Renovation package modelling – terraced, semi-detached & multi-storey dwellings

Energy Systems Research Unit

University of Strathclyde

31-07-2020

Smart Renovation Factory by INDU-ZERO

Interreg North Sea Region INDU-ZERO

European Regional Development Fund

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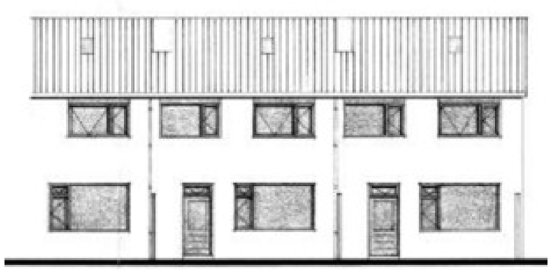
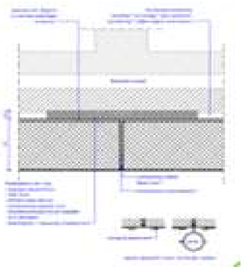
A) Modelling Process Overview

Modelling process



Existing dwelling



Retrofit package description(s)

Weather, occupancy and systems data

High resolution ESP-r input model

ESP-r simulations to confirm upgrade efficacy

Geometry & construction data transfer ESP-r to Blender

Construction process data

Blender animations to confirm constructability

Blender output model

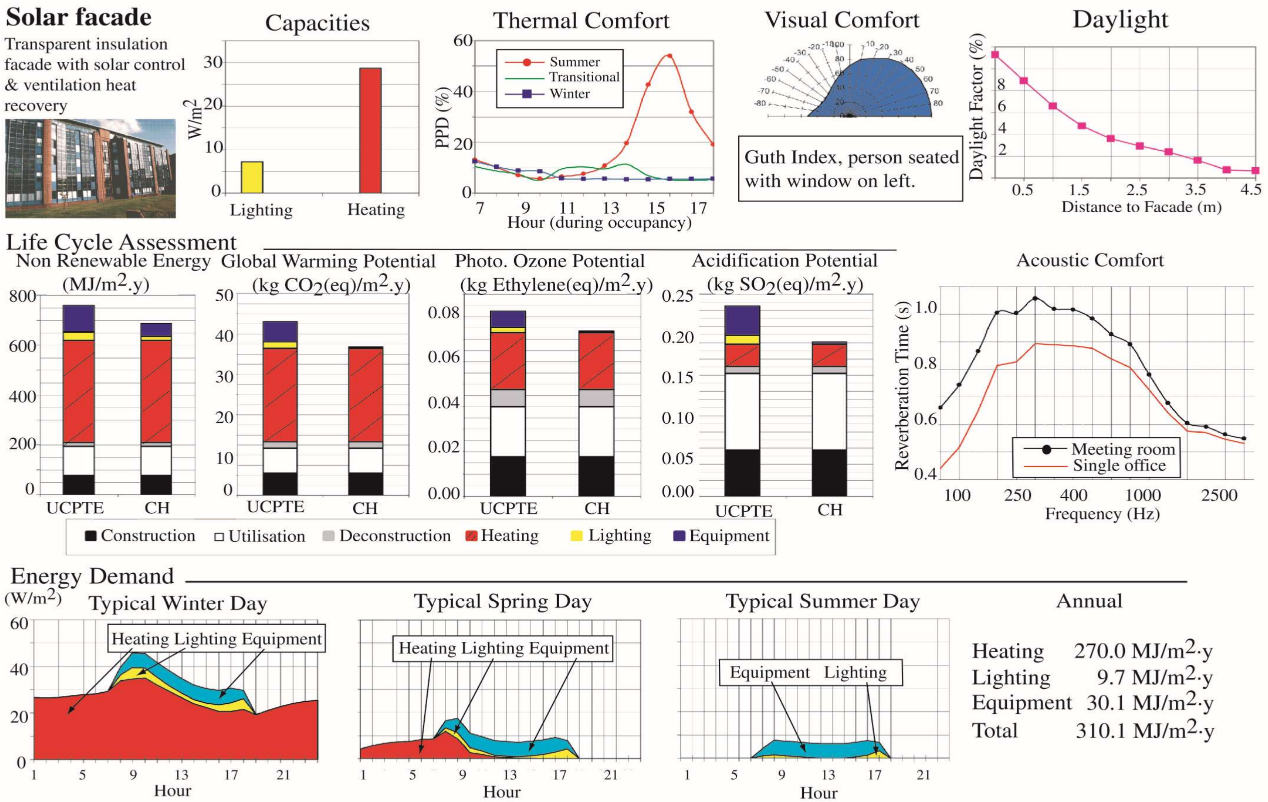
Factory machine settings

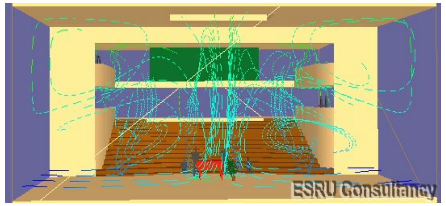
ESP-r summary

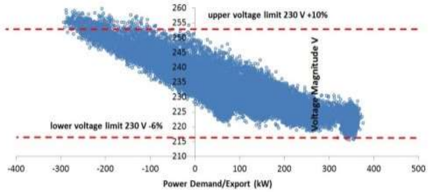
- Free and open source building performance simulation.
- Undertakes integrated performance simulations (energy, thermal & visual comfort, indoor air quality, emissions) allowing upgrade rating.
- Data input requirements include:
  - weather time series;
  - 3D geometry;
  - hygro-thermal properties of construction materials;
  - thermal bridge and leakage distribution details;
  - internal thermal mass locations;
  - operational details (occupancy, lighting and small power);
  - Heating, ventilation, and domestic hot water system details;
  - embedded renewable energy systems.
- Available from http://www.esru.strath.ac.uk/applications/esp-r/.

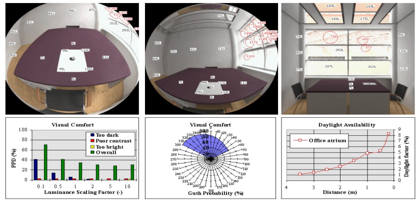
Sources:
BIM model
PHPP spreadsheet
Construction drawings
Manufacturer data
Standards

ESP-r outputs









‘Fit-for-purpose’ performance checklist


Scottish Housing Stock: Description and Examples of Flat, Terrace and Semi-Detached Dwelling Types, Technical Risks.

11 MARCH 2019

ENERGY SYSTEMS RESEARCH UNIT

Housing Upgrades: Quality Assurance, Calculation Methods, and Future Factory Blueprint.

11 MARCH 2019

UPGRADED DWELLING (MONITORED)		
Occupancy, weather and calibration	**Units**	**MEASURED**
Standard patterns	y/n	
Robustness test patterns	y/n	
Model calibration checks	y/n	
Construction Quality**		
Airtightness (@50Pa)	ac/h	
Thermal bypass risk	pass/fail	
Surface temperatures i.e. at bridges >12°C	°C	
Internal construction moisture accumulation	pass/fail	
Energy Performance**		
Envelope heat loss parameter (tfa)	$W/m^2.K$	
Ventilation heat loss parameter (tfa)	$W/m^2.K$	
Space heating demand (th)	$kWh/m^2.a$	
Space heating delivered (e, g)	$kWh/m^2.a$	
Space heating system efficiency	%	
Hot water demand (th)	$kWh/m^2.a$	
Hot water delivered (e, g)	$kWh/m^2.a$	
Hot water system efficiency	%	
Lights and Appliances (e)	$kWh/m^2.a$	
Ventilation (e)	$kWh/m^2.a$	
Total delivered	$kWh/m^2.a$	
PV generation (tfa) (e)	$kWh/m^2.a$	
PV self consumption	$kWh/m^2.a$	
PV self consumption	%	
Net energy at meter	$kWh/m^2.a$	
Indoor Environment Comfort and Health Indicators**		
Fresh Air Supply per occupied room (tfa)	$l/s/m^2$	
% time minimum fresh air supply not met	%	
Humidity - RH and g per room	% / g/kg	
% time humidity criteria not met	%	
Maximum Summer Temperature per room	°C	
Minimum Winter Temperature per room	°C	
% time thermal comfort criteria not met	%	

** as measured or adjusted for occupancy and weather etc.

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ESP-r input to performance checklist

UPGRADED DWELLING (DESIGN)		
Occupancy, weather and calibration	**Units**	**PASS**
Standard patterns	y/n	
Robustness test patterns	y/n	
Model calibration checks	y/n	
Construction Quality*		
Airtightness (@50Pa)	ac/h	
Thermal bypass risk	pass/fail	
Surface temperatures at bridges >12°C	°C	
Internal construction moisture accumulation	pass/fail	
Energy Performance*		
Envelope heat loss parameter (tfa)	$W/m^2.K$	
Ventilation heat loss parameter (tfa)	$W/m^2.K$	
Space heating demand (th)	$kWh/m^2.a$	
Space heating delivered (e, g)	$kWh/m^2.a$	
Space heating system efficiency	%	
Hot water demand (th)	$kWh/m^2.a$	
Hot water delivered (e, g)	$kWh/m^2.a$	
Hot water system efficiency	%	
Lights and Appliances (e)	$kWh/m^2.a$	
Ventilation (e)	$kWh/m^2.a$	
Total delivered	$kWh/m^2.a$	
PV generation (tfa) (e)	$kWh/m^2.a$	
PV self consumption	$kWh/m^2.a$	
PV self consumption	%	
Net energy at meter	$kWh/m^2.a$	
Indoor Environment Comfort and Health Indicators*		
Fresh Air Supply per occupied room (tfa)	$l/s/m^2$	
% time minimum fresh air supply not met	%	
Humidity - relative and abs per room	% / g/kg	
% time humidity criteria not met	%	
Maximum Summer Temperature per room	°C	
Minimum Winter Temperature per room	°C	
% time thermal comfort criteria not met	%	

* assumes building implemented and operated per plans.

UPGRADED DWELLING (MONITORED)		
Occupancy, weather and calibration	**Units**	**MEASURED**
Standard patterns	y/n	
Robustness test patterns	y/n	
Model calibration checks	y/n	
Construction Quality**		
Airtightness (@50Pa)	ac/h	
Thermal bypass risk	pass/fail	
Surface temperatures i.e. at bridges >12°C	°C	
Internal construction moisture accumulation	pass/fail	
Energy Performance**		
Envelope heat loss parameter (tfa)	$W/m^2.K$	
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Space heating delivered (e, g)	$kWh/m^2.a$	
Space heating system efficiency	%	
Hot water demand (th)	$kWh/m^2.a$	
Hot water delivered (e, g)	$kWh/m^2.a$	
Hot water system efficiency	%	
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Indoor Environment Comfort and Health Indicators**		
Fresh Air Supply per occupied room (tfa)	$l/s/m^2$	
% time minimum fresh air supply not met	%	
Humidity - RH and g per room	% / g/kg	
% time humidity criteria not met	%	
Maximum Summer Temperature per room	°C	
Minimum Winter Temperature per room	°C	
% time thermal comfort criteria not met	%	

** as measured or adjusted for occupancy and weather etc.

ESP-r model outputs contribute to a design performance checklist.

ESP-r allows performance assessment across ranges in weather and occupant behaviours.

ESP-r allows monitored data to be adjusted for weather and behaviours.

Blender summary

- Free and open source 3D model creation suite.
- Supports modelling, rigging, animation, simulation, rendering, compositing and motion tracking, and video editing.
- Can export models in different formats for CAD, 3D and VR visualisation.
- Available from https://www.blender.org.

```
# Blender v2.80 (sub 75) OBJ File: 'Terrace_retrofit_v13.blend'
# www.blender.org
mtllib Terrace_retrofit_v13.mtl
o Ground_floor_ceiling_Plane
v -2.864347 2.700018 4.963409
v 0.559655 2.699999 4.961314
v -2.864346 2.699999 -3.488967
v 2.603446 2.699999 -3.488967
v 2.603447 2.699999 4.961311
v 0.559655 2.700018 4.963406
v -2.864347 2.875018 4.963409
v 0.559655 2.874999 4.961314
v -2.864346 2.874999 -3.488967
v 2.603446 2.874999 -3.488967
v 2.603447 2.874999 4.961311
v 0.559655 2.875018 4.963406
v 1.566447 2.699999 1.624445
v 1.566447 2.874999 1.624445
v 2.603445 2.699999 3.286444
v 2.603445 2.874999 3.286444
v 2.603445 2.699999 1.624445
v 2.603445 2.874999 1.624445
v 1.566447 2.699999 3.286445
v 1.566447 2.874999 3.286445
vn -0.0000 -1.0000 0.0000
vn 0.0000 1.0000 -0.0000
vn 0.0000 0.0000 1.0000
vn 1.0000 0.0000 0.0000
vn -1.0000 0.0000 -0.0000
vn 0.0000 0.0000 -1.0000
vn 1.0000 0.0000 -0.0002
usemtl None
```

Data model

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# Blender MTL File: 'Terrace_retrofit_v13.blend'
# Material Count: 57

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Ka 1.000000 1.000000 1.000000
Kd 0.800000 0.800000 0.800000
Ks 0.500000 0.500000 0.500000
Ke 0.0 0.0 0.0
Ni 1.000000
d 1.000000
illum 2

newmtl Cover
Ns 225.000000
Ka 1.000000 1.000000 1.000000
Kd 0.063720 0.063119 0.061336
Ks 0.500000 0.500000 0.500000
Ke 0.0 0.0 0.0
Ni 1.450000
d 1.000000
illum 2

newmtl EPS
Ns 361.000025
Ka 1.000000 1.000000 1.000000
Kd 0.184779 0.126075 0.021874
Ks 0.500000 0.500000 0.500000
Ke 0.0 0.0 0.0
Ni 2.950000
d 1.000000
illum 3
```

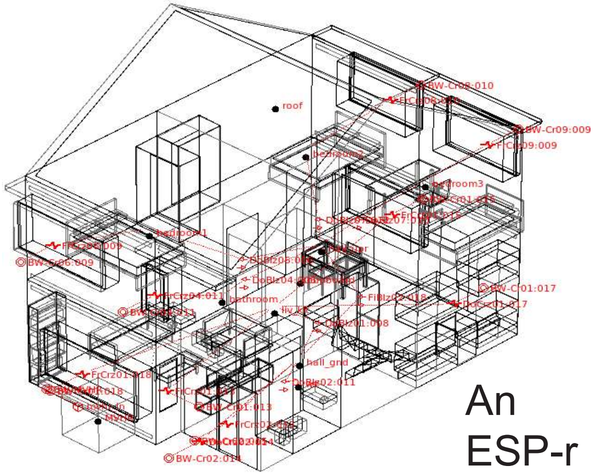
B) Buildings, Upgrade Details and Models

Process prototyping

- ESP-r and Blender have been applied to three dwelling archetypes:
  - Terraced;
  - Semi-detached; and
  - Multi-storey apartments.
- Purpose:
  - to explore the efficacy of proposed upgrades;
  - to determine the required data transfers between the two applications; and
  - to investigate the end-to-end data flow.

Existing dwelling

A Blender model



An ESP-r model

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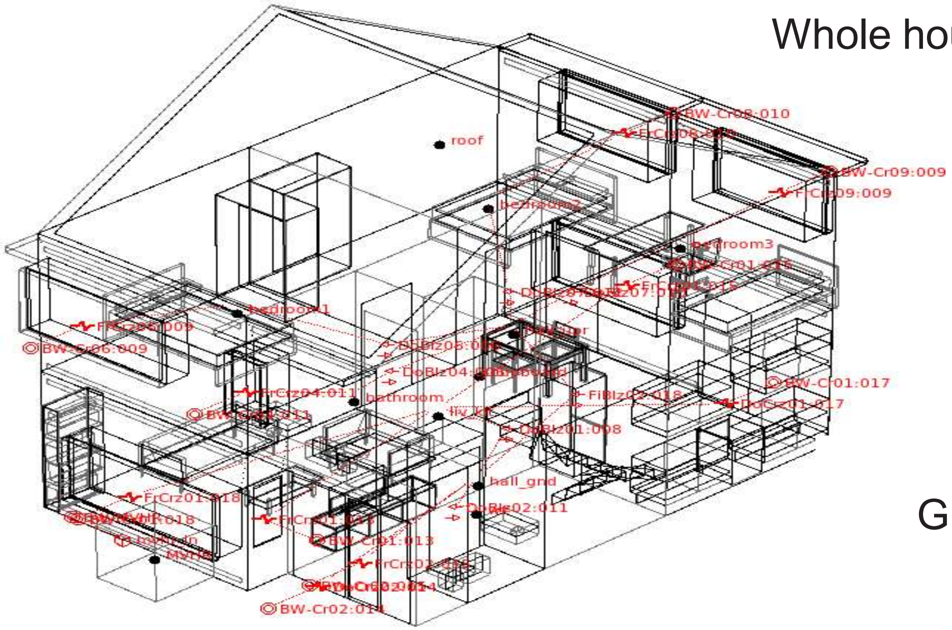
Terraced archetype - details from NL partner

	Area	Thermal insulance	Thermal transmittance
	m^2	$m^2 \cdot K^1 \cdot W^{-1}$	$W \cdot m^{-2} \cdot K^{-1}$
Floor	52,0	0,17	2,33
Roof	65,5	0,86	0,89
Façade - front	40,5	0,43	1,45
Glass (single) - front	4,3	-	5,20
Glass (double) - front	21,3	-	2,90
Façade - side	58,3	0,43	1,45
Glass (double) - side	1,8	-	2,90

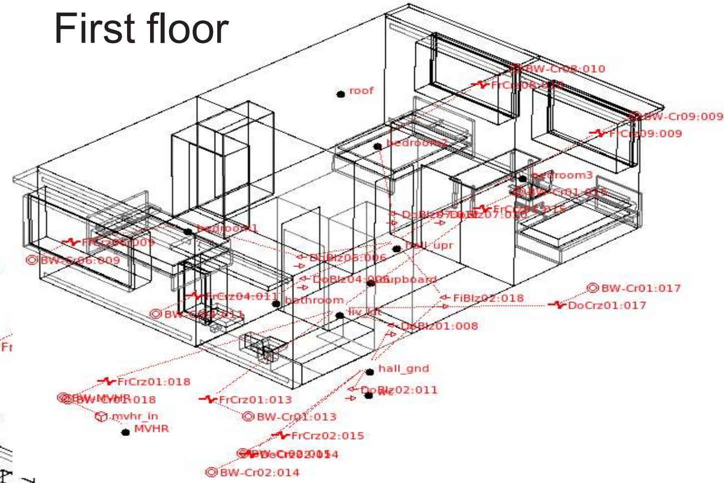
Characteristics (NL)	
Net floor area	106 m^2
Number of occupants	3
External wall	cavity wall / window fills with sandwich panels
Attic	ventilated
Ground floor construction	concrete slab on ground
Ventilation system	window
Heating / DHW system	gas boiler

Terraced - ESP-r high resolution model

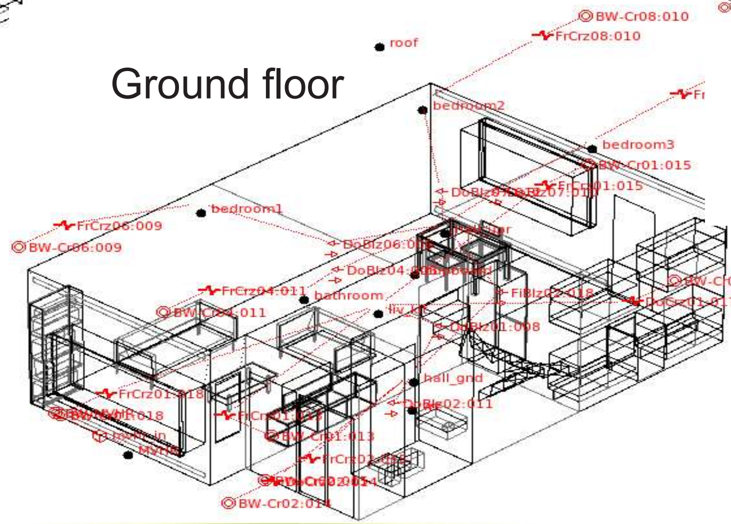
Whole house



First floor



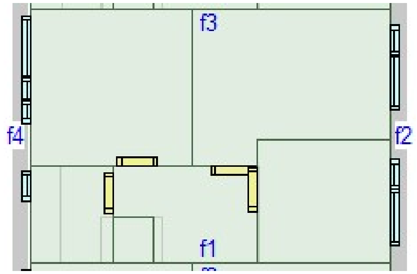
Ground floor

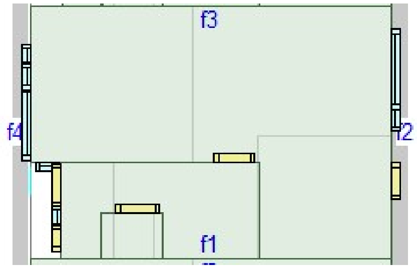


Semi-detached/ end-terrace archetype - details from NL partner

Actual dwelling

Blender model of dwelling





Semi-detached constructions same as terrace.

Characteristics (NL)	
Net floor area	106 m^2
Number of occupants	3
External wall	cavity wall / window fills with sandwich panels
Attic	ventilated
Ground floor construction	concrete slabs
Ventilation system	window
Heating / DHW system	gas boiler

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Semi-detached - ESP-r high resolution model

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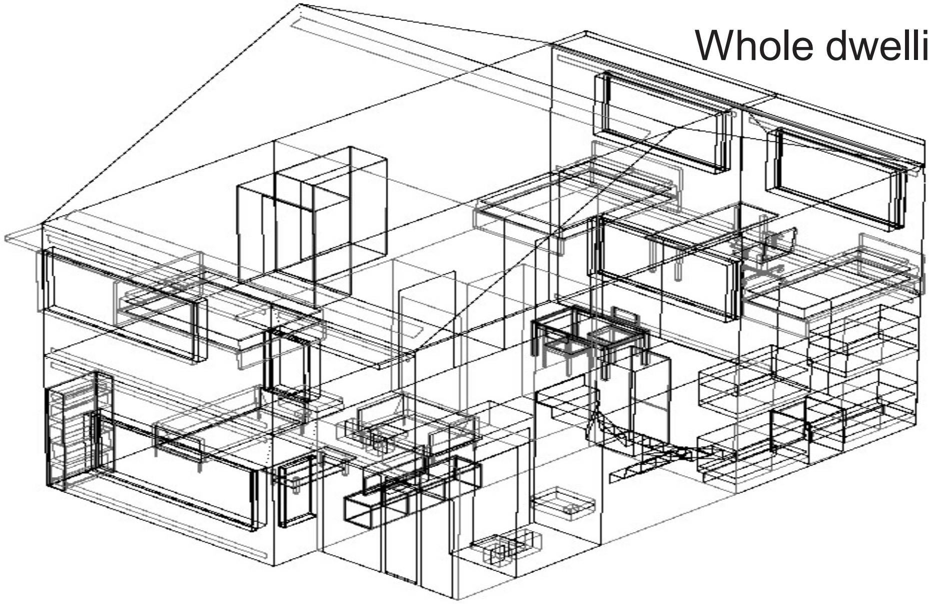
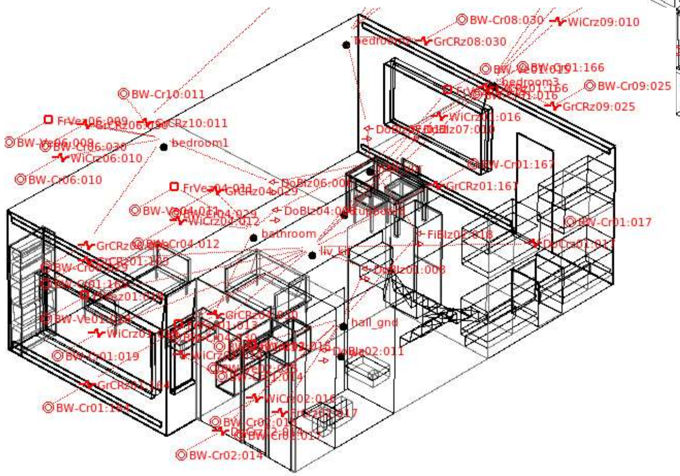
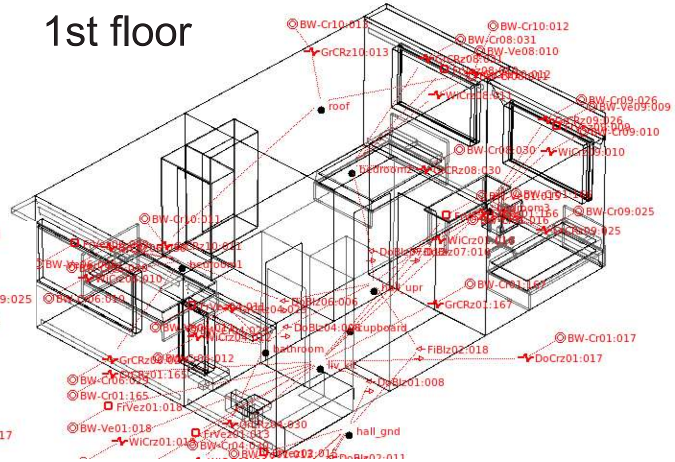
Whole dwelling



Ground floor



1st floor



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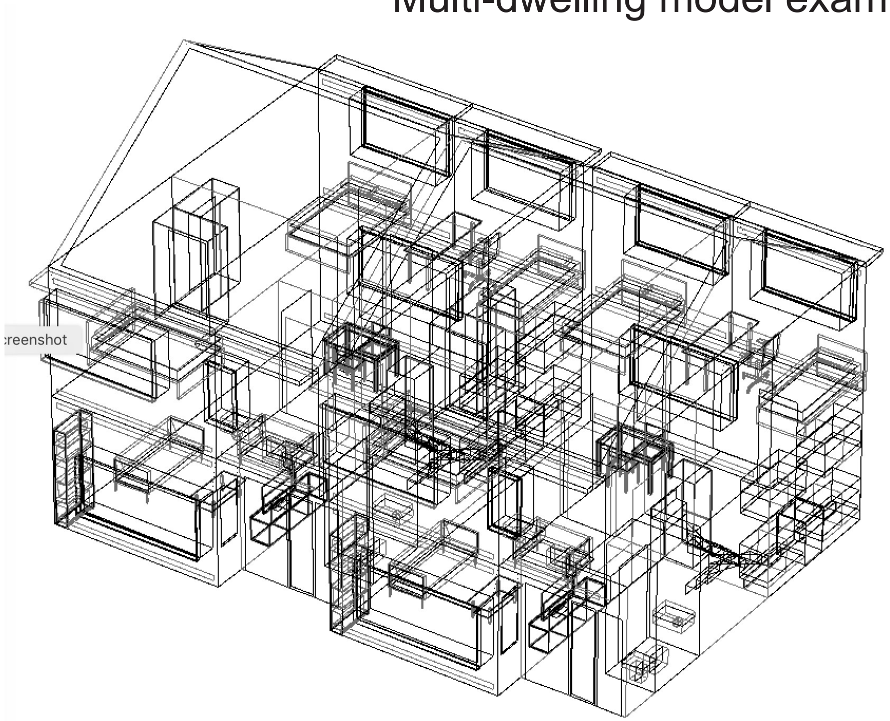
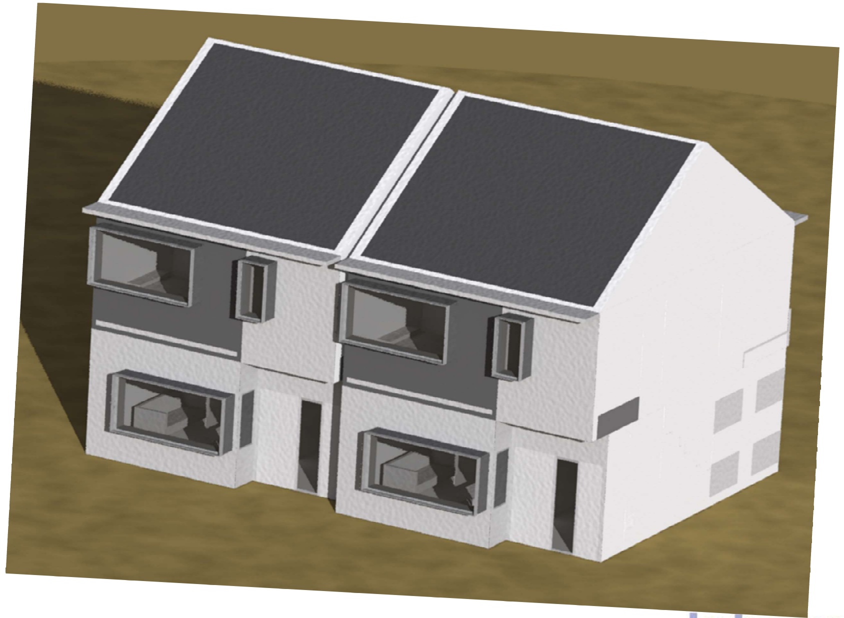
Semi-detached - additional ESP-r images

Multi-dwelling model example





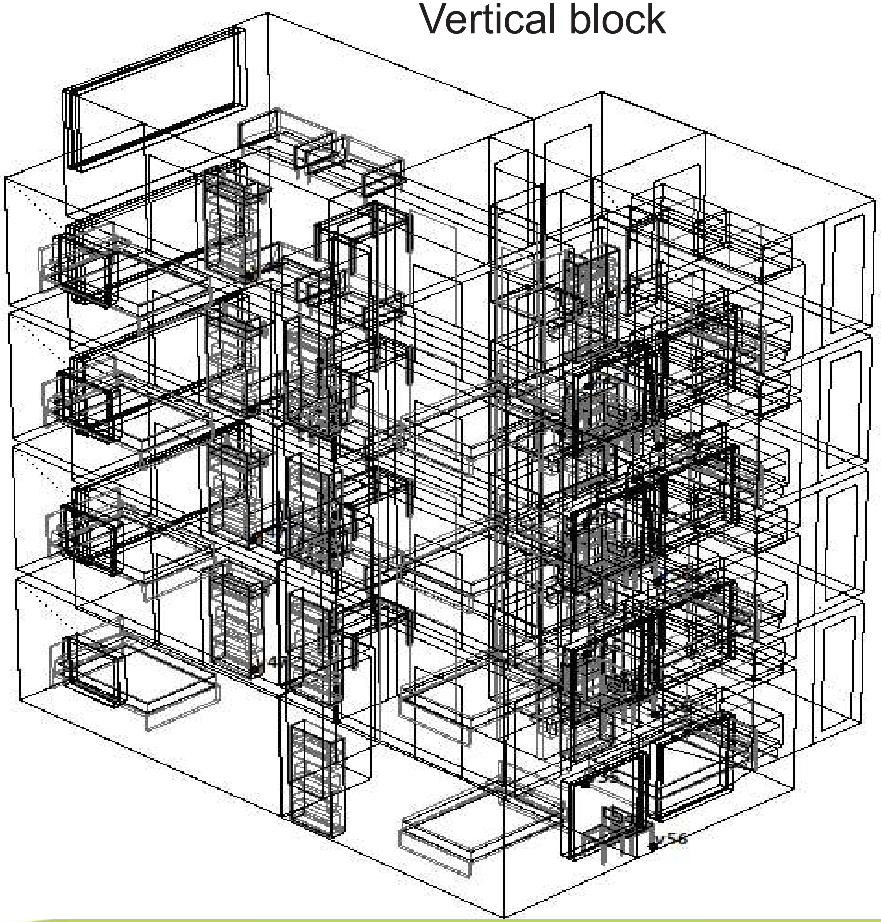
Apartment archetype: details from NL partner

4 storey apartment block.

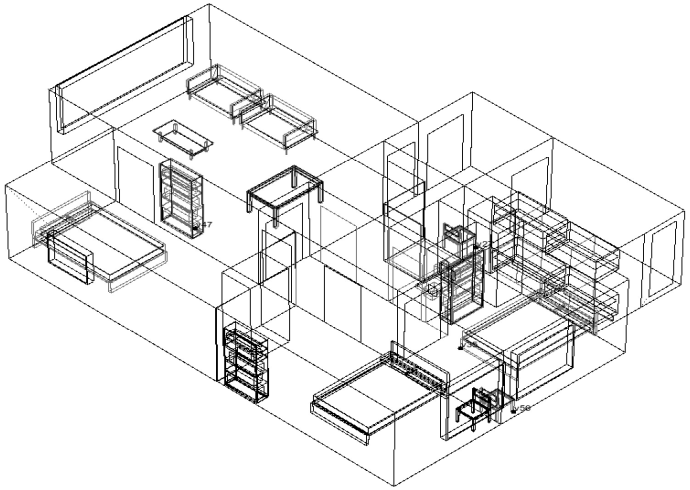
Constructions currently assumed to be the same as for the terrace dwelling.

Apartment archetype - ESP-r hi-res model

Vertical block

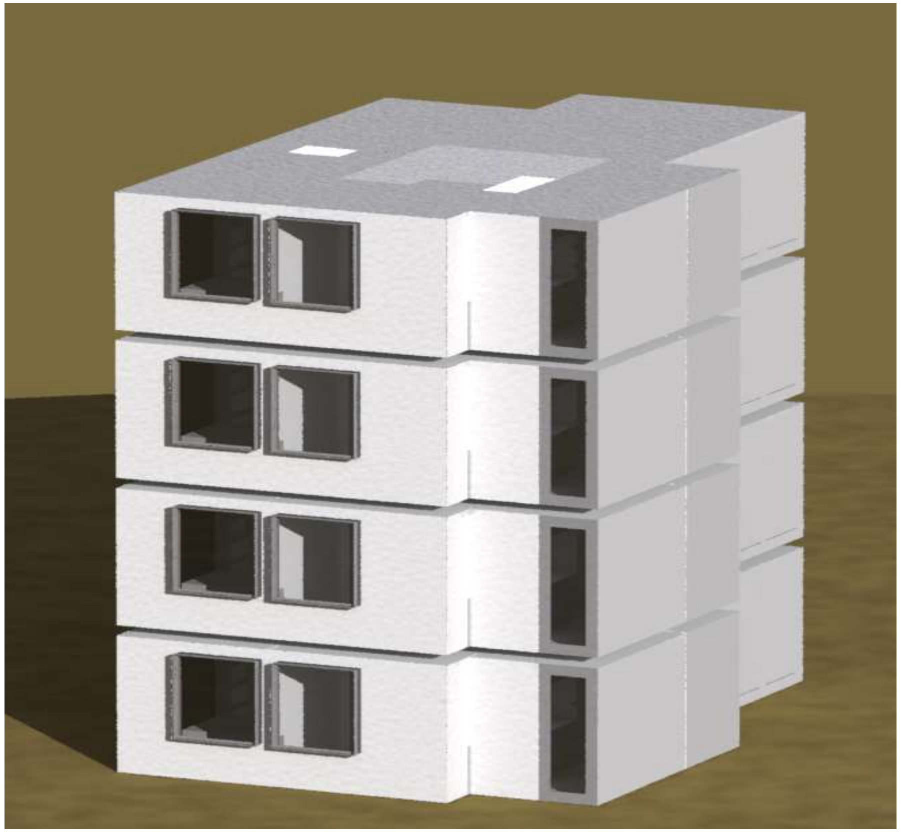


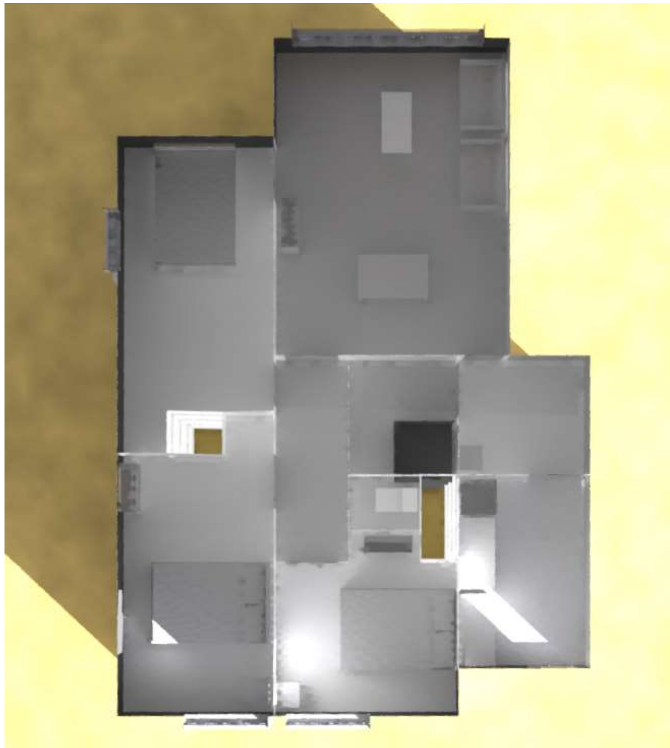
Individual apartment



ground, middle or top storeys have different floor and roof exposures.

Apartment archetype - ESP-r Images





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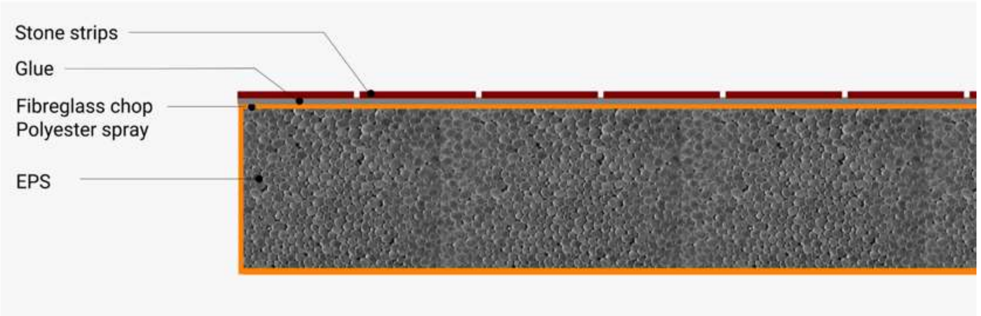
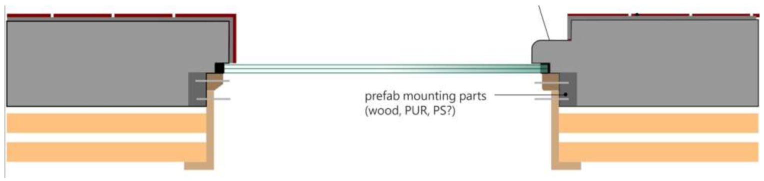
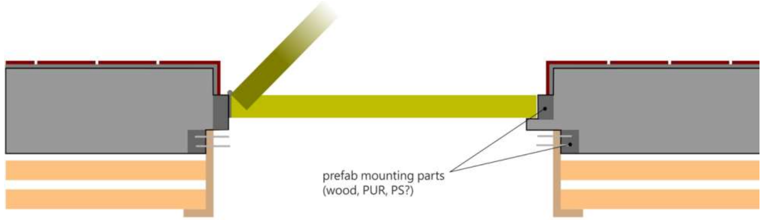
Renovation package (details from NL partner)



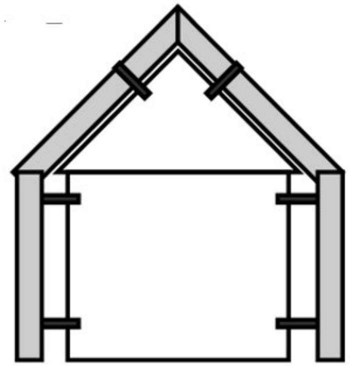
Panel / Section construction



Window / Construction



Door / Construction



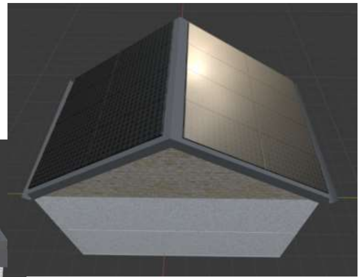
Blender modelling

Pre-upgrade

- Factory settings
- Constructability

Partial upgrade

Post-upgrade



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C) ESP-r Energy Modelling

Hi-res dynamic modelling strategy

For each of the 3 archetypes (Terraced, Semi-detached, Apartment):

- 4 versions of model were analysed:
    1. current dwelling pre-renovation;
    2. dwelling with the renovation package applied;
    3. dwelling with the renovation package plus additional airtightness and MVHR applied;
    4. dwelling fully renovated to meet the official EnerPHit standard.
- In all cases (3 architypes / 4 versions), 3 locations were considered:
    1. Netherlands (NL);
    2. Scotland (SCO);
    3. Norway (N).
- The simulation settings were chosen as:
    1. all simulations were high resolution at a sub-hourly time-step;
    2. a typical weather file was used plus 4 alternative weather files for each location;
    3. the occupancy patterns, behaviours and set-points were selected to align with monthly and annual values used in regulatory standards.
- A high level overview of the modelling strategy giving simplified descriptions for dynamic simulation input parameter settings is given in the following table.

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Hi-res dynamic modelling strategy

	Base Dwelling	Panelled	Panelled plus Airtightness and MVHR	EnerPHit
External planar surfaces heat loss characteristics	**Thermal transmittance ***	**Thermal transmittance ***	**Thermal transmittance ***	**Thermal transmittance***
	$W \cdot m^{-2} \cdot K^{-1}$	$W \cdot m^{-2} \cdot K^{-1}$	$W \cdot m^{-2} \cdot K^{-1}$	$W \cdot m^{-2} \cdot K^{-1}$
External Floor	1,96	1,96	1,96	0,24
External Roof	1,00	0,15	0,15	0,15
External Wall	1,35	0,15	0,15	0,15
Window Glass	2,81	0,9	0,9	0,9
Window Frame	2,03	0,9	0,9	0,9
External Doors	2,90	0,9	0,9	0,9
Thermal bridges at junctions*	**Thermal transmittance ***	**Thermal transmittance ***	**Thermal transmittance ***	**Thermal transmittance ***
	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$
Thermal bridge (roof/wall)	Std values applied	Thermal bridge free	Thermal bridge free	Thermal bridge free
Thermal Bridge (wall/wall)	Std values applied	Thermal bridge free	Thermal bridge free	Thermal bridge free
Thermal bridge (wind/door to wall)	Std values applied	Thermal bridge free	Thermal bridge free	Thermal bridge free
Thermal Bridge (wall/ground)*	Std values applied	Uninsulated floor	Uninsulated floor	Thermal bridge free
Ventilation and	**Inf+vent / MVHR**	**Inf+vent / MVHR**	**Inf+vent / MVHR**	**Inf+vent / MVHR**

Hi-res dynamic modelling strategy

	Base Dwelling	Panelled	Panelled plus Airtightness and MVHR	EnerPHit
Ventilation and infiltration*	**Inf+vent / MVHR**	**Inf+vent / MVHR**	**Inf+vent / MVHR**	**Inf+vent / MVHR**
	Ac · h^{-1} / HR eff	Ac · h^{-1} / HR eff	Ac · h^{-1} / HR eff	Ac · h^{-1} / HR eff
Infiltration (ach.h^{-1}@50Pa)**	10	2	0.6	0.6
Ventilation (inf+vent)*	0.65	0.65	0.5	0.5
MVHR efficiency (HR)*	0	0	0.75	0.75
Energetic Ventilation [inf+(1-HR)*(vent)]*	0.65	0.65	0.1475	0.1475
Gains and operations*	**Gains / Operations**	**Gains / Operations**	**Gains / Operations**	**Gains / Operations**
	W/m2 / t,T	W/m2 / t,T	W/m2 / t,T	W/m2 / t,T
Heating Season Internal Gains and occupancy	Std values applied	Std values applied	Std values applied	Std values applied
Heating Season Operations	living 21C, non living 18C, 15C setback, weekdays 2 periods (6-9, 5-11), weekends 1 (6-11).	living 21C, non living 18C, 15C setback, weekdays 2 periods (6-9, 5-11), weekends 1 (6-11).	living 21C, non living 18C, 15C setback, weekdays 2 periods (6-9, 5-11), weekends 1 (6-11).	living 21C, non living 18C, 15C setback, weekdays 2 periods (6-9, 5-11), weekends 1 (6-11).

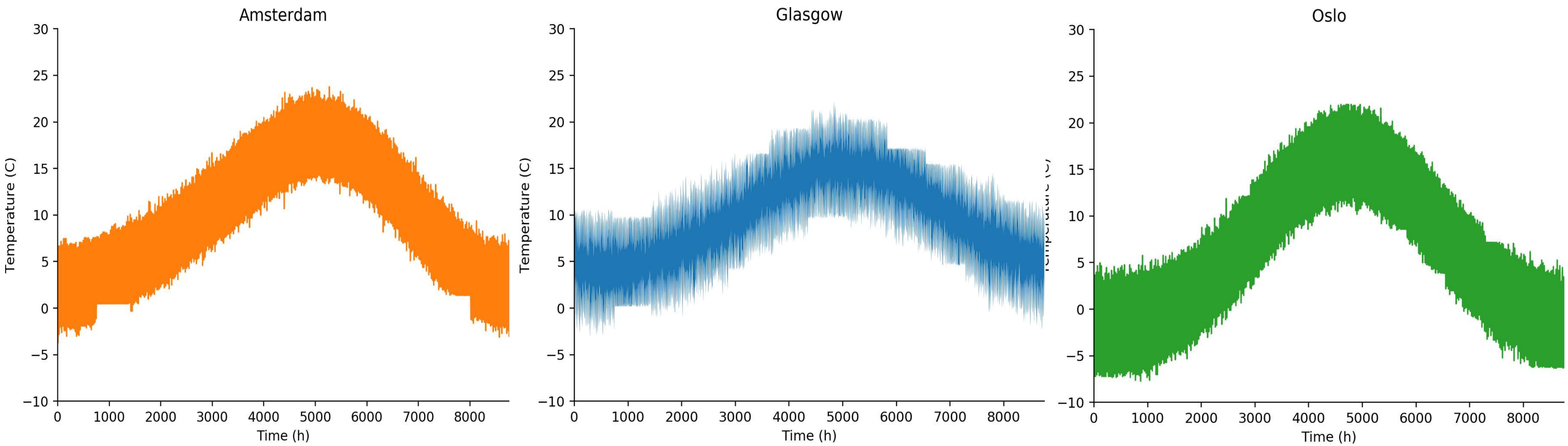
Hi-res dynamic modelling strategy

	Base Dwelling	Panelled	Panelled plus Airtightness and MVHR	EnerPHit
Shading and Climate*				
Shading Applied	overhang and sides 10cm to glass	overhang and sides 10cm to glass	overhang and sides 10cm to glass	overhang and sides 10cm to glass
Climates	5 UK, 5 NL, 5NO representing 100yr weather data	5 UK, 5 NL, 5NO representing 100yr weather data	5 UK, 5 NL, 5NO representing 100yr weather data	5 UK, 5 NL, 5NO representing 100yr weather data
**blower door test or equivalent		*dynamic simulation used - these static values are simplified		

ESP-r, capturing variability

To illustrate the capture of variability in weather, multiple annual simulations were undertaken for Amsterdam, Glasgow & Oslo with 5 weather years selected per location: 1 similar to regulatory standard plus 4 representing +/- variations.

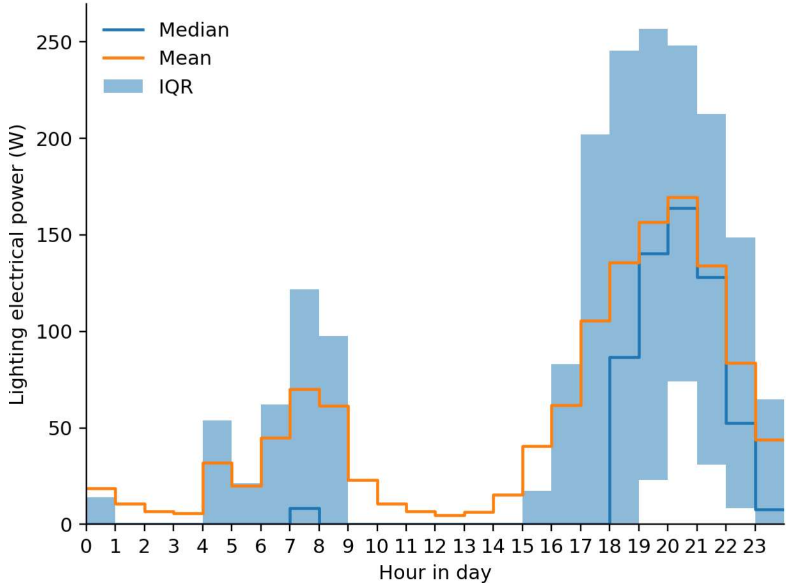
A similar approach can be taken to variability in occupant behaviour however for simplicity a 'typical' occupancy similar to regulatory standard was selected.

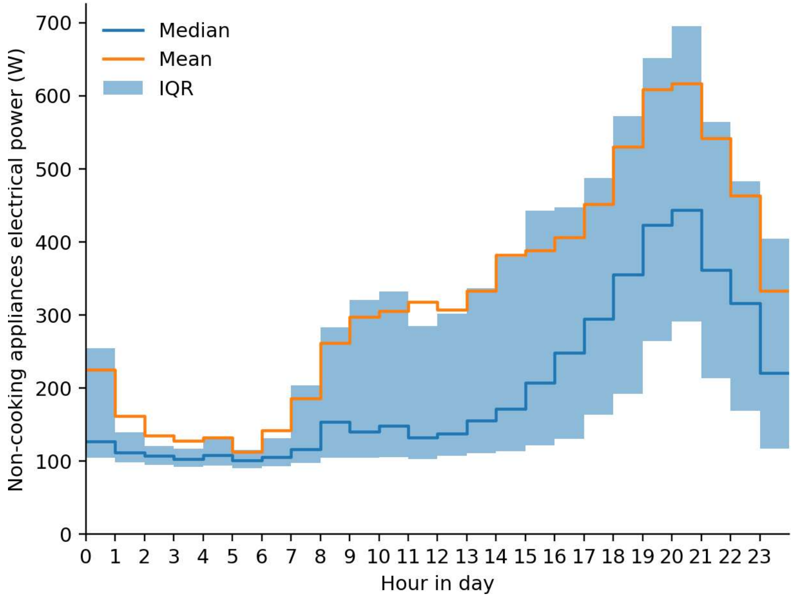


Dynamic weather profiles include temperature, solar radiation, relative humidity, wind speed and direction.

Dwelling models – lighting and appliance use

Wide range of stochastic annual profiles were generated, example days are shown below..

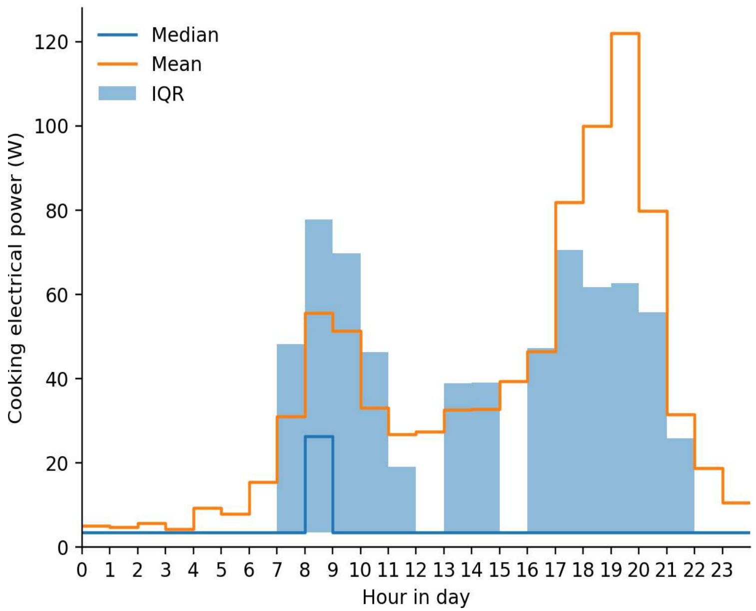


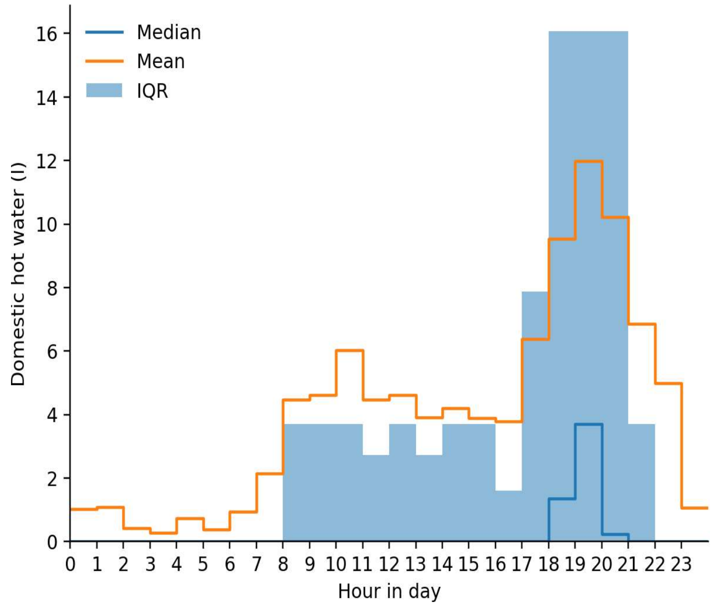


A profile was then selected matched to monthly and annual averages in UK simplified Standard Assessment Procedure (SAP), i.e. E_{lights} = 4.9 kWh/m^2.y, $E_{appliances}$ = 30.0 kWh/m^2.y.

Dwelling models – cooking and hot water use

Wide range of stochastic annual profiles were generated, example days are shown below..

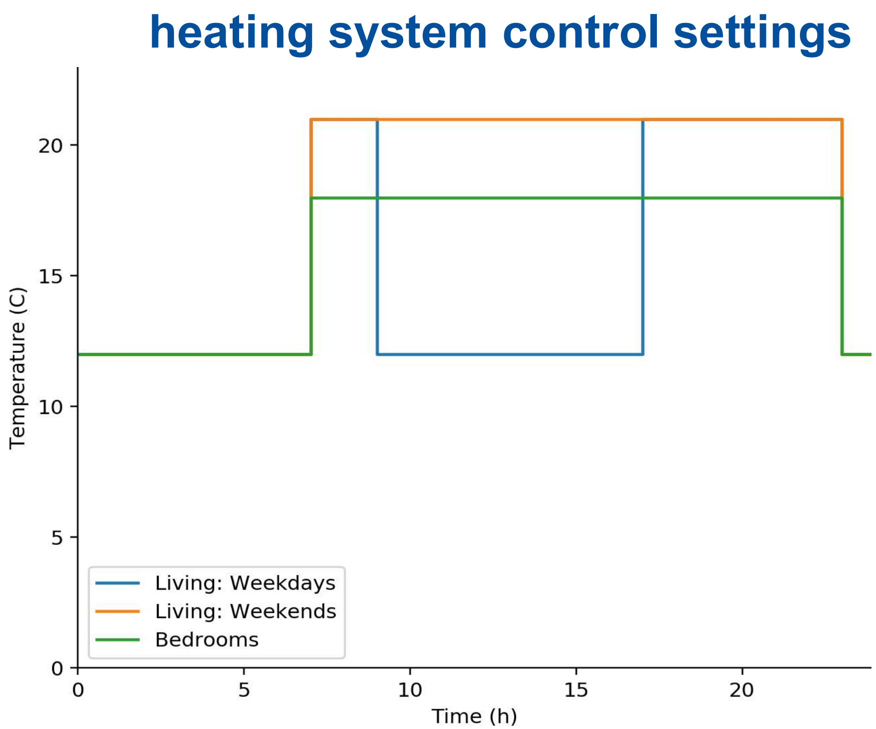




A profile was then selected matched to monthly and annual averages in UK simplified Standard Assessment Procedure (SAP) i.e. $E_{cooking}$ = 3.4 kWh/m^{2}p.a., $E_{hotwater}$ = 16.2 kWh/m^{2}p.a.

Dwelling models – heating system controls

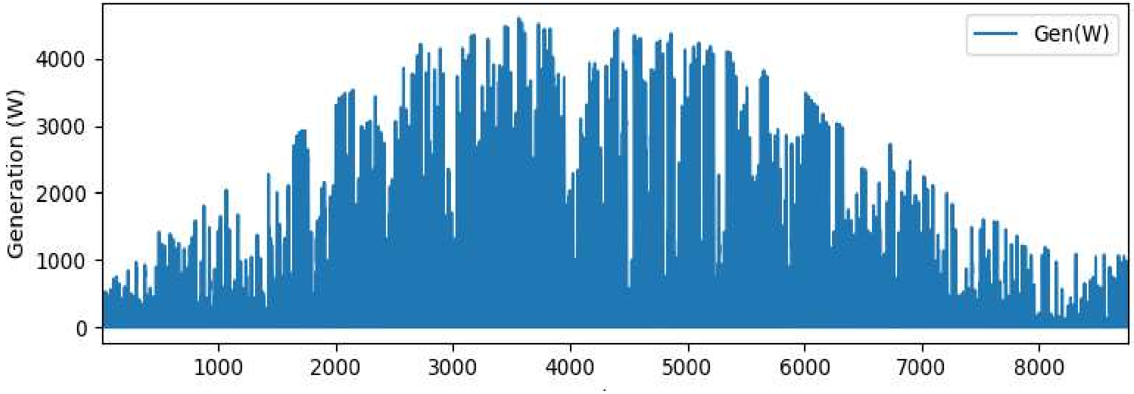
Profile was matched to settings in UK simplified Standard Assessment Procedure (SAP).



ESP-r: photovoltaic power production

A photovoltaic roof was simulated for the Terrace and Semi-detached models for each weather year in each location.

Assumption: both front and rear roof surfaces are covered, giving a total capacity of 5.76 kW_p



D) Energy modelling summary results

ESP-r space heating results: Terrace

Space heating demand (kWh/m^2.y)

Terrace	Amsterdam	Glasgow	Oslo
1. Pre-upgrade	121 ± 2.6	125 ± 3.2	170 ± 3.7
2. + Fabric upgrade package	60 ± 1.8	63 ± 2.5	80 ± 2.4
3. + PH airtightness + MVHR	36 ± 0.8	42 ± 1.3	52 ± 1.4
4. + Certified EnerPHit inc Floor insulation	8 ± 0.9	9 ± 1.3	20 ± 1.2

ESP-r space heating results: semi-detached

Space heating demand (kWh/m^2.y)

End-Terrace / Semi-Detached	Amsterdam	Glasgow	Oslo
1. Pre-upgrade	146.4 ± 2.6	155.8 ± 3.2	203.4 ± 3.7
2. + Fabric upgrade package	61.0 ± 1.8	63.9 ± 2.5	86.3 ± 2.4
3. + PH airtightness + MVHR	38.8 ± 0.8	42.2 ± 1.3	53.0 ± 1.4
4. + Certified EnerPHit inc Floor insulation	10.3 ± 0.9	9.8 ± 1.3	20.8 ± 1.2

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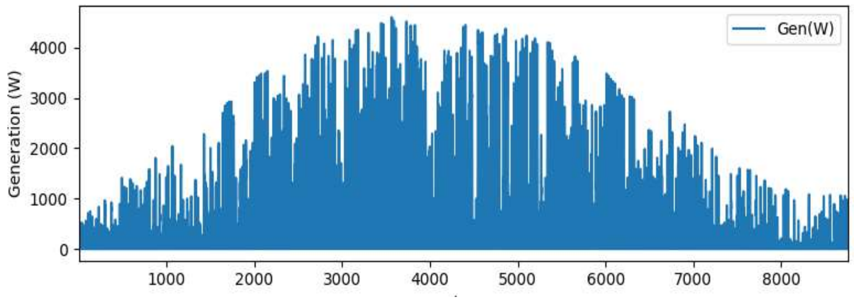
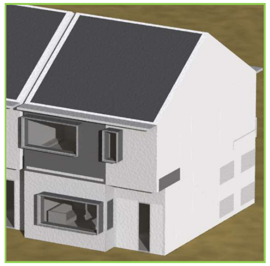
ESP-r space heating results: apartment (ground)

Space heating demand (kWh/m^2.y)

Apartment (Ground Floor)	Amsterdam	Glasgow	Oslo
1. Pre-upgrade	135.1 ± 2.2	147.3 ± 3.1	177.4 ± 3.3
2. + Fabric upgrade package	58.9 ± 2.3	62.1 ± 2.0	80.6 ± 2.7
3. + PH airtightness + MVHR	44.1 ± 1.3	49.2 ± 1.8	63.0 ± 1.6
4. + Certified EnerPHit inc Floor insulation	8.1 ± 0.8	8.9 ± 1.4	15.4 ± 1.5





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ESP-r net-at-the-meter results: semi-detached

Net electricity demand at meter (kWh/m^2 p.a.)

End-terrace / Semi-detached	Amsterdam	Glasgow	Oslo
1. Pre-upgrade	---	---	---
2. + Fabric upgrade package	27.6 ± 1.6	43.8 ± 2.9	58.1 ± 3.0
3. + PH airtightness + MVHR	14.1 ± 0.9	29.0 ± 0.8	31.6 ± 1.9
4. + Certified EnerPHit inc Floor ins	-1.1 ± 0.7	12.8 ± 1.5	13.6 ± 1.4

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E) Discussion and Conclusions

Observations

Current upgrade package:

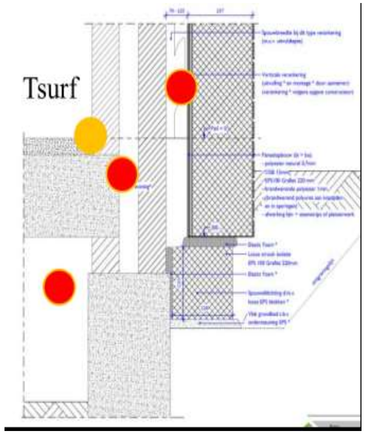
- 58-74% reduction in space heating demand (standard occupancy);
- net-zero at the meter not achieved in any location.

With additional PH air tightness + MVHR + floor insulation (Certified EnerPHit):

- 90-94% reduction in space heating demand;
- progress towards net-zero energy performance.

Significant issues in Scorecard not yet addressed:

- thermal bridges;
- air bypass;
- internal moisture accumulation;
- floor insulation and ground conditions;
- robustness under different occupant behaviours;
- summer temperatures.



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Outcomes and next steps

- Modelling process and ‘fit-for-purpose’ scorecard established for integration in future factory based on ESP-r dynamic simulation and Blender.
- Process piloted for 3 dwelling archetypes (terrace, semi-detached and apartment).
- 3 locations (NL, Sco, N), 3 upgrade levels and multiple weather years simulated.
- Space heating and ‘net zero at the meter’ performance summary produced.
- Initial analysis indicates ‘net zero at the meter’ criteria challenges exist.
- Other ‘fit for purpose’ criteria still to be addressed.
- Next stage is to develop further the modelling process (ESP-r and Blender) for the future factory blueprint; document and apply the process to the INDU-ZERO showcase demonstration exemplar building(s).

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