Building Energy Simulation For Nearly Zero Energy Retrofit Design: The Model Calibration

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***Abstract* — Building energy simulation is an effective tool to design retrofit and management interventions, provided that the simulation model is carefully calibrated. As a first step towards the development of guidelines for using dynamic simulation for the design of retrofit interventions aiming at the nZEB target, in the present study a calibration procedure, consisting in tuning the building walls model first, is demonstrated. Therefore, starting from a real building case study, the walls model is created in parallel within different building simulation environments, namely EnergyPlus, IDA ICE and OpenBPS. The impact of the simulation tool and of the calibration procedure on the model predictions is thus investigated and discussed.**

Keywords—building simulation; model calibration.

I. Introduction

According to the EU EPBD Directive [1], nearly Zero Energy Buildings are high energy performance buildings, having a very low energy demand almost entirely supplied by renewable energy sources, including renewable energy conversion on site. By 2020 all new buildings should comply with the nZEB standard. However, the energy quality of the building stock in EU is generally very poor. Therefore, energy retrofit of existing buildings becomes a crucial issue to reduce the energy consumption of the building sector. Renovating existing buildings towards the nZEB target is a challenging task, requiring cost-effective innovative and integrated solutions. The PRIN Project "Renovation of existing buildings in NZEB vision: a national research network" aims at developing reference methods and solutions to achieve this target in the Italian context.

Among the evaluation methods, dynamic energy simulation of buildings should be considered. While the initial focus of dynamic energy simulation was mainly on the design phase, it is nowadays becoming more and more important in post-construction phases. Indeed building energy simulation is an effective tool to identify the critical issues in running buildings and systems and to design retrofit and management interventions.

However, in order to have a robust prediction of the impact on energy consumption and comfort of the planned interventions, the simulation model has to be calibrated against measured data. The key parameters of the model are identified and their value is adjusted in order to minimize discrepancy with metered data. The calibration process is not straightforward, since there are many parameters and few metered data. The inverse problem is ill-posed and may lead to a non-unique solution.

Different approaches to calibration can be found in literature, regarding the kind and the quality of the metered data, the manual/automatic methodology, the kind of statistical indexes to be used, the uncertainty of the simulation tools etc. [2, 3]. Although several studies based on calibration have been carried out, there is a lack of consensus on the calibration methodology. The few existing guidelines, such as [4], are

This research has been carried out within the "Renovation of existing buildings in NZEB vision (nearly Zero Energy Buildings)" Project of National Interest (Progetto di Ricerca di Interesse Nazionale - PRIN) funded by the Italian Ministry of Education, Universities and Research (MIUR).

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quite simplified. Within this framework, calibration is highly dependent on the user's skill and experience.

As a first step towards the development of guidelines for the use of dynamic simulation for the design of retrofit interventions aiming at the nZEB target, in the present study a calibration procedure, consisting in tuning the building envelope model first, is demonstrated. Metered data to match with refer to walls temperatures as well as heat flows profiles. Starting from a real building case study, the single wall model is created in parallel within different building simulation environments, namely EnergyPlus, IDA Indoor Climate and Energy (IDA ICE) and Open Building Performance Simulation (OpenBPS). The impact of the simulation tool and of the calibration procedure on the model predictions is thus investigated and discussed.

II. CASE STUDY

The case study is a two storey building located nearby Trento (Fig.1). Each storey has a plan surface of 62 m^2. The building has a wooden frame supporting structure and a highly insulated envelope, with design thermal transmittances for the walls, the roof and the slab equal to 0.12 W/(m^2.K), 0.16 W/(m^2.K) and 0.12 W/(m^2.K) respectively. The walls and the roof are slightly ventilated through an open air gap 3.5 cm and 5.5 cm wide respectively.

A continuous monitoring system is installed in the building, measuring indoor air temperature and humidity in the zones and outdoor climatic parameters every 5 minutes. Moreover, the S-SE facing wall and the roof are equipped with heat flow meters and temperature probes positioned on the surfaces and inside the stratigraphy. The present study focuses on the wall stratigraphy thermal properties calibration. Therefore the wall stratigraphy from outside to inside is reported in Table I and shown in Fig. 2. It has to be mentioned that layer # 7 contains some wood spacers. In Fig. 2 the position of the probes can also be noticed. The probes and data acquisition chain accuracy is identified as 0.5°C for the thermocouples named T1A, T2A and T3A and 0.3°C for the Platinum Thermo-Resistances named TSi and TSe. The external heat flow meter sensitivity is 66.1 μV/(W/m^2) (60.8 μV/(W/m^2) for the internal one) and the accuracy is 3% at 100 W/m^2.

Figure 1. The case study building

TABLE I. WALL STRATIGRAPHY FROM OUTSIDE

#	Material	Thickness (cm)
1	Wood panel	1.5
2	Air gap	3.5
3	High density mineral wool	10
4	Laminated Veneer Lumber (LVL) panel	1.25
5	Low density mineral wool	4
6	Laminated Veneer Lumber (LVL) panel	1.25
7	Low density mineral wool	9.5
8	Low density mineral wool	5.5
9	Plasterboard	2.5

III. METHODOLOGY

A. Simulation environments

In order to compare different simulation tools and to generalize the proposed calibration procedure, different simulation environments have been used in parallel, namely EnergyPlus, IDA ICE and OpenBPS.

EnergyPlus is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. EnergyPlus is an integrated simulation environment, where the major parts, building, system, and plant, must be solved simultaneously [5]. In order to solve heat conduction in building envelope, the user can choose between the Conduction Transfer Function (CTF) method and Finite Differences method. In the present study the Finite Difference method, with a Cranck-Nicholson scheme, was chosen, since CTF method does not provide temperature and heat flows inside the wall.

IDA ICE version 4.8, by EQUA Simulation, is a whole year detailed and dynamic multi-zone simulation tool for the study of indoor climate and energy consumption in buildings [6]. It is an equation-based modeling tool, working with symbolic

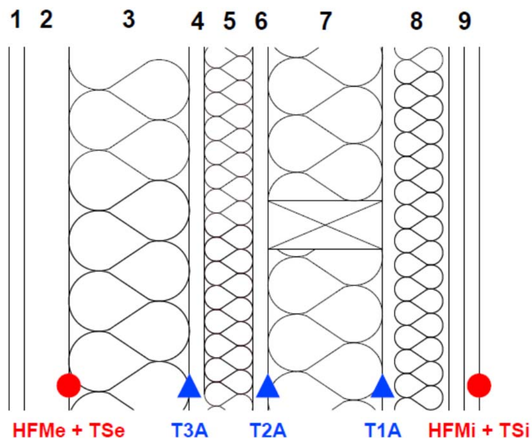

Figure 2. The wall stratigraphy; the probes position is indicated

differential-algebraic equations (DAE) solved with variable timestep [7]. Adaptive features can be activated by defining custom control macros, working in an advanced-level environment instead of standard user interface. From the conduction modeling point of view, Finite Differences approach based on an implicit scheme is implemented in the so-called FD wall model.

OpenBPS is primarily a set of libraries dedicated to building energy analysis and performance simulation, which can be included in any user-oriented interface or commercial software. The main features are the object-oriented modeling of physical phenomena and components, the native code parallelization to take advantage of multi-thread/multi-core processors and the multi-scale calculation time step [8]. Both CTF and Finite Differences can be used to simulate heat conduction in the building envelope. As in EnergyPlus, also in OpenBPS for the present study the Finite Differences method with a Cranck-Nicholson scheme was chosen.

B. *Single wall simulation*

As a first step towards the calibration of the entire building envelope model, the calibration of the thermo-physical properties of the materials composing the wall is addressed. To this purpose, a simulation model of the wall alone is required and measured surface temperature profiles have to be input as boundary conditions. Depending on the dynamic simulation environment, the single wall model is a ready-to-use model (e.g. IDA ICE, at advanced level, OpenBPS) or a proper approach has to be identified in order to make it possible (e.g. EnergyPlus). Indeed within EnergyPlus any model must include at least a thermal zone, namely an air volume enclosed by an envelope, subject to outdoor climate. Therefore the following strategy has been adopted in order to perform a single wall simulation in EnergyPlus:

- a fictitious thermal zone has been created giving to each wall, to the roof and the slab the same construction, namely the wall stratigraphy in Table I;
- a variable indoor air temperature set point has been defined, equal to measured profile of the inside surface temperature of the wall;
- an outside boundary condition has been specified with the measured profile of the outside surface temperature of the wall;
- the external surfaces have been considered exposed neither to solar radiation nor to wind;
- indoor and outdoor convective resistances have been artificially set to a negligible value.

The success of the modeling strategy in EnergyPlus has then been verified by comparing the simulation results with the ones from OpenBPS, adopting both the Finite Differences Cranck Nicholson approach.

In all the simulation models, since the most external surface temperature in the wall is measured on layer #3 surface facing the air gap (Fig. 2), the wall stratigraphy has been limited to layers from 3 to 9 (Table I).

C. *Calibration method*

First of all a base case stratigraphy was defined (Table II), by integrating the thermal properties from the product declaration by the manufacturers (regarding the high density and the low density mineral wool thermal conductivity and density) with literature data [9].

TABLE II. BASE CASE THERMAL PROPERTIES

#	Material	ρ (kg/m³)	λ (W/m.K)	C (J/(kg.K))
3	High density mineral wool	135	0.04	1030
4	LVL panel	530	0.2	1600
5	Low density mineral wool	40	0.035	1030
6	LVL panel	530	0.2	1600
7	Low density mineral wool	40	0.035	1030
8	Low density mineral wool	40	0.035	1030
9	Plasterboard	900	0.21	1000

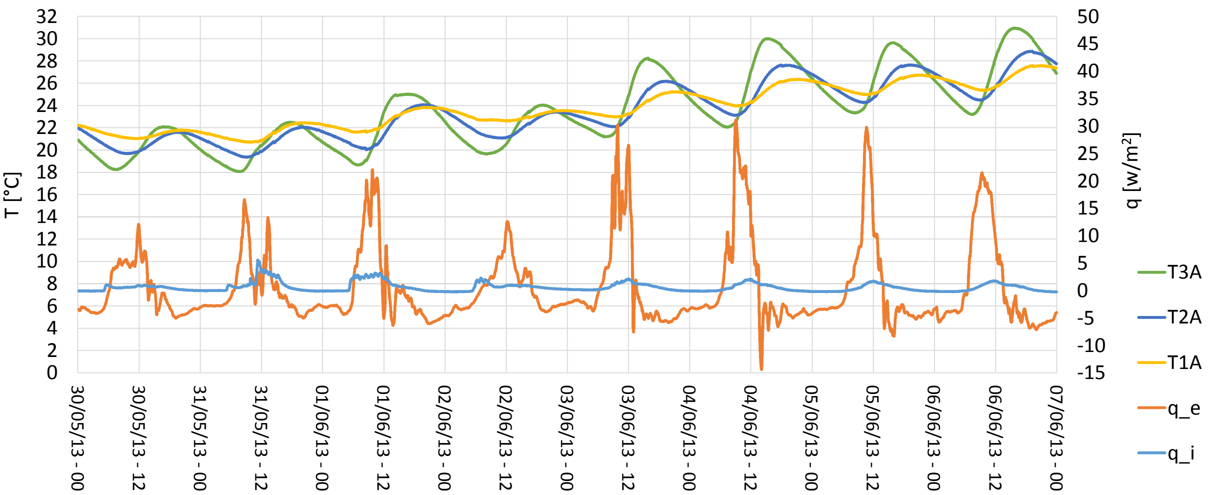

Figure 3. Interface temperatures T1A, T2A and T3A (left axis) and surface heat flow densities q_i and q_e (right axis) versus time during the calibration period

The time interval 30th May – 6th June 2013, where the building was in free floating, was selected as the calibration period. The base case simulation model was created within the three simulation environments and the simulation outputs, in terms of interface temperatures (T1A, T2A, T3A) and surface heat flows (q_i, q_e), have been compared with the corresponding measured quantities. The agreement between measurements and simulations has been quantified by means of the Root Mean Squared Error (RMSE), namely:

$$RMSE =[\sum_k (Y_k - S_k)^2 / N]^{0.5} \quad (1)$$

where Y_k and S_k represent the measured and the simulated value of the generic quantity at time step k, respectively. Then the RMSE was properly normalized. In the case of temperature outputs, since average values depend dramatically on the temperature scale adopted, it was chosen to normalize the RMSE by the temperature range, using the Range Normalized Root Mean Squared Error (RN_RMSE) [10]:

$$RN\_RMSE = RMSE /[max (Y_k) – min (Y_k)] \quad (2)$$

In the case of heat flows outputs, beside the RN_RMSE metric, the Coefficient of Variation of the RMSE (CV_RMSE) [2] was also adopted. However, since heat flows typically exhibit large variations both in absolute value and in sign, leading to an almost null mean value, the effective value rather than the mean was used for the normalization i.e.:

$$CV\_RMSE = RMSE /Y_{eff} \quad (3)$$

After defining the performance metrics, the sensitivity of the results to the simulation time step and to the spatial grid was firstly assessed. Then the calibration of the thermo-physical properties of the layers was carried out in parallel adopting a manual methodology (Polito - EnergyPlus, Polimi - OpenBPS) and an automatic one (Uniro - IDA ICE). The latter was based on the coupling of IDA ICE with the optimization engine GenOpt, used via the parametric-runs macro. The objective function was the sum of the cumulative squared error (CSE) of simulated and measured temperature data at the three positions shown in Fig. 2. A hybrid algorithm given by the combination of Particle Swarm Optimization (PSO), for a first global search, and Hooke-Jeeves (HJ) algorithm for a second local search, minimized the objective function.

IV. RESULTS

A. Measurement data analysis

The measured temperature and heat flow density profiles in the calibration period are shown in Fig. 3. The corresponding maximum, minimum, mean and effective values are reported in Table III. It can be remarked that the temperature variation amplitude decreases going from outdoor to indoor, namely from T3A to T1A. Moreover, a delay in the peak position can be noticed for the innermost probe compared to the most external one. Heat flow densities assume very low values, especially the internal one. In this range the heat flow meters accuracy is expected to be much worse than 3% (section II). Therefore, it was decided to calibrate the simulation models only on the temperature profiles T1A, T2A and T3A.

TABLE III. MEASURED QUANTITIES DURING CALIBRATION PERIOD

	T3A (°C)	T2A (°C)	T1A (°C)	q_e (W/m^2)	q_i (W/m^2)
max	30.9	28.9	27.6	31.1	5.5
min	18.1	19.4	20.7	-14.4	-0.3
Δ	12.9	9.5	6.9	45.4	5.8
mean	23.6	23.5	23.8	0.5	0.6
effective	-	-	-	7.3	1.0

B. Sensitivity to the numerical grid

First of all every research group performed a sensitivity analysis to the numerical grid, within the constraints given by each simulation engine. In Fig. 4 the example of OpenBPS results is shown, namely the RMSE for T3A versus the time step. The different curves are labeled as C = 1, 2 and 3, where $C = \Delta x^2/(\alpha \cdot \Delta t)$ and α is the layer thermal diffusivity. It can be noticed that as the time step decreases to 1 minute, the different spatial grids tend to comply. On this basis the time step was set at 1 minute and C = 2.

C. Base case results

The base case results obtained by means of the different simulation tools are reported in Table IV. In general they are quite similar, in particular EnergyPlus and OpenBPS results. Since for the latter the numerical approach is the same, this outcome represents a validation of the fictitious zone modeling strategy adopted in Energy Plus in order to perform a single wall simulation.

The agreement between simulated and measured temperature profiles is good, although only for the inner temperature T1A the RMSE is below the measurement uncertainty for all the simulation tools. In turn, the agreement in terms of profiles of heat flow density is less satisfactory, but in such range measurements are less accurate, as already remarked above.

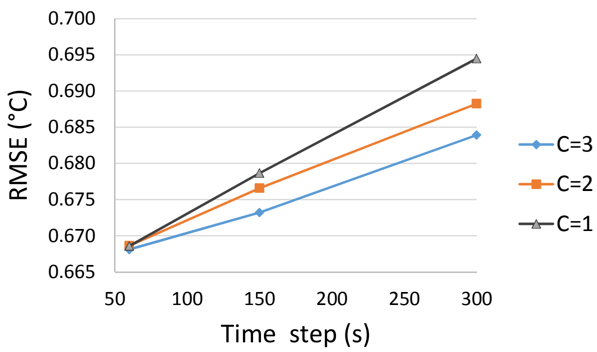

Figure 4. T3A RMSE versus simulation time step for different C values (OpenBPS simulations)

TABLE IV. BASE CASE RESULTS FOR THE DIFFERENT TOOLS

		EnergyPlus	OpenBPS	IDA ICE
T3A	**RMSE (°C)**	0.70	0.67	0.58
	RN_RMSE (%)	5%	5%	5%
T2A	**RMSE (°C)**	0.59	0.59	0.47
	RN_RMSE (%)	6%	6%	5%
T1A	**RMSE (°C)**	0.30	0.30	0.25
	RN_RMSE (%)	4%	4%	4%
q_e	**RMSE (W/m²)**	1.82	1.77	2.24
	RN_RMSE (%)	4%	4%	4%
	CV_RMSE (%)	25%	24%	31%
q_i	**RMSE (W/m²)**	0.44	0.36	0.33
	RN_RMSE (%)	8%	6%	6%
	CV_RMSE (%)	43%	36%	33%

D. Calibration results

Firstly, the possibility to assess the wall total resistance from measurements, following the heat flow meter method in [11], was verified. However, since the measurement data available did not contain any almost steady state period, such method could not be applied.

Manual calibration of the layers thermo-physical properties was performed either:

- through a sensitivity analysis, where the properties were varied in a physically and technologically plausible range (Polimi – Open BPS); the insulation layers properties were identified as the most influent parameters;
- by combining the mineral wool thermal conductivity exponential dependence on temperature stated in [9] with a sensitivity analysis (Polito – EnergyPlus). In this regard, the declared values of the high and low density mineral wool thermal conductivity refer to 10°C, while the mean temperatures measured into the wall during the calibration period are found in the range 23.5°C – 23.8°C (Table III). Therefore the thermal conductivities were increased from the base case values (Table II) to 0.0435 W/(m.K) and to 0.0375 W/(m.K) for the high and the low density insulation respectively.

Both Polimi and Polito research units modified the layer #7 conductivity, density and specific heat capacity in order to take into account the presence of wood spacers (see Fig. 2).

In parallel, automatic calibration (Uniro – IDA ICE) was carried out under the following constraints:

- properties of layers #5 and #8 are the same;
- for all the layers but #7, the properties can vary up to ±20% with respect to the base case;
- a larger range of variation is given to the properties of layer #7 (-50%, +200%), in order to take into account the presence of the spacers.

Each research unit identified an optimal set of thermo-physical properties corresponding to the lowest RMSE (see Tables V, VI and VII). The optimal cases obtained by Polimi and Polito are substantially the same: the insulation layers thermal conductivity is increased, the heat capacity of the high density wool is decreased, the wooden spacers presence is considered. In the optimal case by Uniro more parameters are varied with respect to the base case, as a consequence of the automatic procedure. The RMSE of the three optimal cases are below the measurement accuracy and very similar with each other, as shown in Table VIII, where Polimi optimal case is not shown because it is coincident with Polito's. Further improvements on RMSE for T3A were obtained by considering either a contact resistance between layers #3 and #4 or that the temperature probe T3A can be located a few millimiters inside layer #3.

TABLE V. POLITO – ENERGYPLUS OPTIMAL CASE

#	Material	ρ (kg/m³)	λ (W/m.K)	c (J/(kg.K))
3	High density mineral wool	135	**0,0435**	**840**
4	LVL panel	530	0,2000	1600
5	Low density mineral wool	40	**0,0375**	1030
6	LVL panel	530	0,2000	1600
7	Low density mineral wool	**81**	**0,0420**	**1045**
8	Low density mineral wool	40	**0,0375**	1030
9	Plasterboard	900	0,2100	1000

TABLE VI. POLIMI –OPENBPS OPTIMAL CASE

#	Material	ρ (kg/m³)	λ (W/m.K)	c (J/(kg.K))
3	High density mineral wool	135	**0,048**	840
4	LVL panel	530	0,2	2000
5	Low density mineral wool	40	**0,0385**	1030
6	LVL panel	530	0,2	2000
7	Low density mineral wool	**81**	**0,042**	**1045**
8	Low density mineral wool	40	0,0385	1030
9	Plasterboard	900	0,21	1100

TABLE VII. UNIRO –IDA ICE OPTIMAL CASE

#	Material	ρ (kg/m³)	λ (W/m.K)	c (J/(kg.K))
3	High density mineral wool	**118**	0,040	**915**
4	LVL panel	**553**	**0,226**	**1372**
5	Low density mineral wool	**44**	0,040	**968**
6	LVL panel	**553**	**0,226**	**1372**
7	Low density mineral wool	**68**	**0,038**	**1602**
8	Low density mineral wool	**44**	0,040	**968**
9	Plasterboard	**968**	**0,200**	**1120**

Finally a cross-check of the optimal stratigraphies was carried out, namely every research group simulated with its own tool the others' optimal case (Table VIII). In Fig. 5 base case and optimal cases simulation outputs are compared with measurements. For better readability, only T3A profiles are represented.

TABLE VIII. OPTIMAL CASES PERFORMANCE AND CROSS-CHECK

		RMSE (°C)		
Optimal case	**Tool**	**T3A**	**T2A**	**T1A**
Polito	EnergyPlus	**0.49**	**0.50**	**0.30**
Uniro	IDA ICE	**0.36**	**0.35**	**0.27**
Polito	IDA ICE	**0.37**	**0.38**	**0.24**
Uniro	EnergyPlus	**0.54**	**0.53**	**0.30**

V. DISCUSSION AND CONCLUSIONS

The study demonstrated that a model calibration at the single wall level, allowing to reduce the number of unknown parameters with respect to the whole envelope level, is possible even with a whole building simulation code like EnergyPlus. To this purpose, a fictitious thermal zone and schedule file strategy is proposed and validated.

Calibration at the single wall level clearly requires the availability of monitored quantities regarding the wall itself, which is presently unusual. Moreover, in the case of highly insulated envelopes, heat flow densities are so low that accurate measurements are hardly possible. More easily measured temperature profiles can be used for calibration.

The heat conduction calculation methods of the different simulation tools adopted in this study are all based on the Finite Differences approach. Therefore limited differences in the simulation results are found.

In turn, calibration procedures carried out by different research groups led to identify different optimal stratigraphies. Such outcome is coherent with the ill-posed inverse problem at the basis of the wall parameters identification. In the prosecution of the research the different optimal stratigraphies will be tested at the whole envelope calibration level.

The case study regarded a highly insulated wall composed of porous insulation materials. For this kind of stratigraphy, thermal conductivity dependence on temperature and possibly on moisture content is an important issue that has to be taken into account in the calibration.

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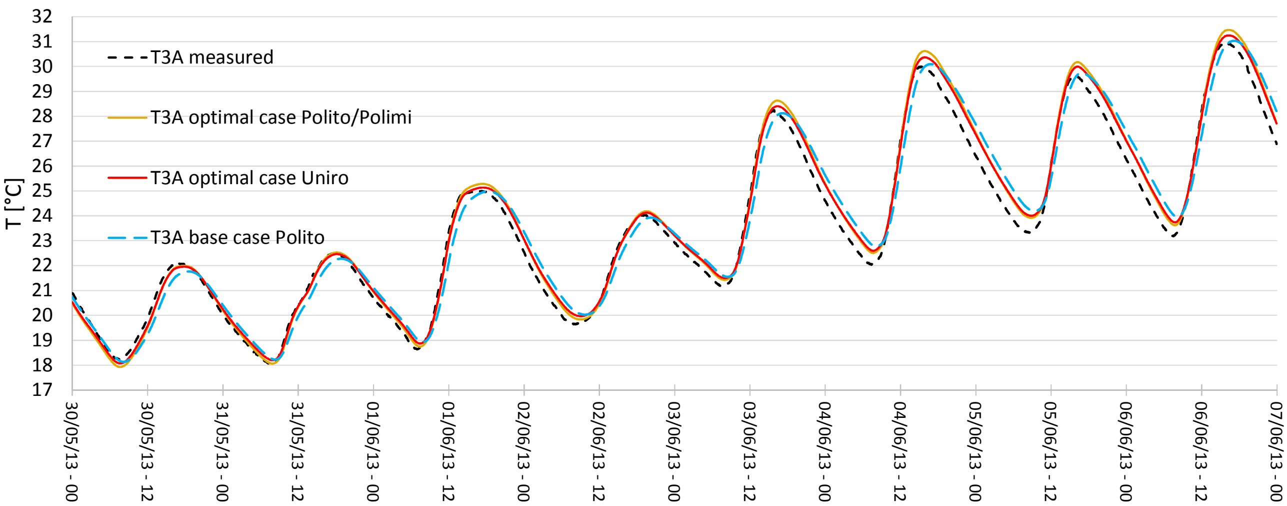

Figure 5. T3A profiles: measured, base case simulated, optimal cases simulated