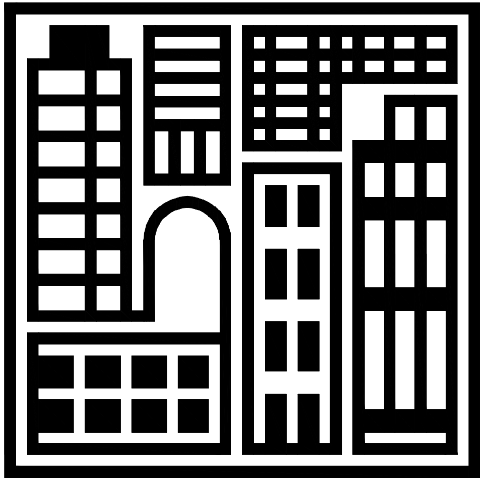
Urban Futures Symposium 2025

Economy and sustainability analysis of sector coupled district energy systems using white-box models in distributed co-simulation



Urban Futures Symposium 2025
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Introduction

Karlsruhe Institute of Technology

Background

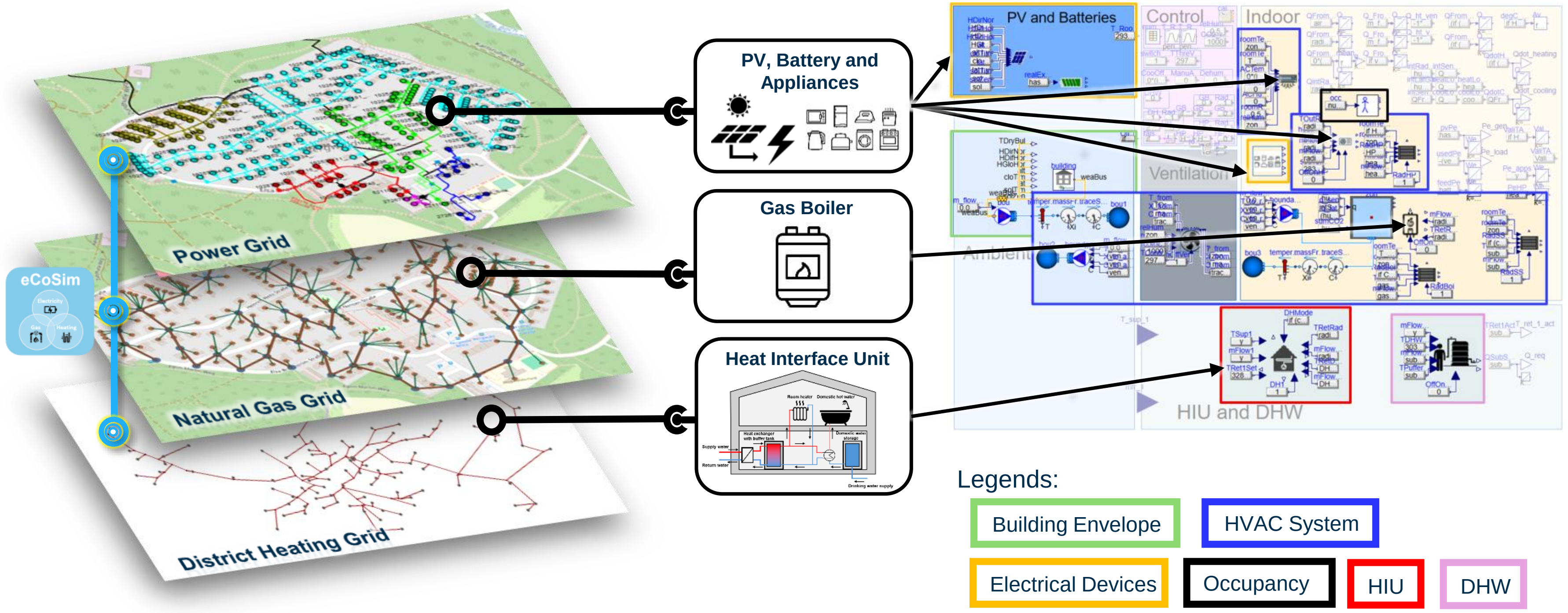
1. Climate goals demand more efficient energy systems;
2. Current building simulation tools lack **modularity** and **integration** capability;
3. A flexible, co-simulation ready model is needed to establish a **multi-physics**-based **digital twin** for the **area** and perform **co-simulation**.

Contribution

1. Multi-modal white-box **building model** using Modelica;
2. Highly modular and configurable for **various scenarios**;
3. Implementation of **economy** and **sustainability** analysis with introduced model;
4. Supports integration in large-scale co-simulations.

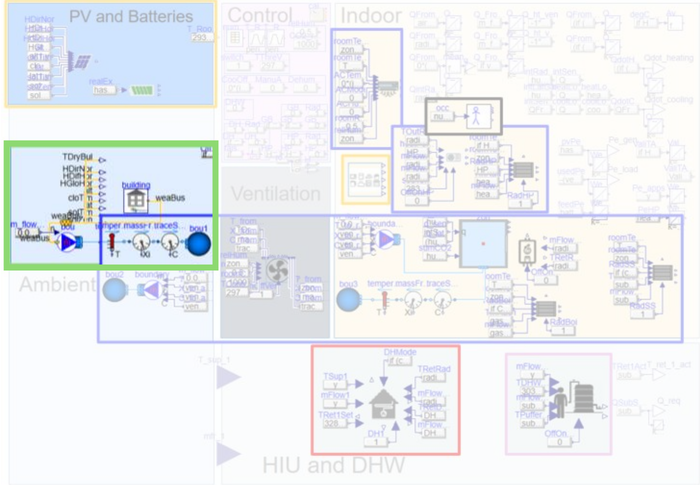
Models Overview

Sector Coupled Models using Modular Building Model



Building Model

1. Building Envelope Parameterization



Legends:

Building Envelope | HVAC System | Electrical Devices | Occupancy | HIU | DHW

- 4 buildings with different **insulation conditions;**
- Configuration using the TABULA building dataset;
- Automating this process using Python code.

	TABULA	Dymola	TABULA	Dymola	TABULA	Dymola	TABULA	Dymola	Comments
Building Code	DE.N.SFH.05.Gen.ReEx.001.001		DE.N.SFH.05.Gen.ReEx.001.002		DE.N.SFH.07.Gen.ReEx.001.001		DE.N.SFH.07.Gen.ReEx.001.002		
Description	Single family house 05, existing state		Single family house 05, refurbishment		Single family house 07, existing state		Single family house 07, refurbishment		
TABULA Image	 DE.N.SFH.05.Gen				 DE.N.SFH.07.Gen				2 single family houses with different construction year
A_roof	168.90	168.90	168.90	168.90	100.80	100.80	100.80	100.80	Roof area [m2]
A_wall	141.20	141.20	141.20	141.20	159.40	159.40	159.40	159.40	Wall area [m2]
surAzi_N	-	3.14	-	3.14	-	3.14	-	3.14	Suppose the building has four sides and faces north, east, south and west
A_floor	115.80	115.80	115.80	115.80	83.40	83.40	83.40	83.40	Floor area [m2]
A_window	27.10	-	27.10	-	27.00	-	27.00	-	Window area [m2]
A_window_N	4.10	4.10	4.10	4.10	3.60	3.60	3.60	3.60	Window area in the north [m2]
A_window_E	5.70	5.70	5.70	5.70	8.70	8.70	8.70	8.70	Window area in the east [m2]
A_window_S	6.30	6.30	6.30	6.30	6.00	6.00	6.00	6.00	Window area in the south [m2]
A_window_W	8.90	8.90	8.90	8.90	8.70	8.70	8.70	8.70	Window area in the west [m2]
g_Fac	0.75	0.75	0.60	0.60	0.75	0.75	0.60	0.60	Energy transmittance of glazings
win_Fra	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	Frame fraction of windows
shaRedFac	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	External shading reduction factor of window
F_red	0.80	-	0.88	-	0.88	-	0.95	-	Temperature reduction factor
b_tr_floor	0.50	-	0.50	-	0.50	-	0.50	-	Adjustment factor soil
U_roof	0.80	0.72	0.41	0.45	0.50	0.53	0.41	0.48	U_values [W/(m2K)]
U_wall	1.20	1.04	0.23	0.29	0.80	0.79	0.21	0.29	
U_floor	1.08	0.51	0.31	0.22	0.65	0.37	0.26	0.22	
U_window	2.80	2.32	1.30	1.23	4.30	3.87	1.30	1.33	
A_c_ref	121.20	121.20	121.20	121.20	215.60	215.60	215.60	215.60	Reference conditioned floor area [m2]
ratSur	-	3.91	-	3.91	-	6.44	-	6.44	Ratio between the internal surfaces area and the floor area
n_air	0.60	0.48	0.60	0.53	0.60	0.53	0.60	0.57	Air change rate [1/h]

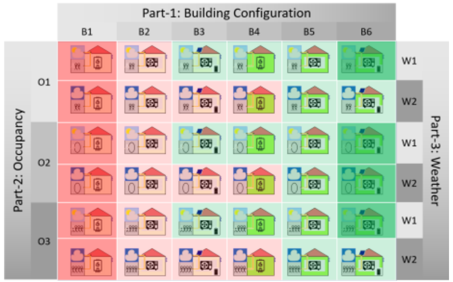
Source: H. Cheng, J. Stock, A. Xhonneux, H. K. Çakmak and V. Hagenmeyer, "Construction and Control of Validated Highly Configurable Multi-Physics Building Models for the Sustainability Analysis of Multi-Energy Systems in a Co-Simulation Setup," *SoutheastCon 2025*, Concord, NC, USA, 2025

Building Model

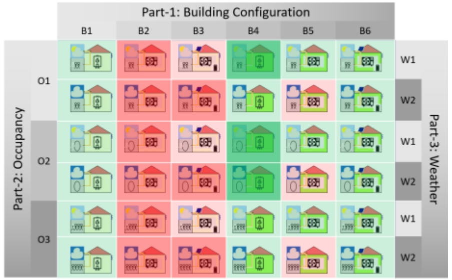
2. Economic and Sustainability Analysis

- **Assumptions:**
  - CO_2 emissions of natural gas: 2.23kg/kg;
  - CO_2 emissions of electricity: 380g/kWh_{el} (according to German power mix in 2023);
  - Basic electricity price: 39.86ct/kWh (Apr. 2024);
  - Spot market price of natural gas: 29.07€/MWh (Apr. 2024).

CO_2 Emissions



Heating Costs



Scenario Code	V_{gas} $[m^3]$	E_{load} $[kWh]$	E_{gen} $[kWh]$	E_{feed} $[kWh]$	$CO_{2,emi}$ $[t]$	Costs [€]
B1O1W1	438.195	-296.523	-	-296.523	0.934	283.155
B1O1W2	535.885	-296.523	-	-296.523	1.116	319.932
B1O2W1	475.661	-54.351	-	-54.351	0.912	200.73
B1O2W2	571.857	-54.351	-	-54.351	1.092	236.944
B1O3W1	428.966	-361.164	-	-361.164	0.941	305.447
B1O3W2	526.779	-361.164	-	-361.164	1.124	342.269
B2O1W1	-	-1856.21	-	-1856.21	0.705	739.885
B2O1W2	-	-2258.76	-	-2258.76	0.858	900.342
B2O2W1	-	-1768.41	-	-1768.41	0.672	704.888
B2O2W2	-	-2127.91	-	-2127.91	0.809	848.185
B2O3W1	-	-1883.27	-	-1883.27	0.716	750.671
B2O3W2	-	-2287.95	-	-2287.95	0.869	911.977
B3O1W1	-	-1856.21	404.9	-1464.91	0.557	583.913
B3O1W2	-	-2258.76	404.9	-1858.47	0.706	740.786
B3O2W1	-	-1768.41	404.9	-1378.16	0.524	549.335
B3O2W2	-	-2127.91	404.9	-1728.83	0.657	689.112
B3O3W1	-	-1883.27	404.9	-1492.36	0.567	594.855
B3O3W2	-	-2287.95	404.9	-1887.84	0.717	752.493
B4O1W1	212.111	-296.523	-	-296.523	0.51	198.045
B4O1W2	269.661	-296.523	-	-296.523	0.618	219.71
B4O2W1	254.625	-54.351	-	-54.351	0.498	117.52
B4O2W2	311.144	-54.351	-	-54.351	0.603	138.796
B4O3W1	203.938	-361.164	-	-361.164	0.519	220.734
B4O3W2	261.63	-361.164	-	-361.164	0.627	242.452
B5O1W1	-	-973.272	-	-973.272	0.37	387.946
B5O1W2	-	-1186.33	-	-1186.33	0.451	472.871
B5O2W1	-	-883.185	-	-883.185	0.336	352.038
B5O2W2	-	-1098.12	-	-1098.12	0.417	437.711
B5O3W1	-	-1003.04	-	-1003.04	0.381	399.812
B5O3W2	-	-1218.42	-	-1218.42	0.463	485.662
B6O1W1	-	-973.272	404.9	-605.212	0.23	241.238
B6O1W2	-	-1186.33	404.9	-810.742	0.308	323.162
B6O2W1	-	-883.185	404.9	-515.471	0.196	205.467
B6O2W2	-	-1098.12	404.9	-723.219	0.275	288.275
B6O3W1	-	-1003.04	404.9	-634.085	0.241	252.746
B6O3W2	-	-1218.42	404.9	-843.771	0.321	336.327

Source: H. Cheng, V. Hagenmeyer and H. K. Çakmak, "Economy and Sustainability Analysis With A Novel Modular Configurable Multi-Modal White-Box Building Model," 2025 Annual Modeling and Simulation Conference (ANNSIM), Madrid, Spain, 2025

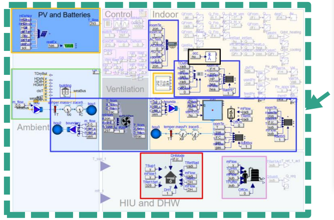
Heat Grid Model

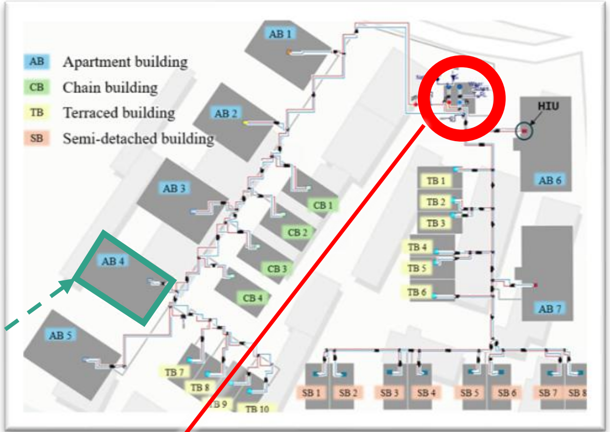
Karlsruhe Institute of Technology

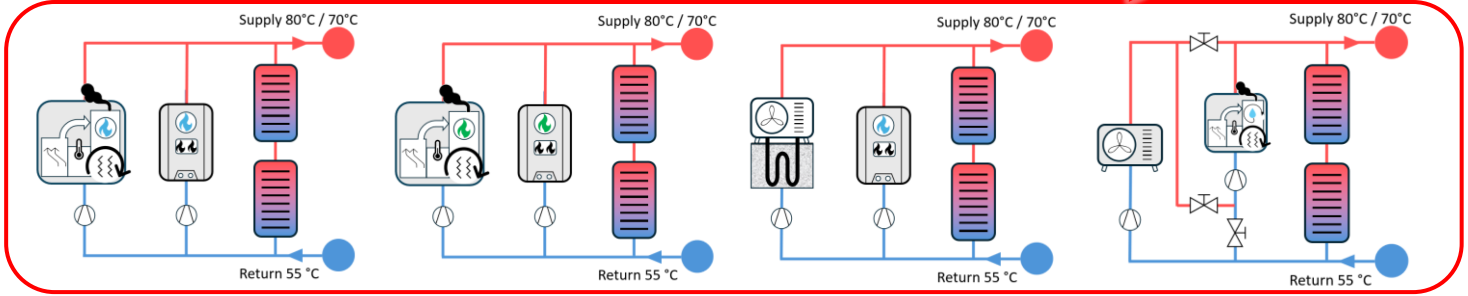
1. Model Construction

- **29 buildings** with different configurations**;**
- **Heat gird** model built using Modelica;
- **4 heating center** variants.

Variants	Basic Load Module	Peak Load Module
Variant-1 CHP-NG + PLB-NG	**CHP - Natural Gas** *2g – g-box 50 plus*	**Peak Load Boiler - Natural Gas** *Viessmann – Vitocrossal 200 CM2*
Variant-2 CHP-BM + PLB-BM	**CHP - Biomethane** *2g – g-box 50 plus*	**Peak Load Boiler - Biomethane** *Viessmann – Vitocrossal 200 CM2*
Variant-3 HP-Geo + PLB-NG	**HP - Geothermal heat** *Viessmann – Vitocal 350-HT Pro*	**Peak Load Boiler - Natural Gas** *Viessmann – Vitocrossal 200 CM2*
Variant-4 HP-A + CHP-H2	**HP - Air** *2g – afilia air M-AEK-sl-4*	**CHP - Hydrogen** *2g –agenitor 404 pure H2*







10 YEARS Urban Energy Systems Laboratory

Source: H. Cheng, V. Buccoliero, A. Kocher, V. Hagenmeyer and H. K. Çakmak, "New Co-Simulation Variants for Emissions and Cost Reduction of Sustainable District Heating Planning," 2024 IEEE PES 16th Asia-Pacific Power and Energy Engineering Conference (APPEEC), Nanjing, China

Heat Grid Model

2. Analysis Results

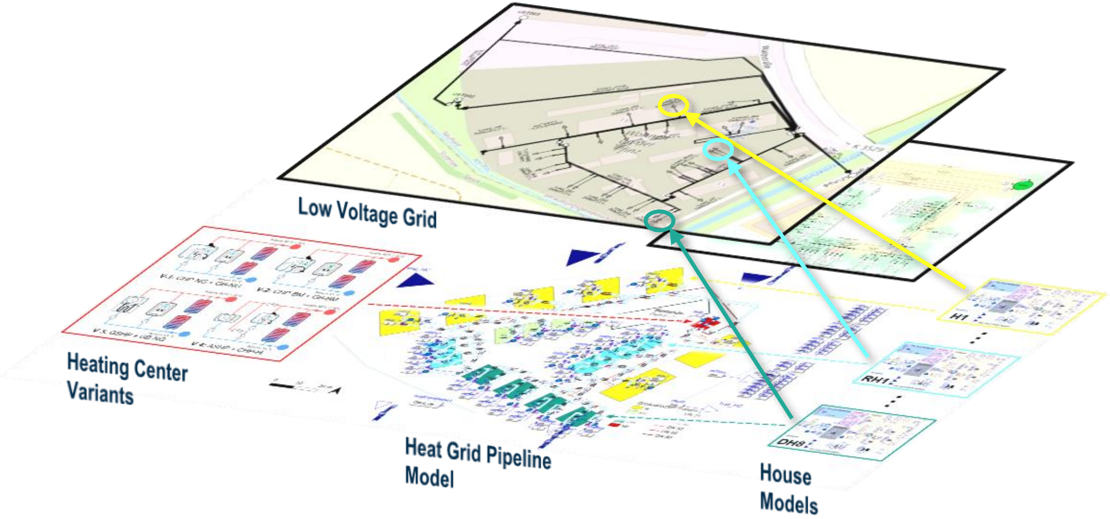
- Taking into account the self-use and sale of CHP power generation.

	Variant-1 CHP-NG + PL-NG		Variant-2 CHP-BM + PL-BM				Variant-3 HP-Geo + PL-NG		Variant-4 HP-A + CHP-H2			
Electricity sales	N	Y	N		Y		N		N		Y	
Heat generation - Base load	CHP		CHP				HP-Geothermal		HP-Air			
Heat generation - Peak load	Peak load boiler		Peak load boiler				Peak load boiler		CHP			
Energy source(s)	Natural gas		Bio-Methan				Electricity + Natural gas		Electricity + Hydrogen			
CO_2-Emissions [t]	136		41	+	41	+	33	+	31	++	31	++
Emission reduction compared to Variant-1	0%		70%	+	70%	+	76%	++	77%	++	77%	++
Heat production costs k [ct/kWh]	14.86	1.83	21.55	-	8.53	-	12.23	++	26.33	--	16.51	-
Fuel energy consumed [MWh]	673		673	0	673	0	264	++	625	+	625	+
Fuel costs [€]	51817		87484	--	87484	--	49242	+	65187	-	65187	-
Fixed costs (investment and maintenance) [€]	27320		27320	0	27320	0	16269	++	75248	--	75248	--
Flexibility and scalability	+		/	+	/	+	/	++	/	+	/	+
Security of supply	++		/	++	/	++	/	++	/	+	/	+

- Variant-3 becomes the most affordable solution if there is no electricity sold.
- It shows the huge potential of H2 and bio-methane for emission reduction.

Real District Digital Twin

➡ 29 Buildings (Modelica), 1 Power Grid (PowerFactory), 1 Heat Grid + Heating Center with 4 Variants (Modelica)

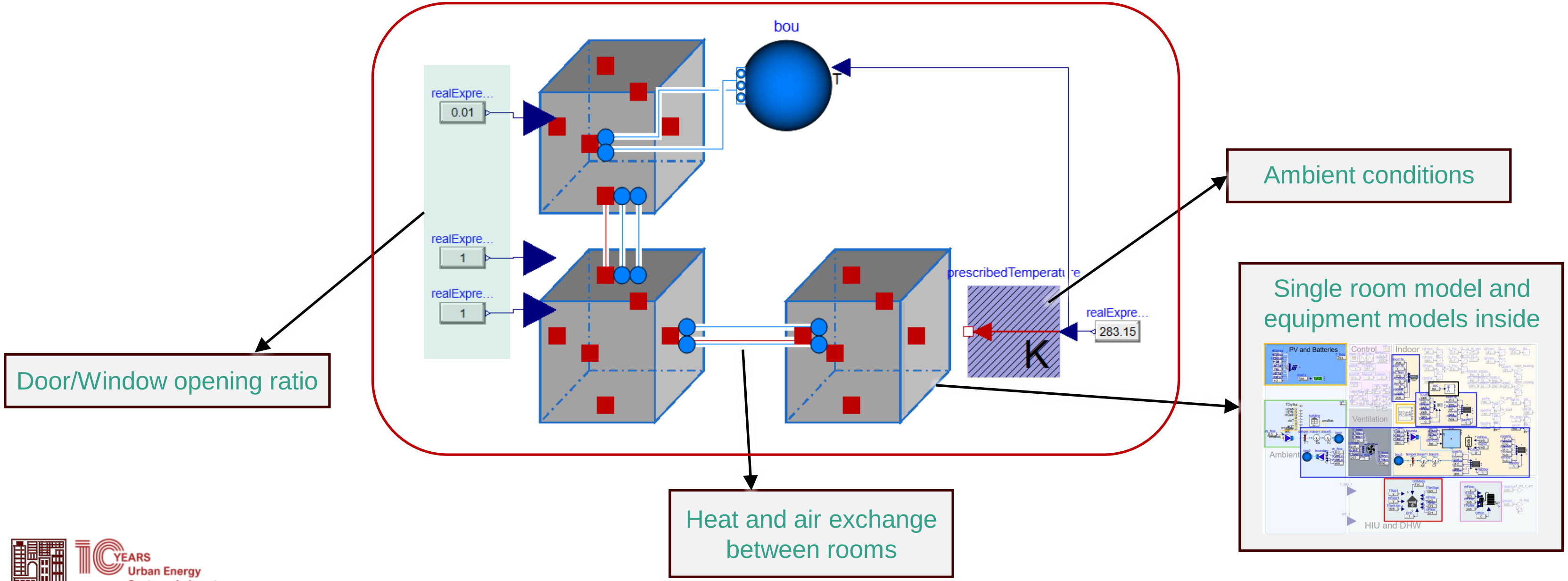


Video introduction:

https://publikationen.bibliothek.kit.edu/1000182805

Work in Progress

- Scaling of sector coupled energy system analysis to urban level with use of parallel computing.
- Building feature estimation with machine learning.
- Modular multi-zone building model using Modelica:



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