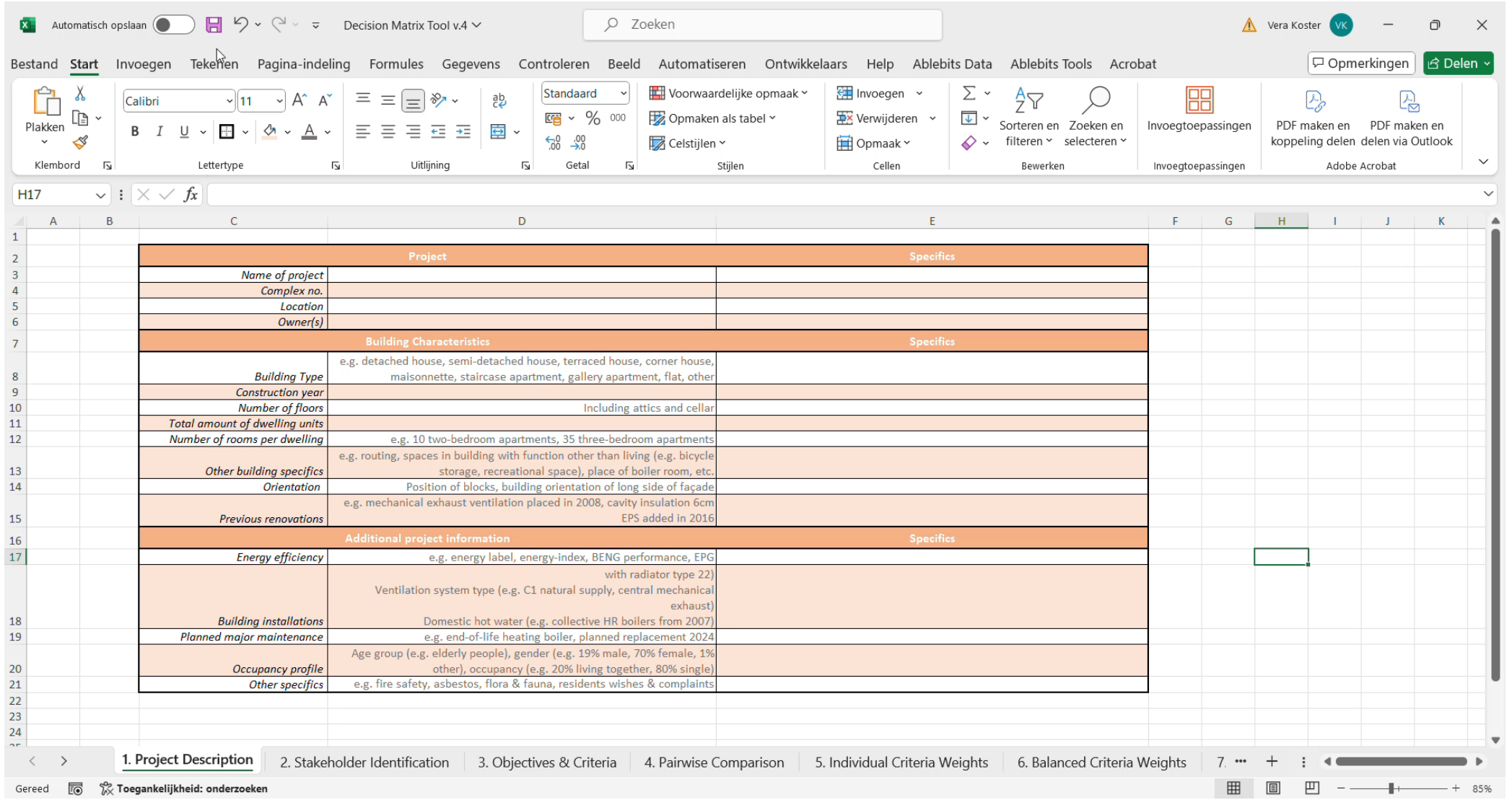
LTH-DS Framework



Decision Support Tool



Project		Specifics
Name of project		
Complex no.		
Location		
Owner(s)		
Building Characteristics		**Specifics**
Building Type	e.g. detached house, semi-detached house, terraced house, corner house, maisonnette, staircase apartment, gallery apartment, flat, other	
Construction year		
Number of floors	Including attics and cellar	
Total amount of dwelling units		
Number of rooms per dwelling	e.g. 10 two-bedroom apartments, 35 three-bedroom apartments	
Other building specifics	e.g. routing, spaces in building with function other than living (e.g. bicycle storage, recreational space), place of boiler room, etc.	
Orientation	Position of blocks, building orientation of long side of façade	
Previous renovations	e.g. mechanical exhaust ventilation placed in 2008, cavity insulation 6cm EPS added in 2016	
Additional project information		**Specifics**
Energy efficiency	e.g. energy label, energy-index, BENG performance, EPG	
Building installations	with radiator type 22) Ventilation system type (e.g. C1 natural supply, central mechanical exhaust) Domestic hot water (e.g. collective HR boilers from 2007)	
Planned major maintenance	e.g. end-of-life heating boiler, planned replacement 2024	
Occupancy profile	Age group (e.g. elderly people), gender (e.g. 19% male, 70% female, 1% other), occupancy (e.g. 20% living together, 80% single)	
Other specifics	e.g. fire safety, asbestos, flora & fauna, residents wishes & complaints	

Validation

Case Study & Workshop

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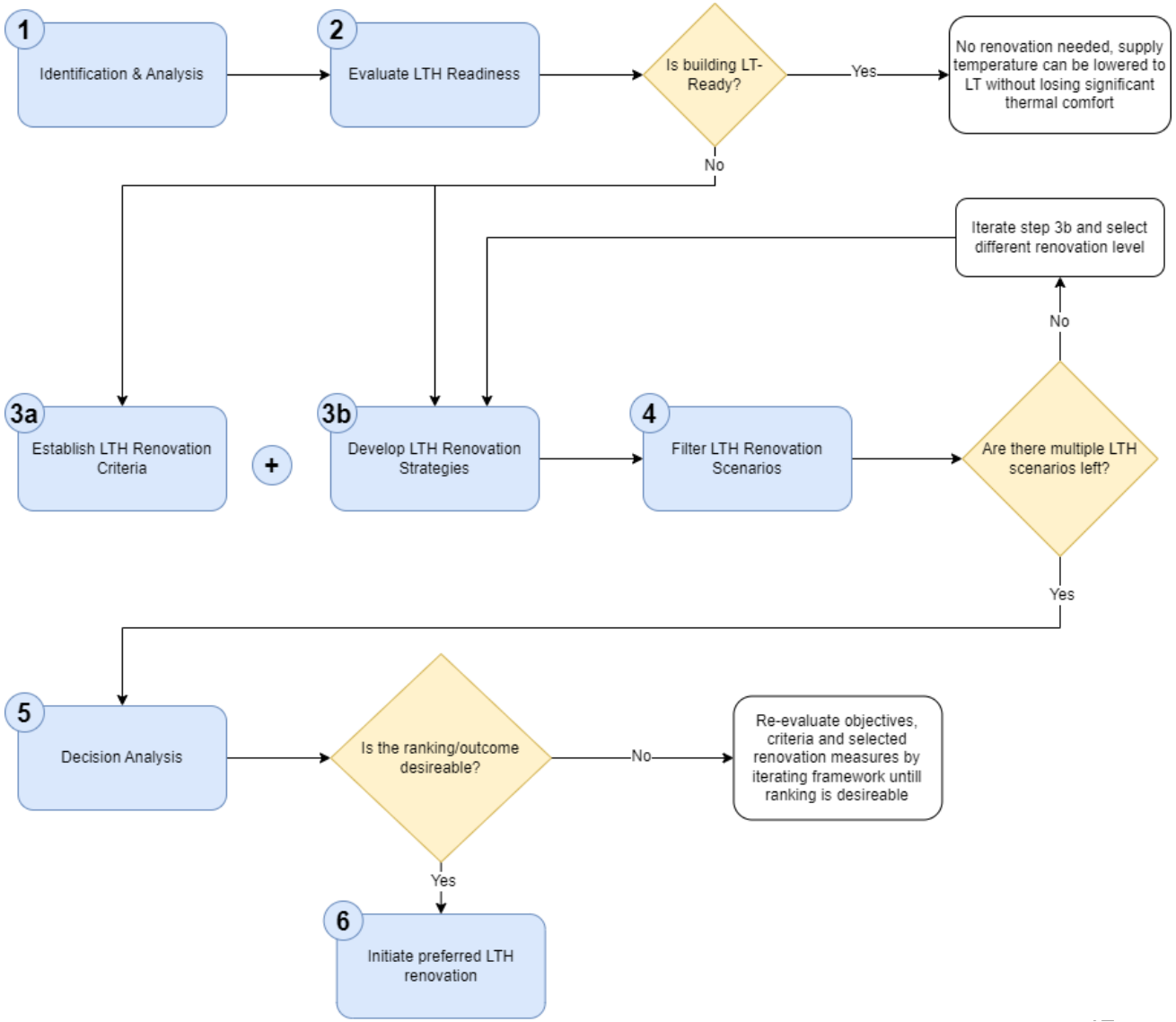
Stakeholder Validation



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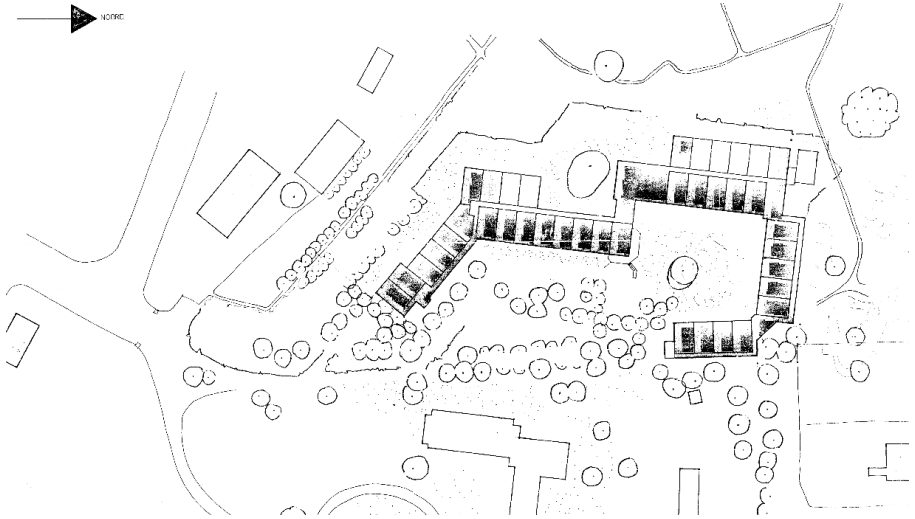
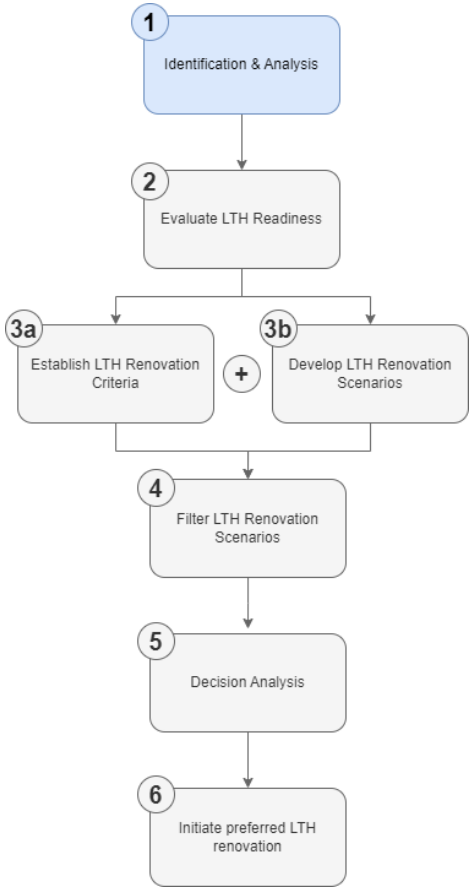
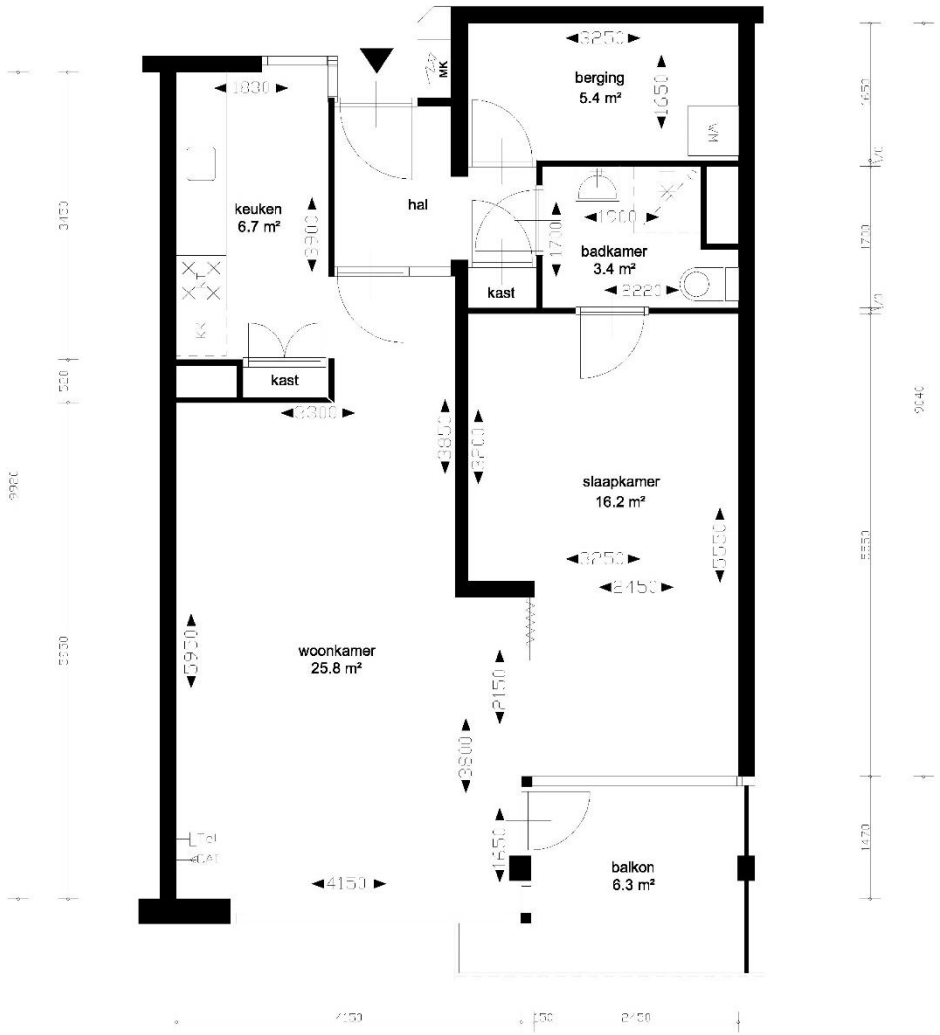
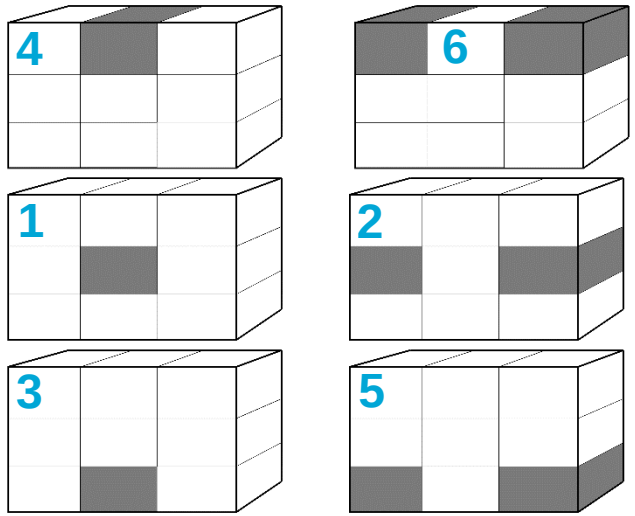
Case Study Application

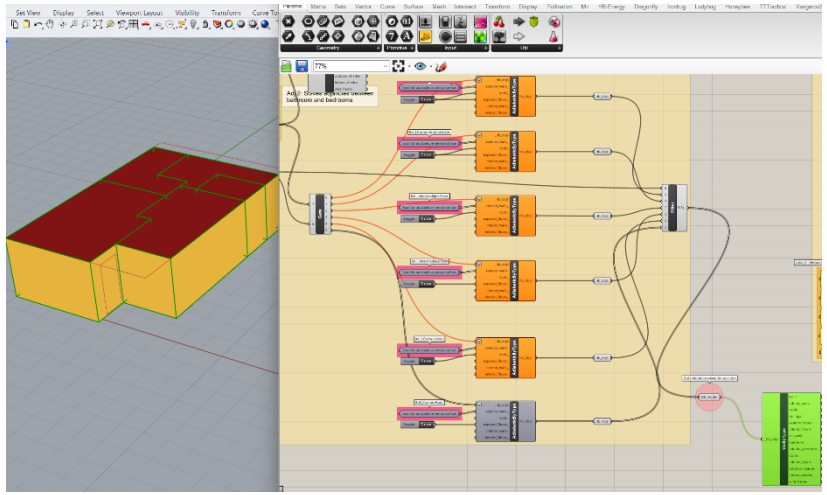


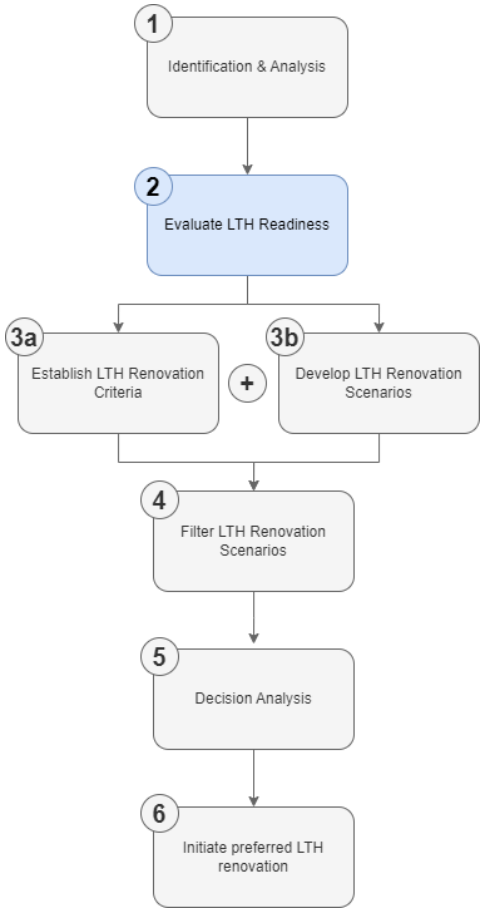


Benchmark Performance

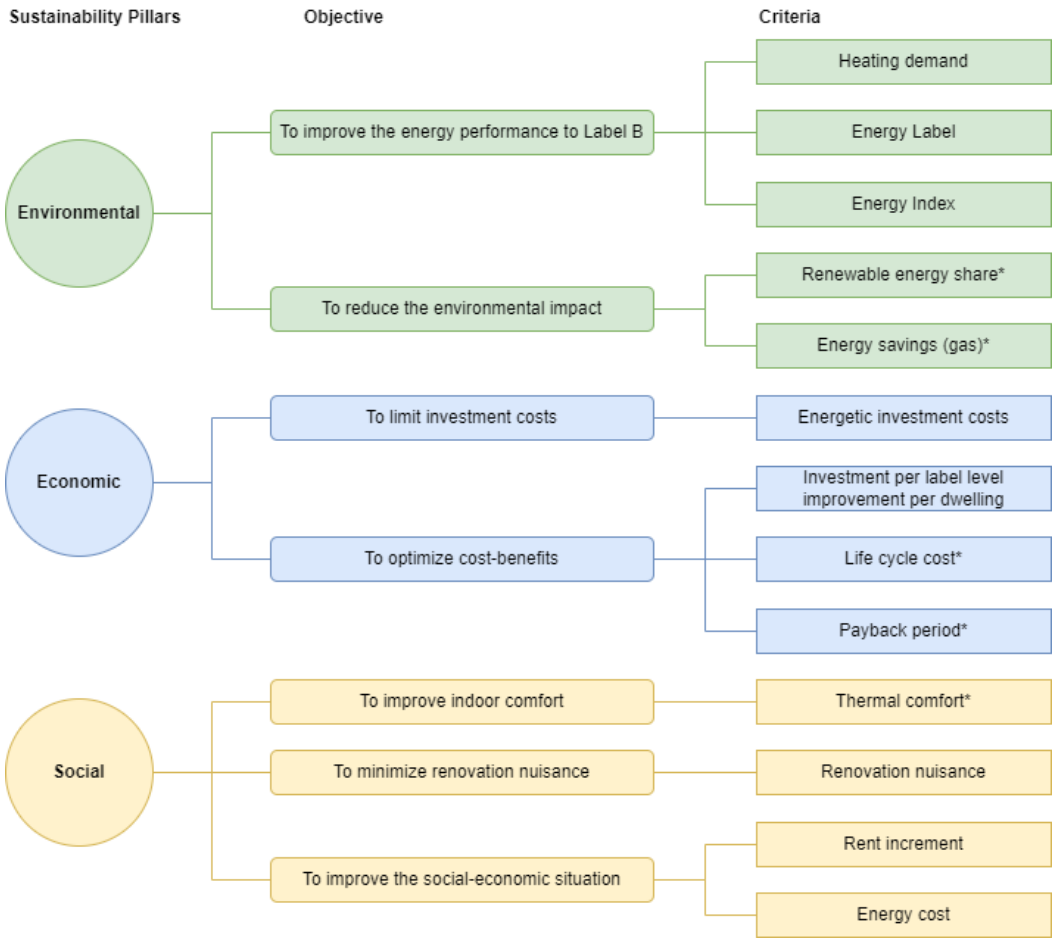


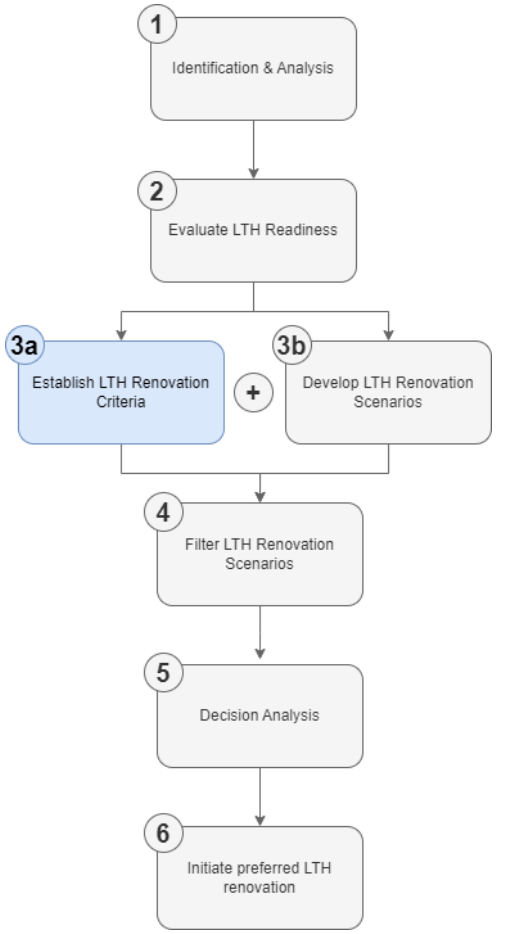






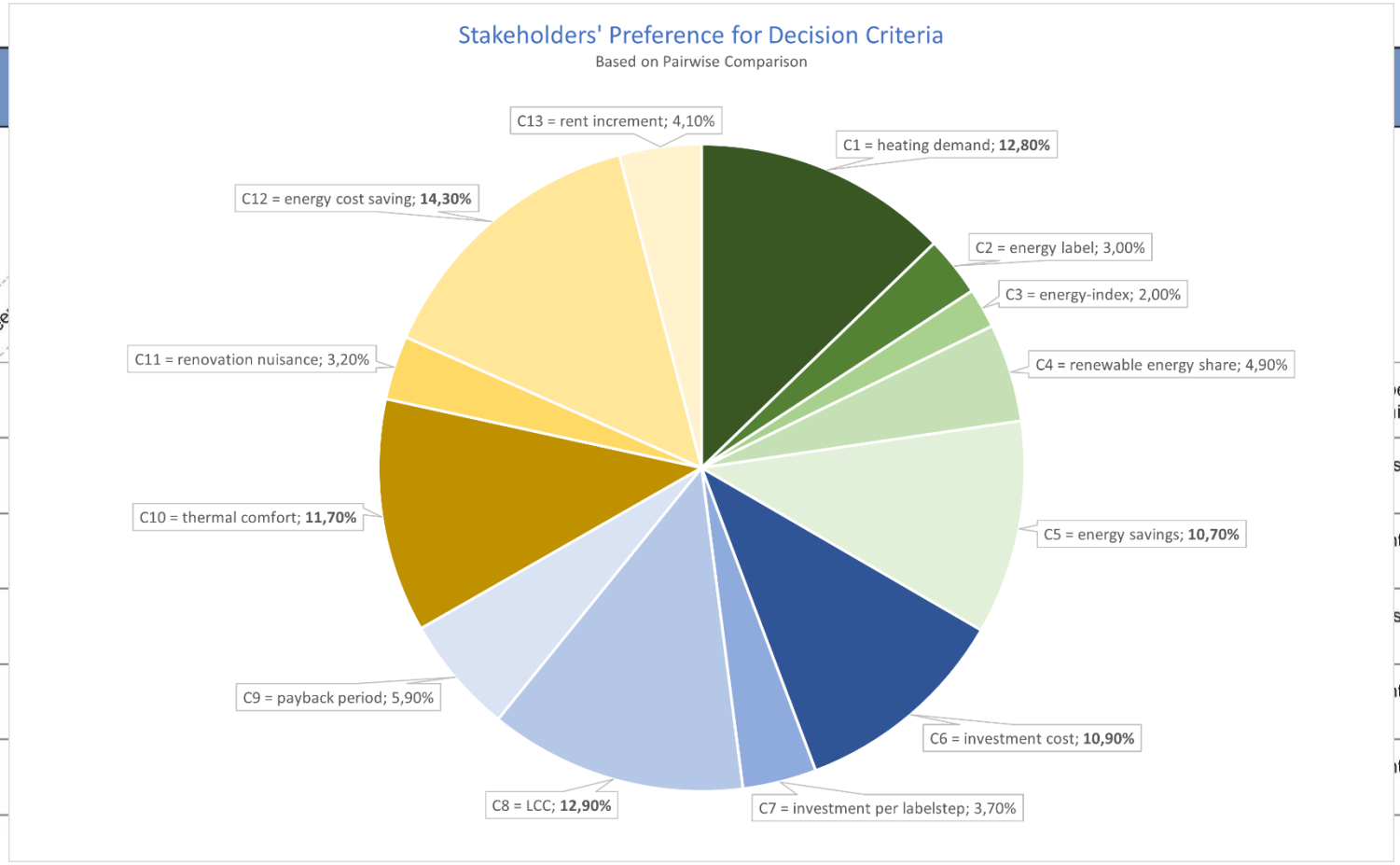
Adapted Criteria Tree

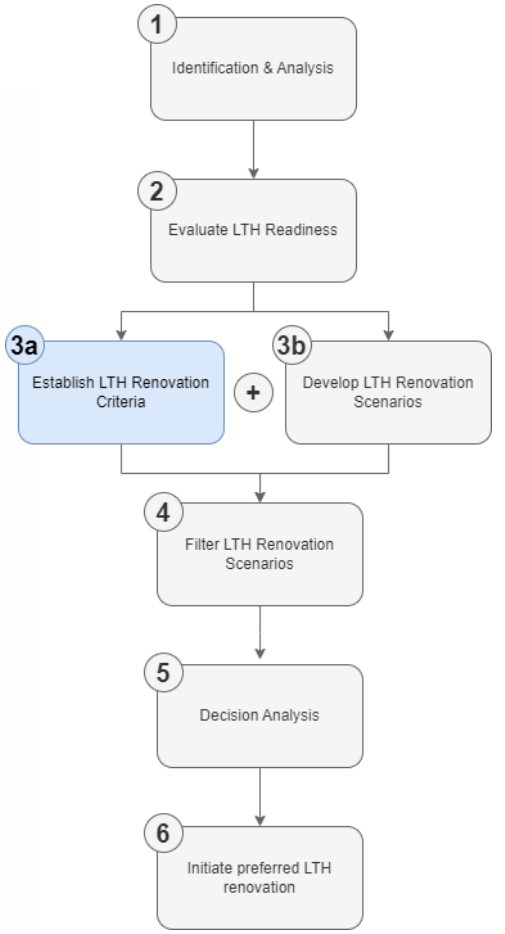




Pairwise Comparison - Criteria Weights

Energetische investeringskosten	C6	9
Energetische investeringskosten	C6	9
Energetische investeringskosten	C6	9
Investering per labelstap per woning	C7	9
Investering per labelstap per woning	C7	9
Life cycle costs (LCC 30 jaar)	C8	9

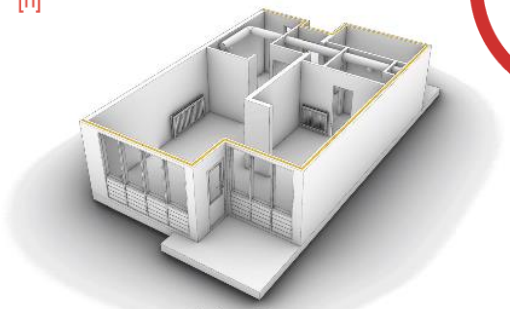




Case Study - Given Scenarios

HT

Heating demand = 174,34 [kWh/m²]
Hours too cold = 263 [h]



A1 - Cavity
HR Boiler

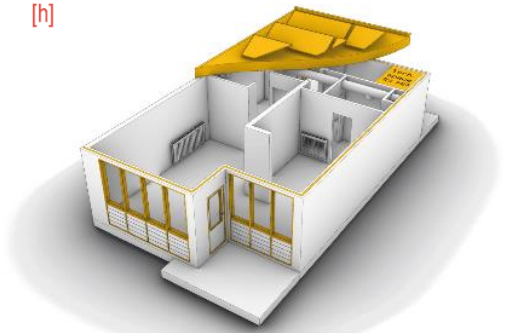
HT

Heating demand = 153,76[kWh/m²]
Hours too cold = 230 [h]

A2 - Roof, Cavity, Airtightness
HR Boiler, PV Panels

LT-READY

Heating demand = 122,80 [kWh/m²]
Hours too cold = 919 [h]

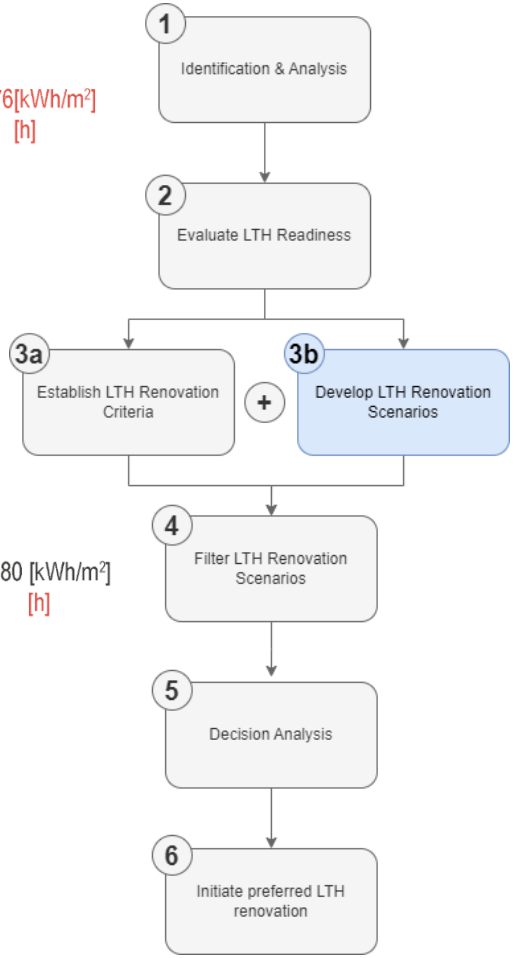


A3 - Roof, Cavity, Airtightness
Heat Pump, PV Panels

LT-READY

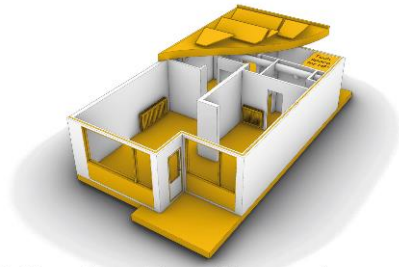
Heating demand = 122,80 [kWh/m²]
Hours too cold = 919 [h]

A4 - Roof, Cavity, Airtightness
Heat Pump, PVT Panels

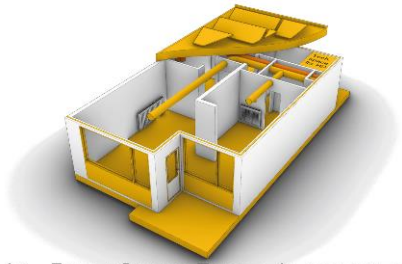


Benchmark HD = 206,88 [kWh/m^2]
Benchmark TC = 326 [h]

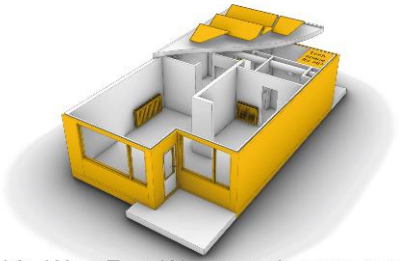
Additional Developed Scenarios



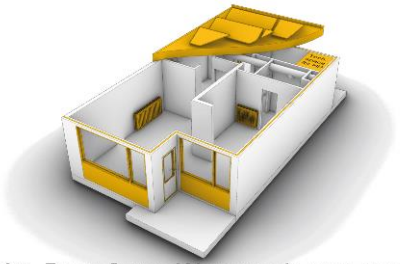
A9 - Roof, Cavity, Floor, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



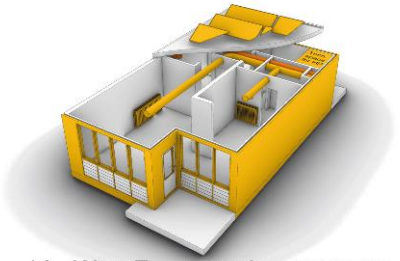
A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PVT Panels, Ventilation D2



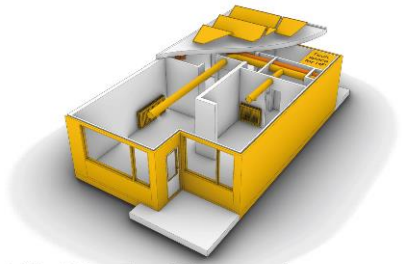
A6 - Wall Ext., Windows, Airtightness
Heat Pump, PVT Panels, Radiators



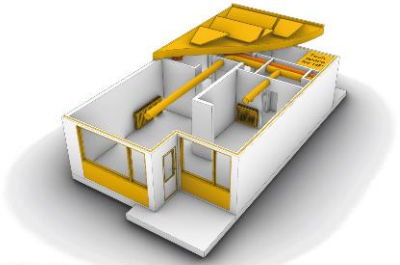
A7 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



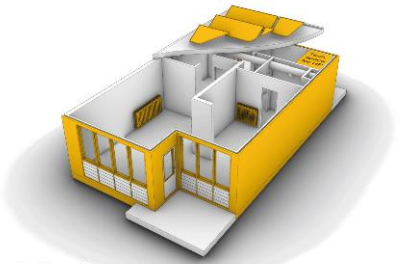
A8 - Wall Exterior, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



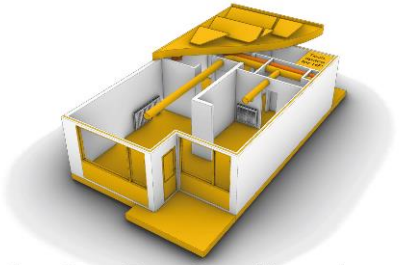
A10 - Wall Ext., Windows, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



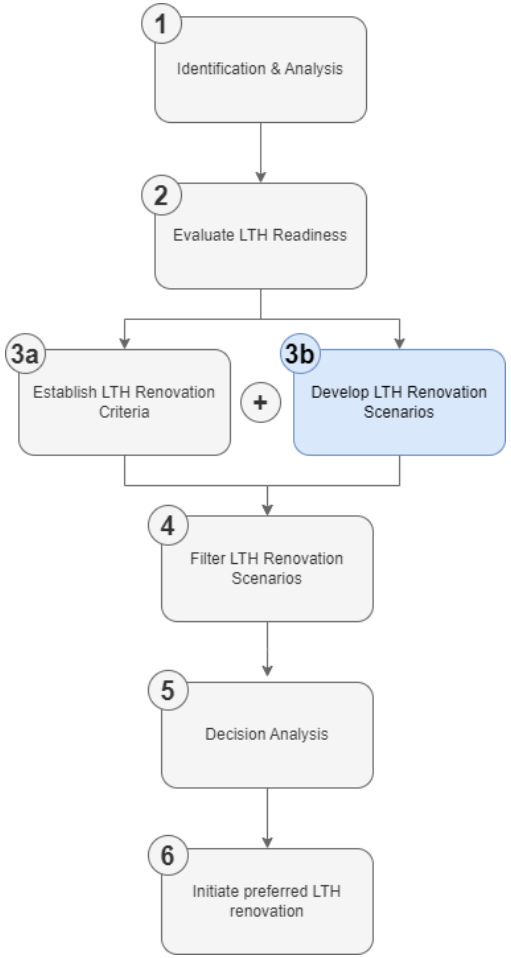
A11 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



A12 - Wall Exterior, Airtightness
Heat Pump, PVT, Radiators



A13 - Roof, Cavity, Floor, Door, Window, Airtightness
Heat Pump, PVT Panels, Ventilation D2



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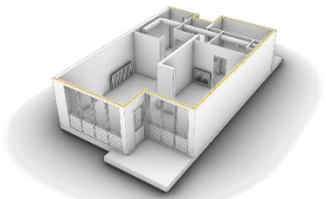
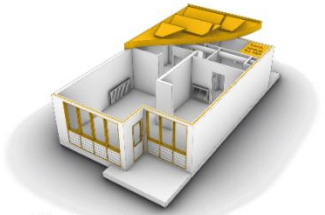
Filter LTH Scenarios

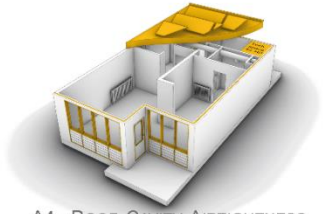


A1 - Cavity
HR Boiler

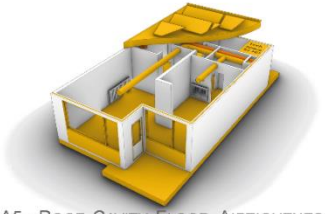
A2 - Roof, Cavity, Airtightness
HR Boiler, PV Panels



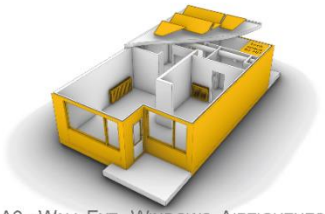
A3 - Roof, Cavity, Airtightness
Heat Pump, PV Panels



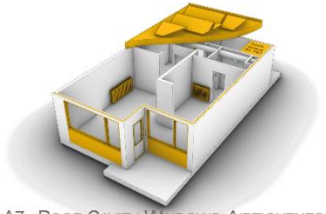
A4 - Roof, Cavity, Airtightness
Heat Pump, PVT Panels



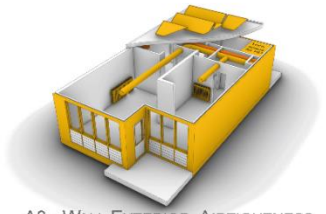
A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PVT Panels, Ventilation D2



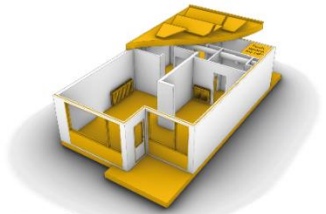
A6 - Wall Ext., Windows, Airtightness
Heat Pump, PVT Panels, Radiators



A7 - Roof, Cavity, Windows, Airtightness
Heat Pump, PVT Panels, Radiators



A8 - Wall Exterior, Airtightness
Heat Pump, PVT, Radiators, Ventilation D2



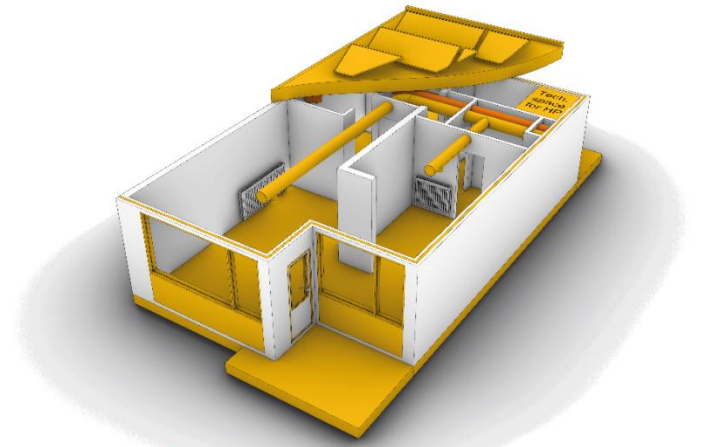
A9 - Roof, Cavity, Floor, Windows, Airtightness
Heat Pump, PVT Panels, Radiators

A10 - Wall Ex... irtightness
Heat Pump, PVT, Radiators, Ventilation D2

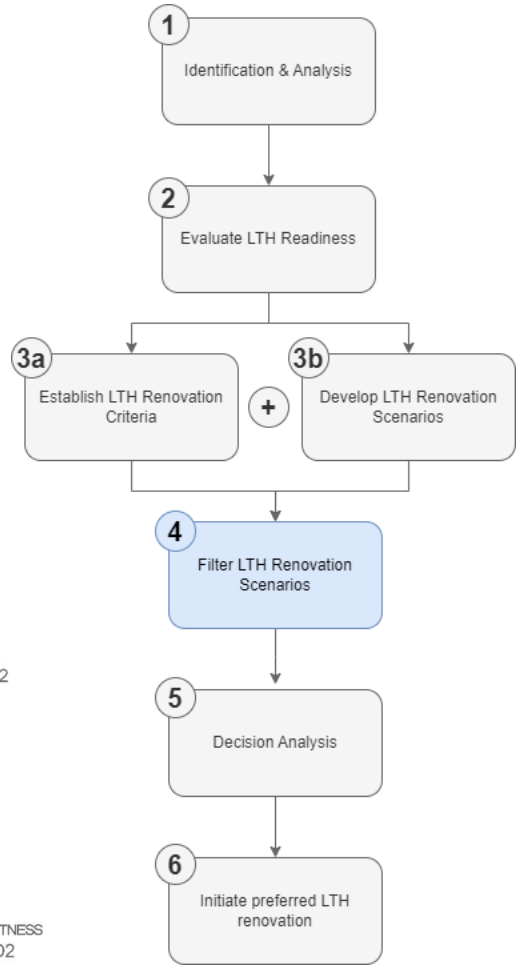
A11 - Roof, Ca... /Airtightness
Heat Pump, PVT, Radiators, Ventilation D2

A12 - Wall... rtightness
Heat Pump, PVT, Radiators

A13 - Roof, Cavity, ... indow, Airtightness
Heat Pump, PVT Panels, Ventilation D2

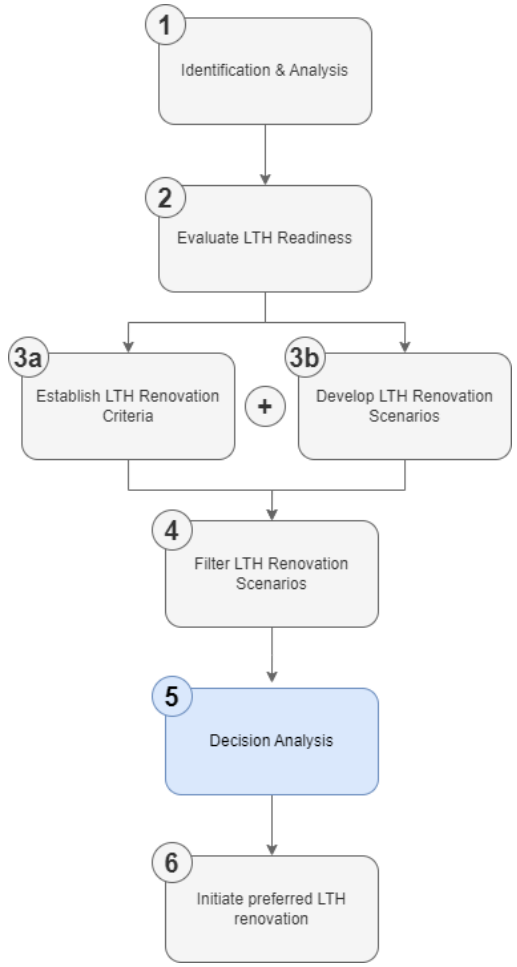


A5 - Roof, Cavity, Floor, Airtightness
Heat Pump, PVT Panels, Ventilation D2



Quantification

	Heating Demand [kWh/m²]	Energy Label [A++, A+, ..., G]	Energy Index [-]	Renewable Energy [%]	Energy Savings [m³]	Energetic Investment [€]	Labelstep Investment [€]	LCC [€]	Payback Period [year]	Thermal Comfort [h too cold]	Renovation Nuisance [descrip. 1-5]	Rent Increment [€/month]	Energy Cost [€/month]
A0	**206,88**	C	1,66	0	0	0	0	0	0	**326**	0	0	0
A1	176,34	C	1,46	0	250	1.260.513,65	27.402	142.593,19	32	**263**	1	5,13	7
A2	153,76	A	1,18	15	407	1.806.737,31	11.732	137.953,67	28	**230**	1	20,83	9
A3	122,80	A	1,01	25	645	1.944.888,39	9.923	137.097,11	19	**919**	1	20,83	19
A4	122,80	A++	0,49	38	645	2.254.026,66	5.471	139.959,50	22	**919**	1	26,53	22
A5	59,92	A++	0,21	38	1127	3.133.626,00	7.606	123.490,32	18	**225**	4	26,53	22
A6	124,50	A++	0,49	38	632	2.933.433,91	7.120	144.240,16	30	**271**	3	26,53	22
A7	188,45	A++	0,47	38	678	2.581.736,28	6.266	137.950,56	24	**210**	2	26,53	22
A8	144,43	A++	0,35	38	709	4.014.916,55	9.745	159.066,80	36	**285**	4	26,53	22
A9	94,63	A++	0,37	38	861	2.782.502,88	6.754	127.849,30	21	**63**	3	26,53	22



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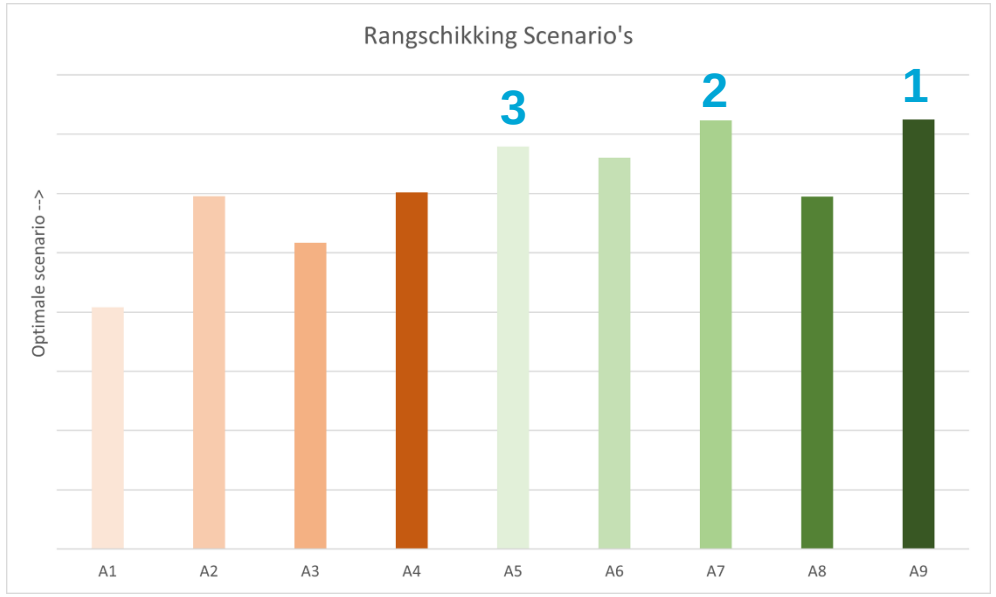
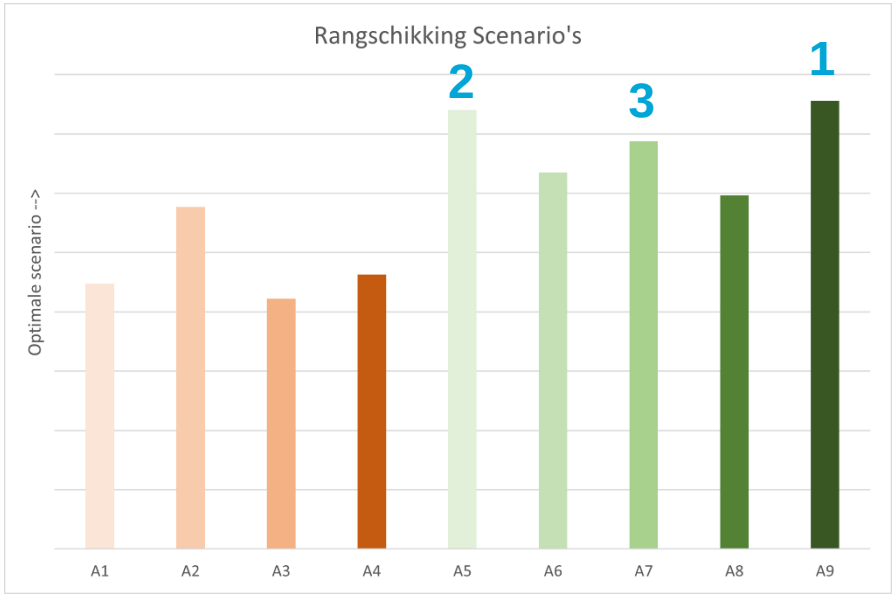
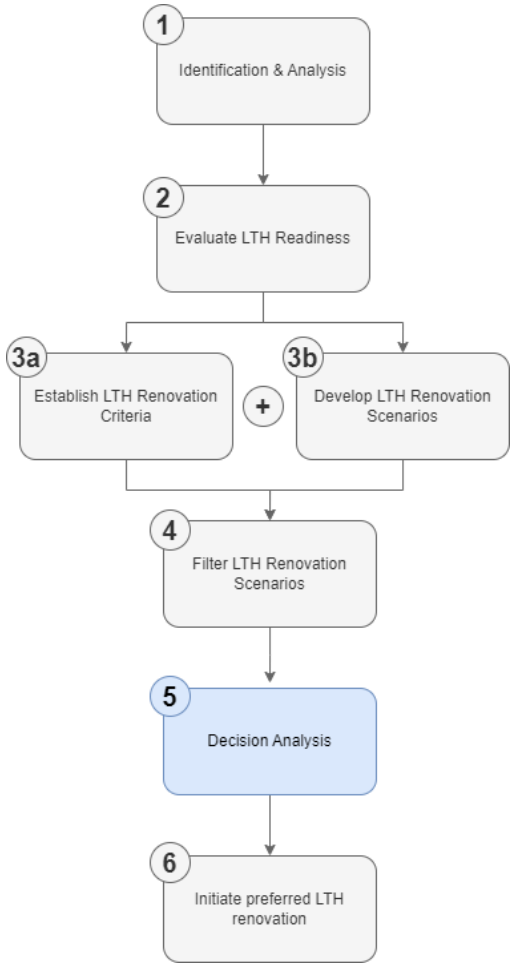
Decision Analysis

Equal Weights



Pairwise Comparison Weights





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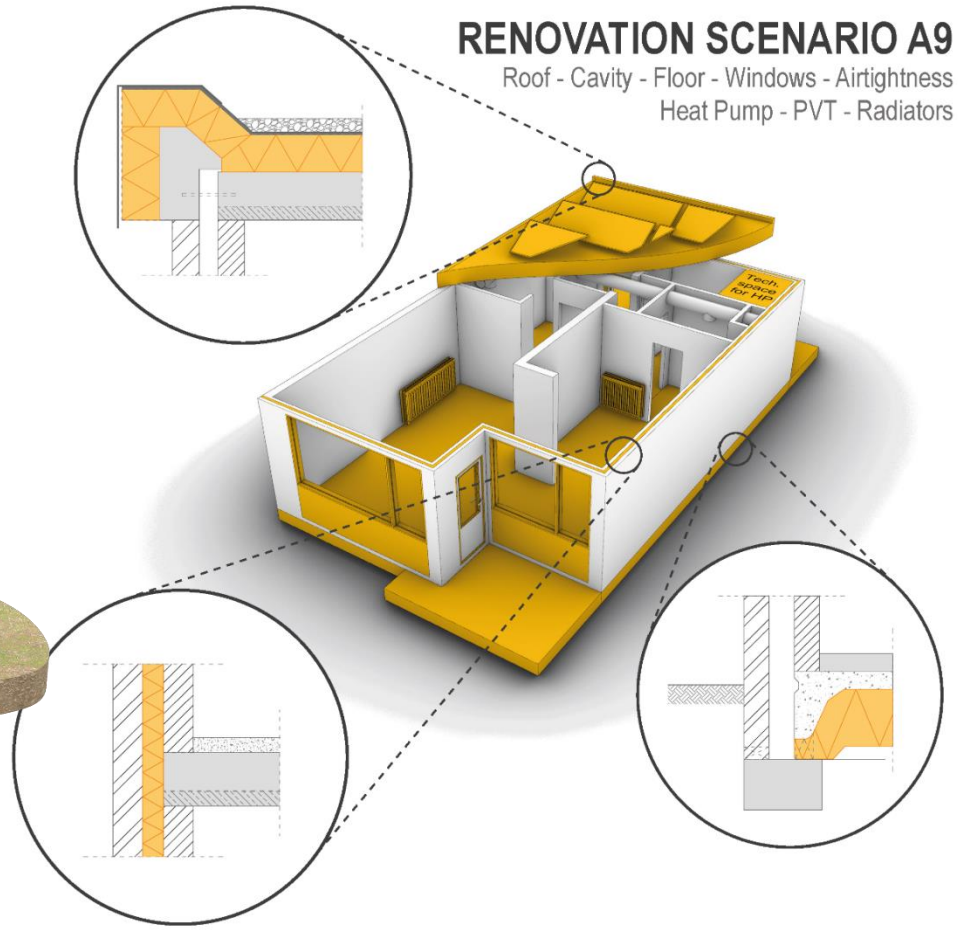
Most Optimal Alternative



LT-READY

Heating demand = 94,63 [kWh/m^2]
Hours too cold = 63 [h]

Airtightness = 0,4

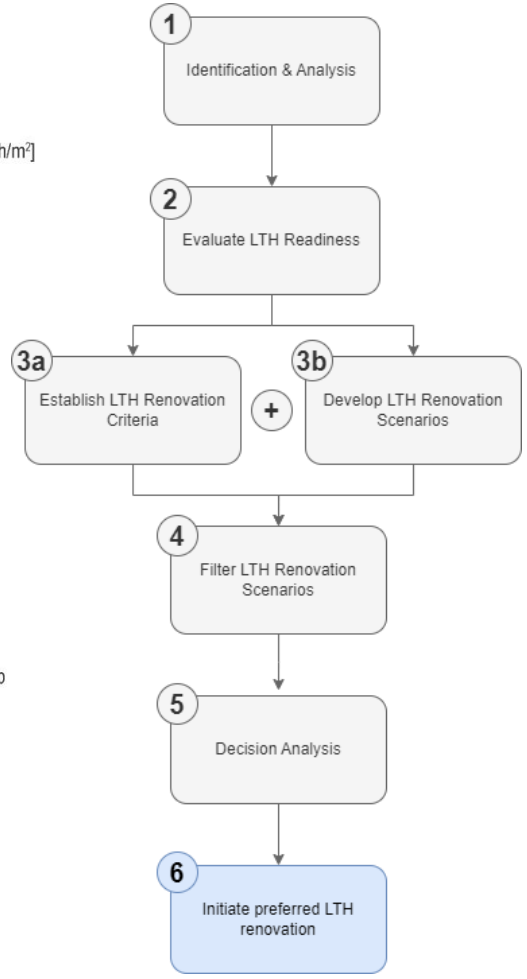
Rc Roof = 5,84 [m^{2}K/W]
Rc Cavity = 1,69 [m^{2}K/W]
Rc Floor = 2,6 [m^{2}K/W]
U Window = 1,0 [W/m^{2}K]

4 PVT panels per apartment

Collective air-water heat pump

Radiator type 22

Ventilation type C2 - Mechanical Exhaust



Benchmark HD = 206,88 [kWh/m^2]
Benchmark TC = 326 [h]

Quantification

	Heating Demand [kWh/m²]	Energy Label [A++, A+, ..., G]	Energy Index [-]	Renewable Energy [%]	Energy Savings [m³]	Energetic Investment [€]	Labelstep Investment [€]	LCC [€]	Payback Period [year]	Thermal Comfort [h too cold]	Renovation Nuisance [descrip. 1-5]	Rent Increment [€/month]	Energy Cost [€/month]
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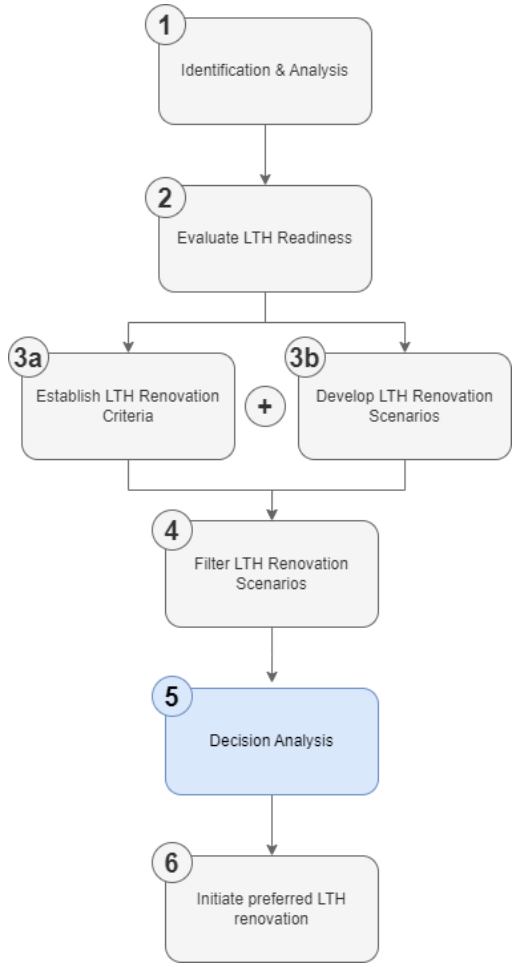

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Discussion & Conclusion

Research Findings

Key Findings

- Framework and tool can support the decision-making process on LT-renovation scenarios

- Pairwise comparison is an excellent method to balances stakeholders' preferences
  - Potential to reflect on policy & preferences
  - Targeted discussion at an early stage

- Evaluating alternatives from a holistic perspective can lead to new perceived optimal solution
  - Better informed decision

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Limitations

Validation

- Select stakeholder group
- Single case study

Tools

- LTH-Grasshopper tool deviates from real-world
- MCDM methods has known limitations
- Accuracy of ranking depends on quantified data & consistency of stakeholders

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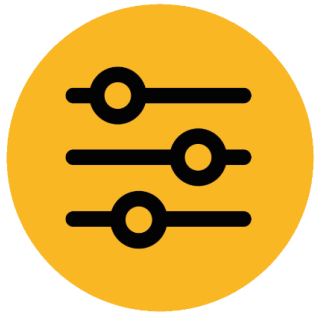
Conclusion



MULTIPLE SCENARIOS

CONFLICTING INTERESTS

UNCLEAR DECISION-MAKING PROCESS

“ How can the **decision-making process** of **selecting an energy renovation concept** be **supported** that aims to make existing residential buildings compatible with **low-temperature heating**? ”

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Questions?

Q&A

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Thank you for your attention

Vera Koster

TU Delft