TECHNISCHE UNIVERSITÄT WIEN

Defining a framework to apply retrofitting optimisation models for long-term and step-by-step renovation approaches

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- Research question
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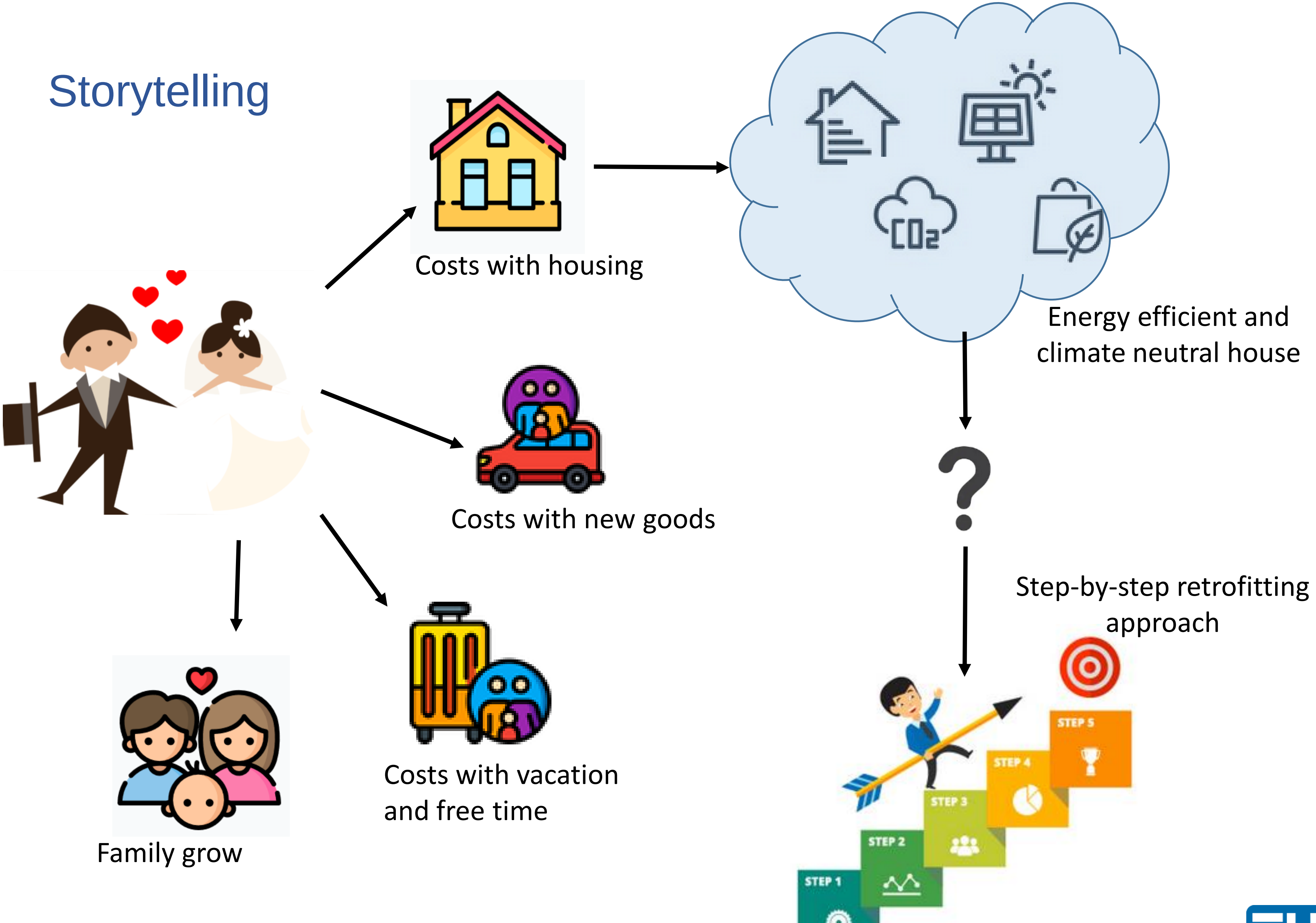
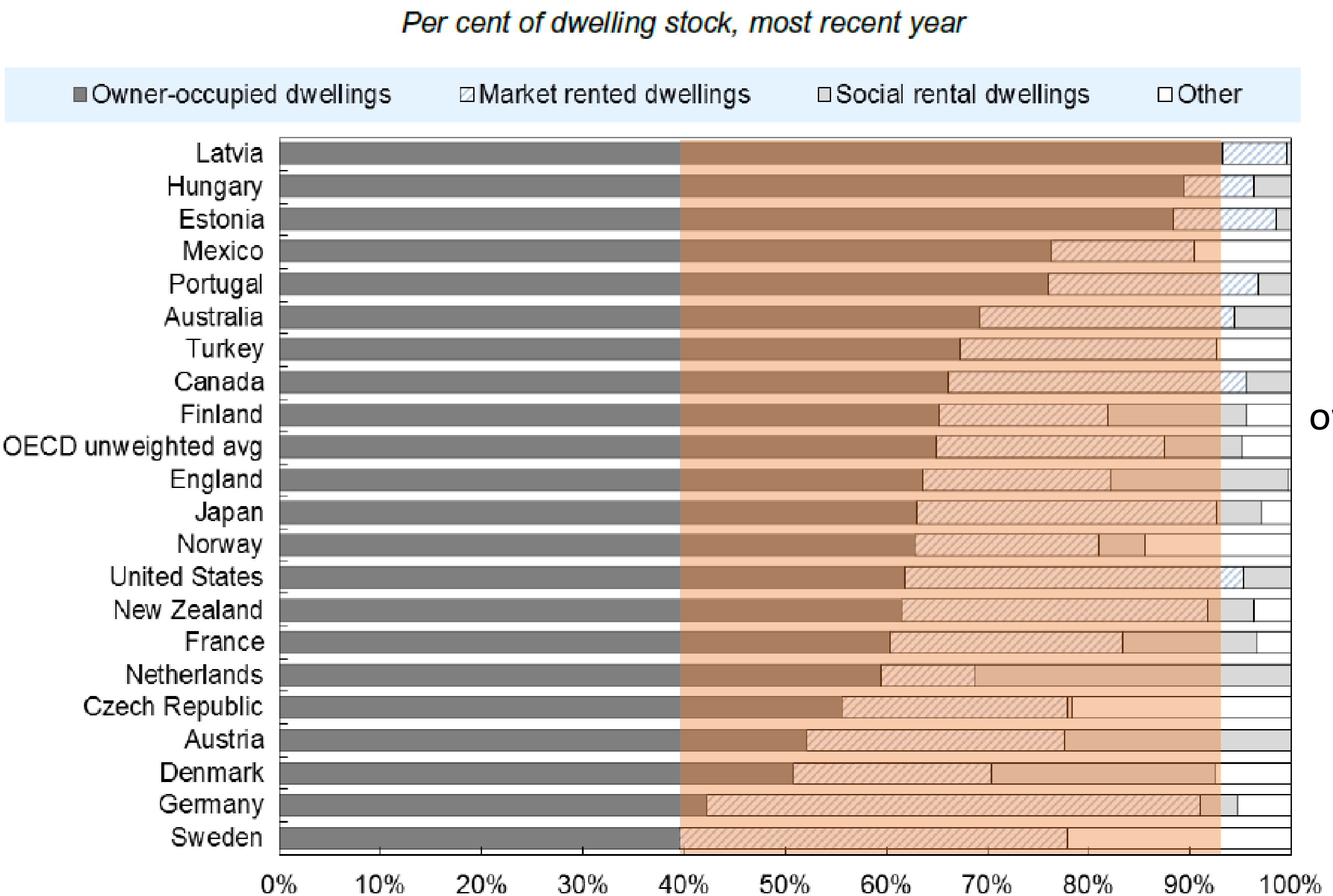
- Results
- Conclusions and Outlook

Storytelling



Introduction: facts about owner-occupied dwellings

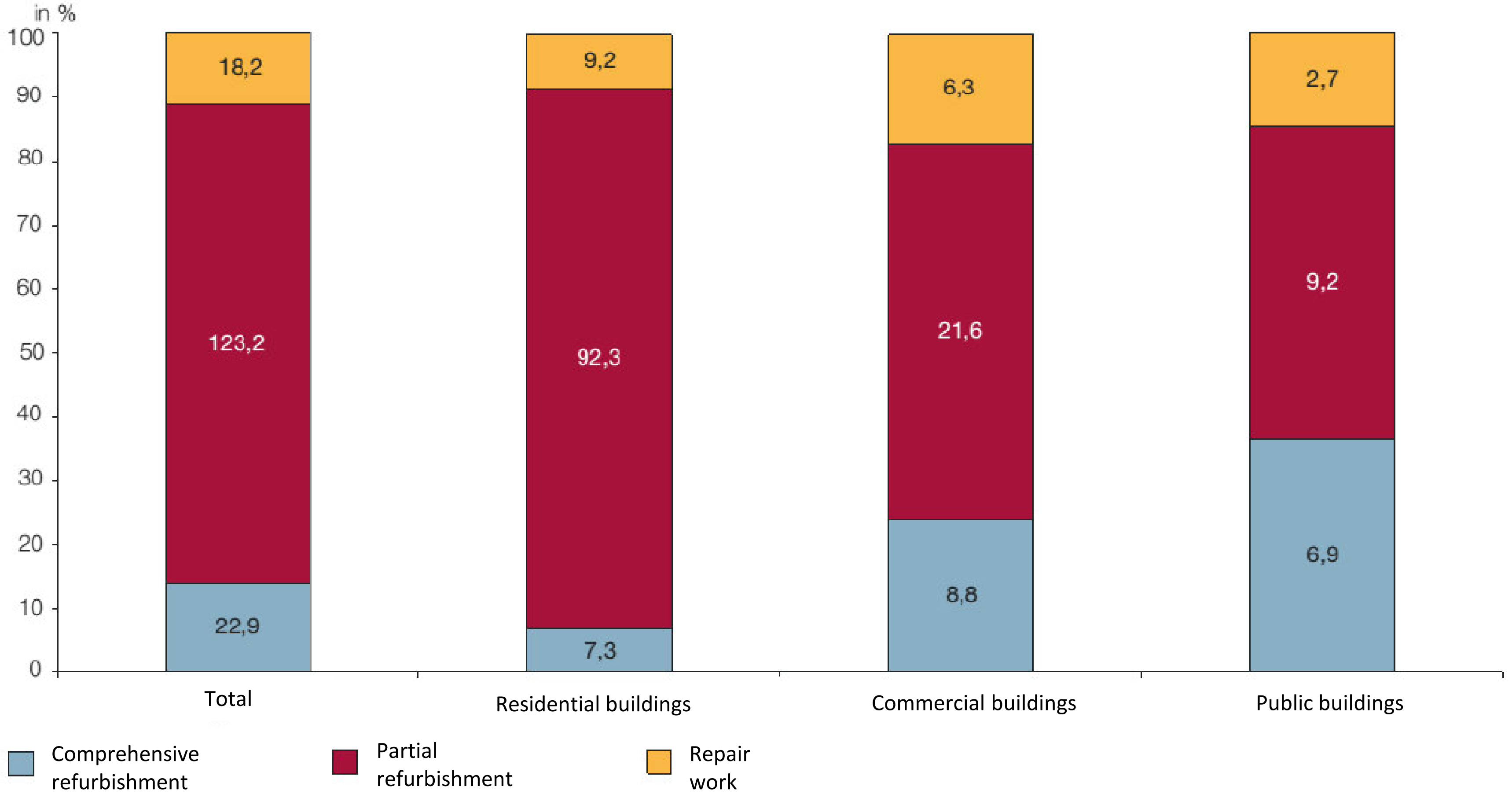


40 – 90% owner-occupied dwellings

Source: Housing tenure across OECD countries, del Pero et al. 2016

Introduction: facts about empirical evidences of step-by-step

Existing Building stock volume of comprehensive and partial refurbishment, as well as repairing (in Mrd. Euro)
Stand: Germany, 2010



Source: adapted from Fehlhaber, 2017 – PhD Dissertation – Bewertung von Kosten und Risiken bei Sanierungsprojekten

Introduction: political context

- Building renovation passports:

  - Energy Performance of Buildings Directive (EPBD) 2018/844/EU introduced in Article 19a:

  "complementary document providing a **long-term** and **step-by-step** renovation roadmap for a specific building"

  - This document should guide and help building owners through the renovation process

Overall objective and research question

- Main objective:
  - Bridge the gap between building stock decarbonisation targets and real renovation processes
  - In **real life**, many renovation processes are performed step-by-step
  - But, most deep renovation **modelling focus** on single stage deep renovation

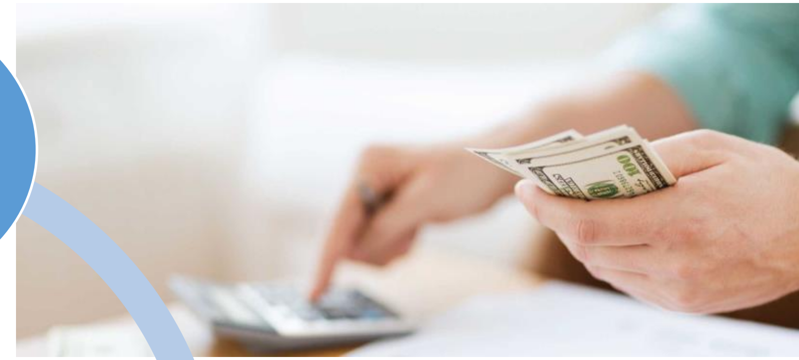
- Model under development: **step-by-step retrofitting optimisation model** focusing on owner-occupied dwellings

- Objective of this paper: explore some aspects of the optimisation's framework

How to break down a single stage in different renovation steps over the time?

Which parameter should determine the time-wise prioritisation of the retrofitting measures?

Key challenges



Different disposable income and affordability to pay for retrofitting

CO2-Reduction until 2050

Building stock with different building typologies and energy efficiency standards

Time when energy performance is improved

Sources: Jürgen Fälchle - Fotolia.com , Amber Taufen - inman.com and Andre Haykal Jr - thriveglobal.com

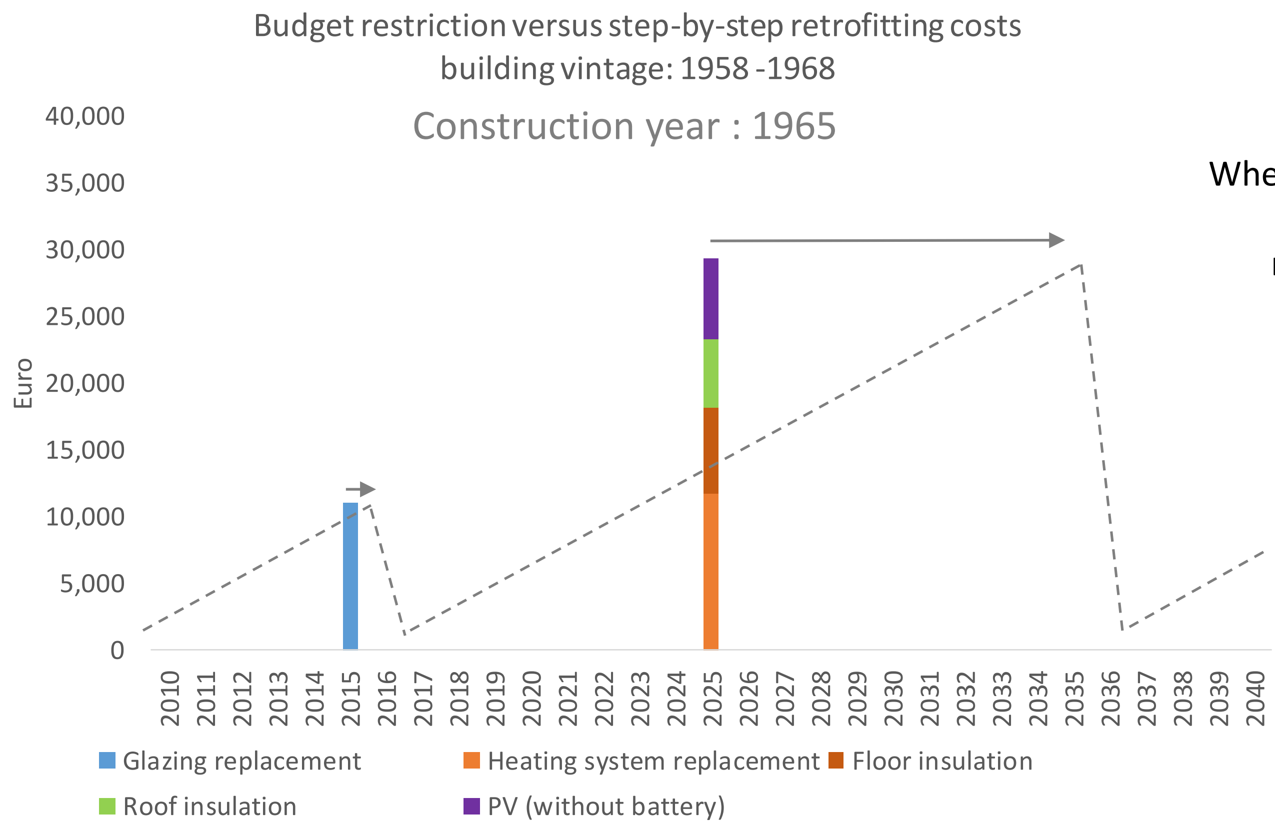
Method: identifying main differences between retrofitting approaches

	Single stage	Step-by-step
Definition	Only major renovation (including whole building envelope)	Retrofit measures performed according to trigger points.
Time dimension	At once	Over years (or decades)
Main risks	If not done right, mistakes take long time (even decades) to be corrected (lock-in effects)	Include missed opportunities and lock-in effects
Effects on climate targets	Faster CO_2 emission reduction (potentially more energy savings)	Gradual CO_2 emission reduction
Main barrier	Disruption and/or affordability	Less information about right sequence of measures
Material Costs	At once – possibility that loans and incentives are available	Cost-shifting – further measures costs can be partially anticipated
Labour / Montage Costs	At once	Scaffolds and other construction site equipment might have to be mounted more than once

Sources: adapted from Topouzi et al.2019 – Deep retrofit approaches: managing risks to minimise the energy performance gap

Graphical presentation of the open question

- Total costs step-by-step: 42000 Euros (including scaffold)
- External wall insulation -> not insulated could have 90 years materials lifetime
- 3. Profile of budget restriction – 5% of share



When is the right time to perform a deep renovation step?

Results: overview of step-by-step optimisation framework

- Objective function: **maximising net present value**

$$\max NPV = \sum_t^T \frac{CF_t}{(1+r)^t} + \frac{L_T}{(1+r)^T}$$

$$CF_t = INC_t * s - IC_{er,t} - EC_t - OMC_t$$

$$L_T = \sum_i \sum_t IC_{er,t,i} * \frac{(T-t)}{t_{L,i}}$$

- Restrictions:
  - Material's aging process
  - Budget restriction

NPV, energy related net present value [EUR];
CF, cash-flow of energy related expenses [EUR];
L, residual value of the retrofitting measures in year T [EUR];
r, interest rate [%];
t, time [a];
T, period of economic consideration [a];
INC, household income [EUR/a];
s, expenditure share of annual income [%/a];
IC_{er}, energy related investment cost of retrofitting measures [EUR];
EC, annual running energy costs [EUR/a];
OMC, operation and maintenance costs [EUR/a];
t_L, technical lifetime [a];
T, optimisation period time [a];

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Results: setting input data, example for SFH in Germany

Building vintage

- Until 1918
- 1919-1948
- 1949-1957
- 1958-1968
- 1969-1978
- 1979-1983
- 1984-1994
- 1995-2001
- 2002-2009

Household income

Income ranges

- Profile 1 – ie. 20000 €/a
- Profile 2 – ie. 31000 €/a
- Profile 3 – ie. 43000 €/a
- Profile 4 – ie. 57000 €/a

Expenditures share

- 6%
- 15%

Retrofitting mesures

- External wall insulation
- Roof insulation
- Ground floor insulation
- Windows replacement
- Heating/cooling system replacement
- DHW system replacement
- PV installation

Material and energy system

- Material costs
- Labour costs
- Energy carrier prices
- Material life time
- Index for price development

Sources: TABULA Episcope,2012, Bundeszentrale für politische Bildung,2018, Eurostat,2018, Pfeiffer,2010 and Invert-EE/Lab,2019

Conclusions and outlook

- **How to break down a single stage in different renovation steps over the time?**
  - Step consists of one or more retrofitting measures
  - Measures: active or passive systems -> building envelope or buidling services
  - Measure by measure cost data (material and labour costs)
  - Different income profile with two different expediture share -> building owner's budget restriction
- **Which parameter should determine the time-wise prioritisation of the retrofitting measures?**
  - Net present value is an appropriate indicator to analyse the economic effects of time dimension of retrofitting approaches
  - Techno-ecomomic parameters: investment costs, budget restrictions, energy demand indicators, technical aging process of material's
- **Outlook**
  - Techno-economic relevant synergies of measures (sequence and dependency of measures)
  - Run first results
  - Sensitivity analysis based on cost and income profile variations, energy prices and political scenarios
  - Upscale to a building stock level

Thank you for your attention!

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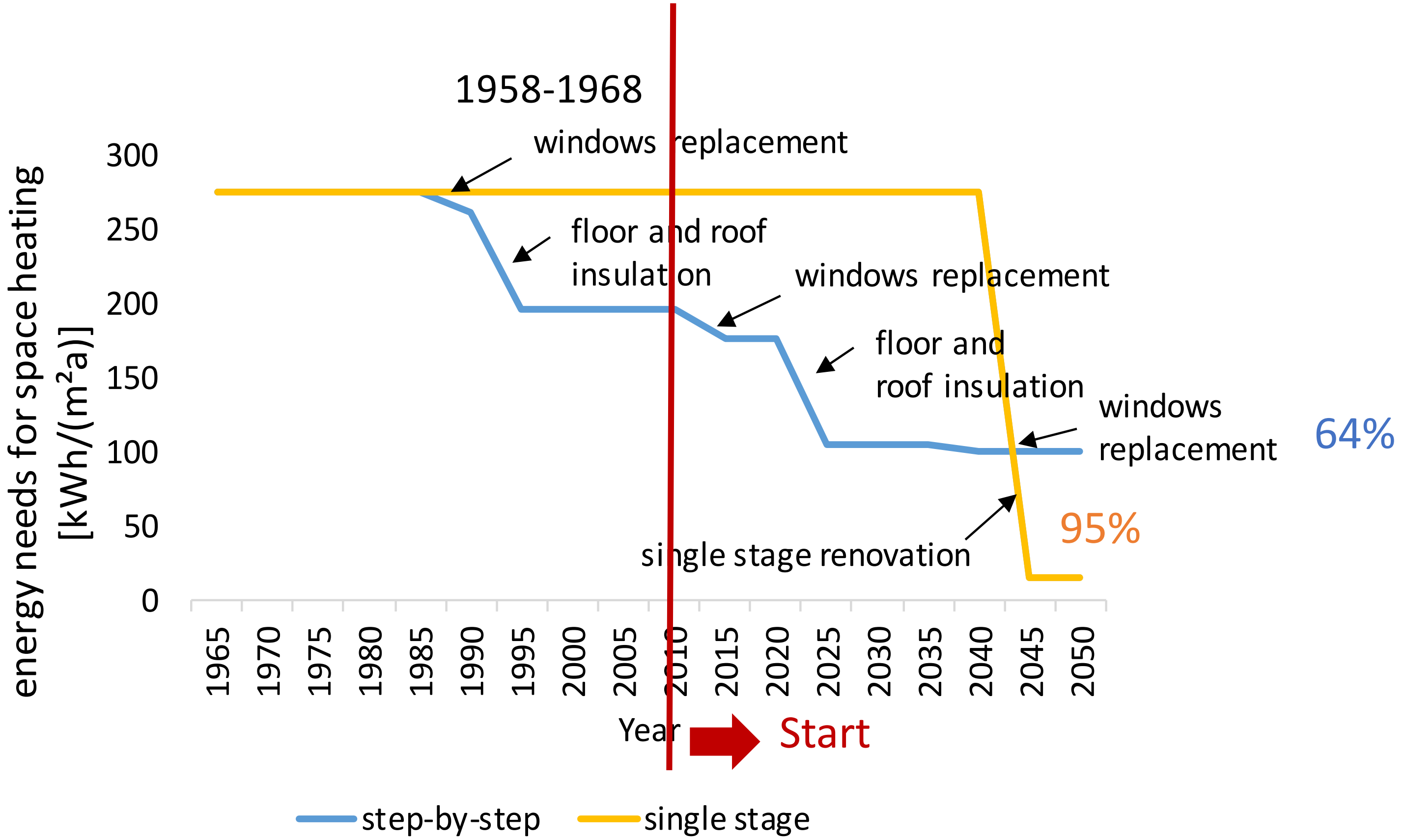
Orig. Photo: Patrick Stargardt

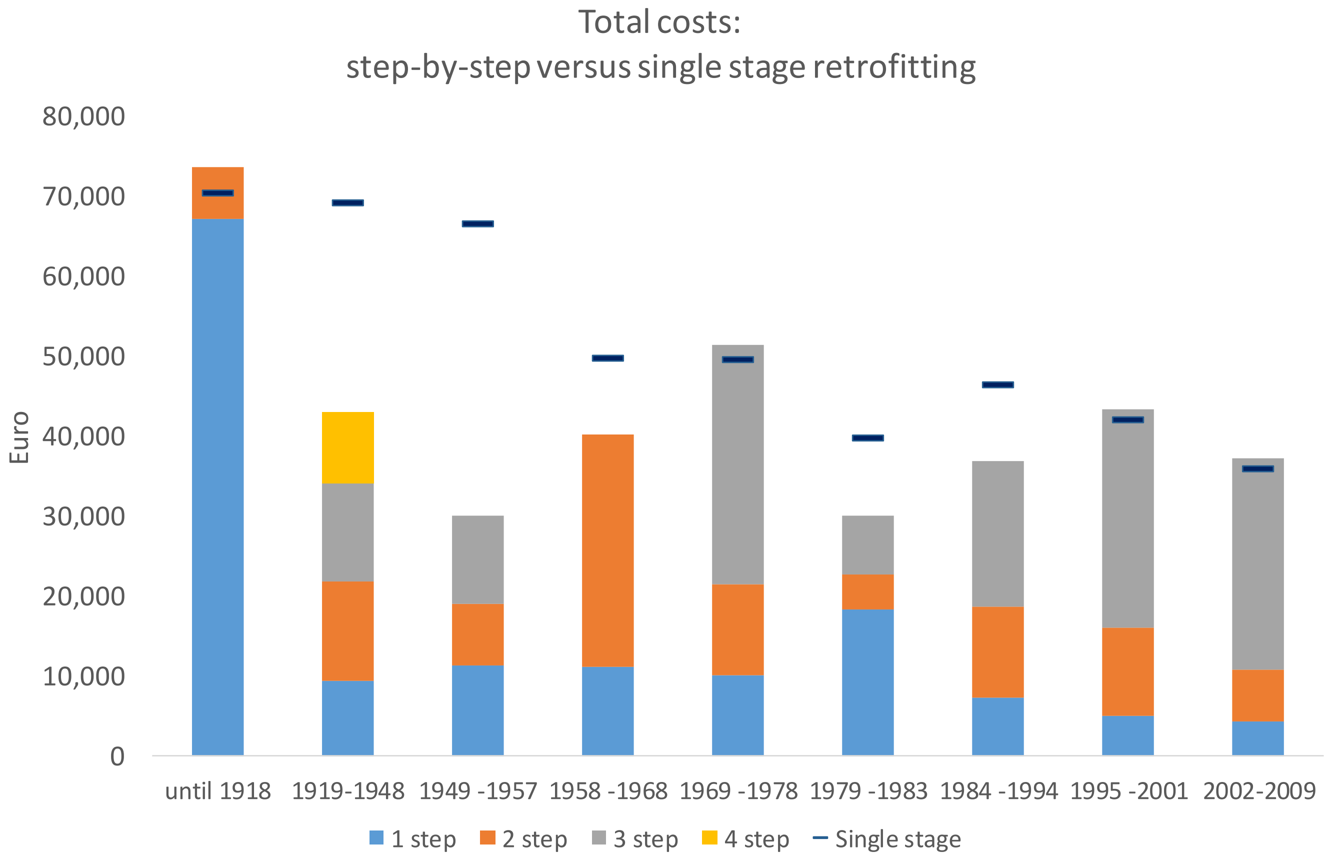
Results: pre-analysis, SFH Germany

- Possible development of energy needs for space heating (concepts step-by-step and single stage)
- Examples: construction vintages 1958-1968



Results: total costs for all reference buildings

- Step-by-step approach is only cheaper in cases, where not all measures are performed
- Older buildings are more expensive to deep retrofit



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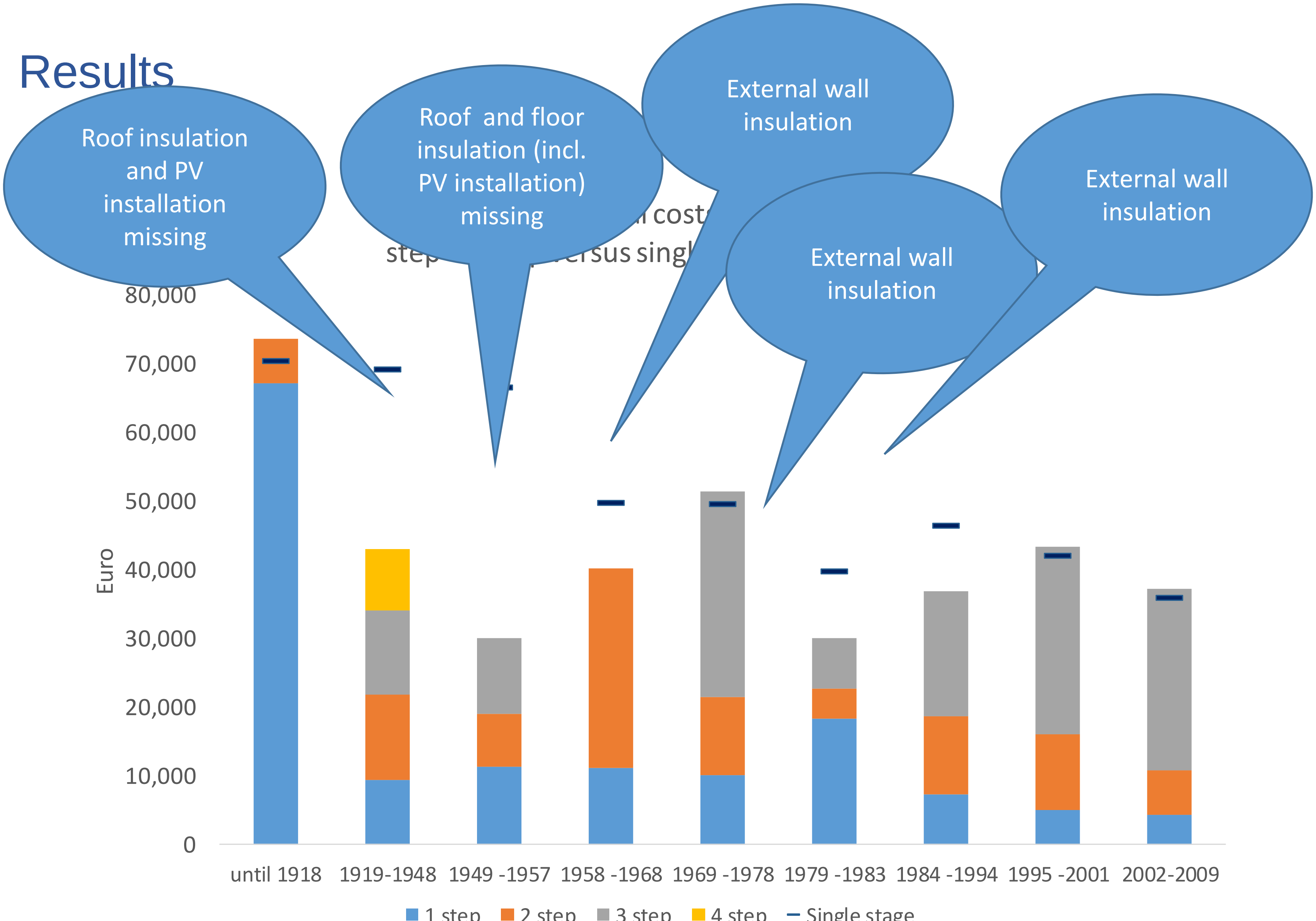
Results



Roof insulation and PV installation missing
Roof and floor insulation (incl. PV installation) missing
External wall insulation
External wall insulation
External wall insulation
Euro
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
until 1918
1919-1948
1949 -1957
1958 -1968
1969 -1978
1979 -1983
1984 -1994
1995 -2001
2002-2009
1 step
2 step
3 step
4 step
Single stage

Results: defining the parameters

- $IC_{er,i,t} = \sum_i [IC_{tot,i} - \ (1 - p_{t,i}) * IC_{man,i}] * \ x_{t,i}$

IC_{man}, maintenance investment cost of renovation measures [EUR]; *x*, binary variable (1 or 0) [-]; *p*, probability of material's aging process [-]; i, building envelope (external wall, window, floor or roof) and active system (heating, cooling, domestic hot water)

- $EC_t \ = \ \sum_i fed_{t,i} * \ pr_{t,i}$

EC, energy costs [EUR/a]; fed, final energy demand [kWh/a]; *pr,* energy price [EUR/kWh]

- $OMC_t = \sum_i IC_{er,t,i} * \ f_{OMC,i}$

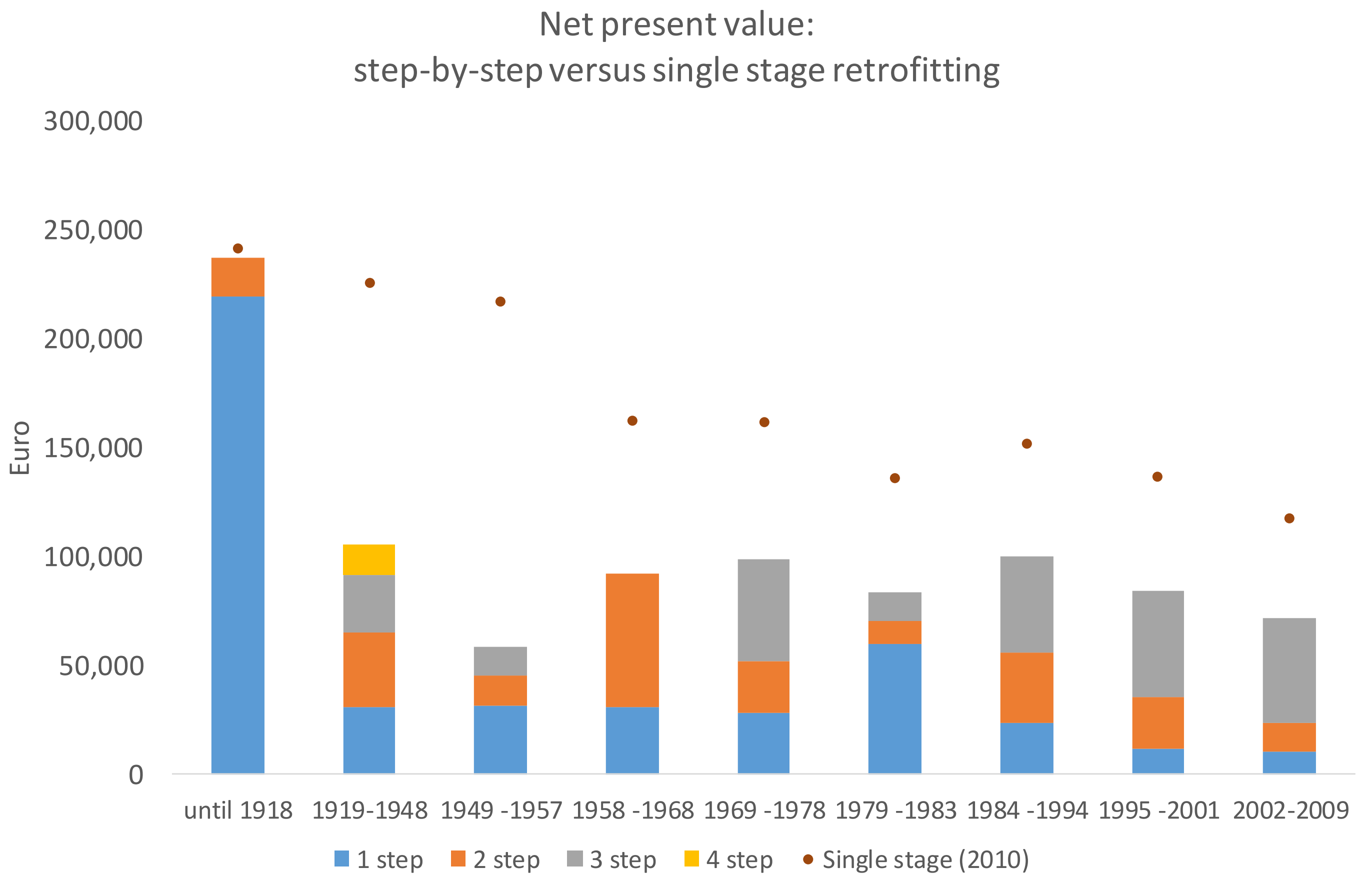
OMC, operation and maintenance costs [EUR/a]; IC_{er}, energy related investment costs of active system [EUR]; f; operation and maintenance factor [%]

- $p_{i,t} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}$, where t, t_0, m>0

p; probability of material's aging process*; m,* aging exponent *[-]; t_L,* technical lifetime [a]; *t_O,* period without failure [a]; *t,* time [a].

Results: net present value for all reference buildings

- Interest rate: 3%
- Single stage has higher NPV than step-by-step in all cases
- Time of retrofitting becomes a relevant parameter



Results: main conditions of the optimisation framework

- Conditions for the step-by-step renovation

for: $p_{i,t} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}$, where t, t_0, m>0

p; probability of material's aging process*; m,* aging exponent *[-]; t_L,* technical lifetime [a]; *t_O,* period without failure [a]; *t,* time [a].

if: $B_t \geq IC_{er,t} + EC_t + OMC_t$ and p_t>0.05

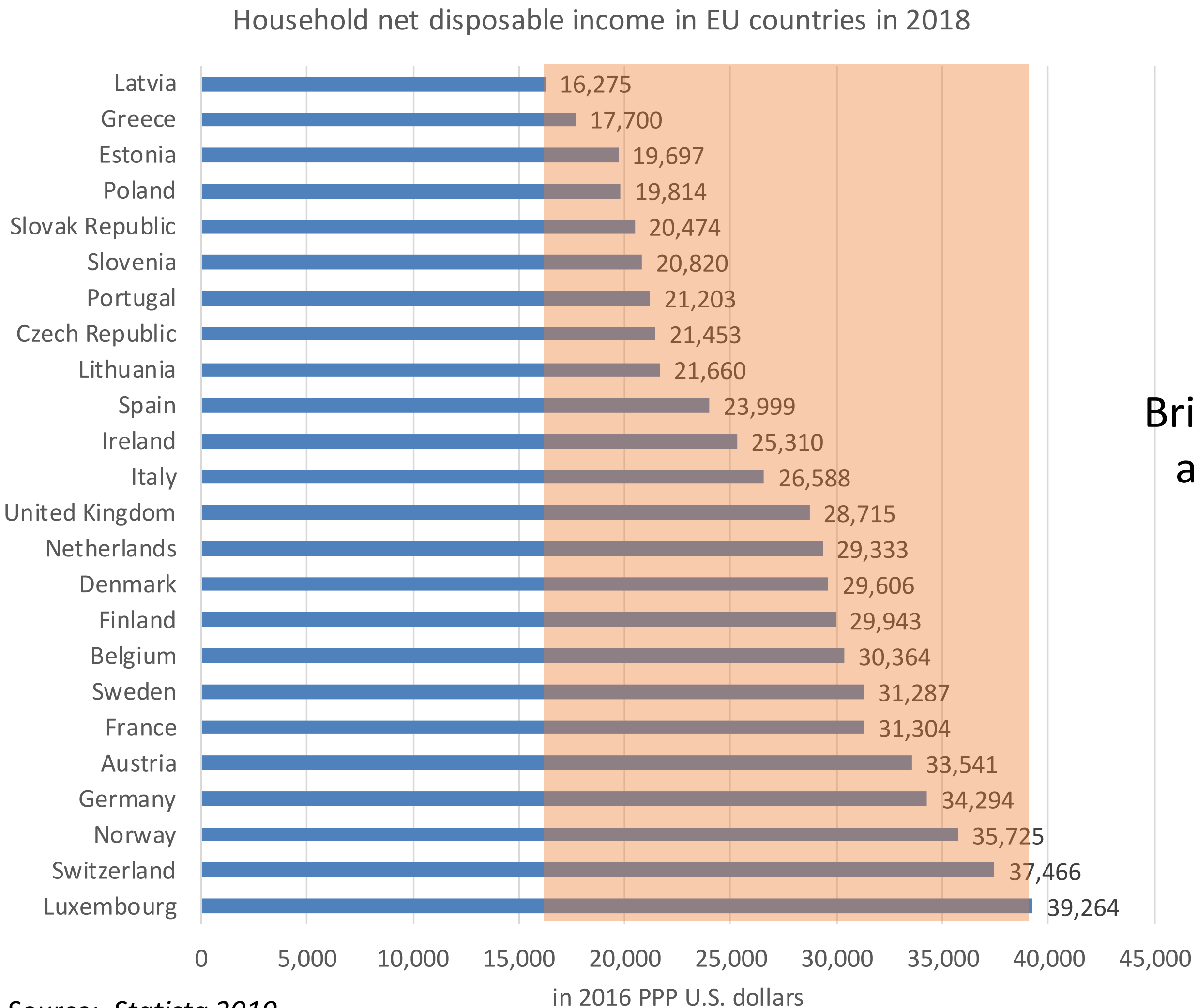
- with $B_t = A_{t-1} * (1 + l)$
- with $A_t = (INC_t * s) - \mathrm{IC}_{er,t} - EC_t - OMC_t + A_{t-1}$

then:

- $fed_{t+1} = fed_t * f(IC_{er,i})$
- $x_{i,t} = 1$ und $p_{i,t+1} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}$ (aging process restarts)

B; budget restriction [B]; *IC_{er},* energy related investment cost of retrofitting measures [EUR]; *EC,* annual running energy costs [EUR/a]; *OMC*, annual running operation and maintenance costs [EUR/a]; l, loan [EUR]; A, cumulated allocated energy related asset [EUR]; INC, household income [EUR]; s, allocation factor of total annual income on energy related expenses [%]; p, probability of material's aging process [%]; fed, final energy demand [kWh/a]; x, binary variable (1 or 0) [-].

Introduction: facts about household net adjusted disposable income in OECD countries in 2018



Bride range between the EU and also inside a country

Source: Statista 2019

Method

- $CF_t = INC_t * s - IC_{er,t} - EC_t - OMC_t$

CF, cash flow of energy related expenses [EUR]; *INC,* household income [EUR/a]; *s,* allocation factor of total annual income on energy related expenses [%]; IC_{er}, energy related investment cost of retrofitting measures [EUR]; *EC, annual running* energy costs [EUR/a]; *OMC*, operation and maintenance costs [EUR/a]

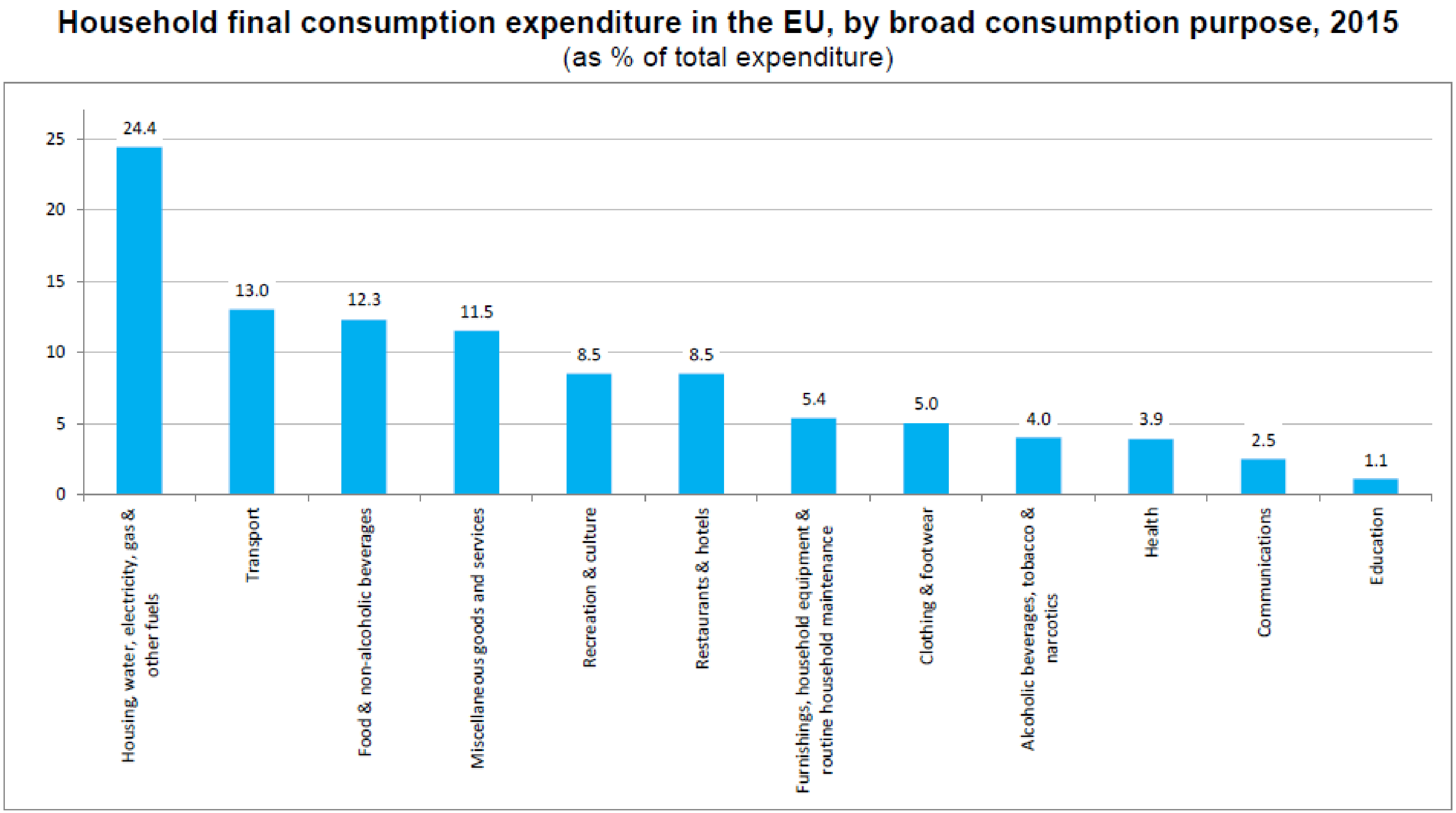
- $IC_{er,i,t} = \sum_i [IC_{tot,i} - (1 - p_{t,i}) * IC_{man,i}] * x_{t,i}$

IC_{man}, maintenance investment cost of renovation measures [EUR]; *x*, binary variable (1 or 0) [-]; *p*, probability of material's aging process [-]; i, building envelope (external wall, window, floor or roof) and active system (heating, cooling, domestic hot water)

- $p_{i,t} = 1 - e^{-\left(\frac{t - t_{i,0}}{t_{i,L} - t_{i,0}}\right)^m}$, where t, t_0, m>0

p; probability of material's aging process*; m,* aging exponent *[-]; t_L,* technical lifetime [a]; *t_O,* period without failure [a]; *t,* time [a].

Methods: setting input data



Retrofitting measure	Constructive solution	Material specification
ROOF INSULATION	Removing the roof and adding a new layer of insulation	30 cm of thermal insulation
ROOF INSULATION	Addition of a thermal insulation layer over the last slab	15 cm of thermal insulation
EXTERNAL WALL INSULATION	External insulation (EIFS System)	10 cm of thermal insulation
EXTERNAL WALL INSULATION	External insulation (EIFS System)	20 cm of thermal insulation
FLOOR INSULATION	Installation of insulation in the outer of the floor slabs	10 cm of thermal insulation
FLOOR INSULATION	Installation of insulation in the outer of the floor slabs	15 cm of thermal insulation
WINDOW REPLACEMENT	Improve the thermal quality of the window	Double glass with air cavity and a low-e glass
ACTIVE SYSTEM	Generation system replacement	Air heat pump + other advices
RENEWABLE	PV panels installation	Panels + other advices

Middle material's life time	Building element	Building's material	until 1918	1919-1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002-2009
		Construction year:	1890	1935	1955	1965	1975	1980	1990	2000	2005
20	heating	heating boiler	x	x	x	x	x	x	x	x	x
25	glazing	multi glazing	x	x	x	x	x	x	x	x	x
30	floor	floor with insulation				x	x	x	x	x	x
30	external wall	ext wall insulation					x			x	x
30	roof	roof insulation				x	x	x	x	x	x
60	floor	cellar wood (load bearing)	x								
70	external wall	ext wall cement							x		
90	external wall	ext wall brick (load bearing)	x	x	x	x		x			
100	floor	cellar natural stone (load bearing)		x	x						
120	roof	roof wood chairs	x	x	x						

Pre-analysis

Substituir

- Relevant parameters: building element‘s material and it‘s lifetime

Y=yes, the building element has the corresponding building material

N=no, the building element does not have the corresponding building material

Building element	Building material	Material's lifetime [yr]	until 1918	1919-1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002-2009
windows	multi glazing	25	y	y	y	y	y	y	y	y	y
floor	insulation	30	n	n	n	y	y	y	y	y	y
external wall	insulation	30	n	n	n	n	y	n	n	y	y
roof	insulation	30	n	n	n	y	y	y	y	y	y
floor	wood (load bearing)	60	y	n	n	n	n	n	n	n	n
external wall	cement	70	n	n	n	n	n	n	y	n	n
external wall	wood	70	n	n	n	n	n	n	n	n	n
windows	single glazing	80	n	n	n	n	n	n	n	n	n
external wall	brick (load bearing)	90	y	y	y	y	n	y	n	n	n
roof	cement reinforced	100	n	n	n	n	n	n	n	n	n
floor	natural stone (load bearing)	100	n	y	y	n	n	n	n	n	n
roof	wood chairs	120	y	y	y	n	n	n	n	n	n

Table 1: Characterization of the reference buildings - building elements, building material and material lifetime (for each building vintage, a reference buildings for single family houses in Germany).
Source: *own table, based on* (TABULA and EPISCOPE project, 2016) *and* (Pfeiffer et al., 2010)

Results

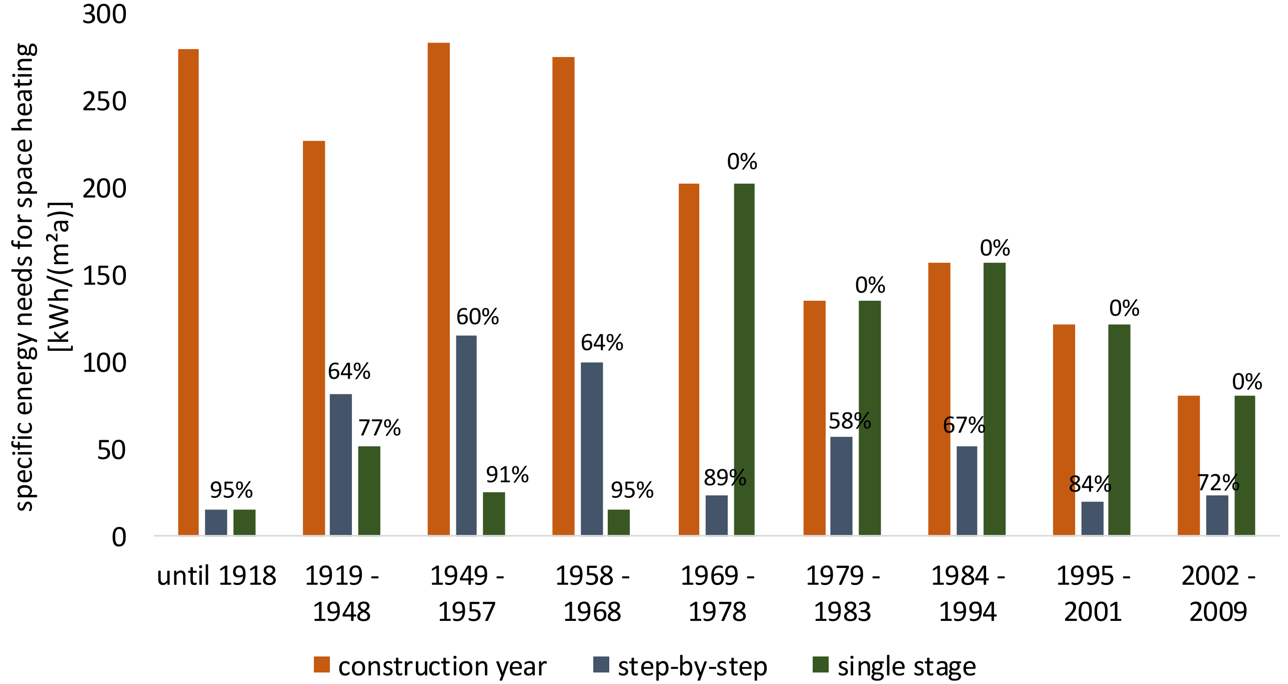
- Year of the last renovation step (step-by-step and single stage concept)

Building vintage		until 1918	1919 - 1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002 - 2009
Construction year of reference building		**1890**	**1935**	**1955**	**1965**	**1975**	**1980**	**1990**	**2000**	**2005**
Step-by-step	**Roof**	2040	no renovation	no renovation	2025	2035	2040	2050	2030	2035
	Floor	2040	2035	no renovation	2025	2035	2040	2050	2030	2035
	External Wall	2040	2025	2045	no renovation	2035	2050	no renovation	2030	2035
	Window	2040	2035	2030	2040	2050	2030	2040	2050	2035
Single stage	**all building elements**	2050	2015	2035	2045	no renovation	no renovation	no renovation	no renovation	no renovation

Table 3: Last renovation year

Results

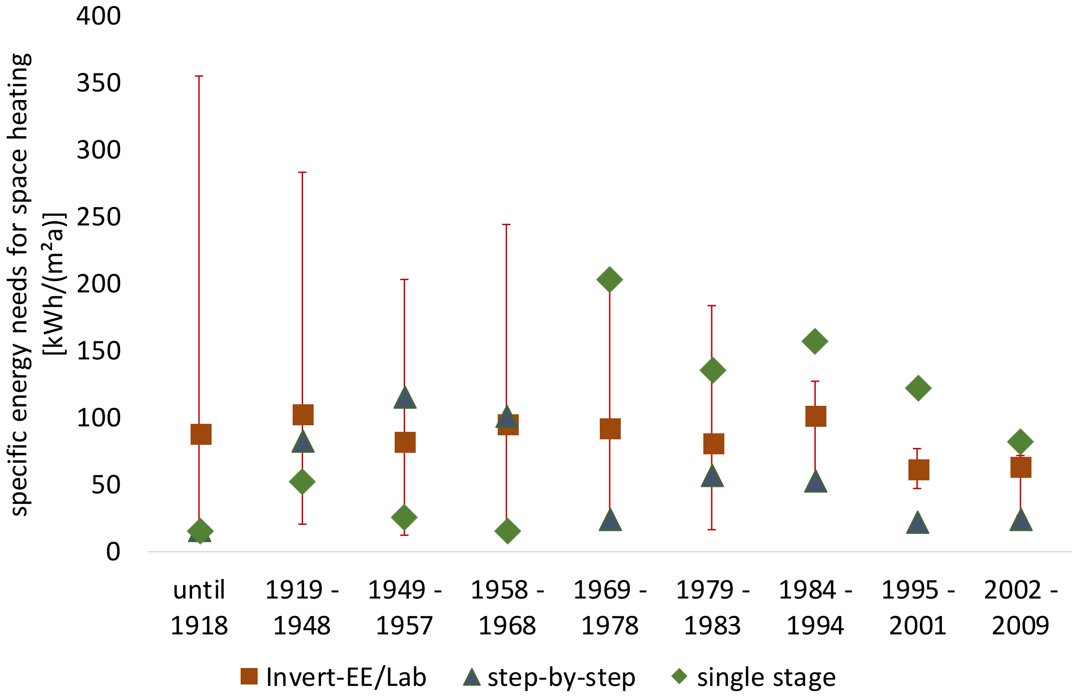
- Specific energy needs in kWh/(m²a) of the construction year and after renovation: step-by-step and single stage concepts (for each building vintage)
- Energy savings (%) based on the energy demand in the construction year



Graph 2: Energy needs (before and after renovation) and energy savings according to both step-by-step and single stage concept, for each building vintage

Results

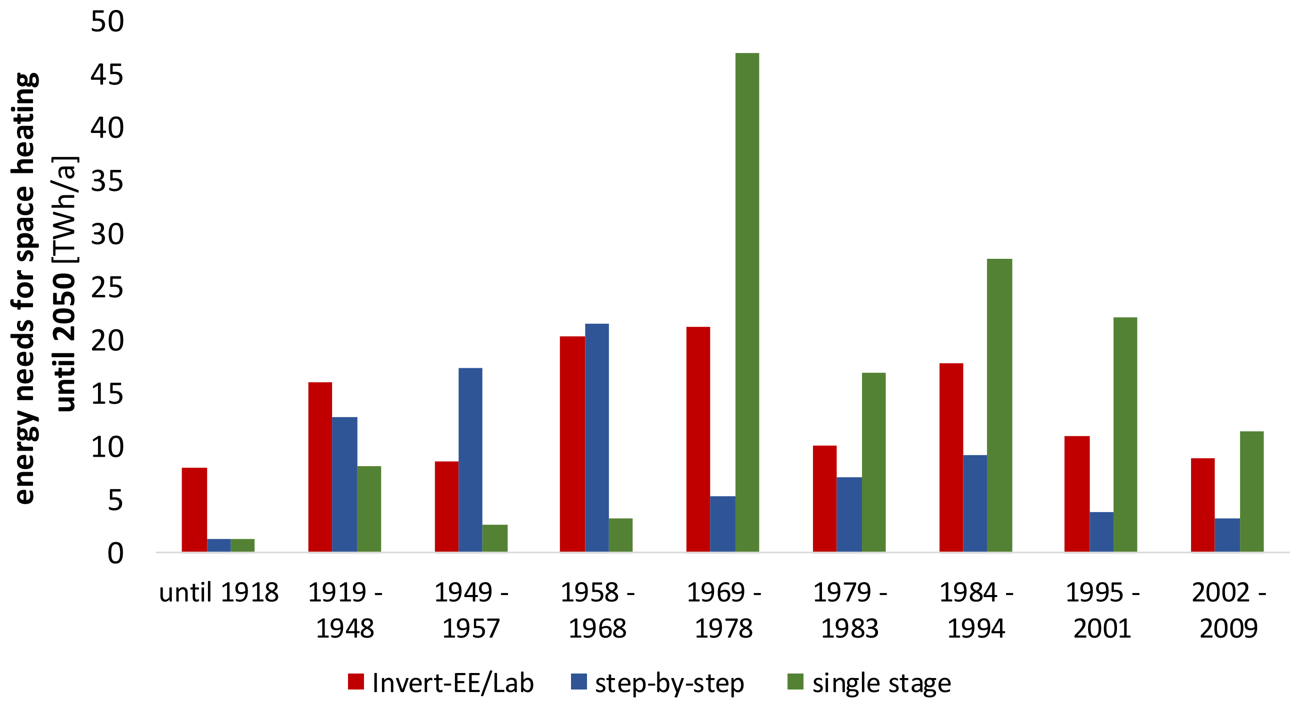
- Specific energy needs for space heating in kWh/(m²a) with step-by-step concept, single stage concept and model Invert/EE-Lab
- Reference building based on the construction year



Graph 3: comparison of specific energy needs for space heating in kWh/(m²a) between step-by-step concept, single stage concept and Invert/EE-Lab model, for a reference building of each building vintage (before 1918 until 2009)

Results

- The total energy needs for space heating in TWh/a in 2050:
  - 122 TWh/a (Invert-EE/Lab)
  - 81 TWh/a (step-by-step)
  - 140 TWh/a (single stage)



Graph 4: comparison of total energy needs for space heating TWh/a between step-by-step concept, single stage concept and Invert/EE-Lab model, for each building vintage

Conclusion

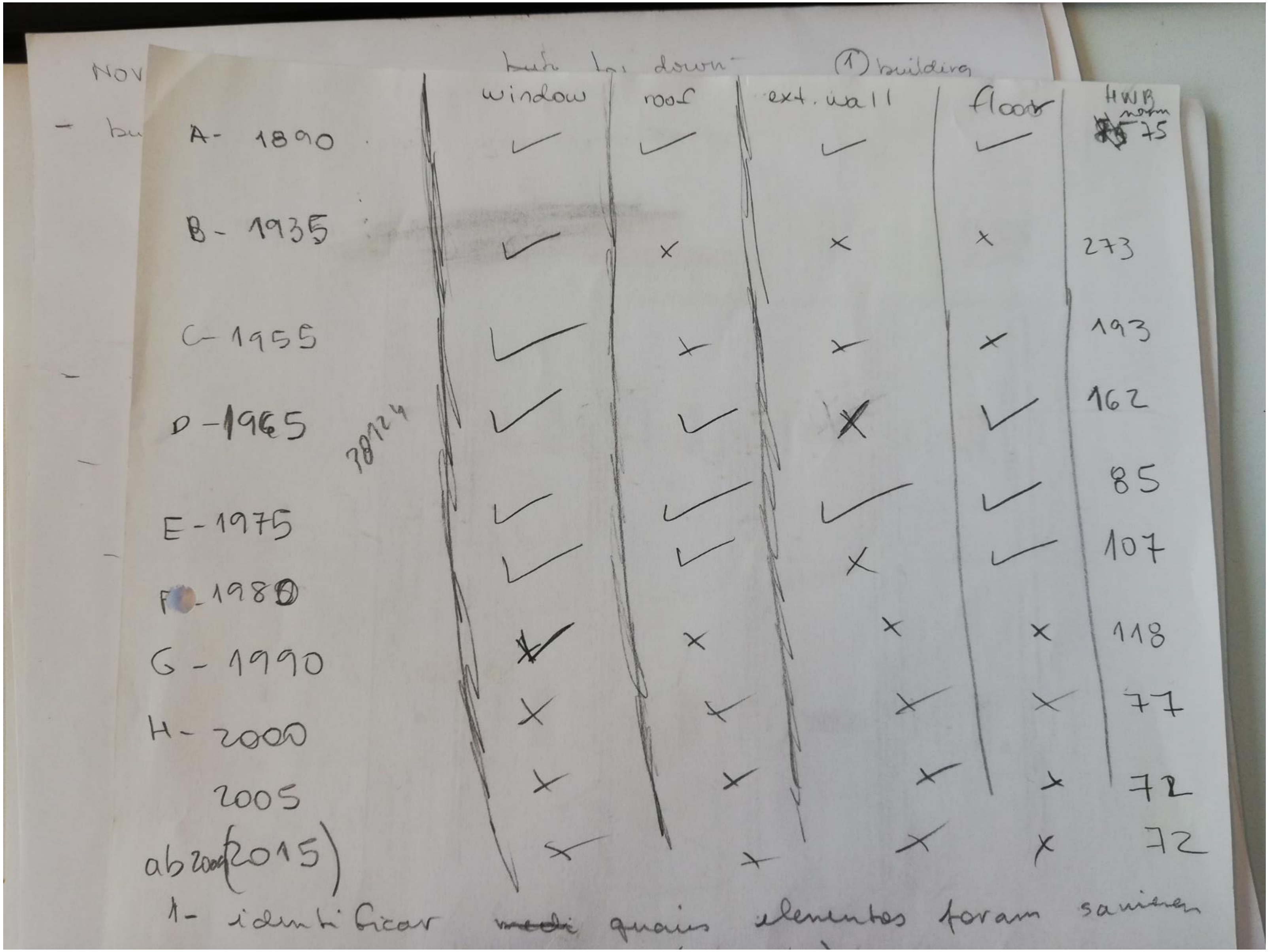
- **Period of time to complete first renovation cycle according to materials lifetime:**
  - non-insulated building elements need longer period to perform the first renovation cycle-> because of insulation lifetime (25-30 years)
  - after the first renovation cycle was completed, the subsequent renovation cycles happen more frequently

- **Comparison between both concepts:**
  - step-by-step concept: faster adaptation of the building elements to the building code in force as insulated building elements need shorter period of time to perform the next renovation cycle than non-insulated ones
  - single stage concept: building element might not have reached its end-of-life by the time of renovation and building's energy performance remains constant over a longer period of time

- **Upscale and comparison with Invert-EE/Lab (SET-Nav Scenario):**
  - distribution of buildings, in terms of number of buildings and their different energy needs, becomes a relevant parameter
  - step-by-step and single-stage present plausible results when compared to the Invert-EE/Lab Model
  - the step-by-step approach resulted in lower energy demand than the single stage approach (comparison until 2050)

Limitations and next steps

- Limitations
  - reference buildings (described according to the chosen database)
  - further: sensitivity analysis
    - reduced or increased time intervals between renovation in the single-stage concept
    - limited information in old building codes for existing buildings
    - we assume that in the future, benchmarks for existing buildings will follow the same threshold as for new buildings
  - choice of the step-by-step renovation measures -> renovation packages
- Next steps
  - integration of replacement of heating systems with hot water preparation;
  - considering a more realistic distribution of the building elements´ lifetimes, e.g. by using a Weibull distribution (as also done in the model Invert/EE-Lab);
  - empirical evaluation of the historical renovation cycles;
  - economic assessment:
    - include accurate estimation of investment costs
    - include investment costs as decision parameter for a deep renovation
    - economic consequences of not reaching materials end-of-life should be taken into account (rest-value of material)


window
roof
ext. wall
floor
HWB norm
A- 1890
75
B- 1935
273
C- 1955
193
D- 1965
162
85
E- 1975
107
F- 1980
G- 1990
118
H- 2000
77
2005
72
ab 2009 (2015)
72
1- identificar quais elementos foram saniert

Building vintage		until 1918	1919 - 1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002 - 2009
construction year	[kWh/(m²a)]	280	227	284	275	203	135	157	122	81
step-by-step	[kWh/(m²a)]	15	82	115	100	23	57	52	20	23
single stage	[kWh/(m²a)]	15	52	25	15	203	135	157	122	81
Energy savings step-by-step	[%]	95	64	60	64	89	58	67	84	72
Energy savings single stage	[%]	95	77	91	95	0	0	0	0	0