Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

BUILDING ENVELOPE MODELLING

The development of simulation and optimization models for energy-flexible operation in the built environment

ZEN MEMO No. 66 – 2025

Benjamin Manrique Delgado, Harald Taxt Walnum, Igor Sartori | SINTEF Community

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Keywords: Energy flexibility, thermal envelope, space heating, load profiles.

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Preface

Acknowledgements
This memo has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the Research Council of Norway, the Norwegian University of Science and Technology (NTNU), SINTEF, the municipalities of Oslo, Bergen, Trondheim, Bodø, Bærum, Elverum and Steinkjer, Trøndelag county, Norwegian Directorate for Public Construction and Property Management, Norwegian Water Resources and Energy Directorate, Norwegian Building Authority, ByBo, Elverum Tomteselskap, TOBB, Snøhetta, AFRY, Asplan Viak, Multiconsult, Civitas, FutureBuilt, Heidelberg Materials, Skanska, GK, NTE, Smart Grid Services Cluster, Statkraft Varme, Renewables Norway and Norsk Fjernvarme.

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities
The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society. Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, Mære Campus, Ydalir in Elverum, Campus Evenstad, Ny by-ny flyplass Bodø, and Zero Village Bergen.

The ZEN Research Centre is a eight year project ending in 2025, and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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Abstract

This memo describes the development process of simulation and optimization models for energy-flexible operation of building envelopes. These models consist of linear time invariant state space models designed to consider space heating q_{sh} as the input and the following inputs as disturbances: outdoor temperature T_{out}, global horizontal solar radiation solGlob, internal gains q_{int} and ventilation heat q_{vent}.

A set of nine archetypes has been developed, consisting of three types of building – *House*, *Apartment*, and *Commercial* – at three energy efficiency levels – *Regular*, *Efficient*, *Very Efficient*. The *House* archetype represents detached and semi-detached houses containing 1.25 dwellings; *Apartment* represents an apartment building with 16 dwellings; and *Commercial* represents a building used for commercial purposes. The efficiency levels represent three categories of heat demand required by the buildings: *Regular* represents a building with energy demand representative of an average of the building stock, *Efficient* represents buildings from 2010 and later adhering to current energy efficiency guidelines, and *Very Efficient* represents buildings with energy demand similar to buildings adhering to a *Passive house* standard.

FLEXor is a simulation and optimization tool for energy generation, demand, and use in the built environment. It is implemented in Python. All the sub-models in FLEXor, including the one described in this memo, are designed to be self-standing. Thus, they are self-contained, and do not include the control and/or optimization of other components. However, these models are to become part of a larger high-level model, FLEXor, that may include DHW tanks, electric vehicles, and other different components. Therefore, the models are designed to be i) linear, ii) in state space form (when applicable), and iii) transparent. This will allow the high-level model to be fast, lean, relatively simple, and able to leave a component out of the optimization process if necessary.

The main intention of FLEXor is the quantification of energy flexibility in buildings. In particular, the envelope model is used to quantify SH flexibility: this is a demand-side management strategy that relies on shifting the supply of heat for space heating away from hours with high energy prices, and/or by reducing its peak power to lower costs related to power-driven grid tariffs.

Contents

1. Model implementation

This section presents the general framework for the building envelope models, and the specific models available in the FLEXor tool, which is available online as a Web app and via API (Application Programming Interface) at the following addresses:

- Web app: https://flexor.jollymeadow-8539f348.norwayeast.azurecontainerapps.io/
- API: https://flexibilitysuite.byggforsk.no/index.html

A ZEN Report describing FLEXor is also in publication, while a presentation of the tool in pdf format is downloadable from the API webpage.

1.1 Linear time invariant state space models

The building envelope models are linear time invariant (LTI) systems that can be described with ordinary differential equations (ODEs). These models can be formulated as continuous state space models in following vectorial form:

Eq. 1a $$\dot{\boldsymbol{x}}(\boldsymbol{t}) = \mathbf{A}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{B}\boldsymbol{u}(\boldsymbol{t}) + \mathbf{E}\boldsymbol{d}(\boldsymbol{t})$$

Eq. 1b $$\boldsymbol{y}(\boldsymbol{t}) = \mathbf{C}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{D}\boldsymbol{u}(\boldsymbol{t})$$

$\dot{x}(t)$ is the state vector, which for the building envelope models represents the internal temperatures of the building (both air and envelope). $u(t)$ is the input vector, which is the heat supplied by the heat sources. $d(t)$ is the disturbance vector, such as outdoor temperature, solar gains, and internal gains. $y(t)$ is the measured output, normally the indoor temperature.

In the domain of grey-box modelling, stochastic differential equations (SDEs) are often used to account for discrepancies between model predictions and measurements, as well as to account for noise in the measurements itself. It is also praxis to formulate the state space model using only the first set of equations (*system equations*), Eq.1a, to describe the dynamics of the system's states. While the second set of equations, Eq.1b, become static equations that relate the measurements, or observations, to the states (*observation equations*)[1]. This means that the matrix D is always null, while the matrix C contains only 0, for non-measurable states, and 1, for measurable states. Thus, $y(t)$ becomes simply the measured output vector.

The focus with FLEXor is to use the models within an optimization problem, to estimate the optimal response to a price signal; it is not to estimate the model's parameters from a set of measurements. This means that the system equations, Eq.1a, are described with ODEs, while the observation equations, Eq.1b, are not relevant.

Applying the "zero order hold" assumption (ref), the continuous formulation can be transformed into discrete form:

Eq. 2 $$\boldsymbol{x}(\boldsymbol{t}+\mathbf{1}) = \mathbf{A}_{\boldsymbol{d}}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{B}_{\boldsymbol{d}}\boldsymbol{u}(\boldsymbol{t}) + \mathbf{E}_{\boldsymbol{d}}\boldsymbol{d}(\boldsymbol{t})$$

Simulation

[1] Thilker, C.A., Junker, R.G., Bacher, P., Jørgensen, J.B., Madsen, H. (2021). Model Predictive Control Based on Stochastic Grey-Box Models. In: Ploix, S., Amayri, M., Bouguila, N. (eds) Towards Energy Smart Homes. Springer, Cham. https://doi.org/10.1007/978-3-030-76477-7_11

In simulation mode, both $u(t)$ and $d(t)$ are known vectors for the whole simulation period. The system can therefore be simulated directly timestep by timestep (k).

Eq. 3 $$\boldsymbol{x_{k+1} = A_d x_k + B_d u_k + E_d d_k}$$

Optimization

In optimization, the supplied heat $u(t)$, for each time step, is the optimization variable. For example, to optimize for cost minimization, the problem can be formulated as follows:

Eq. 4a $$\min\left[\sum_{k=1}^{N_c}(c_k^{var} u_k)\,\Delta t\right]$$

Eq. 4b $$s.t. \quad x_{k+1} = Ax_k + Bu_k + Ed_k$$

Eq. 4c $$\underline{x}_k \le x_k \le x_k$$

Eq. 4d $$0 \le u_k \le \overline{u}_k$$

Where c_k^{var} is the energy cost for each timestep k. $\underline{x}_k$ and x_k are the lower and upper indoor temperature constraints, and $\overline{u}_k$ is the maximum capacity of the heater.

In some applications there is a risk that the only valid solution to the problem is that the internal temperature $x(t)$ is outside the allowed temperature range (e.g. during warm periods). The temperature constraint can therefore be formulated as a soft constraint. The violation of the temperature constraint δ is included in the objective function with a penalty factor ρ. The optimization problem is then formulated as follows:

Eq. 5a $$\min\left[\sum_{k=1}^{N_c}(c_k^{var} u_k + \rho\delta_k)\,\Delta t\right]$$

Eq. 5b $$s.t. \quad x_{k+1} = Ax_k + Bu_k + Ed_k$$

Eq. 5c $$\underline{x}_k - \delta_k \le x_k \le \overline{x}_k + \delta_k$$

Eq. 5d $$0 \le u_k \le \overline{u}_k$$

Eq. 5e $$\delta_k \ge 0$$

1.2 Model structure

In this section, the *TiTe* building envelope model is described. *TiTe* is a two-state formulation where, in addition to the indoor temperature, the internal temperature of the building envelope is calculated. The model is designed to consider q_{sh} as the input and the following inputs as disturbances: outdoor temperature T_{out}, global horizontal solar radiation I_s, internal gains q_{int} and ventilation heat q_{vent}. If any of these disturbances should be neglected, their input time series are set to zero. I_s is multiplied by the parameter gA_w which represents the effective window area multiplied with its g-value. Moreover, the solar radiation, internal gains and ventilation heat are multiplied by the factors α_s, α_i and α_v, respectively. Further details about these factors are given in Section 3. The model can be represented by the following RC-network:

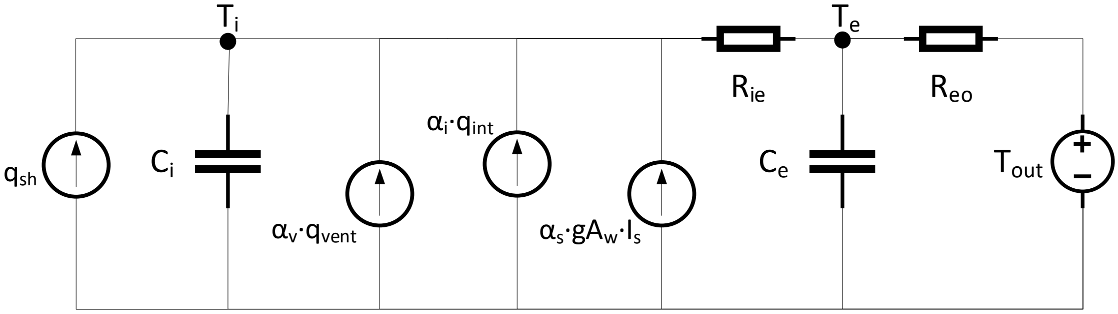

Figure 1. RC-circuit representation of the second order *TiTe* model

And the following differential equations:

$$dT_i = \frac{1}{C_i R_{ie}}(T_e - T_i)dt + \frac{1}{C_i}(q_{sh} + \alpha_s * gA_w * I_s + \alpha_i * q_{int} + \alpha_v * q_{vent})dt$$

$$dT_e = \frac{1}{C_e R_{ie}}(T_i - T_e)dt + \frac{1}{C_e R_{eo}}(T_{out} - T_e)dt$$

States	
T_i	Indoor temperature
T_e	Internal temperature of the building envelope
Parameters	
C_i	Thermal capacity of interior
C_e	Thermal capacity of building envelope
R_{ie}	Thermal resistance between indoor and envelope state
R_{eo}	Thermal resistance between envelope state and outdoor
gAw	Effective window area

As described above, the system can be represented by a continuous state model as

$$\dot{\boldsymbol{x}}(\boldsymbol{t}) = \mathbf{A}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{B}\boldsymbol{u}(\boldsymbol{t}) + \mathbf{E}\boldsymbol{d}(\boldsymbol{t})$$

where:

$$\boldsymbol{x}(\boldsymbol{t}) = \begin{bmatrix} \boldsymbol{T_i(t)} \\ \boldsymbol{T_e(t)} \end{bmatrix}, \qquad \boldsymbol{u}(\boldsymbol{t}) = [\boldsymbol{q_{sh}}], \qquad \boldsymbol{d}(\boldsymbol{t}) = \begin{bmatrix} \boldsymbol{T_{out}} \\ \boldsymbol{I_s} \\ \boldsymbol{q_{int}} \\ \boldsymbol{q_{vent}} \end{bmatrix},$$

$$\mathbf{A} = \begin{bmatrix} -\frac{1}{C_i R_{ie}} & \frac{1}{C_i R_{ie}} \\ \frac{1}{C_e R_{ie}} & -\frac{1}{C_e (R_{ie} + R_{eo})} \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} \frac{1}{C_i} \\ 0 \end{bmatrix}, \qquad \mathbf{E} = \begin{bmatrix} 0 & \frac{\alpha_s * gAw}{C_i} & \frac{\alpha_i}{C_i} & \frac{\alpha_v}{C_i} \\ \frac{1}{C_e R_{eo}} & 0 & 0 & 0 \end{bmatrix}.$$

1.3 Archetypes

A set of nine archetypes has been developed, consisting of three types of building – *House*, *Apartment*, and *Commercial* – at three energy efficiency levels – *Regular*, *Efficient*, *Very Efficient*. The *House* archetype represents detached and semi-detached houses containing 1.25 dwellings; *Apartment* represents an apartment building with 16 dwellings; and *Commercial* represents a building used for commercial purposes. It is meant to be considered an amalgamation of several types of commercial buildings such as offices, schools, shops, etc., created as a weighted average of the accumulated floor area in the building stock for these types of buildings. The geometric characteristics of the archetypes are shown in Table 1.

Table 1 – Main geometric characteristics of the available building types.

	House	Apartment	Commercial
Floor area (BRA) per building [m^2]	150	1120	3600
Floor area (BRA) per dwelling [m^2]	120	70	0
Dwellings per building [#]	1.25	16	0
Nr. floors [#]	2.14	4.16	1.63
Ceiling height [m]	2.4	2.4	2.4
BRA/BTA* ratio [#]	0.85	1	1
BTA [m^2]	176.5	1120	3600
Footprint (roof area) [m^2]	82.5	269.2	2201.3
Ratio footprint/BRA	0.55	0.24	0.61
Area Windows [% BRA]	0.15	0.15	0.15
g-value	0.5	0.5	0.5

The efficiency levels represent three categories of heat demand required by the buildings: *Regular* represents a building with energy demand representative of an average of the building stock, *Efficient* represents buildings from 2010 and later adhering to current energy efficiency guidelines, and *Very Efficient* represents buildings with energy demand similar to buildings adhering to a *Passive house* standard. Each combination of building type and efficiency level has a set of RC values for their representation as RC models. These values are summarized in Table 2. The H-values have been calculated based on Simien shoe-box models for the *Regular* and *Efficient* levels and based on a Simien shoe-box model and on table 2 from NS 3700:2013 for the *Very Efficient* level. The resistances are based on the H-value, where R_i is calculated as 1/(H-value*10) and R_e is calculated as 9*R_i. C_i is calculated as c_{air}*2.4*12, where c_{air} is the specific heat of air with a value of 0.33 Wh/m^3K, 2.4 is the ceiling height in m, and 12 is a multiplier, empirically derived, to account for internal mass in the building and delays between heat emitter and temperature sensors. The resulting value for C_i is 9.5 Wh/m^2K for all archetypes. This is similar to the values reported in other works that have calculated internal thermal capacities of different building types according to the standard method ISO 13786. Johra and Heiselberg (2017)[2] calculate the effective thermal inertia of the internal mass (furniture), while Johra *et al.* (2024)[3] calculate that of the building structure (both external walls and internal partitions) for a 1h modulation, i.e. accounting only for the fastly activated, effective thermal mass. The sum of these two components is the equivalent of C_i in our model, and it has an average value of ca. 8 Wh/m^2K. C_e is based on NS 3031:2014, Tabel B.8.

[2] H. Johra and P. Heiselberg (2017) Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review, *Renewable and Sustainable Energy Reviews*, Vol 69, pp 19-32.
[3] H. Johra, M. Goupy and K. Wittchen (2024) Expanding Building Archetypes to Estimate the Indoor Environment Thermal Storage Capacity in the Danish Building Stock when Performing Demand Response, *E3S Web of Conf.*, 562 (2024) 04002.

The short and long time-constants of the building, τ, are shown in Table 3. τ can be interpreted as the time response to changes in temperature of a building. Short τ is the time constant of the fastly activated thermal mass (indoor air, furniture, first centimeters of internal and external walls, floors, ceilings) and long τ is the time constant of the slowly activated building envelope (deeper penetration of heat into internal and external walls, floors, ceilings).

Table 2 – RC values of the nine building archetypes available.

Building type	Efficiency	H-value [W/m^{2}K]	R_i [m^{2}K/W]	R_e [m^{2}K/W]	C_i [Wh/ m^{2}K]	C_e [Wh/ m^{2}K]
House	Regular	1.41	0.071	0.638	9.50	65
	Efficient	0.74	0.135	1.216	9.50	65
	Very eff.	0.54	0.185	1.667	9.50	65
Apartment	Regular	1.30	0.077	0.692	9.50	112
	Efficient	0.69	0.145	1.304	9.50	112
	Very eff.	0.50	0.200	1.800	9.50	112
Commercial	Regular	1.01	0.099	0.891	9.50	112
	Efficient	0.56	0.179	1.607	9.50	112
	Very eff.	0.40	0.250	2.250	9.50	112

Table 3 – Long and short τ of the nine building archetypes available.

Building type	Efficiency	Long τ [h]	Short τ [min]
House	Regular	48	35
	Efficient	91	67
	Very eff.	124	92
Apartment	Regular	84	40
	Efficient	159	76
	Very eff.	219	105
Commercial	Regular	108	52
	Efficient	195	94
	Very eff.	274	131

2. Optimization modes

2.1 Proxy temperature and temperature delta

The main intention of FLEXor is the quantification of energy flexibility in buildings. In particular, the envelope model is used to quantify SH flexibility: this is a demand-side management strategy that relies on shifting the supply of heat for space heating away from hours with high energy prices, and/or by reducing its peak power to lower costs related to power-driven grid tariffs. However, such shifting actions inherently lead to different temperatures inside the building compared to those under typical operation. One approach to avoid unacceptable disruptions of the thermal comfort inside the building is to 1) identify the thermal conditions inside the building under typical operation, 2) determine acceptable deviations from those thermal conditions, and 3) setup the bounds of the optimization model according to the acceptable deviations.

Even though the first step can be directly calculated using the LTI models described above, the implementation presented in this memo takes advantage of PROFet. PROFet is an energy demand load profiles estimator. It consists of a statistical model based on a database with energy measurements from 2.5 mill m^2 of building area. PROFet can be called by FLEXor to obtain load profiles for space heating, domestic hot water, and electric specific demand of one or more buildings. The PROFet model is run for a given type of building with an outdoor temperature profile, and the resulting SH demand profile is given as input to the model to be run in simulation mode. The indoor temperature profile resulting from this simulation becomes the "proxy indoor temperature" for the following steps. This is the indoor temperature that in the model corresponds exactly to the PROFet energy demand for space heating. If the model would be simulated in a reverse mode, i.e. giving this proxy indoor temperature profile as an input, the output would be exactly the space heating profile as known from PROFet.

Regarding the second and third steps, in this investigation the acceptable deviation with respect to the baseline thermal condition is set to be a temperature range, where the lower bound is the proxy temperature calculated in the previous step, and the upper bound is a 2 °C increase with respect to the lower bound. This window of operation is called the "temperature delta" and is included in the model as a reformulation of Eq. 3d as

Eq. 5 $$\boldsymbol{y_{proxy,k} < y_k < y_{proxy,k} + 2}$$

It is also possible to implement this as a soft constraint by adding δ to the lower and upper bounds. A penalty must then be associated to δ in the objective function to prevent the model from using it freely.

2.2 Initialization process

The initial temperatures in the RC model are given as input to the model and influence the calculated temperatures during the initial period of the optimization. As shown in the values for long τ, they can influence the temperature of the building envelope for several days. Therefore, an initialization process can be activated to mitigate the consequences of inaccurate initial temperatures. This process consists of pre-running the envelope model using PROFet data calculated using weather profile for this specific purpose and setting the final temperatures of said pre-run as initial temperatures in the main optimization. To do this, a weather profile of n timesteps is read or created, where n can be user-given and has a default value of 336 hours (14 days): if the weather profile of n timesteps before the start time of the optimization is given as input, this profile is used; if the profile is not given, the weather profile is created with the values for the first hour of the optimization.

Once the weather profile for the initialization is available, a calculation of the absolute temperatures in the envelope for $8 * n$ timesteps is performed. The long period is set to ensure that the initialization process is longer than the long τ. The final temperatures in the envelope model during the initialization process are then set as the initial temperatures for the main optimization.

3. Input specification

Ventilation

The ventilation losses can be given as an input timeseries to FLEXor, or they can be calculated based on default values. It is assumed that ventilation is at a constant rate in the *House* and *Apartment* archetypes. As consequence of this assumption, the ventilation losses become a constant value throughout the year and are thus implicitly represented in the *R* values of the model. On the contrary, it is assumed that *Commercial* buildings have ventilation rates corresponding to *occupied* and *unoccupied* times. The default values for ventilation in *Commercial* buildings are shown in Table 4. An average temperature difference between room T_i (e.g. 22 °C) and ventilation T_{supply} (e.g. 18 °C) of 4 degrees is used for this calculation. The mass exchange rates are based on NS 3031:2014 Appendix A. During holiday periods, the *unoccupied* rates are applied throughout the day.

Table 4 – Default values for the calculation of ventilation losses.

		ΔT = 4 °C	Occupied (6h - 18h)		Unoccupied (18h - 6h, weekends and holidays)	
Building type	**Efficiency**	c_{air}*ΔT [Wh/m³]	m [m³/m²h]	q_{vent} [W/m²]	m [m³/m²h]	q_{vent} [W/m²]
Commercial	Regular	1.32	7	-9.24	2	-2.64
	Efficient	1.32	7	-9.24	2	-2.64
	Very eff.	1.32	6	-7.92	1	-1.32

Factors on disturbances

As mentioned above, the timeseries for solGlob, q_{int} and q_{vent} are multiplied by the factors α_s, α_i and α_v, respectively. The purpose of these factors is to regulate the effect that these disturbances have on the building thermal conditions. The standard values used in FLEXor for these factors are shown in Table 5. Note that even if single values are given for each factor and archetype in this table, it is possible to give up to 12 values for each factor to represent monthly variations. The values were calculated through an iteration process seeking to reach sensible monthly indoor temperatures throughout the year – ranging between 18.7 and 28.8 °C, with an average of 21.4 °C – while being as simple as possible (hence the unique annual values).

Table 5 – Values of the factors applied to the disturbances.

Building type	Efficiency	α_s	α_i	α_v
House	Regular	1	0.3	-
	Efficient	0.4	0.3	-
	Very eff.	0.3	0.2	-
Apartment	Regular	1	0.3	-
	Efficient	0.4	0.4	-
	Very eff.	0.3	0.3	-
Commercial	Regular	0.3	0.4	1
	Efficient	0.35	0.2	1
	Very eff.	0.35	0.1	1

4. Testing and evaluation

A set of optimizations have been calculated to showcase the temperature profiles resulting from the envelope model in FLEXor. The weather profile from NS 3031:2014 is used as input, and the timeseries for space heating demand and internal gains are calculated with PROFet as described above.

4.1 Proxy temperature

The average monthly indoor temperature *Ti* of the building archetypes was calculated using the NS3031:2014 standard climate data; the values are shown in Table 6. These temperatures represent the proxy indoor temperature in the archetypes in steady state, using average monthly values of outdoor temperatures, of solar and internal gains, and of space heating. These values can be useful as initial conditions for *Ti* in FLEXor.

Table 6 – Average values of proxy indoor temperature in steady state operation for the nine building archetypes, using the NS3031:2014 standard climate data.

	House			Apartment			Commercial		
Month	**Reg**	**Eff**	**Vef**	**Reg**	**Eff**	**Vef**	**Reg**	**Eff**	**Vef**
January	18.67	19.66	19.78	19.59	20.55	20.71	20.26	19.98	20.27
February	18.67	19.96	19.96	19.48	20.69	20.78	20.93	20.52	20.60
March	19.46	20.54	20.97	19.90	20.82	21.43	20.83	20.65	21.02
April	21.38	22.19	23.12	21.36	21.89	23.13	20.20	19.69	19.51
May	23.06	22.36	22.98	22.63	21.51	22.51	20.74	20.41	20.78
June	24.88	24.04	23.94	24.06	22.71	23.04	24.46	24.49	25.32
July	24.31	24.21	24.17	23.59	23.05	23.41	25.54	26.17	28.81
August	24.42	22.96	22.87	23.95	22.09	22.31	23.34	23.50	24.63
September	21.73	20.08	20.71	21.72	19.78	20.63	18.58	18.51	19.55
October	20.91	20.56	21.73	21.36	20.88	22.17	17.78	17.40	17.63
November	19.45	19.96	20.55	20.19	20.65	21.30	19.14	18.86	19.07
December	19.10	19.86	20.10	20.01	20.74	21.01	19.67	19.42	19.79

The hourly proxy indoor temperatures of houses, apartments and commercial buildings at the three energy efficiency levels are shown for one year in Figure 2, Figure 3 and Figure 4, and closeups into

January are shown in Figure 5, Figure 6 and Figure 7. The minimum proxy indoor temperatures throughout the year range between 15.8 and 19.7 °C, the average temperatures range between 20.9 and 21.9 °C, and the maximum temperatures range between 24.6 and 29.8 °C.

The influence of the internal gains on the daily temperature cycles can be seen in the January profiles. In Houses and Apartments, the higher electricity demand during the morning and evening peak hours is reflected in the proxy indoor temperatures. These daily variations, however, are different in Commercial buildings, where the internal gains and ventilation losses are rather influenced by the working hours. The effect of these disturbances on the proxy indoor temperatures are visible in the January profiles of Commercial buildings. Notably, starting January 7th and 14th, periods of relatively steady proxy indoor temperatures can be seen. These periods correspond to weekends, when the buildings are not occupied and thus have less internal gains and lower ventilation losses.

The temperature profiles during January do not show a steady increase or decrease during the first weeks of the optimization period, which is an indication that the initial temperatures calculated by the initialization process are suitable and allow the envelope to start in a stable condition.

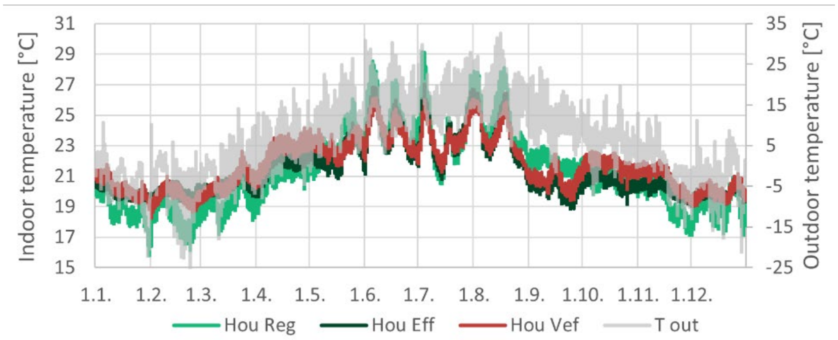

Figure 2 – The hourly proxy indoor temperatures of the House archetype for one year using a standard weather profile.

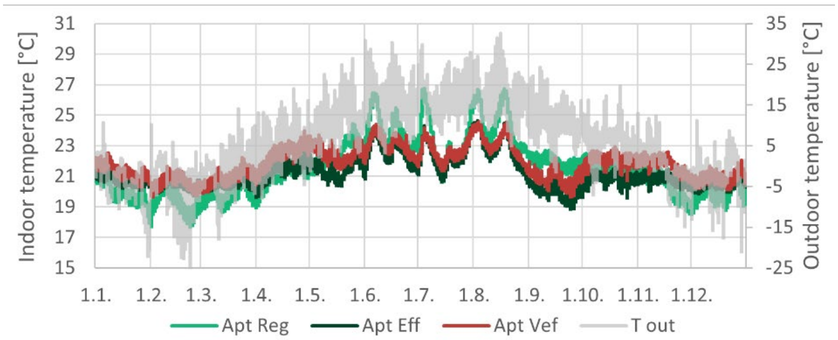

Figure 3 – The hourly proxy indoor temperatures of the Apartment archetype for one year using a standard weather profile.

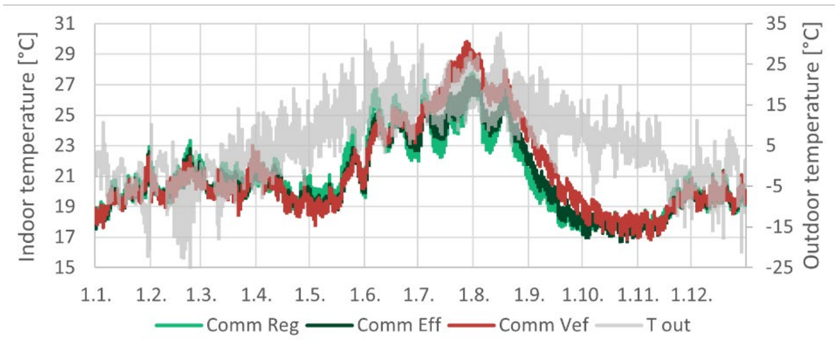

Figure 4 – The hourly proxy indoor temperatures of the Commercial archetype for one year using a standard weather profile.

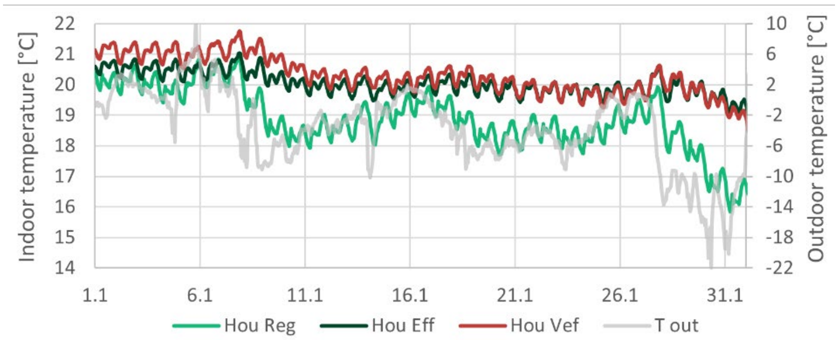

Figure 5 – The hourly proxy indoor temperatures of the House archetype for January using a standard weather profile.

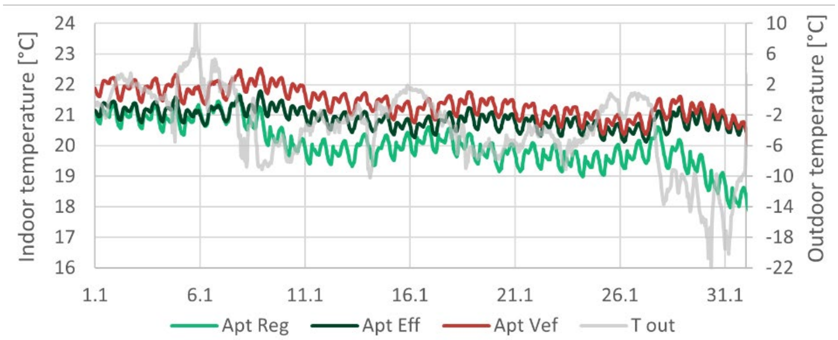

Figure 6 – The hourly proxy indoor temperatures of the Apartment archetype for January using a standard weather profile.

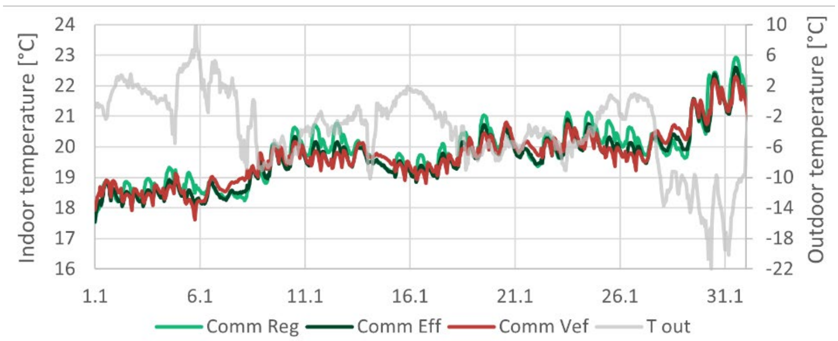

Figure 7 – The hourly proxy indoor temperatures of the Commercial archetype for January using a standard weather profile.

4.2 Temperature delta

An example calculation of the indoor temperature delta for a *regular* Apartment is shown in Figure 8. It consists of a minimization of operation costs. The spot price profile used for this purpose is also shown in Figure 8. The behavior of the temperature delta shows how the envelope is used for enabling flexibility. During hours with low prices, the indoor temperature is increased to the allowed limit (+2 °C) to store heat in the building; this stored heat is later depleted during hours with high spot prices. This process of increasing the heat input to the envelope when prices are low and reducing it when prices are high directly leads to lower energy imports when prices are high.

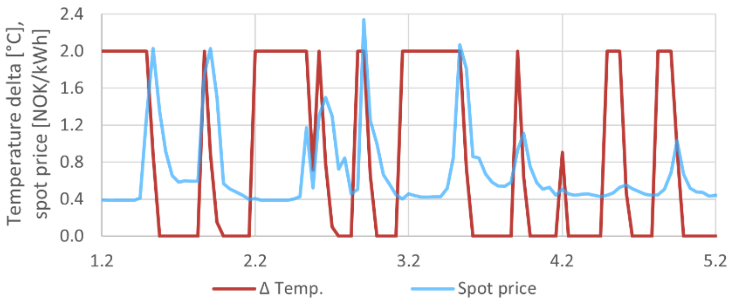

Figure 8 – The calculated indoor temperature delta in a *regular* Apartment during four days in February for a cost saving optimization.

Another example calculation of the indoor temperature delta for a *regular* Apartment is shown in Figure 9. It consists of an optimization aiming to flatten the profile of electricity import from the grid. The resulting electricity import profile is also shown in Figure 9, segregated into electricity imported to cover the electric specific demand [ESP], domestic hot water preparation [DHW] and space heating [SH]. The behavior of the temperature delta shows how the envelope is used for enabling flexibility. The indoor temperature is optimized within the allowed comfort band of 2 °C to allow the electricity use for space heating to smoothen the total electricity import when added to the electricity used to cover the other needs of the building.

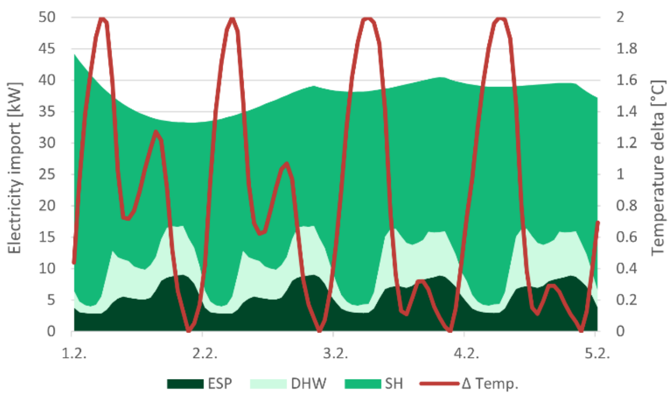

Figure 9 – The electricity import for electric specific demand [ESP], domestic hot water preparation [DHW] and space heating [SH], and the calculated indoor temperature delta, in a *regular* Apartment during four days in February for a flattening optimization.

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