POLITECNICO DI MILANO

Faculty of Architecture, Urban Design and Buildings Constructions

Master of Science in Building and Architectural Engineering

Dynamic building modelling using an extensive RC network according to ISO 52016: numerical implementation and testing

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Abstract

Buildings account for 40% of the total energy consumption in Europe and there has been a lot of effort to reduce the energy consumption. The importance of energy analysis of buildings has grown over time but sometimes it is still done by using a simple approach. A dynamic energy modeling of the building could lead to energy savings improving the building design and the HVAC system control. The European Standard ISO 52016-1:2017 which specifies the hourly calculation procedure of sensible energy needs for heating, cooling, and internal temperatures was published in June 2017 superseding the previous standard ISO 13790:2008. The hourly calculation method in ISO 52016-1 is more advanced than the simplified hourly method given in ISO 13790:2008. The main difference is that the building elements are not aggregated to a few lumped parameters, but kept separate in the new model proposed in the standard. The purpose of this thesis work is to implement and compare this newly proposed extensive RC network model with the TRNSYS Type 56 dynamic model. The developed Matlab model has been tested for lightweight and heavyweight class of construction with free-floating, continuous, and intermittent HVAC system control strategies. Each case is tested for weather data files of drycold weather, Milan, and Palermo. The lightweight construction case in drycold weather with continuous control strategy has an 11 percent difference in the calculated energy needs and the similar case in free-floating condition has a 0.3 second running time and an R^2 value of 0.86 for internal air temperature compared to the TRNSYS Type 56 dynamic model. The Matlab model could be used for simulation purpose to study the building energy performances and also as a smart control in the Model Predictive Control systems saving energy consumption for the HVAC systems as it could produce a dynamic behavior closes to the reality and detect the time horizon much better than the simplified dynamic models.

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1 Introduction

1.1 Background

Buildings account for nearly 40% of the total energy consumption in Europe [1] and around 50% of the energy consumption in the office buildings are due to the Heating, Ventilation and Air conditioning systems (HVAC) [2]. The importance of energy analysis of buildings has grown over time, but still is often done using a simple static calculation [3]. So, it is necessary to consider the importance of dynamic models both during early design stages of the building and also when executing the retrofitting solution of the existing buildings [4] as effective design strategies could improve its overall energy performance.. A more accurate and computationally light dynamic model used in the advanced control techniques could significantly contribute to reduce the energy demands for HVAC systems [4]

The Directive on the EPBD (Energy Performance of buildings) [5] is the main legislative in the European Union to set the energy performance of the buildings from 2002. The directive publishes a number of standards to implement the directive.

The EN ISO 52016-1:2017 one among the part of EPBD standards is a new regulation published (June 2017) for the European Union member countries describing the calculation procedure for the energy needs of heating and cooling and to calculate the internal air temperature. This new standard supersedes the ISO 13790:2008 which specifies a simple hourly calculation model using five resistances and one capacitance (5R1C model) to calculate the energy needs. Instead, the EN ISO 52016-1:2017 uses a more complex and an extensive RC network model to perform the hourly calculation and they pose a great advantage both in terms of their usage as a simulation tool as well as a control tool for the HVAC systems.

Advantages of EN ISO 52016-1 as simulation tool for the calculation of energy needs

The hourly method in EN ISO 52016-1 is more advanced than the simplified hourly method given in EN ISO 13790:2008. The main difference is that the building elements are not aggregated to a few lumped parameters, but kept separate in the model. This is illustrated in the Figure 1-1 and Figure 1-2.
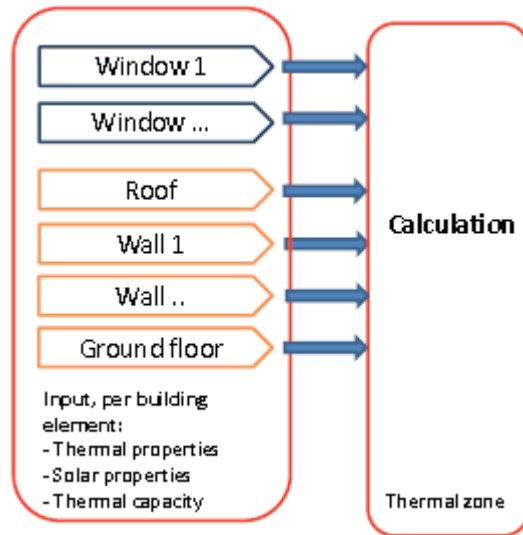
Figure 1-1: Improved hourly calculation method in ISO 52016-1 [7]
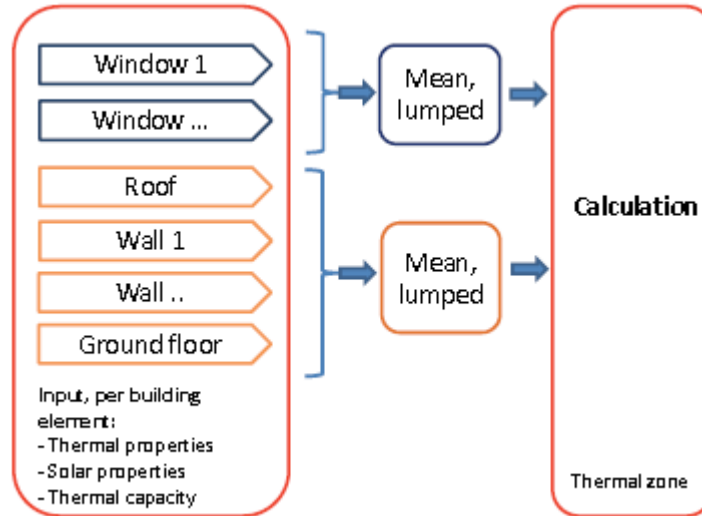
Figure 1-2: Simple hourly calculation method in ISO 13790:2008 [7]

This makes the model more transparent and more widely usable compared to ISO 13790:2008, since:

- There is no difficulty in the consideration to combine the heat flow through the roof and through the ground floor, with their very different boundary conditions (solar radiation on the roof and ground temperature and ground inertia in the ground)
- The thermal capacity of the building can be specified per building element and there is no need to have a mean lumped overall thermal capacity for the building or thermal zone.

The mean radiant temperature (the mean indoor surface temperature) can be clearly identified and distinct from the indoor air temperature.

Advantages of EN ISO 52016-1 as simulation tool for the control tools in the real building

Problems in the implementation of comprehensive software like TRNSYS in the control strategies in the real building is due to their requirement of detailed description of the building both in terms of geometry and physical properties.

These methods require a high computational effort and cannot be readily interfaced with optimization solvers; thus, they are unsuitable for simulations like model predictive control. The main problem with their application in MPC is due to their inability to explicitly initialize all variables at the beginning of a new planning horizon period.

These problems were the motives to choose a simple dynamic model (RC) model like 5R1C model in the ISO 13790:2008.

In the simplified models, the building elements are discretized into a set of nodes connected by thermal resistances and capacitance. These parameters can be identified analytically, by model order reduction or by tuning the model to a temperature and energy consumption dataset.

The RC model adopted in EN ISO 52016-1 is more advanced that consists of 5 nodes per building element and a capacitance for each building element inside a thermal zone. This could be a better replacement to the existing adopted RC models in the control strategies as they could predict the dynamic behavior as close to the comprehensive software like TRNSYS.

Drawbacks of EN ISO 52016-1

- This being said, the drawbacks in the implementation could be that the RC model adopted in the EN ISO 52016-1 requires higher inputs of building properties and dimension which may not be available all the time.

- Secondly due the high number of state variables the system could become very complex by itself when considered for the whole building.

1.2 Aim of the work

The purpose of this thesis work is to implement and compare the newly proposed model from EN ISO 52016-1:2017 for the BESTEST cases given in ANSI/ASHRAE 140 [6]. The BESTEST series from ANSI/ASHRAE 140 involves testing the thermal zone for two different class of construction, lightweight and heavyweight with three different thermostat control strategies i.e. Free-Floating, Continuous and Intermittent heating and cooling system.

The EN ISO 52016-1:2017 being the newly published standard, not a lot of research work has been done on the hourly dynamic calculation method proposed in this standard. Thus, an attempt has been made in this work to test the model and also test its accuracy with a more comprehensive TRNSYS Type 56 dynamic model.

A preliminary analysis has been done on the 5R1C model suggested in the ISO 13790:2008 and the indoor air temperature has been calculated after which the more advanced model from the new regulation is studied and tested.

The numerical was done in a Matlab code. Then the implementation was tested with excel spreadsheet accompanied by the standard. Lastly, a comparison with the comprehensive TRNSYS Type 56 has been done.

2 EN 52016 RC model

This chapter describes the procedures to implement the hourly calculation for heating and cooling energy needs and indoor temperatures using an extensive RC network model from ISO 52016-1 for a building/thermal zone.

```
┌─────────────────────┐   ┌─────────────────────┐   ┌─────────────────────┐
│  Building Elements   │   │   Window Elements    │   │  Internal air node   │
│   in a building      │   │   in a building/     │   │                      │
│  /thermal zone       │   │  thermal zone        │   │                      │
│  element - 1,2….n    │   │  element - 1,2….n    │   │                      │
└─────────────────────┘   └─────────────────────┘   └─────────────────────┘

┌─────────────────────┐   ┌─────────────────────┐   ┌─────────────────────┐
│ Each element is      │   │ Each element is      │   │                      │
│ discretized in to    │   │ discretized in to    │   │                      │
│ layers of 5 nodes    │   │ two nodes            │   │ An additional node   │
│                      │   │                      │   │ to solve the heat    │
│ Node 1 - external    │   │ Node 1 - external    │   │ balance on the       │
│ suface node          │   │ suface node          │   │ internal air node    │
│ Node 2,3,4 - inside  │   │ Node 2 - internal    │   │ of the zone          │
│ nodes                │   │ surface node         │   │                      │
│ Node 5 - internal    │   │                      │   │                      │
│ surface node         │   │                      │   │                      │
└─────────────────────┘   └─────────────────────┘   └─────────────────────┘

            ┌───────────────────────────────────┐
            │ Construct energy balance          │
            │ equation for each nodes of the    │
            │ building element and for the      │
            │ intenal air node                  │
            └───────────────────────────────────┘

            ┌───────────────────────────────────┐
            │ Solve the equations to determine  │
            │ the indoor temperatures and hourly│
            │ heating  and cooling energy needs │
            └───────────────────────────────────┘
```

Figure 2-1: Overview of improved hourly calculation procedure ISO 52016 - 1

The Figure 2-1 describes the overview of the procedure to calculate the heating/cooling energy needs and indoor air temperatures using an extensive RC network model.

2.1 Series of nodes

The formulae for the building elements in ISO 52016-1:2017, consists of series of layers:

Each building element is divided (discretized) into a number of parallel layers, separated by nodes: the internal (zone facing) surface node, the external surface node and nodes inside the building element [7].

The sensible energy balance is set up for each node pli= 1, 2, …, pln of the building element eli . The balance formula for each building element is presented per square meter.

The numbering of layers (nodes) in the construction elements is from outside (node number pli=1) to inside (node number pli =pln)

The power injected to a node can be, depending on the type of construction and the position of the layer: absorbed solar radiation, emitted long wave radiation to the sky, internal heat gains and heating or cooling load.

The conductance from the external surface to the external environment consists of the surface heat transfer coefficients by convection and (thermal) radiation, connected to the outdoor air temperature.
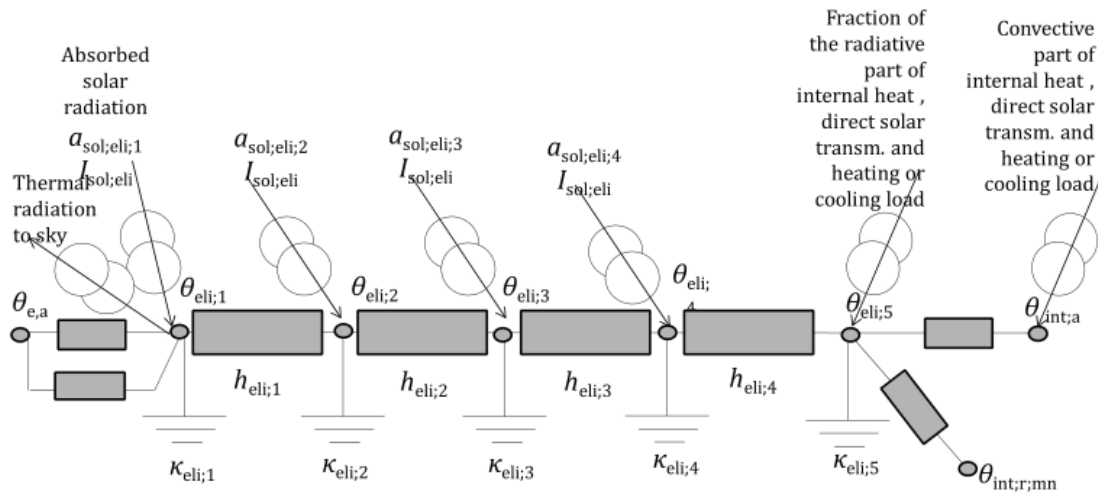
Figure 2-2: RC model for single building element [7]

The conductance from the internal surface to the internal environment consists of the surface heat transfer coefficient by convection connected to the indoor air temperature and the surface heat transfer coefficient by (thermal) radiation, connected to the internal surfaces of other construction elements in the thermal zone (radiative heat exchange with view factors).

In addition to the sensible energy balance formulae for each building elements multiplied by the number of nodes, there is one extra formula to solve the heat balance on the internal air node in the zone: this node is connected to all internal surfaces by surface heat transfer coefficients and is connected to the outdoor air by thermal bridges, ventilation supply air temperature via the air flow rate and specific heat capacity of air, is connected also to the convective parts of the internal heat gains and the heating or cooling load and to the convective part of the solar radiation that is transmitted through transparent building elements.

2.2 Overall Sensible energy balance for a thermal zone

The EN ISO 52016-1 suggests provisions to set up one sensible energy balance for each node of the building element [8] and a sensible energy balance for the internal air node (Eq.1).

This leads to have 5 times the sensible energy balance for each building element (one for each node in the building element) and 2 times the sensible energy balance for each window in the thermal zone (the window is considered not to have any inside nodes) and one sensible energy balance for the internal air node.

So, in the BESTEST cases, there will be 33 sensible energy balance equations in total given by 30 sensible energy balance equations from the building elements and 2 equations by the window and one equation from the Internal air node.

2.2.1 Sensible energy balance on zone level (Internal air node)

$$
\begin{aligned}
\left(C_{int;ztc}\right) \cdot \frac{T_{int;a;t} - T_{int;a;t-1}}{\Delta t} \\
= -\left[\sum_{eli=1}^{eln}\left(A_{eli} \cdot h_{ci;eli}\right) + \sum_{vei=1}^{ven} H_{ve;vei;t} + H_{tr;trb;ztc}\right] \\
+ \sum_{eli=1}^{eln}\left(A_{eli} \cdot h_{ci;eli} \cdot T_{pln;eli;t}\right) \qquad \text{(Eq.1)} \\
+ \sum_{vei=1}^{ven}\left(H_{ve;vei;t} \cdot T_{sup;vei;t}\right) + H_{tr;trb;ztc} \cdot T_{e;t} + f_{int;c} \\
\cdot \varphi_{int;t} + f_{sol;c} \cdot \varphi_{sol;t} + f_{\frac{H}{C};c} \cdot \varphi_{HC;t}
\end{aligned}
$$

where, for building element *eli* at time interval t:

$C_{int;ztc}$ - internal heat capacity of the zone, in J/K;

Δt - length of the time interval t, in s;

$T_{int;a;t}$ - internal air temperature, in °C;

$T_{int;a;t-1}$ - internal air temperature in the zone at previous time interval (t-Δt), in °C;

A_{eli} - area of the building element *eli,* in m^2;

$h_{ci;eli}$ - internal convective surface heat transfer coefficient of the building element *eli,* in W/m^2.K;

$T_{pln;eli;t}$ - internal surface temperature of the building element *eli,* in °C;

$H_{ve;vei;t}$ - overall heat exchange coefficient by ventilation, for ventilation flow element *vei,* in W/K;

$T_{sup;vei;t}$ - supply temperature, for ventilation flow element *vei,* in °C;

$T_{e;a;t}$ - external air temperature, in °C;

$H_{tr;trb;ztc}$ - overall heat transfer coefficient for thermal bridges, in W/K;

$f_{int,c;ztc}$ - convective fraction of the internal gains;

$f_{sol,c;ztc}$ - convective fraction of the solar radiation;

$f_{H/C,c;ztc}$ - convective fraction of the heating or cooling system;

$\varphi_{int;ztc;t}$ - convective fraction of the internal gains, in W;

$\varphi_{sol;ztc;t}$ - convective fraction of the internal gains, in W;

$\varphi_{HC;ztc;t}$ - convective fraction of the internal gains, in W;

2.2.2 Sensible energy balance on building element level

2.2.2.1 Internal surface node

For pli = n;

$$
\left(\kappa_{pli;eli}\right) \cdot \frac{T_{pli;eli;t} - T_{pli;eli;t-1}}{\Delta t}
$$

$$
= h_{pli-1;eli} \cdot T_{pli-1;eli;t}
$$

$$
- \left[h_{ci;eli} + h_{ri;eli} \cdot \sum_{elk=1}^{eln} \left(\frac{A_{elk}}{A_{tot}} \right) + h_{pli-1;eli} \right] \cdot T_{pli;eli;t}
$$

$$
+ h_{ci;eli} \cdot T_{int;a;t} + \sum_{elk=1}^{eln} \left(\frac{A_{elk}}{A_{tot}} \cdot h_{ri;eli} \cdot T_{pli;elk;t} \right) \qquad \text{(Eq.2)}
$$

$$
+ \frac{1}{A_{tot}} \left[\left(1 - f_{int;c}\right) \cdot \varphi_{int;t} + \left(1 - f_{sol;c}\right) \cdot \varphi_{sol;t} \right.
$$

$$
\left. + \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t} \right]
$$

where, for building element *eli* at time interval t:

A$_{elk}$ - area of the building element *elk,* in zone ztc in m^2;

A$_{tot}$ - sum of areas A_{elk} of all the building element *elk=1...eln,* in zone ztc in m^2;

T$_{pli;eli;t}$ - temperature at node *pli*, in °C;

T$_{pli-1;eli;t}$ - temperature at node *pli-1*, in °C;

h$_{pli-1;eli;t}$ - conductance between node *pli-1* and the node *pli* in W/m^2.K;

$\kappa_{pli;eli;t}$ - areal heat capacity og the node *pli* in J/m^2.K;

$h_{ci;eli}$ - internal convective surface heat transfer coefficient of the building element *eli,* in W/m^2.K;

$h_{ri;eli}$ - internal radiative surface heat transfer coefficient of the building element *eli,* in W/m^2.K;

$T_{pli;eli;t-1}$ - temperature at node *pli* at previous time interval (t-Δt), in °C;

2.2.2.2 Inside node

For *pli* = 2, …, pln-1 (each inside node)

$$
\begin{aligned}
\left(\kappa_{pli;eli}\right) \cdot \frac{\left(T_{pli;eli;t} - T_{pli;eli;t-1}\right)}{\Delta t} \\
= h_{pli-1;eli} \cdot T_{pli-1;eli;t} - \left(h_{pli;eli} + h_{pli-1;eli}\right) \cdot T_{pli;eli;t} \\
+ h_{pli;eli} \cdot T_{pli+1;eli;t}
\end{aligned}
\tag{Eq.3}
$$

where, for building element *eli* at time interval t:

$T_{pli+1;eli;t}$ - temperature at node *pli+1*, in °C;

$h_{pli;eli}$ - conductance between node *pli+1* and the node *pli* in W/m^2.K;

and with the other variables declared in the previous formulae or in sensible energy balance of the internal air node.

2.2.2.3 External surface node

For *pli* = 1 (surface node facing 'external' side)

$$\left(\kappa_{pli;eli}\right) \cdot \frac{\left(T_{pli;eli;t} - T_{pli;eli;t-1}\right)}{\Delta t}$$

$$= -\left(h_{ce;eli} + h_{re;eli} + h_{pli;eli}\right) \cdot T_{pli;eli;t} + h_{pli;eli} \quad \text{(Eq.4)}$$

$$\cdot T_{pli+1;eli;t} + \left(h_{ce;eli} + h_{re;eli}\right) \cdot T_{e;t} + a_{sol}$$

$$\cdot \left(I_{sol;dif;t} + I_{sol;dir;t}F_{sh;obst;op}\right) - \varphi_{sky;t}$$

where, for building element *eli* at time interval t:

$T_{e;a;t}$ - external air temperature, in °C;

$h_{ce;eli}$ - external convective surface heat transfer coefficient of the building element *eli,* in $W/m^2.K$;

$h_{re;eli}$ - external radiative surface heat transfer coefficient of the building element *eli,* in $W/m^2.K$;

a_{sol} - solar absorption coefficient at the external surface;

$I_{sol;dir;tot;eli;t}$ - direct part of the solar irradiance on the element, in W/m^2;

$I_{sol;dif;tot;eli;t}$ - diffuse part of the solar irradiance on the element, in W/m^2;

$F_{sh;obst;eli;t}$ - shading reduction factor for external obstacles for the element;

$\varphi_{sky;eli;t}$ - extra thermal radiation to the sky, in W/m^2;

and with the other variables declared in the previous formulae or in sensible energy balance of the internal air node.

2.2.3 Calculation of construction dependent properties of the nodes

2.2.3.1 Opaque elements (walls, roofs)

Number of nodes:

The number of nodes, pln =5.

Node Conductances:

The Conductances between nodes pli and node pli-1, for both the light weight and heavy weight cases, are given by:

$h_{pl4eli} = h_{pl1eli} = 6/R_{c;eli}$;

$h_{pl2eli} = h_{pl3eli} = 3/R_{c;eli}$;

where,

$R_{c;eli}$ is the thermal resistance of the opaque element in $m^2.K/W$

Node heat capacities:

The standard gives the provision to calculate the node heat capacities depending on the class type of the building element.

Depending on the class of construction with respect to the distribution of the mass in the construction, the area heat capacity of node *pli* of opaque element *eli* per unit area is divided over the nodes as follows:

Class D (equally distributed)

In the light weight case, the building element roof and external walls have the class D construction type and while in the heavy weight case, the building element roof still has the Class D but the external walls are given Class I.

$$\kappa_{pl1;eli} = \kappa_{pl5;eli} = \kappa_{m;eli}/8;$$

$$\kappa_{pl2;eli} = \kappa_{pl3;eli} = \kappa_{pl4;eli} = \kappa_{m;eli}/4;$$

Class I (mass concentrated at internal side)

$$\kappa_{pl5;eli} = \kappa_{m;eli};$$

$$\kappa_{pl1;eli} = \kappa_{pl2;eli} = \kappa_{pl3;eli} = \kappa_{pl4;eli} = 0;$$

where, $\kappa_{m;eli}$ is the area heat capacity of the opaque element *eli*, in $J/m^2.K$;

2.2.3.2 Elements in contact with ground

Number of nodes:

The number of nodes, pln =5.

Node Conductances:

The Conductances between nodes pli and node pli+1, for both the light weight and heavy weight cases, are given by:

$$h_{pl4eli} = 4/R_{c;eli};$$

$$h_{pl3eli} = 2/R_{c;eli};$$

$$h_{pl3eli} = 1/((R_{c;eli}/4)+ /((R_{gr;eli}/2));$$

$h_{pl1eli} = 2/R_{gr;eli}; = 0.1$ W/m^2.K in the BESTEST cases;

where,

$R_{c;eli}$ is the thermal resistance of the opaque element in m^2.K/W

$R_{gr;eli}$ is the thermal resistance of the fixed ground layer in the model for the ground floor element *eli*, in m^2.K/W

Node heat capacities:

Class I (mass concentrated at internal side)

$\kappa_{pl5;eli} = \kappa_{m;eli};$

$\kappa_{pl1;eli} = \kappa_{pl2;eli} = \kappa_{pl3;eli} = \kappa_{pl4;eli} = 0;$

where, $\kappa_{m;eli}$ is the area heat capacity of the opaque element *eli*, in J/m^2.K;

2.2.3.3 Windows

Number of nodes:

The number of nodes, pln =2.

The window element just has the internal and external surface node and there are no inside nodes like the other building elements.

Node Conductances:

The Conductances between nodes pli1 and node pli2, for both the light weight and heavy weight cases, are given by:

$h_{pl1eli} = 1/R_{c;eli};$

where,

$R_{c;eli}$ is the thermal resistance of the opaque element in $m^2.K/W$

Node heat capacities:

The areal heat capacity, $\kappa_{pli;eli}$ of node *pli* of transparent element *eli*;

$\kappa_{pl1;eli} = \kappa_{pl2;eli} = 0;$

2.2.4   Calculation of Ventilation, gains and thermal radiation to the sky

2.2.4.1 Heat transfer coefficient by ventilation

The heat transfer coefficient by ventilation for air flow element k, $H_{ve,k;t}$, is obtained on an hourly basis based on the formula:

$$H_{ve,k;t} = \rho_a \cdot c_a \cdot q_{v,k;t} \tag{Eq.5}$$

where, for time interval t in the BESTEST cases:

$H_{ve,k;t}$ - heat transfer coefficient by ventilation air flow element k, in W/K;

ρ_a - density of the air in kg/m^3;

c_a - heat capacity of dry air in J/ kg.K;

$q_{v,k;t}$ - air flow rate of air flow element k in m^3/s; in the BESTEST cases there is no ventilation but a constant infiltration.

2.2.4.2 Internal heat gains

The internal heat gains for the thermally conditioned zone from the internal heat sources are given by:

$$\varphi_{int;ztc;t} = q_{int,ztc;t} \cdot A_{use} \qquad\qquad (Eq.6)$$

where, for time interval t in the BESTEST cases:

$\varphi_{int;ztc;t}$ - internal heat gains for the thermal zone in W;

$q_{int,ztc;t}$ - specific heat flow rate inside the thermal zone in W/m^2;

A_{use} - Useful floor area in m^2;

2.2.4.3 Solar heat gains into a thermal zone

The direct solar gains into the zone, summed over all transparent building elements (windows $wi = 1…n$) are given by:

$$\varphi_{sol;dir;ztc;t} = \sum_{wi=1}^{n} \big[g_{gl,wi;t} \cdot (I_{sol;dif;wi;t} + I_{sol;dir;wi;t} \\ \cdot F_{sh;obst;wi;t}) \cdot A_{wi} \cdot (1 - F_{fr}) \big] \qquad (Eq.7)$$

where, for thermal zone ztc at time interval t, for the BESTEST case:

$\varphi_{sol;dir;ztc;t}$ - direct solar gains into the zone, at time interval t in W;

$g_{gl;wi;t}$ - total solar sensible energy transmittance of the window;

A_{wi} - area of the window in m^2;

$I_{sol;dir;tot;eli;t}$ - direct part of the solar irradiance on the element, in W/ m^2;

$I_{sol;dif;tot;eli;t}$ - diffuse part of the solar irradiance on the element, in W/ m^2;

$F_{sh;obst;eli;t}$ - shading reduction factor for external obstacles for the element;

2.2.4.4 Thermal radiation to the sky

The extra thermal radiation to the sky is given by:

$$\varphi_{sky;eli;t} = F_{sky,eli} \cdot h_{re;eli} \cdot \Delta T_{sky;t} \qquad \text{(Eq.8)}$$

where for time interval t, in the BESTEST cases

$\varphi_{sky;eli;t}$ - extra thermal radiation to the sky from the element in W/m^2;

$F_{sky,eli}$ - view factor to the sky;

$h_{re;eli}$ - external radiative heat transfer coefficient, in $W/m^2.K$

$\Delta T_{sky;t}$ - average difference between the apparent sky temperature and the air temperature in K (11 K)

3 Case studies

3.1 The BESTEST case studies

The hourly calculation procedure on the thermal zone has been used for the relevant cases from the BESTEST series by ANSI/ASHRAE 140 which is the Standard Method of Test for the Evaluation of Building Sensible Energy Analysis Computer Programs which is an internationally recognized methodology for comparing the results of energetic simulations of buildings in a dynamic calculation.

The model has been verified for sensible energy needs for heating/cooling and internal air temperature for the Test winter (January) and Test summer (June).

The BESTEST series consists of cases with different class of construction such as lightweight and heavyweight and testing each class of construction with different control strategies.

3.2 Geometric characteristics and thermophysical properties

The various test cases in the BESTEST series refers to a geometry of a single thermal zone with two different types of construction envelope: lightweight and heavyweight.
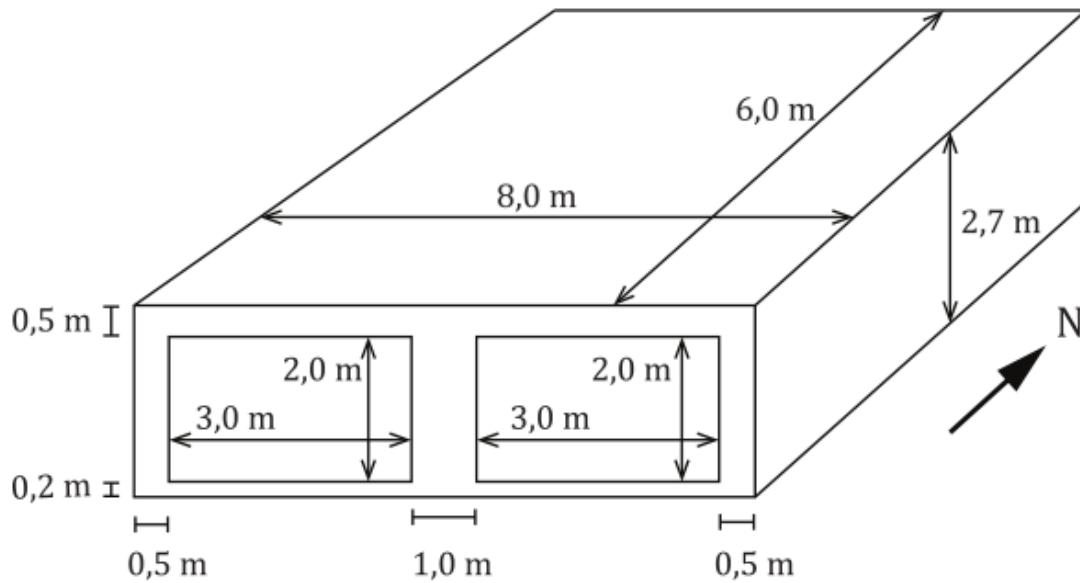
Figure 3-1: Geometry of the room [6]

Building Element	Area (m^2)
Wall (North)	9.6
Wall (East)	16.2
Wall (West)	21.6
Wall (South)	12.0
Floor	48.0
Ceiling	48.0
Volume	126.6 m^3

Table 1: Room data

3.2.1 Thermophysical properties of lightweight opaque elements

In the BESTEST series, both the lightweight and heavyweight elements have almost the same values for the thermal resistance of the opaque elements but different capacities for the building elements. The BESTEST case for lightweight constructions elements consists of very thin layers of elements with low capacities which shows greater responsiveness to

outdoor temperature changes which can be beneficial by cooling more rapidly at night in warmer climates.

The Table 2 shows the building thermal properties for the BESTES case.

Structure	D	λ	R	$\kappa_{m;op}$	ρ	c
	m	W/(m·K)	m²·K/W	J/(m²·K)	kg/m³	J/(kg·K)
External wall (inside to outside)						
Plasterboard	0,012	0,160	0,075	9576	950	840
Fiberglass quilt	0,066	0,040	1,650	665	12	840
Wood siding	0,009	0,140	0,064	4293	530	900
Total surf-surf			1,789			
For application of ISO 52016-1:				Very light		
- Class specific heat capacity				Evenly (D)		
- Class of distribution						
Floor (inside to outside)						
Timber flooring	0,025	0,140	0,179	19500	650	1200
Insulation [a]	1,003	0,040	25,075	0 [b]	0 [b]	0 [b]
Total surf-surf			25,254			
For application of ISO 52016-1:				Very light		
- Class specific heat capacity				Internal (I)		
- Class of distribution						
Roof (inside to outside)						
Plasterboard	0,010	0,160	0,063	7980	950	840
Fiberglass quilt	0,1118	0,040	2,794	1127	12	840
Roofdeck	0,019	0,140	0,136	9063	530	900
Total surf-surf			2,992			
For application of ISO 52016-1:				Very light		
- Class specific heat capacity				Evenly (D)		
- Class of distribution						

[a] To reduce uncertainty regarding testing the other aspects of simulating the building envelope, the floor insulation (below the actual floor construction) has been made very thick in the test case description, with the purpose to effectively decouple the floor thermally from the ground.

For the application of this document this means that the floor plus insulation is modelled as an opaque construction to outdoor air; this implies that the thermal resistance of the floor has to be used in the calculations instead of the effective thermal resistance ($R_{c;f;eff}$) in case of a ground coupled floor. To ensure that the thermal mass of the actual floor is modelled as part of the actual floor and not distributed over the actual floor and the artificial thick thermal insulation layer, the thermal resistance of the thick thermal insulation layer is imposed on the first (most outdoor) conductance which does not take part in the attribution of the thermal mass of the Class I type of construction (see 5.6.7.2); so: $h_1 = 0,04$ W/(m²·K).

[b] Underfloor insulation has the minimum density and specific heat the program being tested will allow, but not < 0. For the application of this document the density, specific heat and specific heat capacity of the underfloor insulation are assumed to be zero.

Table 2: Thermophysical properties of the opaque elements if the lightweight case

3.2.2 Thermophysical properties of heavyweight opaque elements

The heavyweight elements which has higher durability and low maintenance than the light weight elements have been studies for the BESTEST cases. The heavyweight elements have good thermal mass and are most suited for climates with diurnal temperature range i.e. the variation between a maximum and minimum temperature that occur at the same day.

The heavyweight elements shown in Table 3: Thermophysical properties of the opaque elements if the heavyweight case has a higher massive element with high capacity values.

But, the thermal resistance of the overall building elements for both the lightweight and heavyweight remains the same which allows us to study the behavior with respect to different thermal mass.

The floor elements in both the heavyweight and lightweight has been made very thick with a very high insulation having a total R value around 25 m^2.K/W. It is done in the BESTEST cases to reduce the uncertainty regarding the other aspects of the building simulation in the building envelope. For the calculation in the BESTEST cases for the model developed in the Matlab using the extensive RC network of EN ISO 52015-1, the floor elements are considered as an opaque construction element to the outdoor air which implies that the thermal resistance (R) has been used for the simulation instead of $R_{c;eff}$ (effective thermal resistance) which has to be used in general for the ground coupled floor.

Another important consideration for the floor elements made is to have the artificial thick insulation layer is placed outside as in open to the outdoor air in order to ensure that the thermal mass of the actual floor is modelled as part of the actual floor without being distributed over all the floor elements.

Structure	D	λ	R	$\kappa_{m;op}$	ρ	c
	m	W/(m·K)	m²·K/W	J/(m²·K)	kg/m³	J/(kg·K)
External wall (inside to outside)						
Concrete block	0,100	0,510	0,196	140000	1400	1000
Foam insulation	0,0615	0,040	1,537	861	10	1400
Wood siding	0,009	0,140	0,064	4293	530	900
Total surf-surf			1,797			
For application of ISO 52016-1:				Heavy		
- Class specific heat capacity				Internal (I)		
- Class of distribution						
Floor (inside to outside)						
Concrete slab	0,080	1,130	0,071	112000	1400	1000
Insulation [a]	1,007	0,040	25,175	0 [b]	0 [b]	0 [b]
Total surf-surf			25,246			
For application of ISO 52016-1:				Medium		
- Class specific heat capacity				Internal (I)		
- Class of distribution						
Roof (inside to outside) [c]						
Plasterboard	0,010	0,160	0,063	7980	950	840
Fiberglass quilt	0,1118	0,040	2,794	1127	12	840
Roofdeck	0,019	0,140	0,136	9063	530	900
Total surf-surf			2,992			
For application of ISO 52016-1:				Very light		
- Class specific heat capacity				Evenly (D)		
- Class of distribution						

Table 3: Thermophysical properties of the opaque elements if the heavyweight case

3.3 Control Strategies

The case studies have been done for two different class of construction elements (heavyweight and lightweight) for different types of thermostat control strategies for the building HVAC system which enables us to identify the behavior of the building with varying control inputs which is the heating/cooling gains.

3.3.1 Free-Floating

In the Free-Floating condition, there is no heating or/and cooling gains to the thermal zone/building considered for the case studies. But, the building is subjected to other gains such as internal heat gains, constant infiltration from the external environment. The study of Free-Floating condition allows us to study the behavior of the construction elements with respect to the environment and could be used during the design phase of the modeling of the building systems.

3.3.2 Continuous

The case studies have been made with a continuous heating/cooling system which acts with a heating set-point of 20 °C and a cooling set-point of 27 °C. The system is continuous all over the day giving heating or/and cooling gains to the thermal zone.

3.3.3 Intermittent

The intermittent system used for the thermal zone has a night-time set back temperature for the heating system while the cooling part is continuous all over the day. This means that while there is a need for the cooling, the system is continuous and always have a set-point temperature of 27 °C. On the other hand, the heating system have a lower set-point of 10 °C during the night time from 23.00 to 07.00 and 20 °C from 07.00 to 23.00.

3.4 Other common properties

Specific heat capacity of air and furniture

The specific heat capacity of air and furniture is considered as $C_{m;int}$ = 10 000 J/(m^2.K)

Properties of glazing

The window consists of double pane glazing, with the following properties:

$g_{wi} = 0.789$

Considering a correction factor for non-scattering glazing $F_w = 0.9$

Consequently $g_{wi} = 0.71$

The following inputs has been adopted for the BESTEST cases

$U_w = 2.984$ W/(m2.K) [Thermal transmittance of the window]

$F_{fr} = 0$ [Window to Frame fraction]

Solar absorption coefficient

The solar coefficient for all opaque surfaces are considered as $\alpha_{sol} = 0.6$

View factor to the sky

The view factor to the sky shall be:

$F_{sky} = 1.0$ for the roof

$F_{sky} = 0.5$ for the walls

Convective fractions

The convective fractions are as follows

$f_{int;c} = 0.40$

$f_{sol;c} = 0.10$

$f_{HC;c} = 1.0$

Boundary conditions

The values of the conventional heat transfer coefficients on the boundaries are as follows

Heat transfer coefficient W/(m²·K)	Symbol	Direction of heat flow		
		Upwards	Horizontal	Downwards
convective coefficient; internal surface	$h_{c;i}$	5,0	2,5	0,7
convective coefficient; external surface	$h_{c;e}$	20	20	20
radiative coefficient; internal surface	$h_{lr;i}$	5,13	5,13	5,13
radiative coefficient; external surface	$h_{lr;e}$	4,14	4,14	4,14

Table 4: Conventional heat transfer coefficients

Internal heat flow rates

The total internal heat flow rate shall be 200 W continuously (24 hours per day for the full year), which results in a specific heat flow rate q_{int} = 1.453 W/m²

Ventilation

The infiltration rate is 0.41 air changes /h continuously (24 hours per day for the full year), which results in a specific heat flow rate q_v = 0.0148 m³/s

There is no ventilation system

Available heating and cooling capacity

The maximum available heating and cooling capacity is effectively infinite:

Qdot$_{HC;\ avail}$ = 1000 kW

3.5 Extensive RC network energy balance for Case studies

The test cases consist of lightweight and heavyweight envelopes with different construction elements.

EN ISO 52016-1:2017 gives specific ways to calculate the construction dependent properties of the elements. The lightweight cases in the BESTEST series consists of building elements with Class D for roof and walls and Class I for ground. Similarly, the heavyweight cases in

the BESTEST series have building elements with Class D for roof and Class I for the walls and floor.

The elements with Class D has the total areal heat capacity $\kappa_{m,}$ is distributed to each elements of the nodes while for the Class I elements the total areal heat capacity is concentrated to the internal surface of the node. According to this direction the consequent sensible energy balance equations have been developed for the test cases.

The window elements are also considered to have zero heat capacities resulting in a steady-state behavior.

Considering the above stated provisions given by the standard, all the nodes with building element heat capacities equal to zero are considered to be in steady-state condition. The sensible energy balance equations have been rearranged in such a way that they are used in the other subsequent sensible energy balance equation with heat capacity.

So, the sensible energy balance equations for the nodes *pli* = 1…4 for the class I are substituted to the Internal surface node of the same building element pli = 5;

For the window, since both the heat capacities are zero, the steady-state equation derived has been substituted thereof in all the state equation where there is a contribution of the window elements.

3.5.1 Sensible energy balance for Window elements

The window elements having zero heat capacities in both the nodes *pli=1 and pli=2* are considered to have a steady-state behavior. In order to consider their contribution in the sensible energy balance of the whole thermal zone, the equations derived from the steady-state sensible energy balance has been substituted in the internal surface node for all the building elements where there is a contribution due to the windows and also to the internal air node sensible energy balance.

3.5.1.1 External surface node (pli=1)

The sensible energy balance for the external surface node element has been derived from Eq.4

$$T_{1;wit} = \frac{1}{\beta_1}\left[h_{1;wi} \cdot T_{2;wi;t} + \left(h_{ce;wi} + h_{re;wi}\right) \cdot T_{e;t} + a_{sol}\right.$$
$$\left. \cdot \left(I_{sol;dif;t} + I_{sol;dir;t}F_{sh;obst;op}\right) - \varphi_{sky;wi;t}\right] \tag{Eq.9}$$

where,

$$\beta_1 = \left(h_{ce;wi} + h_{re;wi} + h_{1;wi}\right)$$

$T_{1;wi;t}$ is the external surface temperature of the window element;

3.5.1.2 Internal surface node (pli=2)

The internal surface node for the window element is derived from Eq.2 and the Equation.32 has been substituted to have a single steady-state equation which gives;

$$T_{2;wi;t} = \frac{1}{\beta_2}\left[\frac{h_{1;wi}}{\beta_1}\left[\left(h_{ce;wi} + h_{re;wi}\right) \cdot T_{e;t} + a_{sol}\right.\right.$$
$$\left.\left. \cdot \left(I_{sol;dif;t} + I_{sol;dir;t}F_{sh;obst;op}\right) - \varphi_{sky;wi;t}\right] + h_{ci;wi}\right.$$
$$\cdot T_{int;a;t}$$
$$+ \frac{1}{A_{tot}}\left[\left(1 - f_{int;c}\right) \cdot \varphi_{int;t} + \left(1 - f_{sol;c}\right) \cdot \varphi_{sol;t}\right.$$
$$\left. + \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t}\right] \tag{Eq.10}$$

where,

$$\beta_2 = \left[h_{ci;wi} + h_{1;wi} - \frac{h^2{}_{1;wi}}{\beta\_1} \right]$$

$T_{2;wi;t}$ is the internal surface temperature of the window element;

3.5.2 Sensible energy balance for Class D elements

The Class D elements have their thermal mass uniformly distributed resulting to have the total areal heat capacities distributed to all the 5 nodes in the building elements. That being said these elements will have 5 state equations for all the 5 nodes i.e. one each for external and internal surface node and 3 inside nodes for each building elements.

The sensible energy balance from Eq.11 to Eq.15 represents the typical equations for all the elements with Class D.

3.5.2.1 External Surface node (pli=1)

The sensible energy balance equation derived for the external surface node from equation (4) is the same for the all the building elements with the Class D.

$$\begin{aligned}
\left(\kappa_{1;i} \right) \cdot \frac{\left(T_{1;i;t} - T_{1;i;t-1} \right)}{\Delta t} \\
= -\left(h_{ce;i} + h_{re;i} + h_{1;i} \right) \cdot T_{1;i;t} + h_{1;i} \cdot T_{2;i;;t} \\
+ \left(h_{ce;i} + h_{re;i} \right) \cdot T_{e;t} + a_{sol} \\
\cdot \left(I_{sol;dif;t} + I_{sol;dir;t} F_{sh;obst;op} \right) - \varphi_{sky;t}
\end{aligned} \qquad \text{(Eq.11)}$$

where,

i - external walls, window, roof and floor.

3.5.2.2 Inside node (pli=2)

The Eq.33 to Eq.35 for all the inside nodes with respect to the concerned building elements have been derived from Eq.3.

$$\left(\kappa_{2;i}\right) \cdot \frac{T_{2;i;;t} - T_{2;i;t-1}}{\Delta t} = h_{1;i} \cdot T_{1;i;t} - \left(h_{2;i} + h_{1;i}\right) \cdot T_{2;i;;t} + h_{2;i} \cdot T_{3;i;t} \qquad \text{(Eq.12)}$$

3.5.2.3 Inside node (pli=3)

$$\left(\kappa_{3;i}\right) \cdot \frac{T_{3;i;t} - T_{3;i;t-1}}{\Delta t} = h_{2;i} \cdot T_{2;i;;t} - \left(h_{3;i} + h_{2;i}\right) \cdot T_{3;i;t} + h_{3;i} \cdot T_{4;i;t} \qquad \text{(Eq.13)}$$

3.5.2.4 Inside node (pli=4)

$$\left(\kappa_{4;i}\right) \cdot \frac{T_{4;i;t} - T_{4;i;t-1}}{\Delta t} = h_{3;i} \cdot T_{3;i;t} - \left(h_{4;i} + h_{3;i}\right) \cdot T_{4;i;t} + h_{4;i} \cdot T_{5;i;t} \qquad \text{(Eq.14)}$$

where,

i - external walls, roof and floor.

Since the window elements just has the internal and external surface nodes the inside nodes need not be considered.

3.5.2.5 Internal surface node (pli=5)

The internal surface node for each of the building element is considered also for the radiative contribution due to all the building elements inside the thermal zone.

The below equation gives the sensible energy balance for the internal surface node, the Eq.2 has been substituted for the contribution from the window elements;

$$\left(\kappa_{5;i}\right) \cdot \frac{T_{5;i;t} - T_{5;i;t-1}}{\Delta t}$$

$$= h_{4;i} \cdot T_{4;i;t} - \left[h_{ci;i} + h_{ri;i} \cdot \sum_{eli=1}^{6} \left(\frac{A_{eli}}{A_{tot}}\right) + h_{4;i}\right]$$

$$\cdot T_{5;i;t} + h_{ci;i} \cdot T_{int;a;t}$$

$$+ \left(\left(\frac{A_i}{A_{tot}}\right) \cdot h_{ri;i} \cdot T_{5;i} + \left(\frac{A_{wall;E}}{A_{tot}}\right) \cdot h_{ri;wall;E}\right.$$

$$\cdot T_{5;wall;E} + \left(\frac{A_{wall;S}}{A_{tot}}\right) \cdot h_{ri;wall;S} \cdot T_{5;wall;S} + \left(\frac{A_{wall;W}}{A_{tot}}\right)$$

$$\cdot h_{ri;wall;W} \cdot T_{5;wall;W} + \left(\frac{A_{roof}}{A_{tot}}\right) \cdot h_{ri;roof} \cdot T_{5;roof}$$

$$+ \left(\frac{A_{floor}}{A_{tot}}\right) \cdot h_{ri;floor} \cdot T_{5;floor} + \left(\frac{A_{wi;N}}{A_{tot}}\right) \qquad \text{(Eq.15)}$$

$$\cdot h_{riwi} \left[\frac{1}{\beta_2}\left[\frac{h_{1;wi}}{\beta_1}\left[\left(h_{ce;wi} + h_{re;wi}\right) \cdot T_{e;t} - \varphi_{sky;wi;t}\right]\right]\right.$$

$$+ h_{ci;wi} \cdot T_{int;a;t}$$

$$+ \frac{1}{A_{tot}} \left[\left(1 - f_{int;c}\right) \cdot \varphi_{int;t} + \left(1 - f_{sol;c}\right) \cdot \varphi_{sol;t}\right.$$

$$+ \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t}\right]\right)$$

$$+ \frac{1}{A_{tot}} \left[\left(1 - f_{int;c}\right) \cdot \varphi_{int;t} + \left(1 - f_{sol;c}\right) \cdot \varphi_{sol;t}\right.$$

$$+ \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t}\right]$$

where,

i - external walls, roof and floor elements.

3.5.3 Sensible energy balance for Class I elements

The building elements with Class I are heavyweight elements which is considered to have the mass concentrated in the internal surface of the element.

Therefore, the total areal heat capacity κ_m of the building element is given totally to the internal surface node *pli=5*. Thus, for every building elements with Class I there is only one state equations which has the contribution from all the other nodes *pli=1...n-1* that has a steady-state behavior due the zero node heat capacities.

The sensible energy balance Eq.16 to Eq.20 are used for all the elements with the Class I, while Eq.20 alone being the state equation.

3.5.3.1 External Surface node (pli=1)

The steady-state balance for the external surface node equation derived from Eq.27

$$T_{1;i;t} = \frac{1}{\alpha_{1;i}} \big[h_{1;i} \cdot T_{2;i;;t} + \big(h_{ce;i} + h_{re;i} \big) \cdot T_{e;t} + a_{sol}$$
$$\cdot \big(I_{sol;dif;t} + I_{sol;dir;t} F_{sh;obst;op} \big) - \varphi_{sky;t} \big]$$

(Eq.16)

where,

$$\alpha_{1;i} = \big(h_{ce;i} + h_{re;i} + h_{1;i} \big)$$

i - external walls, roof and floor

$T_{1;i;t}$ - Internal surface temperature of the *i* building elements

3.5.3.2 Inside node (pli=2)

The steady-state sensible energy balance Eq.17 to Eq.19 has been derived for the inside nodes from Eq.3

$$
\begin{aligned}
T_{2;i;;t} = \frac{1}{\alpha_{2;i}} \Bigg[\frac{h_{1;i}}{\alpha_1} \Big[\left(h_{ce;i} + h_{re;i}\right) \cdot T_{e;t} + a_{sol} \\
\cdot \left(I_{sol;dif;t} + I_{sol;dir;t} F_{sh;obst;op}\right) - \varphi_{sky;t} \Big] + h_{2;i} \\
\cdot T_{3;i;t} \Bigg]
\end{aligned}
\qquad \text{(Eq.17)}
$$

where,

$$
\alpha_{2;i} = \left(h_{2;i} + h_{1;i} - \frac{h^2{}_{1;i}}{\alpha_1} \right)
$$

i - external walls, roof and floor

$T_{2;i;t}$ - Temperature at *pli=2* of the i building elements

3.5.3.3 Inside node (pli=3)

$$
\begin{aligned}
T_{3;i;t} = \frac{1}{\alpha_{3;i}} \Bigg[\frac{h_{2;i}}{\alpha_2} \Bigg[\frac{h_{1;i}}{\alpha_1} \Big[\left(h_{ce;i} + h_{re;i}\right) \cdot T_{e;t} + a_{sol} \\
\cdot \left(I_{sol;dif;t} + I_{sol;dir;t} F_{sh;obst;op}\right) - \varphi_{sky;t} \Big] \Bigg] + h_{3;i} \\
\cdot T_{4;i;t} \Bigg]
\end{aligned}
\qquad \text{(Eq.18)}
$$

where,

$$\alpha_{3;i} = \left(h_{3;i} + h_{2;i} - \frac{h^2{}_{2;i}}{\alpha_2} \right)$$

i - external walls, roof and floor

T$_{3;i;t}$ - Temperature at *pli=3* of the *i* building elements

3.5.3.4 Inside node (pli=4)

$$T_{4;i;t} = \frac{1}{\alpha_{4;i}} \left[\frac{h_{3;i}}{\alpha_3} \left[\frac{h_{2;i}}{\alpha_2} \left[\frac{h_{1;i}}{\alpha_1} \left[\left(h_{ce;i} + h_{re;i} \right) \cdot T_{e;t} + a_{sol} \right. \right. \right. \right.$$

$$\left. \left. \left. \cdot \left(I_{sol;dif;t} + I_{sol;dir;t} F_{sh;obst;op} \right) - \varphi_{sky;t} \right] \right] + h_{4;i} \quad \text{(Eq.19)}$$

$$\left. \cdot T_{5;i;t} \right]$$

where,

$$\alpha_{4;i} = \left(h_{4;i} + h_{3;i} - \frac{h^2{}_{3;i}}{\alpha_3} \right)$$

i - external walls, roof and floor

T$_{4;i;t}$ - Temperature at *pli=4* of the *i* building elements

3.5.3.5 Internal surface node (pli=5)

The steady-state equations for *pli=1…n-1* derived from Eq.16 to Eq.19 is substituted into the internal surface node of the building elements thereby giving their contribution to the state node.

The steady-state equation Eq.10 giving the window contribution to the internal surface node has been considered in the internal surface node equation.

$$
\left(\kappa_{5;i}\right) \cdot \frac{T_{5;i;t} - T_{5;i;t-1}}{\Delta t}
$$

$$
= \frac{h_{4;i}}{\alpha_4}\left[\frac{h_{3;i}}{\alpha_3}\left[\frac{h_{2;i}}{\alpha_2}\left[\frac{h_{1;i}}{\alpha_1}\left[\left(h_{ce;i} + h_{re;i}\right)\cdot T_{e;t} + a_{sol}\right.\right.\right.\right.
$$

$$
\left.\left.\left.\left.\cdot \left(I_{sol;dif;t} + I_{sol;dir;t}F_{sh;obst;op}\right) - \varphi_{sky;t}\right]\right]\right]\right]
$$

(Eq.20)

$$
- \left[h_{ci;i} + h_{ri;i} \cdot \sum_{eli=1}^{6}\left(\frac{A_{eli}}{A_{tot}}\right) + h_{4;i} - \frac{h^2_{4;i}}{\alpha_4}\right]\cdot T_{5;i;t}
$$

$$
+ h_{ci;i} \cdot T_{int;a;t} + \gamma_1 + \gamma_2
$$

$$\gamma_1 = \left(\left(\frac{A_{wall;N}}{A_{tot}}\right) \cdot h_{ri;wall;N} \cdot T_{5;wall;N} + \left(\frac{A_{wall;E}}{A_{tot}}\right) \cdot h_{ri;wall;E} \cdot T_{5;wall;E} + \left(\frac{A_{wall;S}}{A_{tot}}\right) \right.$$

$$\cdot h_{ri;wall;S} \cdot T_{5;wall;S} + \left(\frac{A_{wall;W}}{A_{tot}}\right) \cdot h_{ri;wall;W} \cdot T_{5;wall;W} + \left(\frac{A_{roof}}{A_{tot}}\right) \cdot h_{ri;roof}$$

$$\cdot T_{5;roof} + \left(\frac{A_{floor}}{A_{tot}}\right) \cdot h_{ri;floor} \cdot T_{5;floor} + \left(\frac{A_{wi;N}}{A_{tot}}\right)$$

$$\cdot h_{riwi} \left[\frac{1}{\beta_2} \left[\frac{h_{1;wi}}{\beta_1} \left[(h_{ce;wi} + h_{re;wi}) \cdot T_{e;t} - \varphi_{sky;wi;t} \right] \right] + h_{ci;wi} \cdot T_{int;a;t} \right.$$

$$\left. \left. + \frac{1}{A_{tot}} \left[(1 - f_{int;c}) \cdot \varphi_{int;t} + (1 - f_{sol;c}) \cdot \varphi_{sol;t} + \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t} \right] \right] \right)$$

$$\gamma_2 = \frac{1}{A_{tot}} \left[(1 - f_{int;c}) \cdot \varphi_{int;t} + (1 - f_{sol;c}) \cdot \varphi_{sol;t} + \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t} \right]$$

where,

i - external walls, roof and floor elements

Therefore, the building elements with Class I will have just one state equation from *pli=5* which considers the contribution from all the other nodes.

3.5.4 Sensible energy balance for the internal air node element

The energy balance equation of the internal air node element has been derived from Eq.1

$$
\left(C_{int;ztc}\right) \cdot \frac{T_{int;a;t} - T_{int;a;t-1}}{\Delta t} \tag{Eq.21}
$$

$$
= -\big[(A_{wall;N} \cdot h_{ci;wall;N} + A_{wi} \cdot h_{ci;wi} + A_{wall;E}
$$

$$
\cdot h_{ci;wall;E} + A_{wall;S} \cdot h_{ci;wall;S} + A_{wall;W} \cdot h_{ci;wall;W}
$$

$$
+ A_{roof} \cdot h_{ci;roof} + A_{floor} \cdot h_{ci;floor}) + H_{ve;t}
$$

$$
+ H_{tr;tb;ztc}\big] \cdot T_{int;a;t}
$$

$$
+ \Big[(A_{wall;N} \cdot h_{ci;wall;N}) \cdot T_{5;wall;N} + (A_{wi} \cdot h_{ci;wi})
$$

$$
\cdot \frac{1}{\beta_2}\left[\frac{h_{1;wi}}{\beta_1}\big[(h_{ce;wi} + h_{re;wi}) \cdot T_{e;t} - \varphi_{sky;wi;t}\big]\right]
$$

$$
+ h_{ci;wi} \cdot T_{int;a;t}
$$

$$
+ \frac{1}{A_{tot}}\left[(1 - f_{int;c}) \cdot \varphi_{int;t} + (1 - f_{sol;c}) \cdot \varphi_{sol;t}\right.
$$

$$
\left. + \left(1 - f_{\frac{H}{C};c}\right) \cdot \varphi_{HC;t}\right] + (A_{wall;E} \cdot h_{ci;wall;E})
$$

$$
\cdot T_{5;wall;E} + (A_{wall;S} \cdot h_{ci;wall;S}) \cdot T_{5;wall;S}
$$

$$
+ (A_{wall;W} \cdot h_{ci;wall;W}) \cdot T_{5;wall;W}
$$

$$
+ (A_{roof} \cdot h_{ci;roof}) \cdot T_{5;roof} + (A_{floor} \cdot h_{ci;floor})
$$

$$
\cdot T_{5;floor}\Big] + H_{ve;t} \cdot T_{e;t} + H_{tr;tb;ztc} \cdot T_{e;t} + f_{int;c}
$$

$$
\cdot \varphi_{int;t} + f_{sol;c} \cdot \varphi_{sol;t} + f_{\frac{H}{C};c} \cdot \varphi_{HC;t}
$$

3.6 Weather data

The dynamic energy simulation results are highly affected due to the various type of inputs that affects the end performance between the actual simulation results and real performance [9].. The weather analysis is done for the three-different climate file which has been used for the case studies. The monthly average external air temperature and the monthly total horizontal radiation has been calculated and studied for the climate files drycold weather, Milan and Palermo.

3.6.1 Weather data 1 - drycold weather

The drycold weather data is the actual climate file provided in the standard ISO 52016-1 which has been used as the primary climate data for analysis and testing of the different models. It is similar to the Colorado (USA) weather.
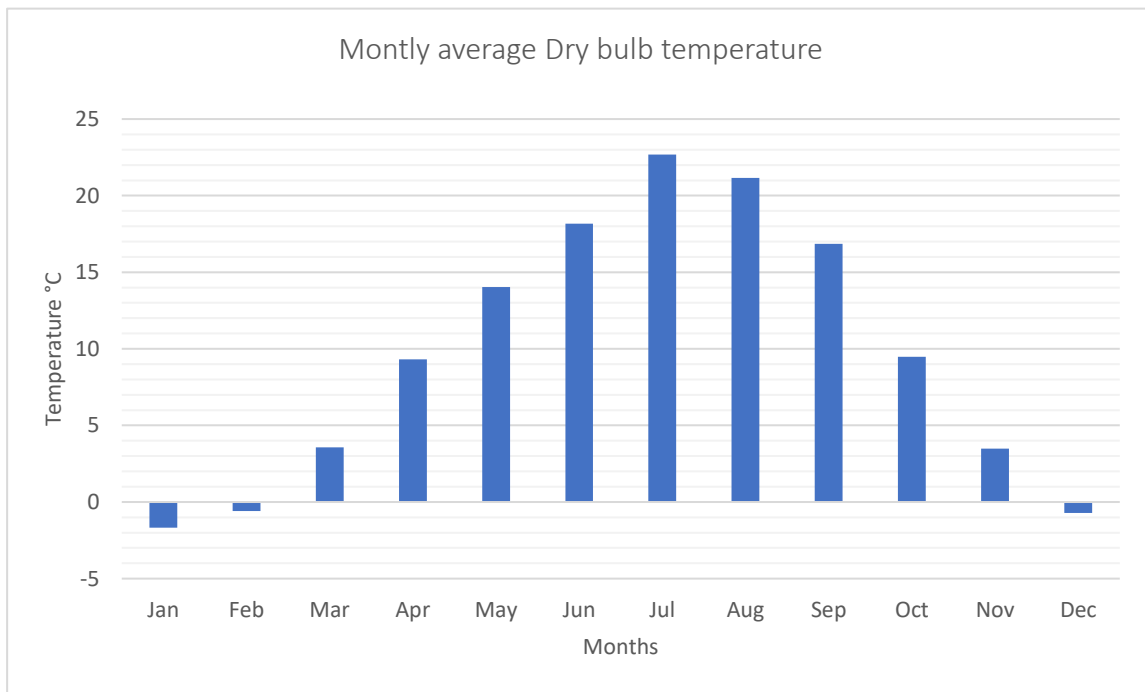

Figure 3-2: Monthly average temperature - *drycold weather*

The monthly average temperature shows that the drycold weather climate has a cold winter season having the monthly average temperature as low as -2 °C and warm summer climate.
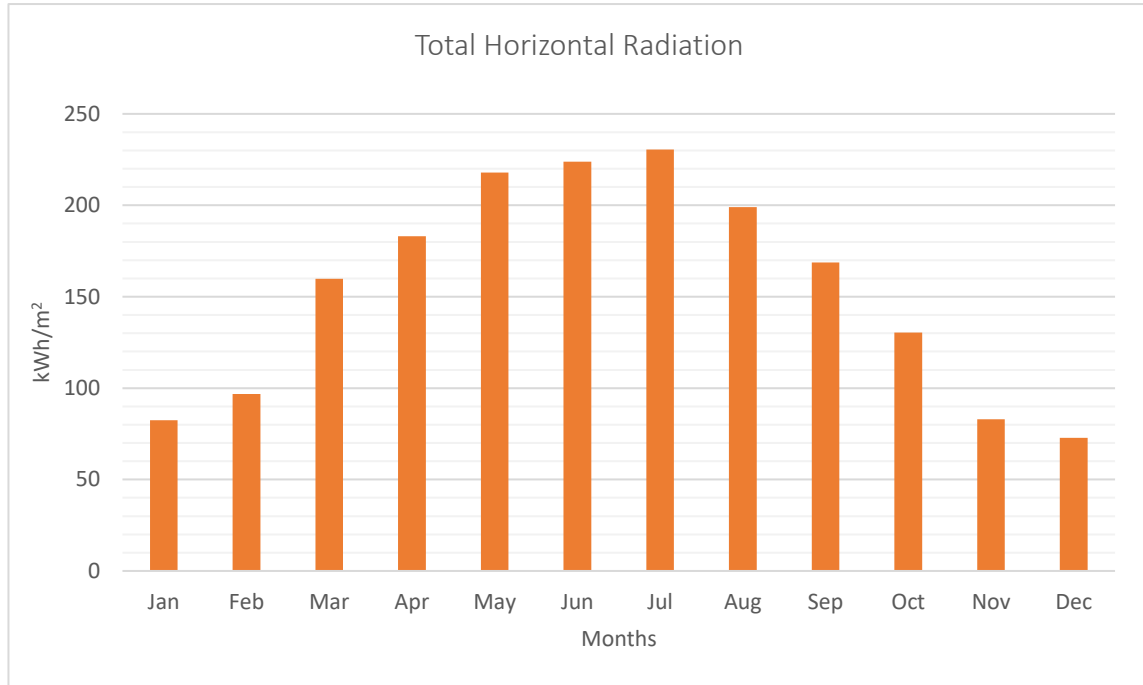

Figure 3-3: Monthly horizontal radiation - *drycold weather*

The Figure 3-3 shows that the climate file has a higher radiation also during the winter. In the January, the climate file has an exceptionally high radiation while the temperature is very low all over the month.

3.6.2 Weather data 2 - Milan

In addition to the standard proposed climate file, an additional two climate files (Milan and Palermo) from the Italy has been considered for the simulation. The two climate data files adopted have diverse climates and for the same reason it is chosen for the case studies.
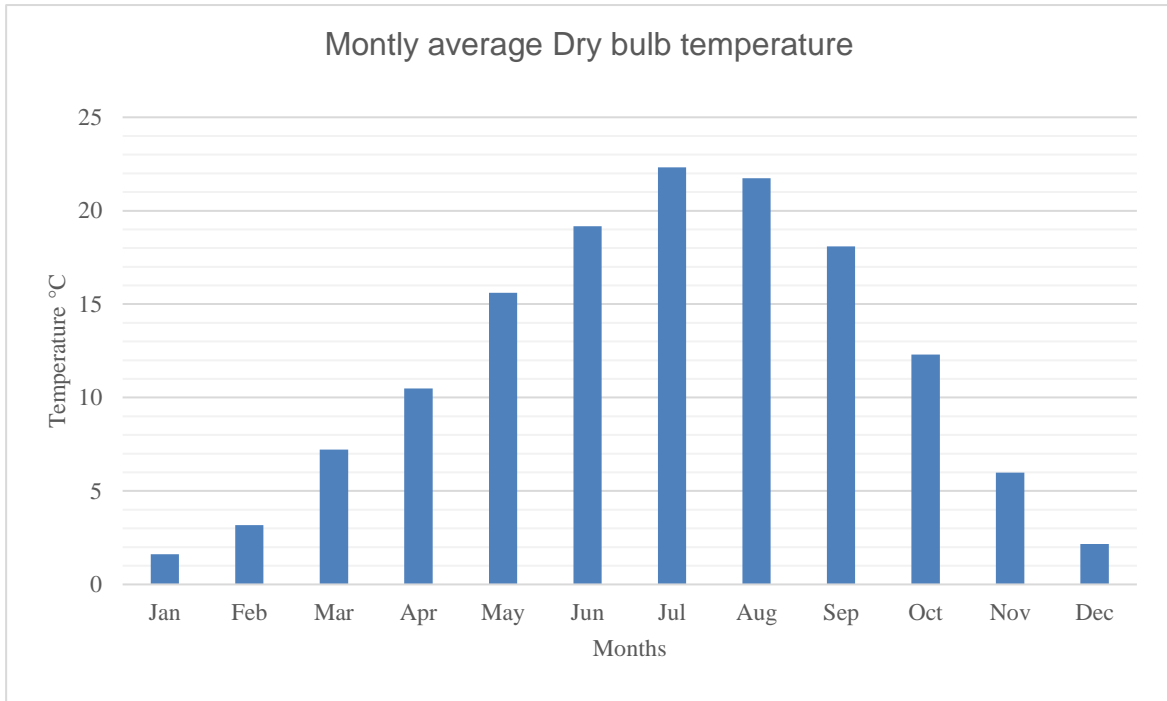

Figure 3-4: Monthly average temperature - *Milan*

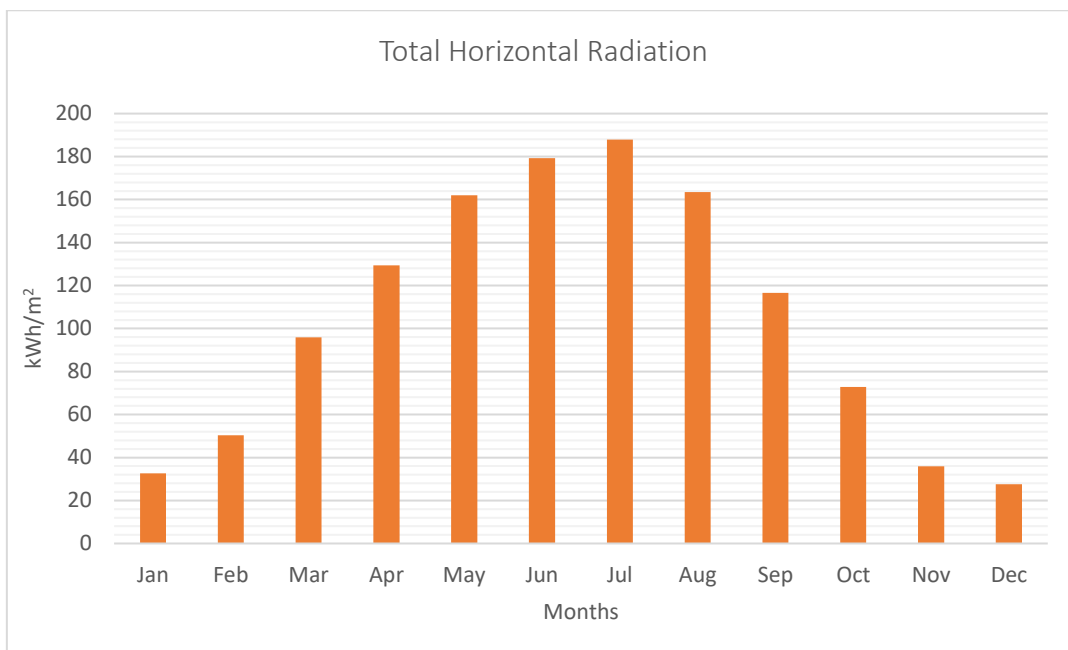The Figure 3-4 shows that the Milan has a cold winter even though not as cold as the drycold weather.

Figure 3-5: Monthly horizontal radiation - *Milan*

The radiation during the summer period is really low and the summer has a high radiation. These facts show that there is a need for both the heating/cooling system in the building zone.

3.6.3 Weather data 3 -Palermo

The climate file of Palermo, Italy has been chosen for the case studies as it has a very varied climate with respect to Northern Italy.
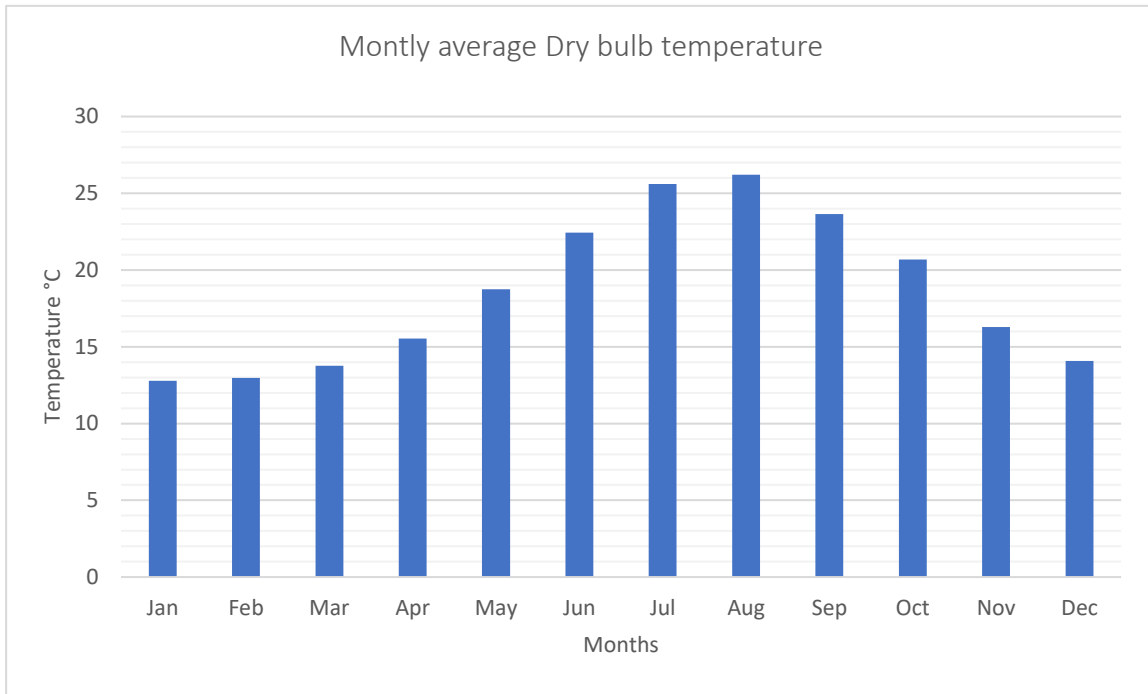

Figure 3-6: Monthly average temperature - *Palermo*

The Palermo has a high monthly average temperature all over the year with respect to the season comparted in the Northern Italy. The month of January has an average monthly temperature of around 14 °C.
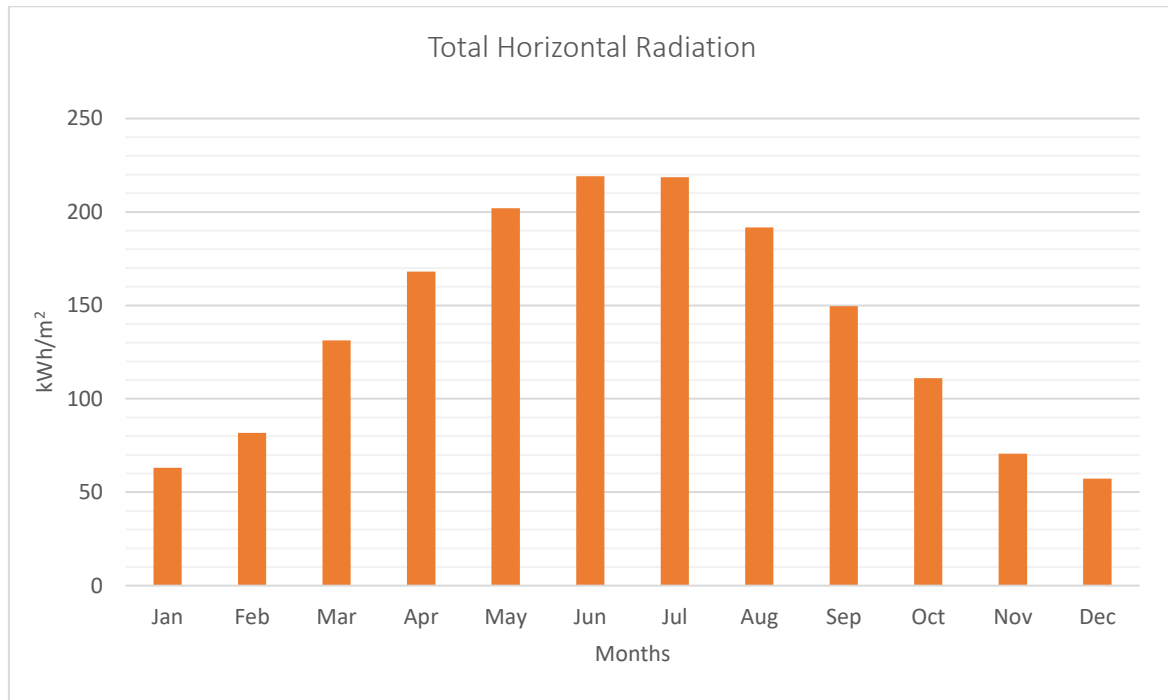
Figure 3-7: Monthly horizontal radiation - *Palermo*

The Figure 3-7 shows that the Palermo has a very high horizontal radiation during the summer with values as high as above 200 kWh/m^2.

All the three climate files analyzed have been used for the case studies. So, the case studies have been done for three different climates for two different seasons with varying class of construction and control strategies.

4 Numerical Implementation

The BESTEST cases has been modeled in Matlab with an extensive RC network model from the EN 52016-1 and a simple 5R1C model from 13790:2008. In addition, the case studies have been carried out using the excel spreadsheet accompanied by the standard and also with an extensive software as TRNSYS.

4.1 Simple 5R1C model of ISO 13790:2008 in Matlab

Background

The European standard EN ISO 13790:2008 describing the procedures to calculate the sensible energy performance of buildings covers two different type of methods:

- Quasi-steady-state methods, calculating the heat balance over a sufficiently long time (typically one month or a whole season), which enables one to take dynamic effects into account by an empirically determined gain and/or loss utilization factor
- Dynamic methods, calculating the heat balance with short times steps (typically one hour) considering the heat stored in, and released from, the mass of the building.

The dynamic methods include the simple hourly calculation method using five resistances and one capacitance model (5R1C) model. The Resistance-Capacitance model could be used in the dynamic model of the building due to the similarity between flow of electric current and heat flux.

The 5R1C model is a simplified dynamic calculation method, that uses an hourly time step and all the building and system input data has to modified in to hourly basis. The model has a limited set of equations for the dynamic calculation and it requires less number of inputs.

The model is able to make a distinction between the internal air temperature (T_a) and mean temperature (T_s)of the internal surfaces (mean radiant temperature). This helps its use for

thermal comfort checks and increasing the accuracy of considering the radiative and convective parts of sola and internal heat gains, although the simple hourly results are not reliable [10].

The calculation method is based on the simplifications of the heat transfer between the internal and external environment, as shown in Figure 4-1.
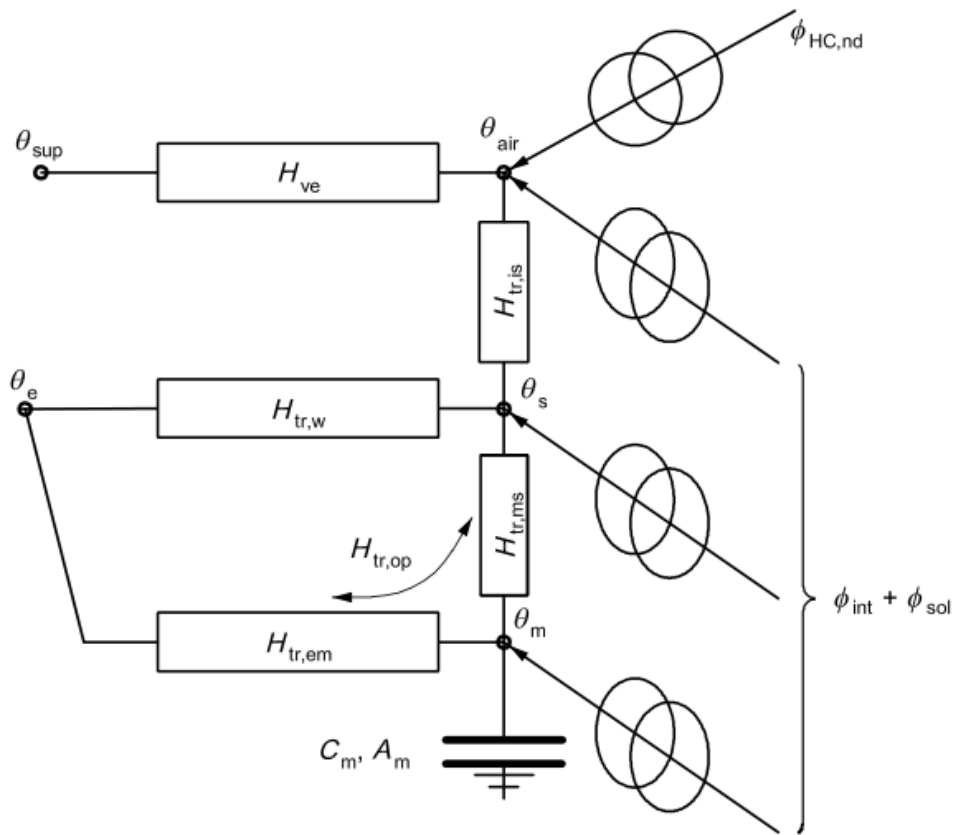

Figure 4-1: 5R1C model of the ISO 13790:2008 [10]

The EN ISO 13790 standard presents a full description of the 5R1C model of a building (or zone).

The heating or cooling power (φ_{HC}) is supplied to or extracted from the indoor air node (T_i) to maintain a certain room set point temperature: $T_{int,H,set}$ for heating or $T_{int,C,set}$ for cooling.

The heat flow rates due to internal heat sources (φ_{int}) and due to solar heat sources (φ_{sol}) are split into three parts which are φ_{ia}, φ_{st}, φ_m. These three parts are connected to the indoor air (T_i), internal environment (T_s) and thermal mass (T_m) nodes respectively.

The heat transfer by ventilation (H_{ve}) is connected with the supply air temperature (T_{sup}) and internal air temperature (T_i). The heat transfer coefficient by transmission for windows ($H_{tr,w}$) is taken as having no thermal mass. The heat transfer coefficient by transmission for opaque elements ($H_{tr,op}$) is split into the external ($H_{tr,em}$) and internal ($H_{tr,ms}$) parts, connected to the single thermal capacity (C_m), representing the thermal mass of the building (or zone). The internal air node (T_i) and central node (T_s) are connected to through the coupling conductance $H_{tr,is}$.

Numerical Calculations

The 5R1C model specified in the ISO 13790:2008 has been modeled in the Matlab in order to study the dynamic behavior of the model and compare it with a more advanced as in EN ISO 52016-1.

The EN ISO 13790 standard gives the procedure to calculate all the elements of the 5R1C network model.

1. Heat Transfer coefficient by transmission for windows $H_{tr,w} = A_{wi} * U_{wi}$ [W/K]
2. Heat Transfer coefficient by transmission for opaque $H_{tr,op} = A_{wall} * U_{wall}$ [W/K]
    2.1. The internal part of the opaque $H_{tr,ms} = h_{ms} * A_m$ [W/K]
    2.2. The external part of the opaque $H_{tr,em} = 1/(1/H_{tr,op})-(1/H_{tr,ms})$ [W/K]
3. Heat transfer coefficient due to the coupling conductance $H_{tr,is} = h_{is} * A_{tot}$ [W/K]
4. Heat transfer coefficient due to ventilation $H_{ve} = m_a * c_{p\_da} * 1000$ [W/K]
5. Thermal Capacitance $C_m = C_a * 1000$ [J/K]

where,

h_{ms} - 9.1 [W/m^{2}K]

A_m is the effective mass area [m^2] - 3*A_{floor} {Heavy Class Buildings}

h_{is} - 3.45 [W/m^{2}K]

A_{tot} is the area of all surfaces facing the building zone[m^2] - 4.5*A_{floor}

m_a is the mass flow rate of air [kg/hr] - V_{IAQ} * ρ_a = 45*person*1.2

c_{p_da} is the specific heat capacity of dry air [kJ/kg_da/K] - 1.005

C_a is the room air heat capacity

The sensible energy rate balance equation is given by

$$\frac{dE}{dt} = \dot{Q}_t + \dot{Q}_{sol} + \dot{Q}_{p\_s} + \dot{Q}_{v,in} - \dot{Q}_{v,out} \qquad \text{(Eq.22)}$$

$$C_m * \frac{dT_a}{dT} = \dot{Q}_t + \dot{Q}_{sol} + \dot{Q}_{p\_s} + \dot{Q}_{v,in} - \dot{Q}_{v,out} \qquad \text{(Eq.23)}$$

Applying the sensible energy rate equation to each lumped node on the 5R1C model would give us the following linear equations to solve and determine the respective temperatures.

$$T'_m = \frac{(T_e - T_m) * H_{tr,em} + \dot{Q}_{sol,tot} + (T_s - T_m) * H_{tr,ms} + (\dot{Q}_{p,s}/3)}{C_m} \qquad \text{(Eq.24)}$$

$$T_a = \frac{T_e * H_{ve} + \dot{Q}_{HC,nd} + T_s * H_{tr,is} + (\dot{Q}_{p,s}/3)}{H_{ve} + H_{tr,is}} \qquad \text{(Eq.25)}$$

$$T_s = \frac{T_e * H_{tr,w} + T_m * H_{tr,ms} + T_a * H_{tr,is} + (\dot{Q}_{p,s}/3)}{H_{tr,w} + H_{tr,ms} + H_{tr,is}} \qquad \text{(Eq.26)}$$

The above linear equations have been written in the state-space form in order to solve them for multiple input and output variables.

State - Space form:

$$x' = Ax + Bu + q \qquad \text{(Eq.27)}$$

$$y = Cx + Du \qquad \text{(Eq.28)}$$

The energy balance equations written in Matrix form for the dynamic simulation,

$$A = [-H_{tr,em} - H_{tr,ms}] \qquad \text{(Eq.29)}$$

$$B = [0 \quad H_{tr,ms}] \qquad \text{(Eq.30)}$$

$$C = \begin{bmatrix} H_{tr,ms} \\ 0 \end{bmatrix} \qquad \text{(Eq.31)}$$

$$D = \begin{bmatrix} -H_{tr,is} & H_{tr,w} + H_{tr,ms} + H_{tr,is} \\ H_{ve} + H_{tr,is} & -H_{tr,is} \end{bmatrix} \qquad \text{(Eq.32)}$$

$$x = [T_m] \tag{Eq.33}$$

$$u = \begin{bmatrix} T_a \\ T_s \end{bmatrix} \tag{Eq.34}$$

$$y = \begin{bmatrix} T_e * H_{tr,w} + (\dot{Q}_{p,s}/3) \\ T_e * H_{ve} + \dot{Q}_{HC,nd} + (\dot{Q}_{p,s}/3) \end{bmatrix} \tag{Eq.35}$$

$$q = \dot{Q}_{sol,tot} + \dot{Q}_{p,s} + T_e * H_{tr,em} \tag{Eq.36}$$

The above values have been given as an input for the Matlab coding and the results have been calculated which is then compared with the behavior of the advanced RC network modeling.

4.2 Extensive RC network modeling in Matlab

In this section, it has been developed the numerical implementation of the calculated energy balance equation from the BESTEST cases according to the new model. Once, the sensible energy balance equation has been developed for all the cases. The equations have been converted to state-space form which enables us to perform dynamic calculation in Matlab.

$$x' = A + B \cdot u \tag{Eq.37}$$

$$y = C \cdot x + D \cdot u \tag{Eq.38}$$

In the above notation, x is the state vector and u is the control (input vector) while y is the output vector. A is the system matrix, B is the input matrix while C and D are the output and feed forward matrix.

In the lightweight case, there are 27 state variables and for the heavyweight there are 11 state variables. The number of state variables have been set up from the total number of sensible energy balance equations.

There are totally 9 input vectors for both light weight and heavy weight cases. They are solar radiation from all the four directions and the horizontal radiation, thermal radiation losses to the sky, internal heat gains, heating or cooling sensible energy needs and the external air temperature.

The following are the structure of the state-space models given as an input in the Matlab coding:

Let A = [a$_{ij}$], and x = [x$_i$] be m x n and m x 1 matrices respectively. Then we have,

$$A \cdot x = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mj} & \cdots & a_{mn} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_m \end{bmatrix}$$ (Eq.39)

Similarly, B = [b$_{ij}$], and u = [u$_i$]

$$B \cdot u = \begin{bmatrix} b_{11} & \cdots & b_{1j} & \cdots & b_{1n} \\ b_{21} & \cdots & b_{2j} & \cdots & b_{2n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ b_{i1} & \cdots & b_{ij} & \cdots & b_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mj} & \cdots & b_{mn} \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_i \\ \vdots \\ u_m \end{bmatrix}$$ (Eq.40)

Let C = [c$_{ij}$], and x = [x$_i$] be m x n and m x 1 matrices respectively. Then we have,

$$C \cdot x = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1j} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2j} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_{i1} & c_{i2} & \cdots & c_{ij} & \cdots & c_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mj} & \cdots & c_{mn} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_m \end{bmatrix} \qquad \text{(Eq.41)}$$

Similarly, $D = [d_{ij}]$, and $u = [u_i]$

$$D \cdot u = \begin{bmatrix} d_{11} & \cdots & d_{1j} & \cdots & d_{1n} \\ d_{21} & \cdots & d_{2j} & \cdots & d_{2n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ d_{i1} & \cdots & d_{ij} & \cdots & d_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mj} & \cdots & d_{mn} \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_i \\ \vdots \\ u_m \end{bmatrix} \qquad \text{(Eq.42)}$$

Once the matrix has been converted into state-space form using the *sys* command, the dynamic simulation of my output vector could be calculated using the *lsim* command. Therefore, by having an identity C matrix (output matrix), the state variables could be identified which in our BESTEST case is the temperature at each node for the building elements and the internal air node temperature.

The calculation of the sensible energy needs for the heating/cooling has been done using a rule based controller in the Matlab coding having known the thermostat control strategy for all the test cases.

4.2.1 Rule based control for the calculation of Energy needs in Matlab

In order to calculate the energy needs consumption for the continuous and intermittent heating system, a rule-based control approach for each time step has been used for the same.

1. Calculation of Internal air temperature in Free-Floating ($T_{air;FF}$) in each time step with zero heating or/and cooling gains;

2. If $T_{H;set} \leq T_{air;FF} \leq T_{C;set}$, the energy need is zero for the time step;

3. In a for loop the condition statement $T_{air;FF} > T_{C;set}$ is checked on if it is true , switch on the cooling system which means giving negative values of the HC(Heating/Cooling) gains and the for loop runs by giving step increase values for the HC gains until the statement is false. Once the state is false the code breaks out of the loop and calculated the energy consumed by the thermal zone.

4. The same process is done for the heating system, conditional statement $T_{air;FF} < T_{C;set}$ is cheked and if it is true, the system starts giving the positve values of the HC gains and calculates the indoor air temperature using *lsim* command and the calculated value is checked again for the conditional statement and if it false it comes out of the loop and calculate the energy consumed.

4.3 ISO 52016-1:2017 Excel spreadsheet

The EN ISO 52016-1:2017 has provided an excel spreadsheet that has to be used by the software developers implementing the model of the standard for the calculation of sensible energy needs for heating/cooling and internal air temperature. So, all the BESTEST cases calculated using the Matlab modeling has to verified with the spreadsheet calculation having the same inputs and boundary condition in order to valid the model.

So, for all the test cases in the BESTEST series, the sensible energy needs and internal air temperature has been calculated using the excel spreadsheet and their results have been compared.

4.4 Type 56 dynamic model TRNSYS modeling

The thermal zone of the BESTEST cases has been modeled in the TRNSYS with the same boundary conditions to test the validity of the model with a more advanced tool like Type 56 dynamic model TRNSYS.

The type 56 component of the TRNSYS has been used to model the thermal zone and to calculate the internal air temperature of the zone and the sensible energy needs for heating and cooling.

The results from the TRNSYS model has been verified with the Matlab model to test the validity of the model developed.

5 Results and Comparison

The results of the hourly energy needs consumption and the hourly internal air temperature have been calculated for all the test cases. The results are calculated for two typical months January and June which are given in the standard as the test winter and test summer months.

Weather data	Months	Test No.	BESTEST case identifier	Type of construction	Thermostat control strategy
1.drycoldweather 2.Milan 3.Palermo	1.January 2. June	1	600FF	Lightweight	Free-Floating
		2	900FF	Heavyweight	Free-Floating
		3	600	Lightweight	Continuous
		4	900	Heavyweight	Continuous
		5	640	Lightweight	Intermittent
		6	940	Heavyweight	Intermittent
Note: The 6 different cases have been carried out for the 3 different climate files for two different seasons					

Figure 5-1: Case description

5.1 Weather data 1 - drycold weather

The drycold weather is the climate file giver in the verification cases for the BESTEST series in the EN ISO 52016-1. So, the drycold weather file has been used to verify the BESTEST cases with the developed Matlab model and the excel spreadsheet and also it has been compared with the results obtained from the TRNSYS Type 56 dynamic model.

5.1.1 ISO 13790 Vs EN 52016-1:2017

As a preliminary study, the 5R1C model from the ISO 13790 has been studied and calculated for the internal air temperature for the case 600FF in the BESTEST series.
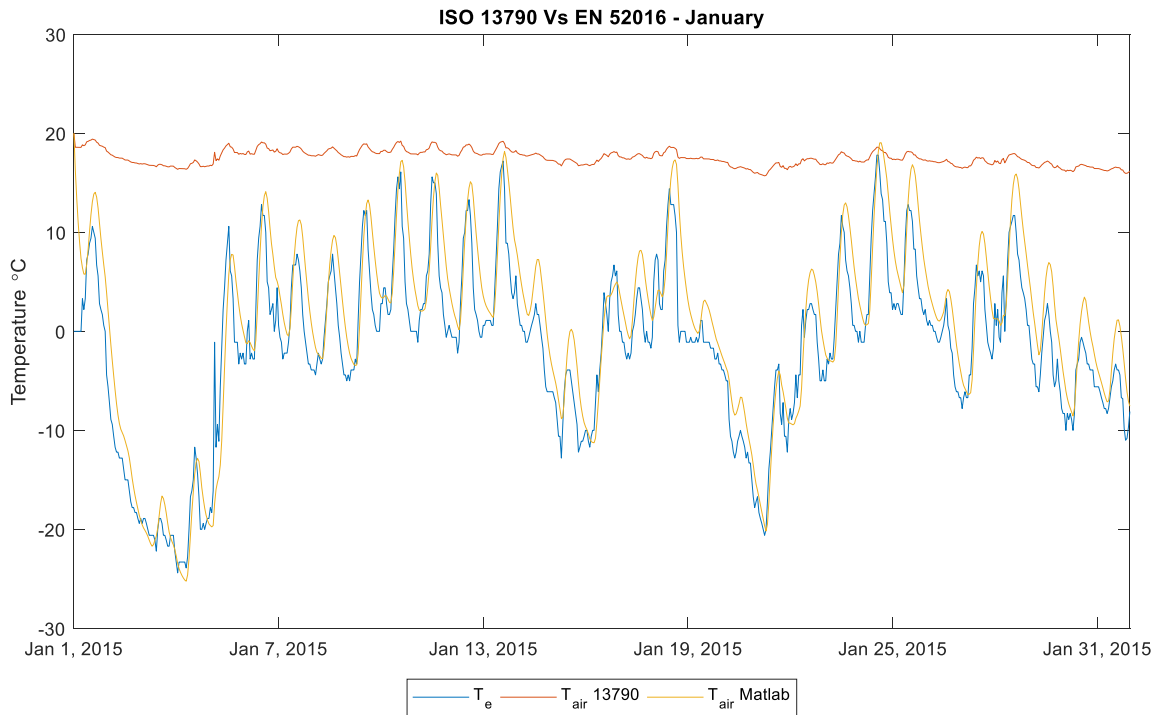
Figure 5-2: 5R1C model Vs Extensive RC network model (January) - *drycold weather*
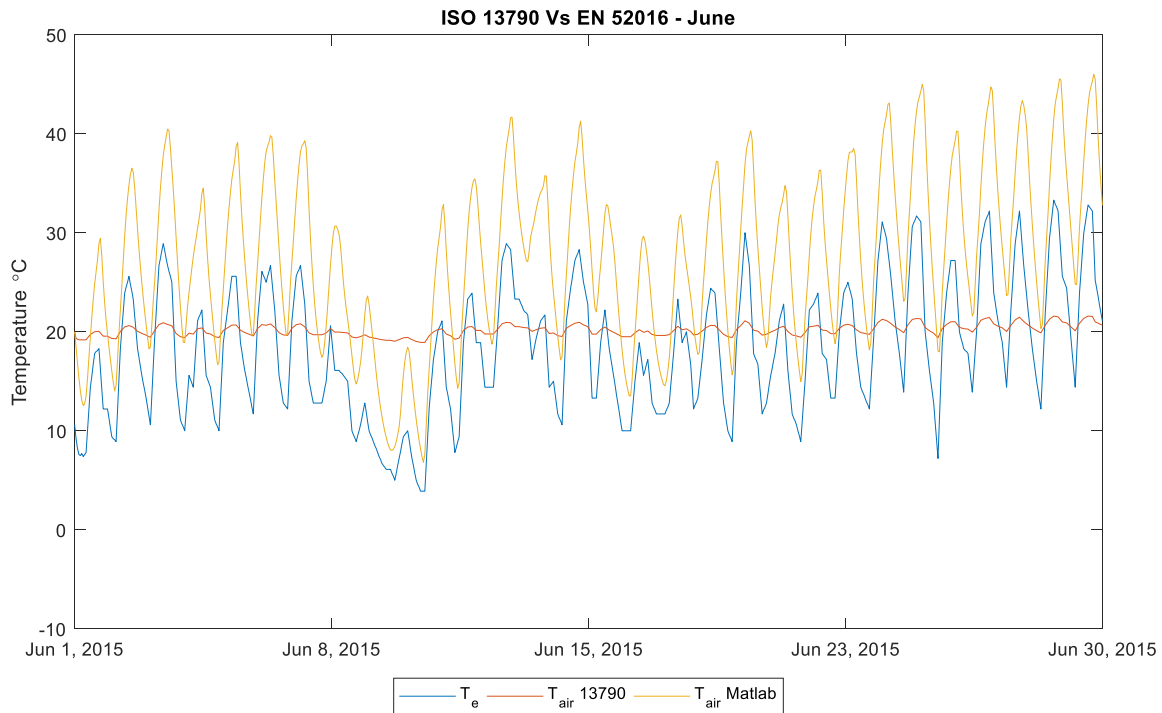
Figure 5-3: 5R1C model Vs Extensive RC network model (June) - *drycold weather*

The above comparison of the internal air temperature calculated using the simple hourly calculation model from ISO 13790 and the extensive RC network modeling of EN 52016-1. The Figure 5-3 illustrates the inaccuracy of the previous model with respect to the reality. The 5R1C model which lumps the elements into few parameters is easy to handle but does not gives a dynamic model like the extensive RC network model. In the BESTEST 600FF and 900FF, due to the absence of heating system it is expected a behavior similar to the hourly values calculated using EN 52016-1.

The R^2 value for the indoor air temperature calculated, using 5R1C model is -3.07 compared to the EN 52016-1.

5.1.2 Free-Floating

In the BESTEST series, there are two test cases 600FF and 900FF which has the free-floating thermostat condition for the respective lightweight and heavyweight cases.

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5.1.2.1 Lightweight Opaque elements

The Figure 5-4 shows the hourly internal air temperature for the lightweight case in Free-Floating calculated using the Matlab model developed using the extensive RC network and then using the excel spreadsheet from the standard for the testing and also compared with the TRNSYS.
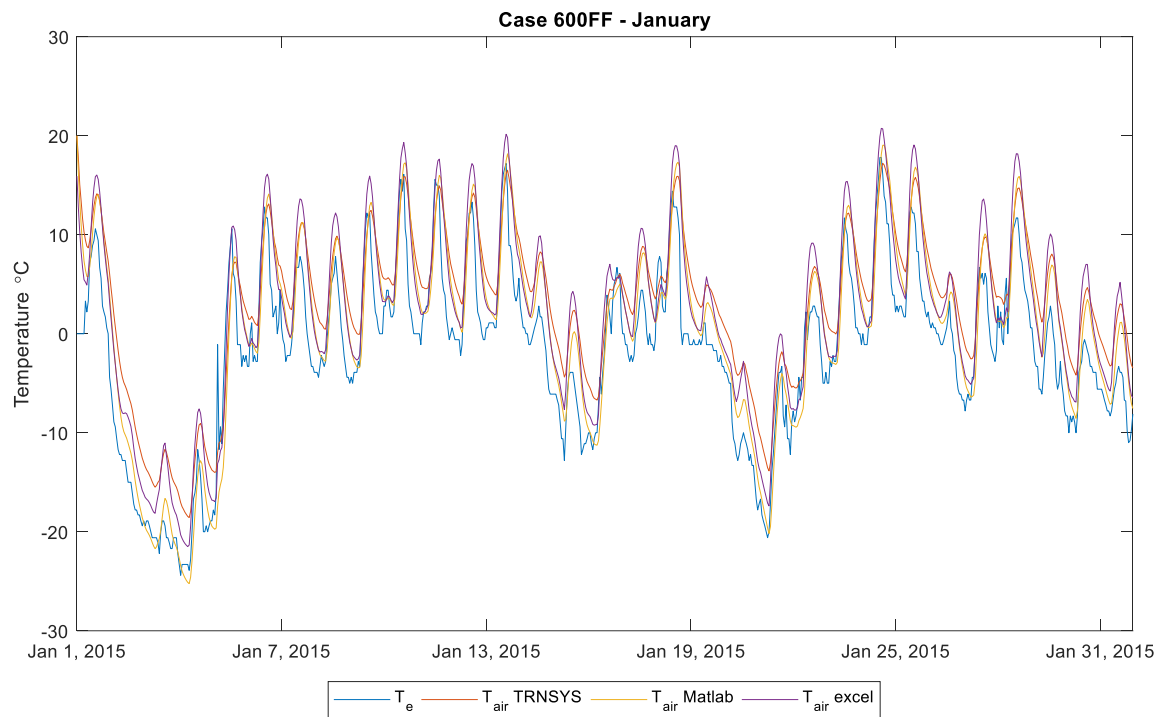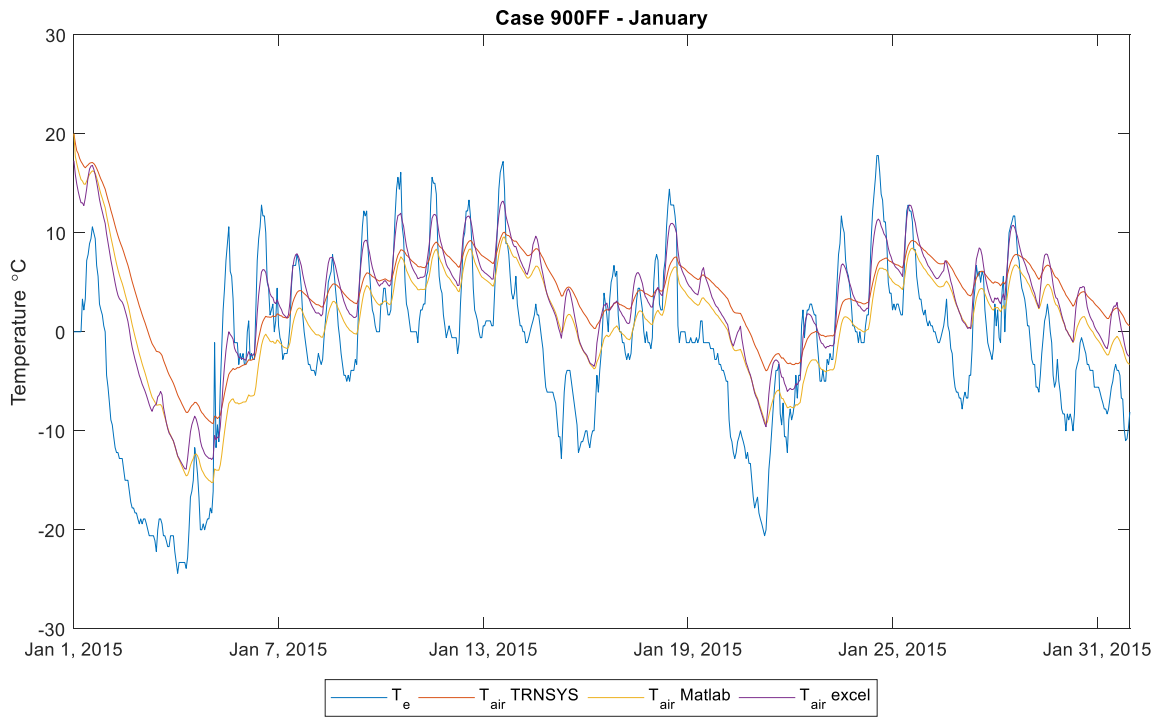

Figure 5-4: Case 600FF - Hourly Internal air temperature (January) - *drycold weather*
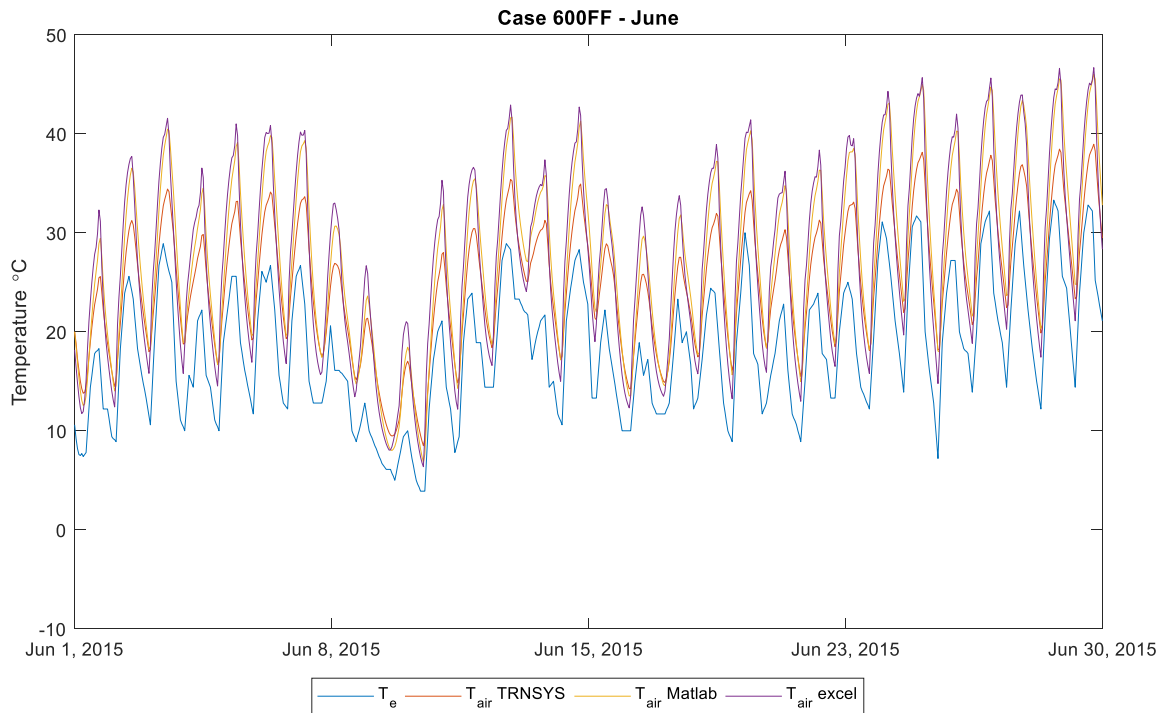
Figure 5-5: Case 600FF - Hourly Internal air temperature (June) - *drycold weather*

The R^2 values calculated for the case 600FF shows that the EN 52016-1 model has a value of 0.92 compared to the excel spreadsheet and a value of 0.86 compare to the Type 56 dynamic model TRNSYS.

5.1.2.2 Heavyweight opaque elements

The Figure 5-6 shows the coherence of the trend also in the heavy weight case for the models. While comparing the trend between the lightweight case 600FF, the heavyweight case shows a light delay in the external air temperature due to the higher capacitance of the building elements considered in the latter.

It could be seen that in the 600FF the Matlab model and Excel model have exactly the same behavior while there is a higher peak in the 900FF which could be due way the model considers the external radiation inside the thermal zone.
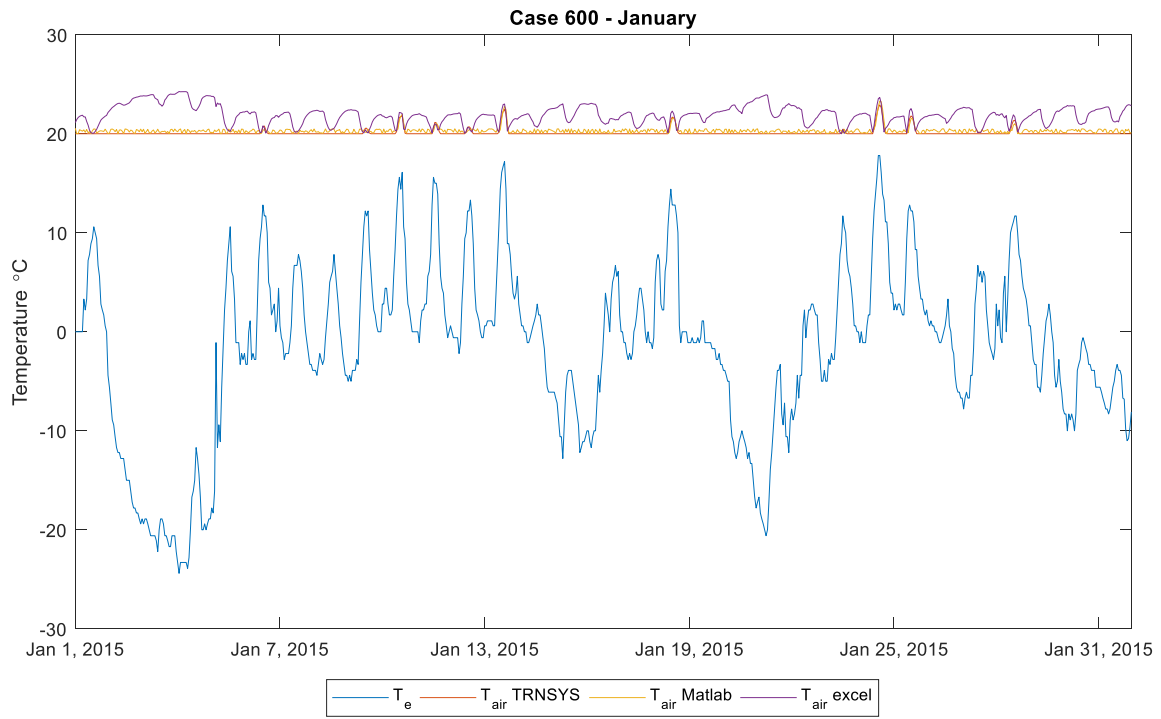
Figure 5-6: Case 900FF - Hourly Internal air temperature (January) - *drycold weather*
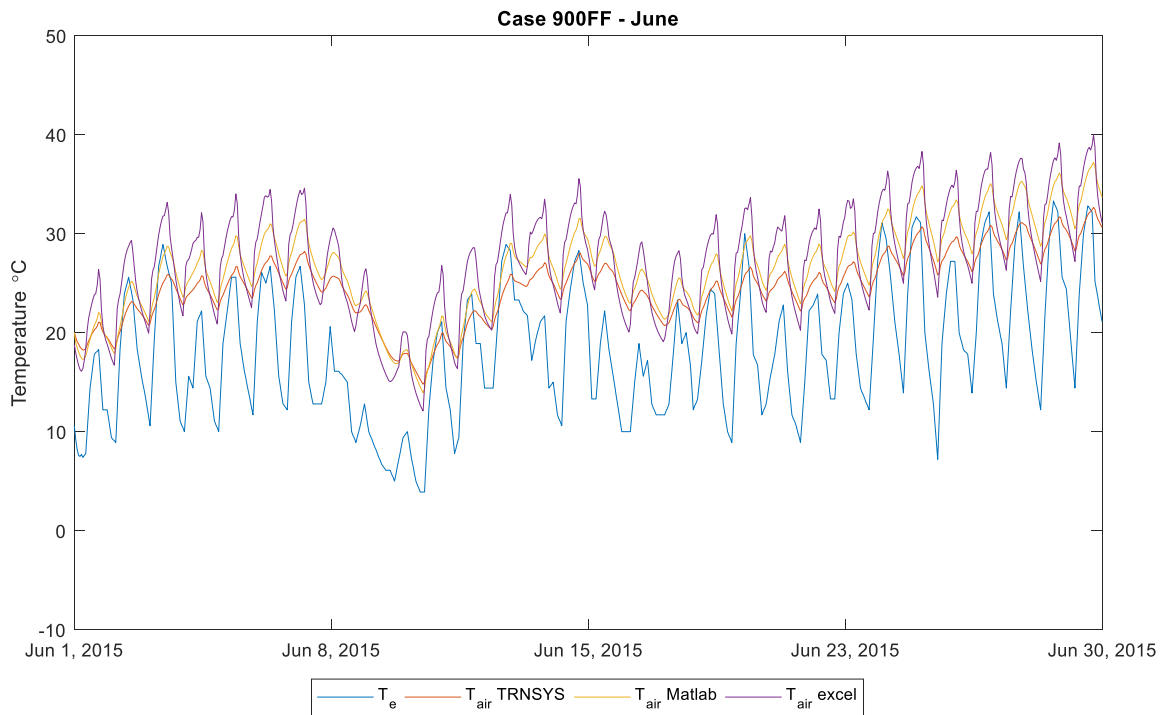
Figure 5-7: Case 900FF - Hourly Internal air temperature (June) - *drycold weather*

The TRNSYS model behavior is not exactly the same in both the cases but are very much similar. It could be due to the simplification done while considering the long-wave radiation in the dynamic calculation of the building/thermal zone as explained below:

- The thermal radiation part in the extensive RC network model is a simplification, ignoring long wave emissivities, thus long wave reflections. In the sum over all building elements (elk) i.e. all the building elements inside the thermal zone, the actual building element (eli) itself is one of the elements. The radiation exchange is approximated using the radiosity method (shape factors) with view factors approximated as if all elements are on the surface of a globe: the surface eli sees also itself [7].
- On the other hand, the Type 56 dynamic model in TRNSYS accounts for the long-wave radiation exchange between the surfaces within the zone and convective heat flux from the inside surfaces to the zone air [11].

5.1.3 Continuous

The simulation has been done having a continuous heating/cooling system that works all day. It has been calculated the internal air temperature and the energy consumed for each hour in all the models.

5.1.3.1 Lightweight opaque elements

The Figure 5-8 and Figure 5-9 shows the internal air temperature of the thermal zone with the set-point temperature. It is seen that the model developed using the Matlab has exactly the same hourly trend in both the lightweight cases.

Figure 5-8: Case 600 - Hourly internal air temperature (January) - *drycold weather*
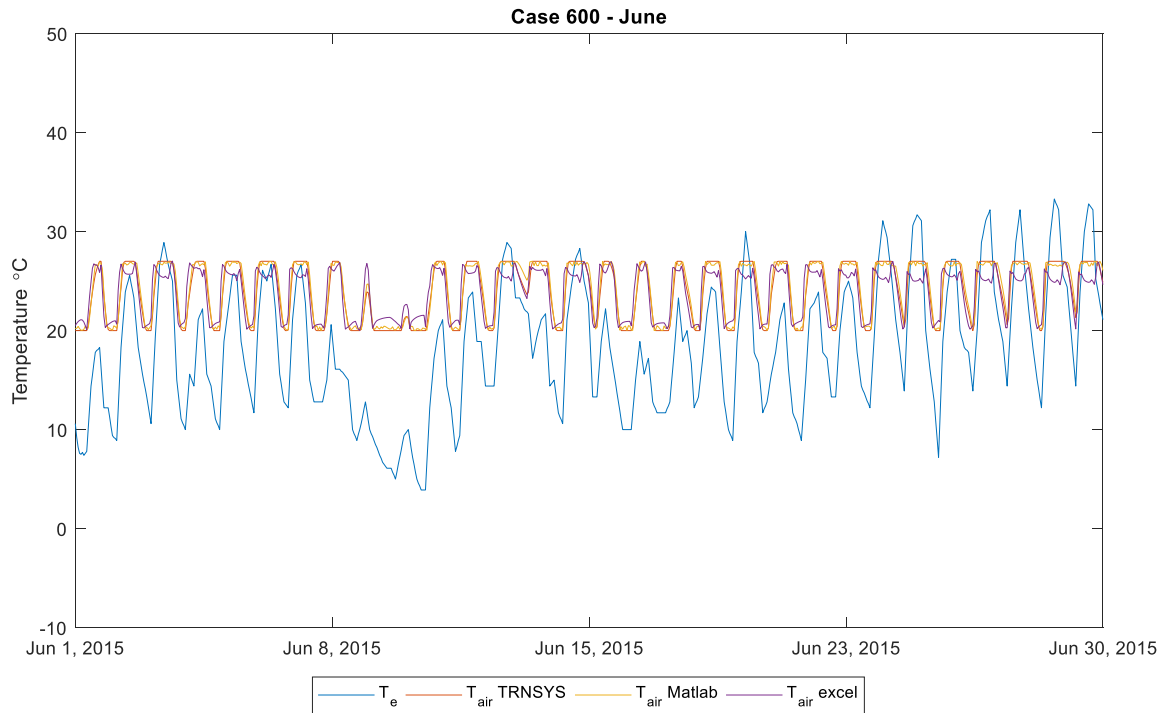
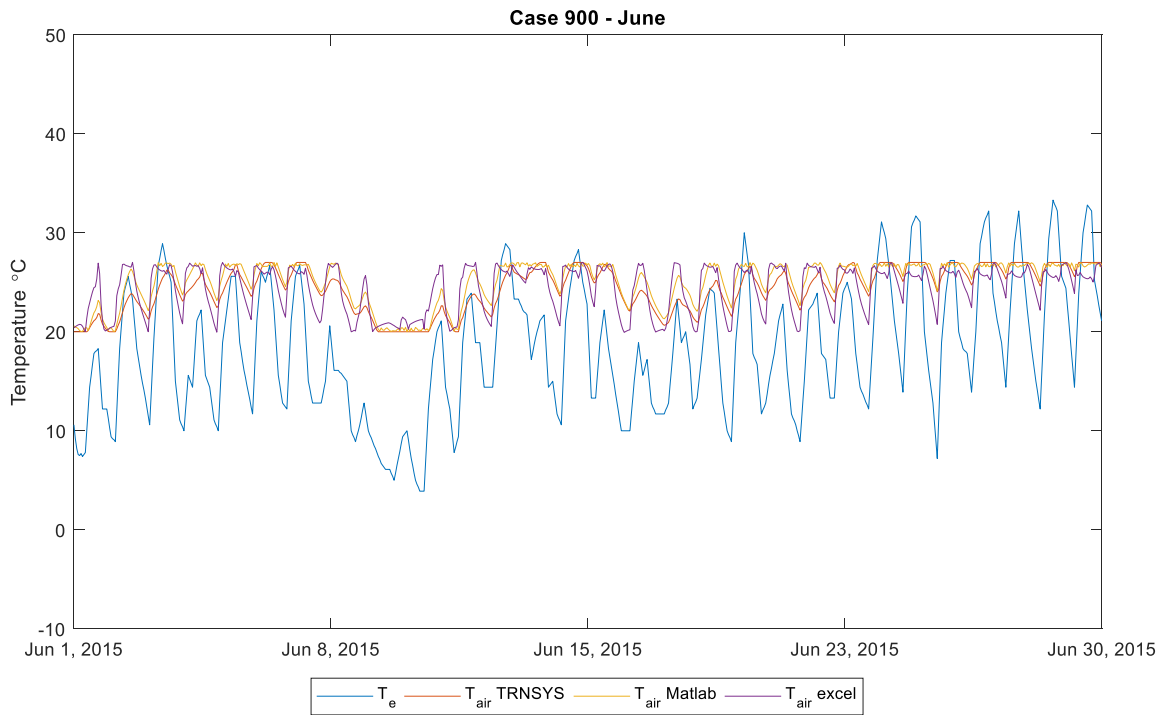Figure 5-9: Case 600 - Hourly internal air temperature (June) - *drycold weather*

The Figure 5-10 shows the hourly energy demand for the lightweight case and the energy demand for the Matlab model and the demand calculated using the standard accompanying excel spreadsheet are very similar and there is a light difference between the TRNSYS model which is related to the type of approach used to calculate the energy demand.

The Figure 5-11 which shows the energy demand of the case study also have the same trend as of the test winter case. It shows the accuracy of the model in both the heating/cooling energy needs.
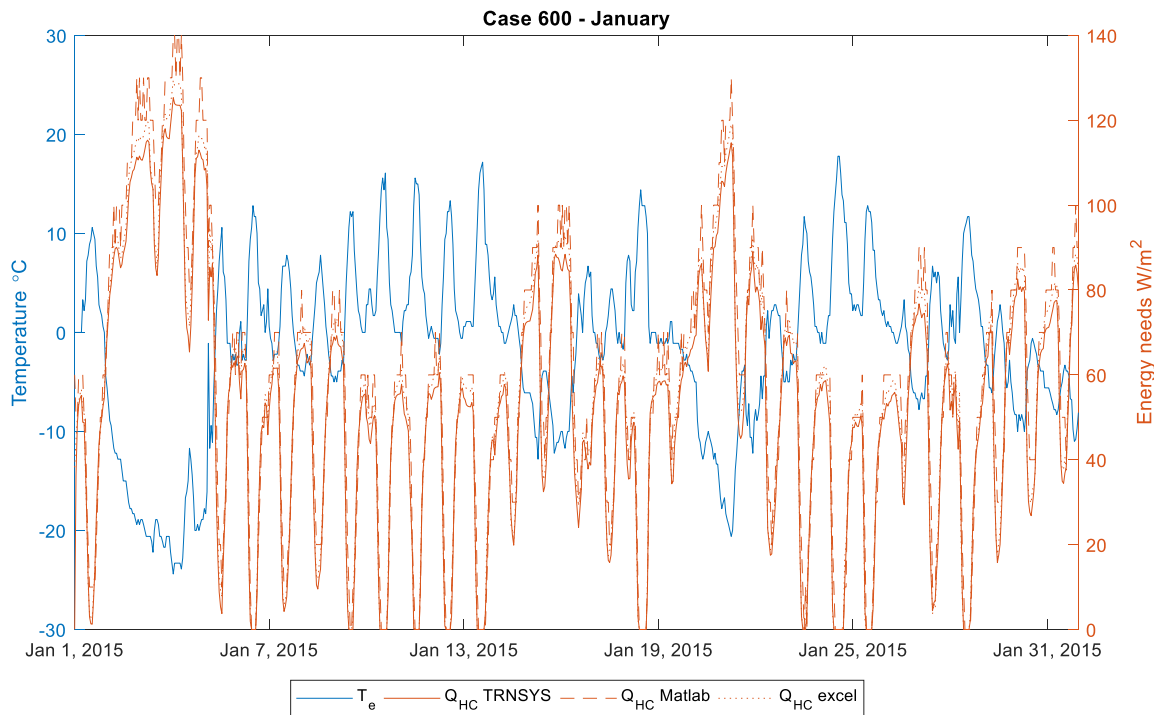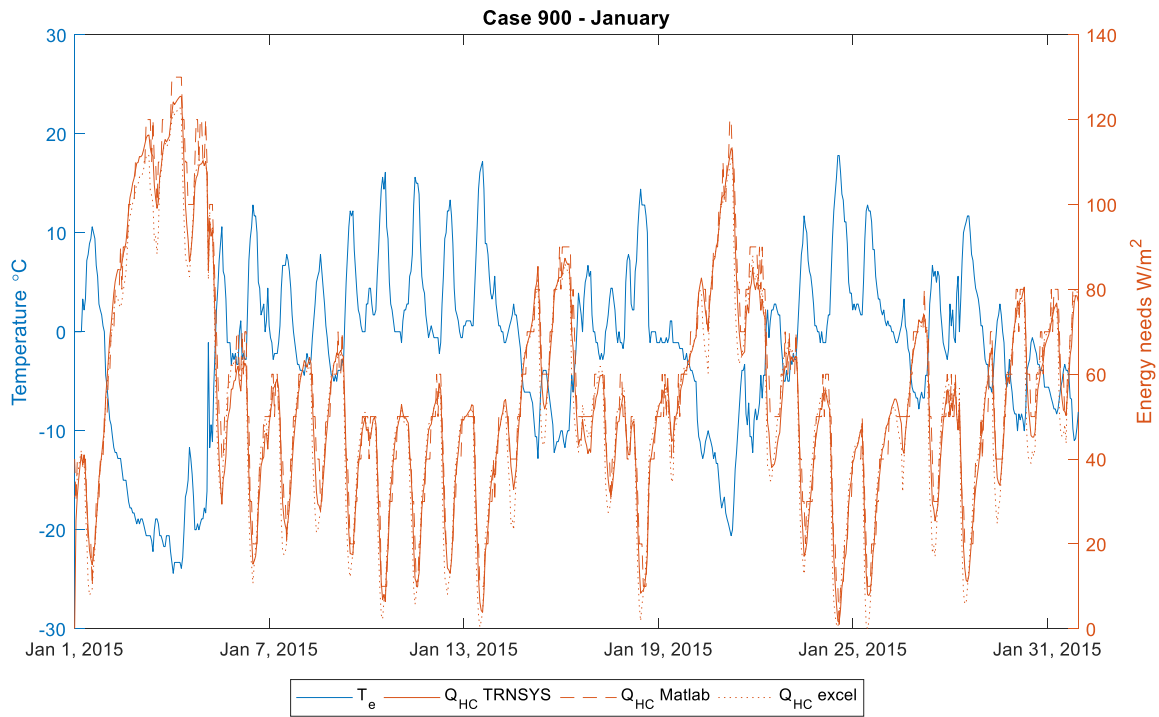

Figure 5-10: Case 600 - Hourly building energy demand (January) - *drycold weather*
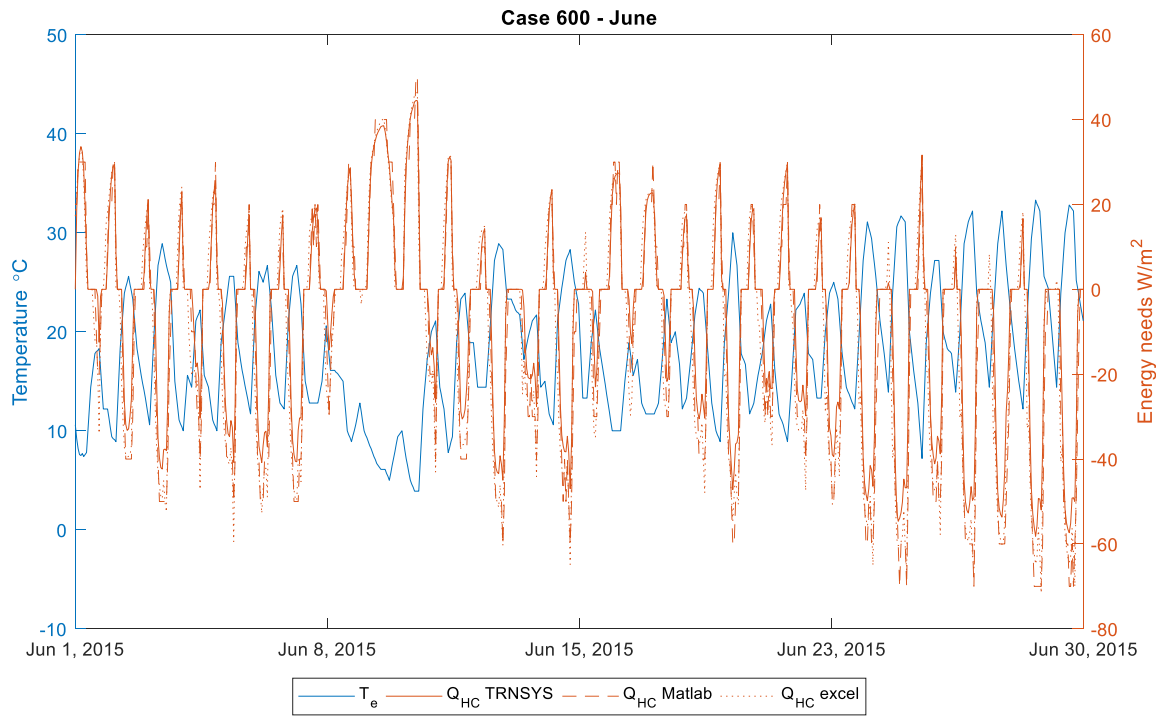
Figure 5-11: Case 600 - Hourly building energy demand (June) - *drycold weather*

5.1.3.2 Heavyweight opaque elements
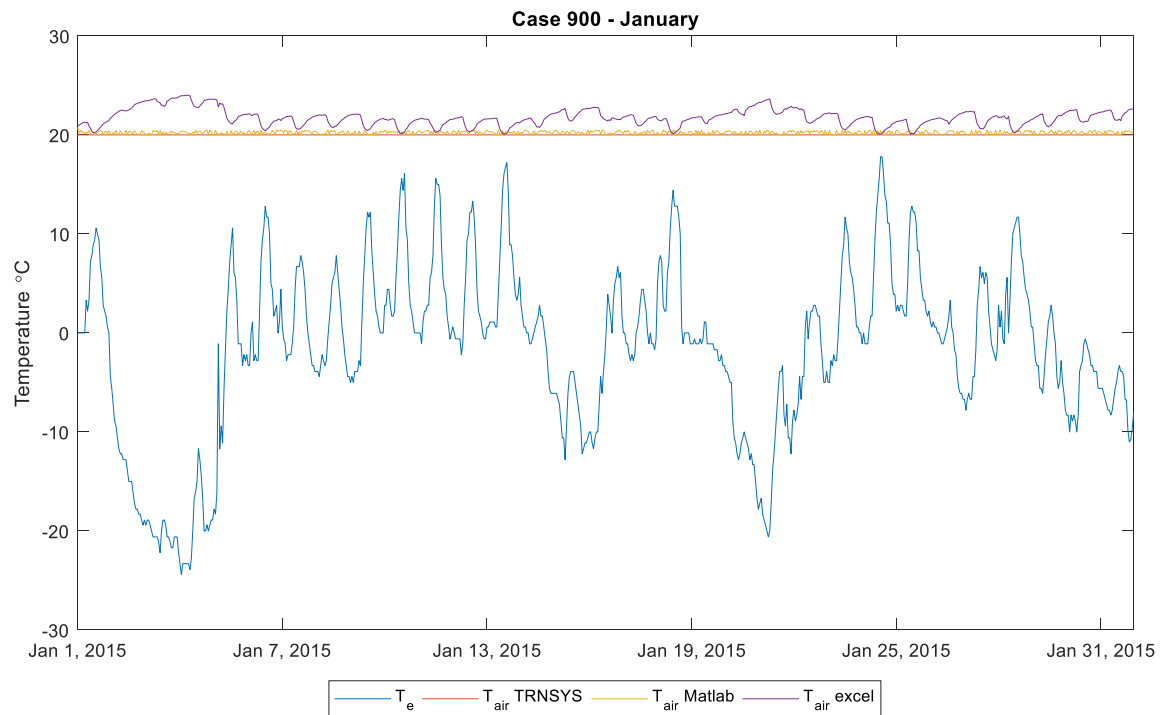
Figure 5-12: Case 900 - Hourly internal air temperature (June) - *drycold weather*

In both the lightweight and heavyweight case, the internal air temperature calculated using the standard accompanying excel spreadsheet is higher which could be an error.

The Figure 5-13 showing the hourly trend shows that all the three models have exactly the same trend. It is a positive fact that the temperature trend is the same as it demonstrates again that the Matlab model developed has a more real time dynamic behavior and proves its validity for its usage in the building simulation.

Figure 5-13: Case 900 - Hourly internal air temperature (June) - *drycold weather*

The Figure 5-14 and Figure 5-15 shows the hourly energy demand for the heavyweight construction elements in all the three cases compared with three different models. It could be seen that the models have the same trend even thought, there is a difference in the demand during the peaks. This should be the effect of control strategies used to calculate the energy demand in the respective cases. In Matlab model, it is used a rule-based controlled approach with discrete change in the values of the heating/cooling gains while the excel spreadsheet and the Type 56 dynamic model TRNSYS have a different control approach.

Figure 5-14: Case 900 - Hourly energy demand (January) - *drycold weather*
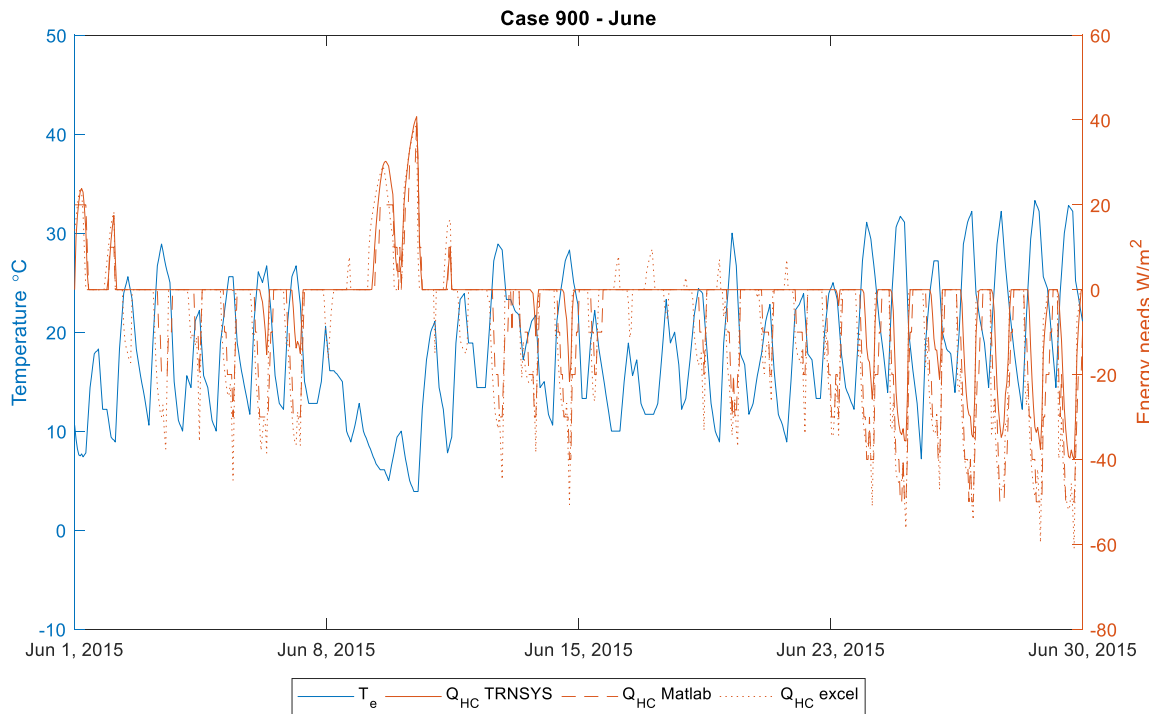
Figure 5-15: Case 900 - Hourly energy demand (June) - *drycold weather*

5.1.4 Intermittent

The cases 640 and 940 have a night-time set-back for the heating system with a set-point control of 20 °C from 23.00 to 07.00 IST and 10 °C from 07.00 to 23.00 IST for the winter and a continuous system with 27 °C for the summer without set-back.

5.1.4.1 Lightweight opaque elements

The Figure 5-16 shows the hourly trend of the indoor air temperature calculated having an intermittent heating/cooling system. It could be seen that the controller of the model works in accordance with the other two models while there are still the higher peaks in the temperature profile calculated using the excel spreadsheet.
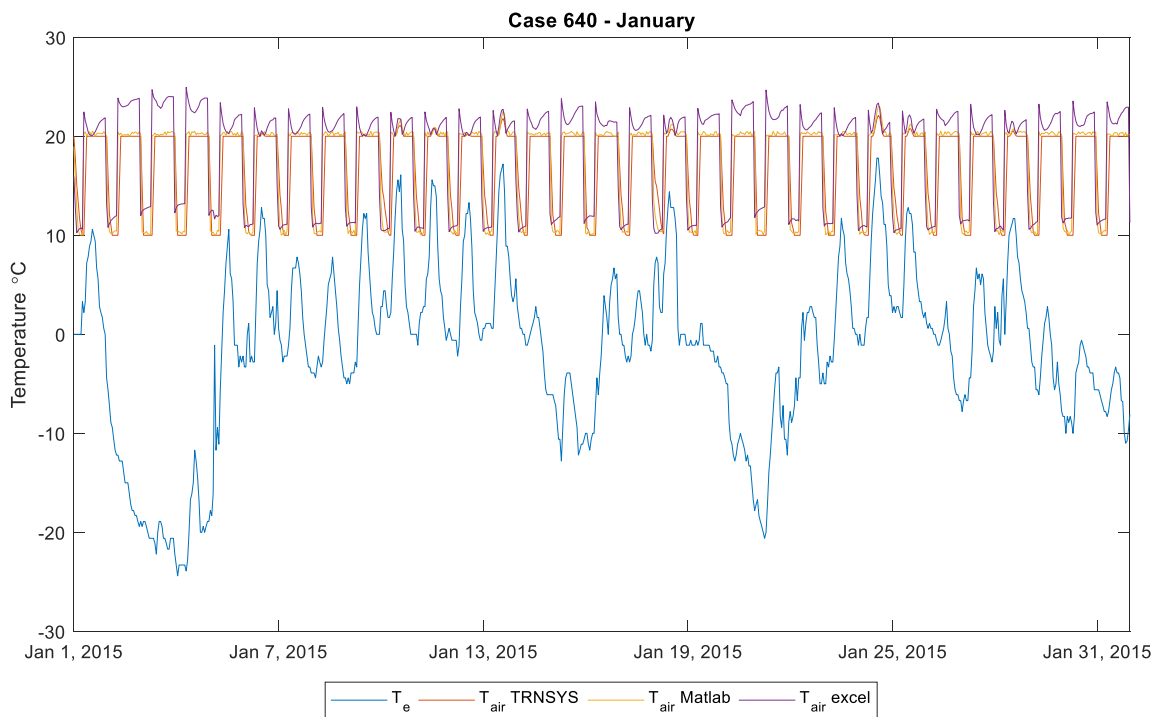
Figure 5-16: Case 640 - Hourly internal air temperature (January) - *drycold weather*

The Figure 5-17 showing the hourly temperature profile during the period of June is very the same showing the accuracy of the model with respect to also the intermittent heating/cooling system.
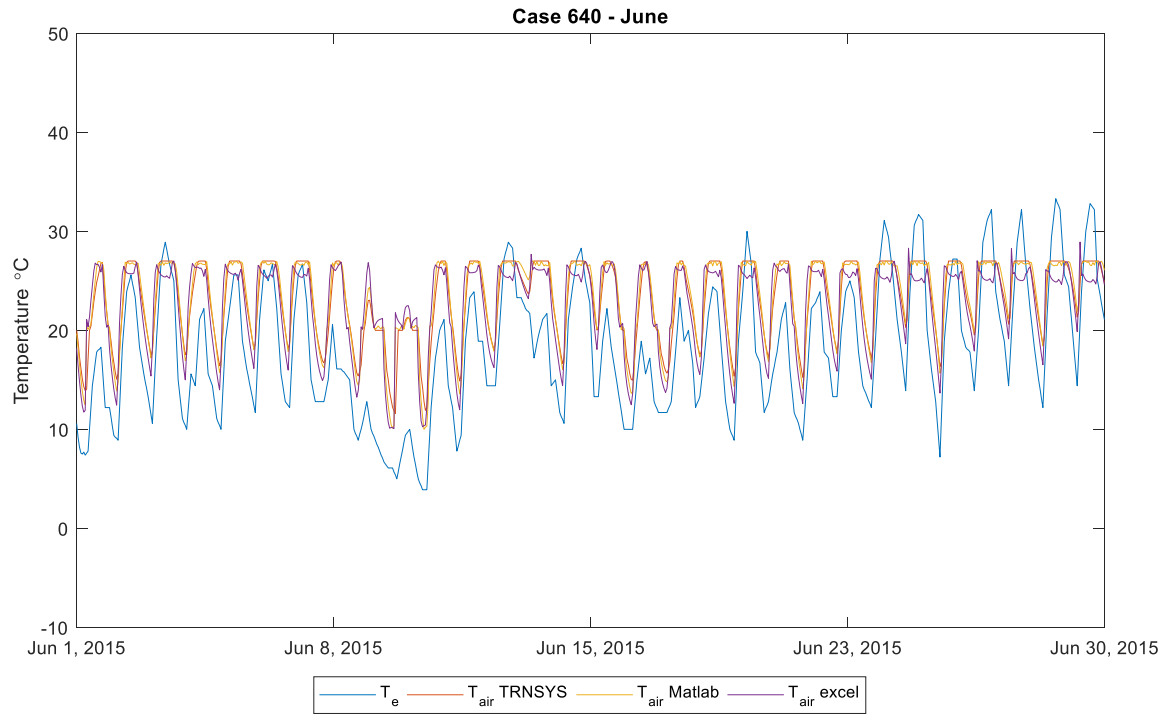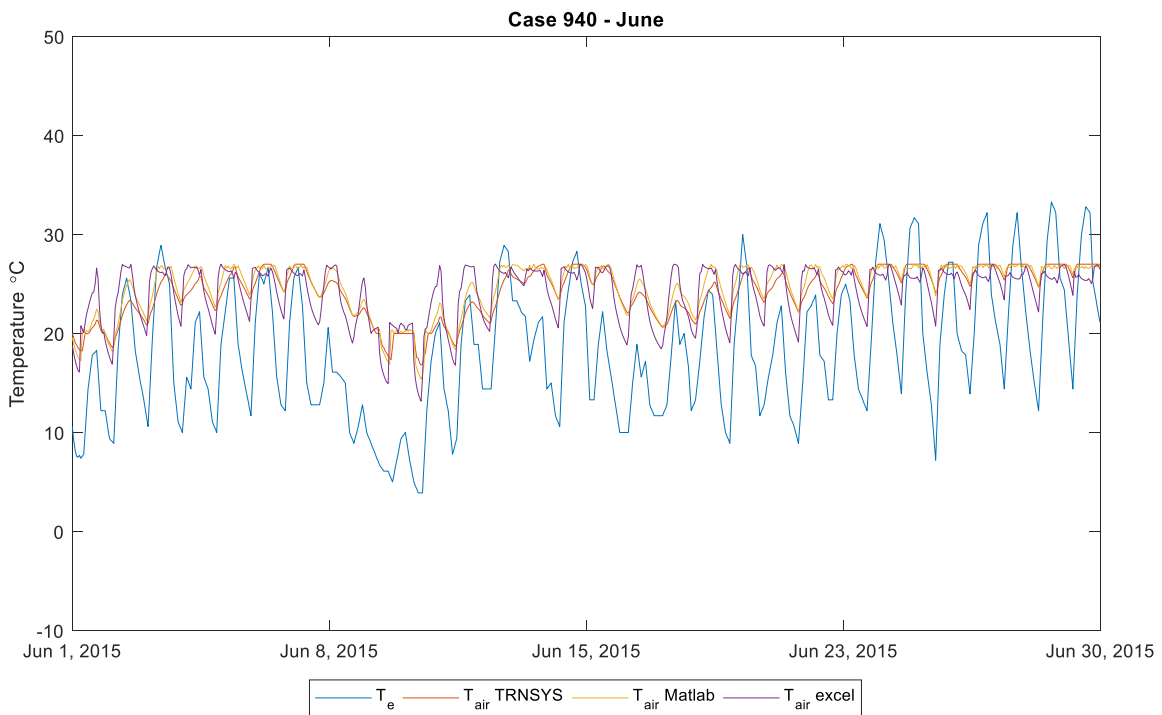

Figure 5-17: Case 640 - Hourly internal air temperature (June) - *drycold weather*

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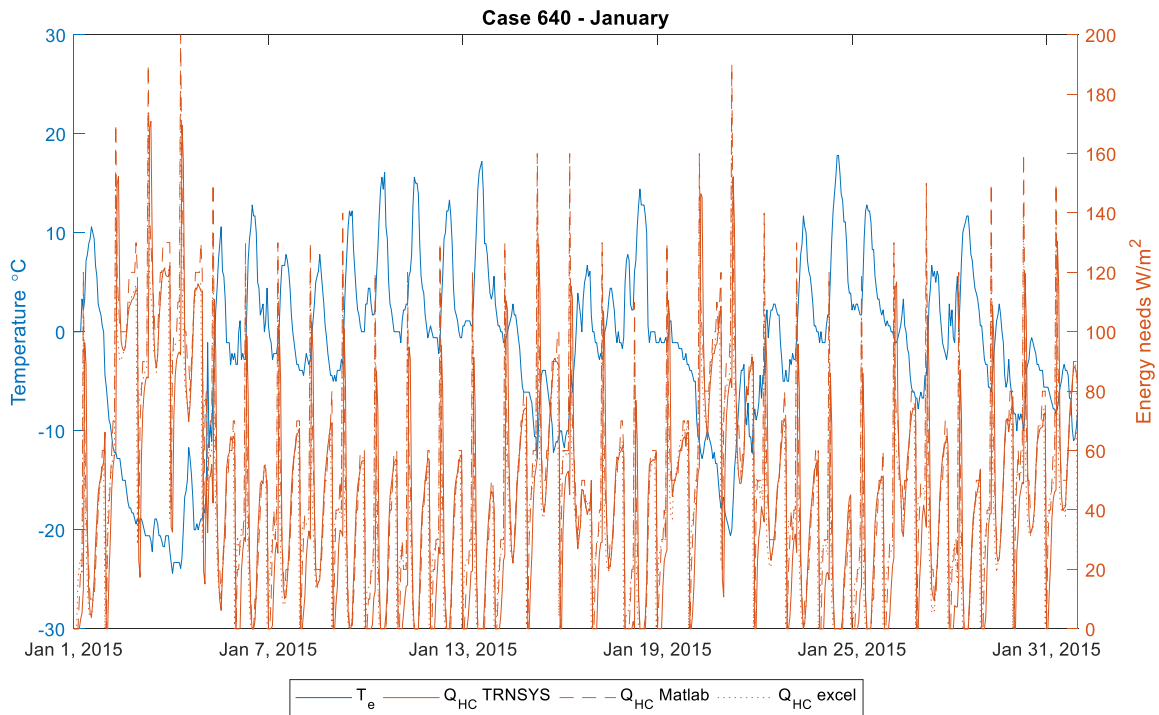
Figure 5-18: Case 640 - Hourly building energy demand (January) - *drycold weather*

The Figure 5-18 shows that the maximum building energy demand is a lot compared to the continuous case which is related to the initializing phase of the HVAC system. The trend is very similar in all the three models which shows that the model has a good validity also in the intermittent heating/cooling system. The Figure 5-19 shows the energy demand calculated using the three models for the summer case
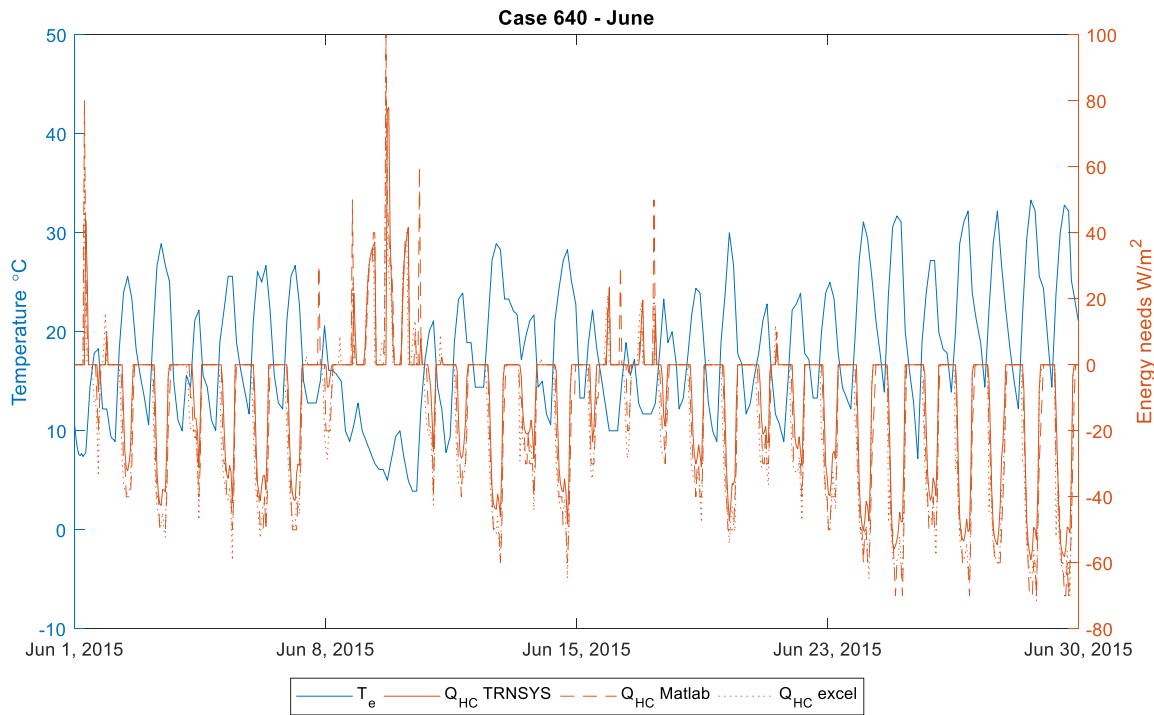
Figure 5-19: Case 640 - Hourly building energy demand (June) - *drycold weather*

5.1.4.2 Heavyweight opaque elements

The Figure 5-20 shows the indoor air temperature profile for heavy weight case. Also in the heavyweight cases, the models show the same behavior enhancing the validity of the model. The temperature calculated in the excel have some peaks during the January but still the results are in the controlled boundary set-point levels.

The Figure 5-22 and Figure 5-23 shows that the calculate energy hourly energy demand for the heavyweight models are in accordance and have the similar trend as like the previous cases.
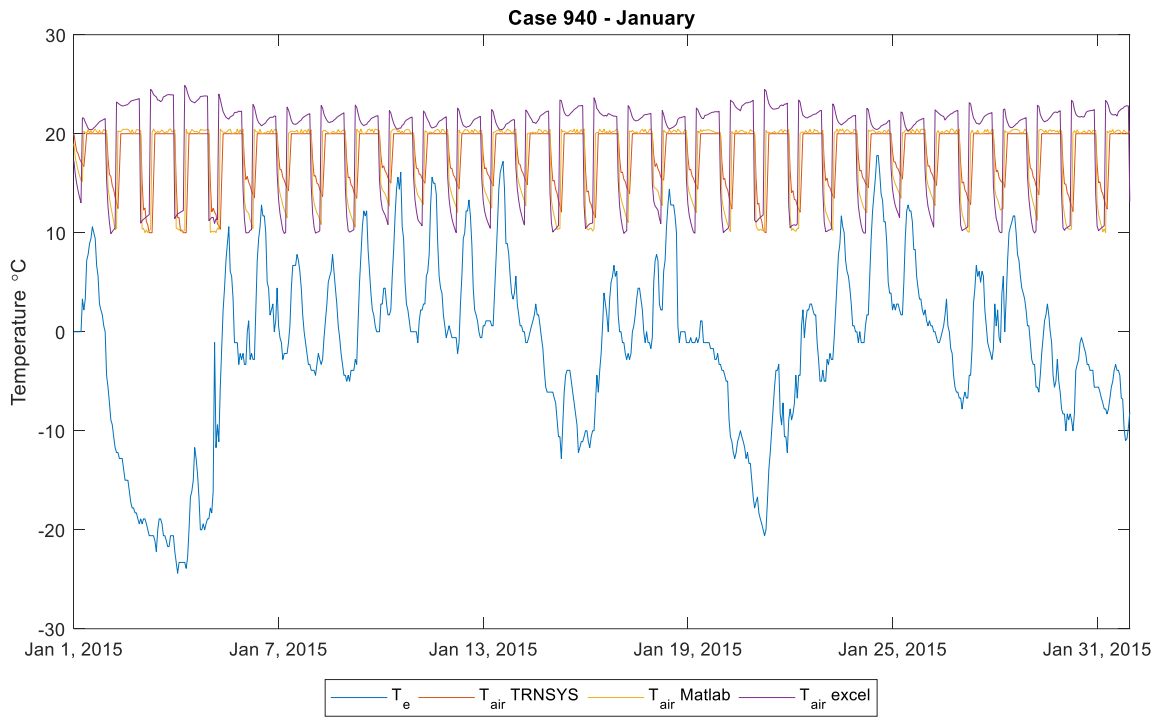
Figure 5-20: Case 900 - Hourly internal air temperature (January) - *drycold weather*

Figure 5-21: Case 940 - Hourly internal air temperature (June) - *drycold weather*
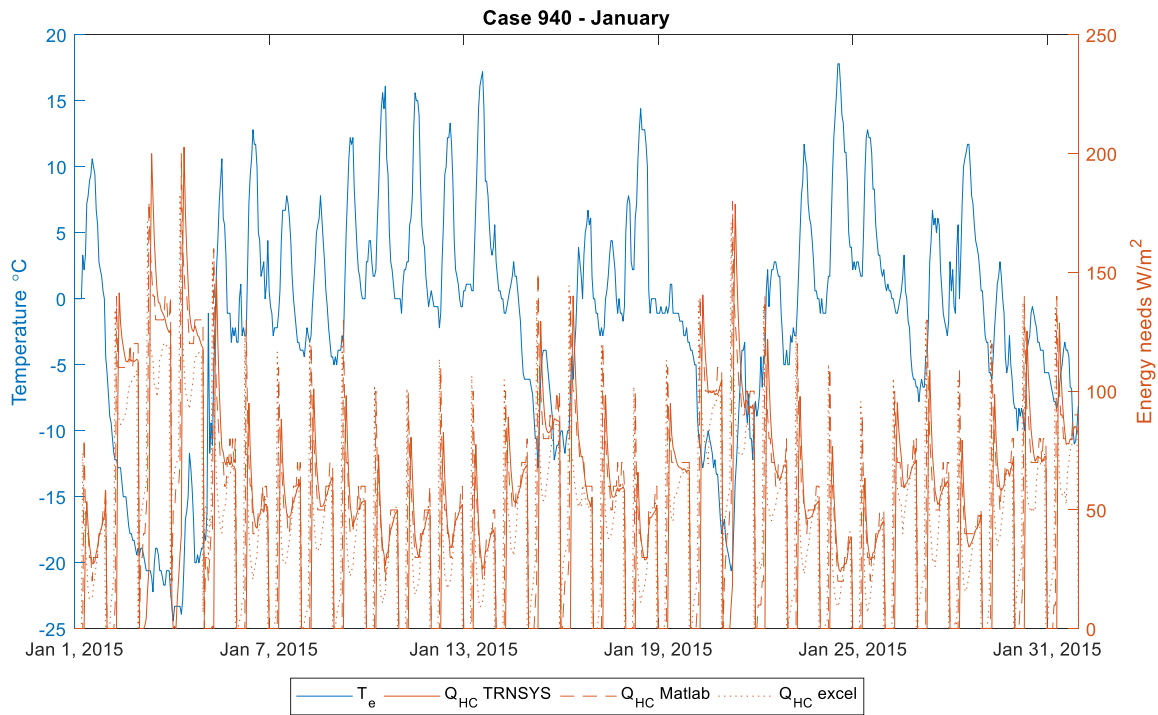
Figure 5-22: Case 940 - Hourly building energy demand (January) - *drycold weather*
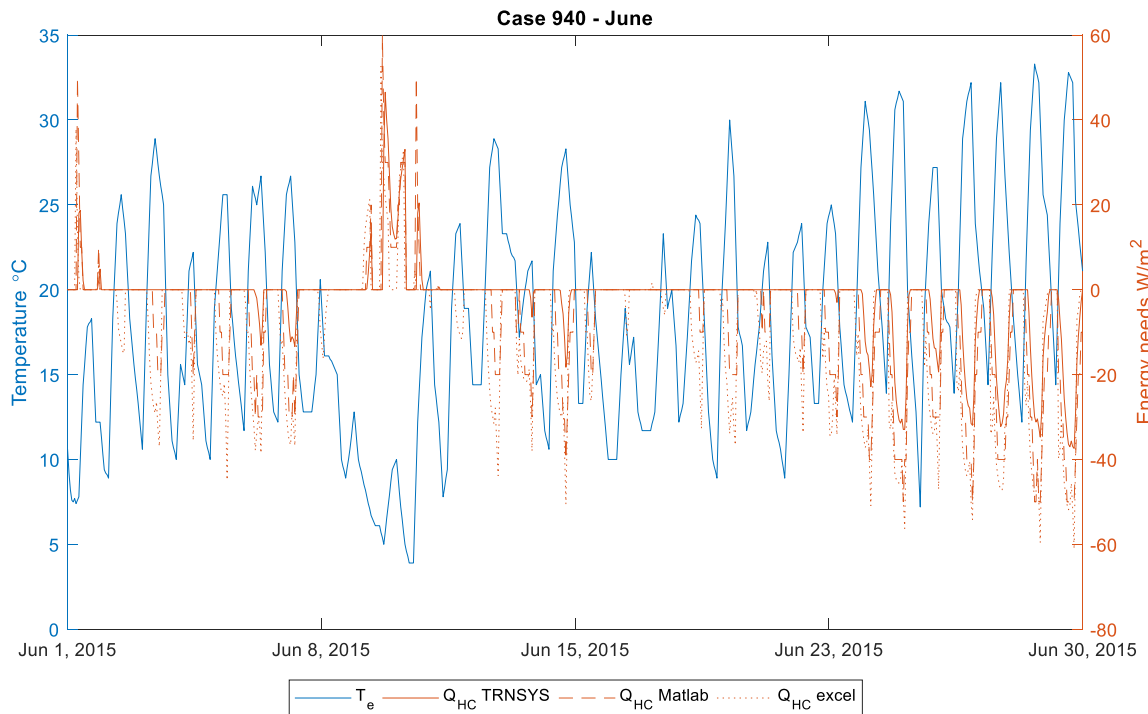

Figure 5-23: Case 940 - Hourly building energy demand (June) - *drycold weather*

5.2 Weather data 2 - Milan

The Matlab model developed using the EN ISO 52016-1 tested for the BESTEST cases using the drycold weather climate file has proven its validity with the standard as seen with the results in the chapter Weather data 1 - drycold weather.

In order to test the developed Matlab model for even more reliability in the simulation, the BESTEST cases have been tested for the Milan, Italy.

5.2.1 Free Floating

5.2.1.1 Lightweight opaque elements

The Figure 5-24 shows the hourly internal air temperature calculated using the Matlab model and the Type 56 dynamic model TRNSYS compared to the external air temperature of the building.

The accuracy of the model with respect to the TRNSYS is demonstrated by using the R^2 value calculated for the indoor temperature from both the models. The Matlab model has a R^2 value of 0.88 with respect to the TRNSYS which shows the fitting of goodness with the Type 56 dynamic model of the TRNSYS.
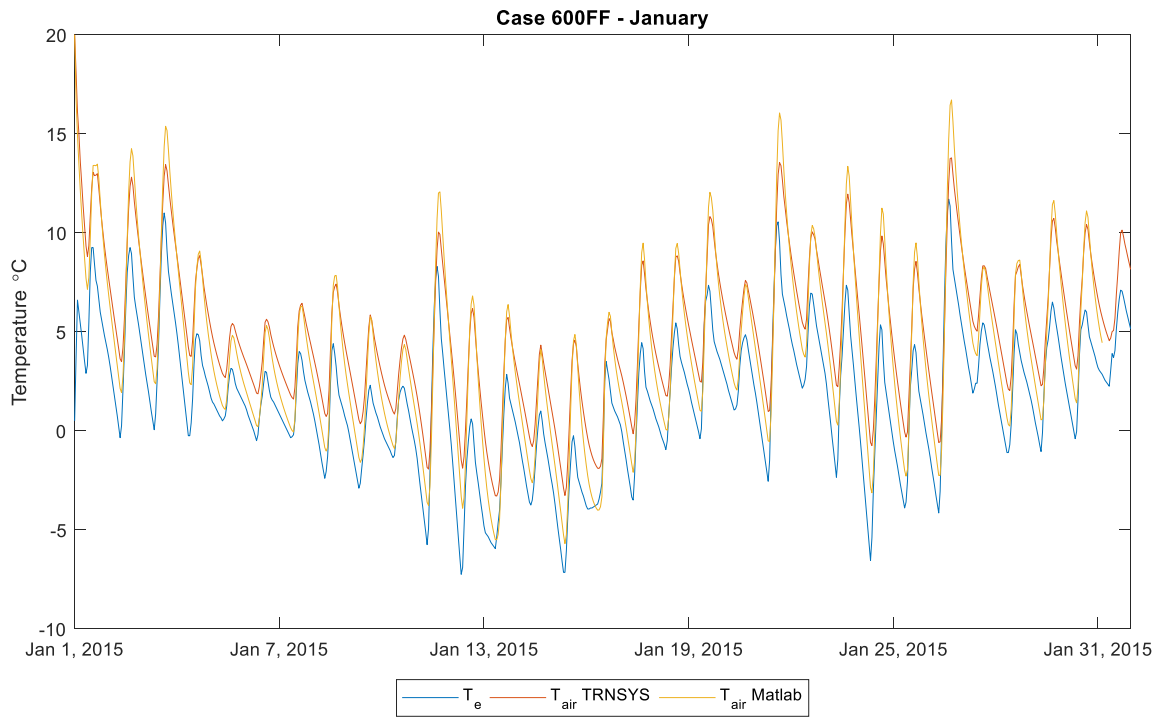
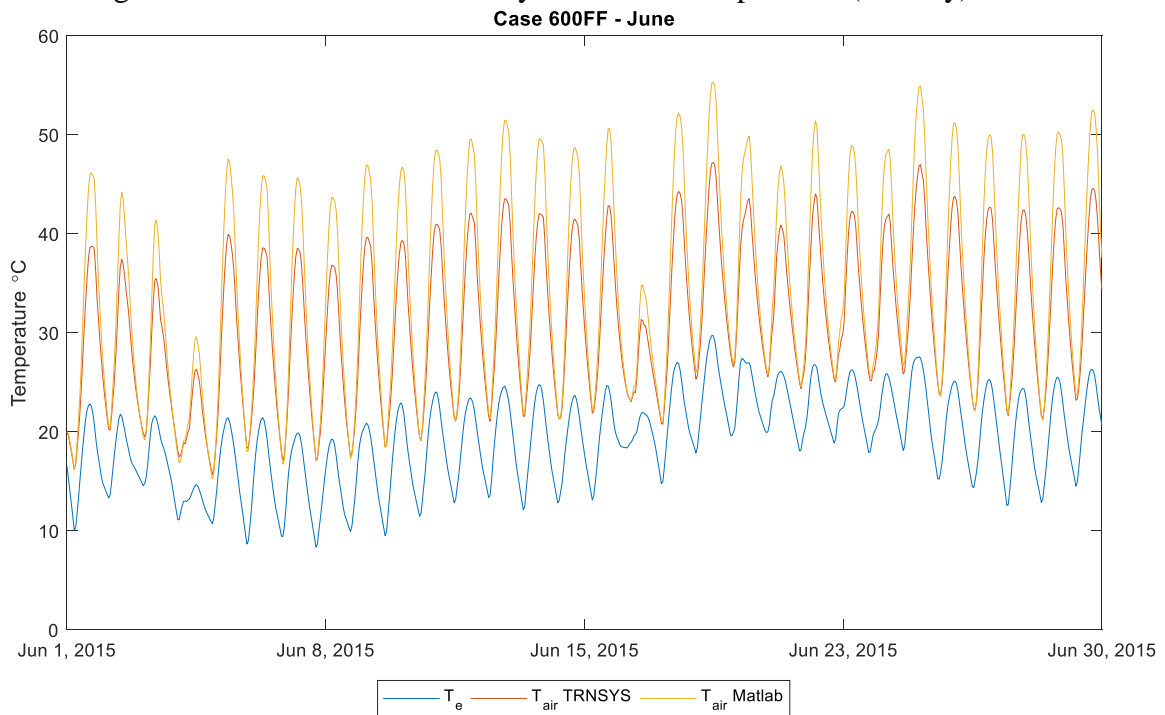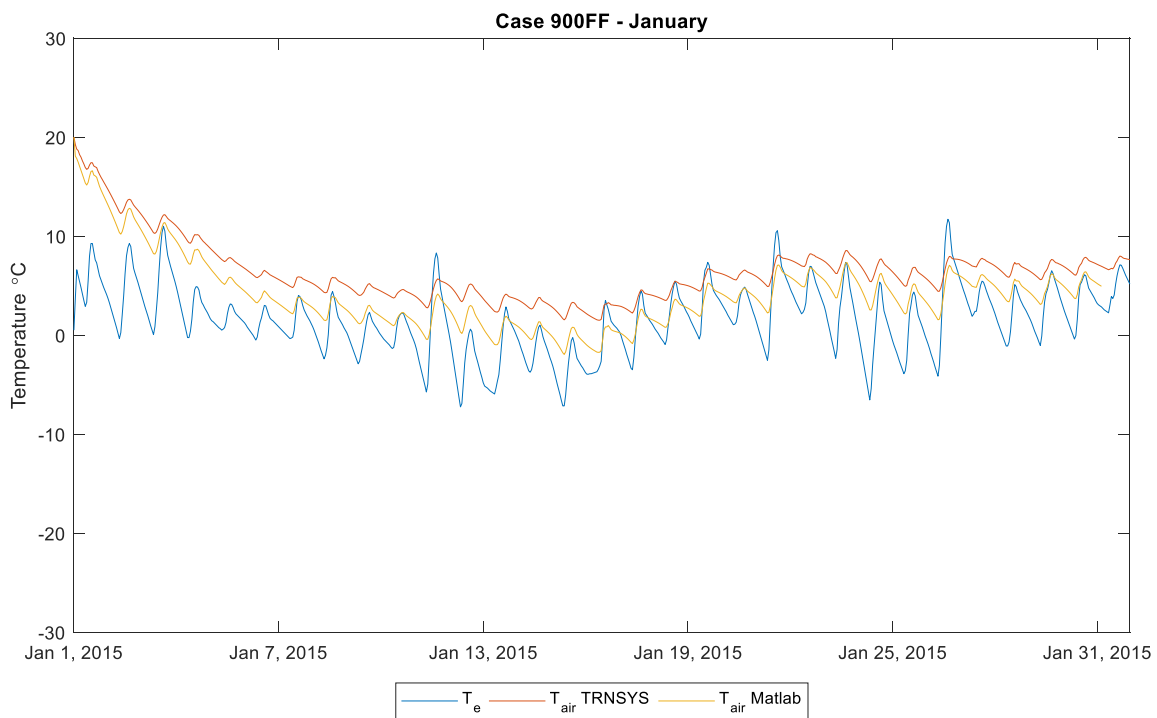Figure 5-24: Case 600FF - Hourly internal air temperature (January) - Milan

Figure 5-25: Case 600FF - Hourly internal air temperature (June) - *Milan*

5.2.1.2 Heavyweight opaque elements

The Figure 5-26 and Figure 5-27 shows the trend of the hourly temperature for the heavy weight case for the BESTEST with Milan. The Matlab model has a slightly lower trend and a higher trend in the January and June respectively which shows the possibility for the difference the in accountability of the radiation in the energy balance of both the models. Apart from that, the building behaves in such a way that the developed RC network model proves its validity with reference to the Type 56 model.

Figure 5-26: Case 900FF - Hourly internal air temperature (January) - *Milan*
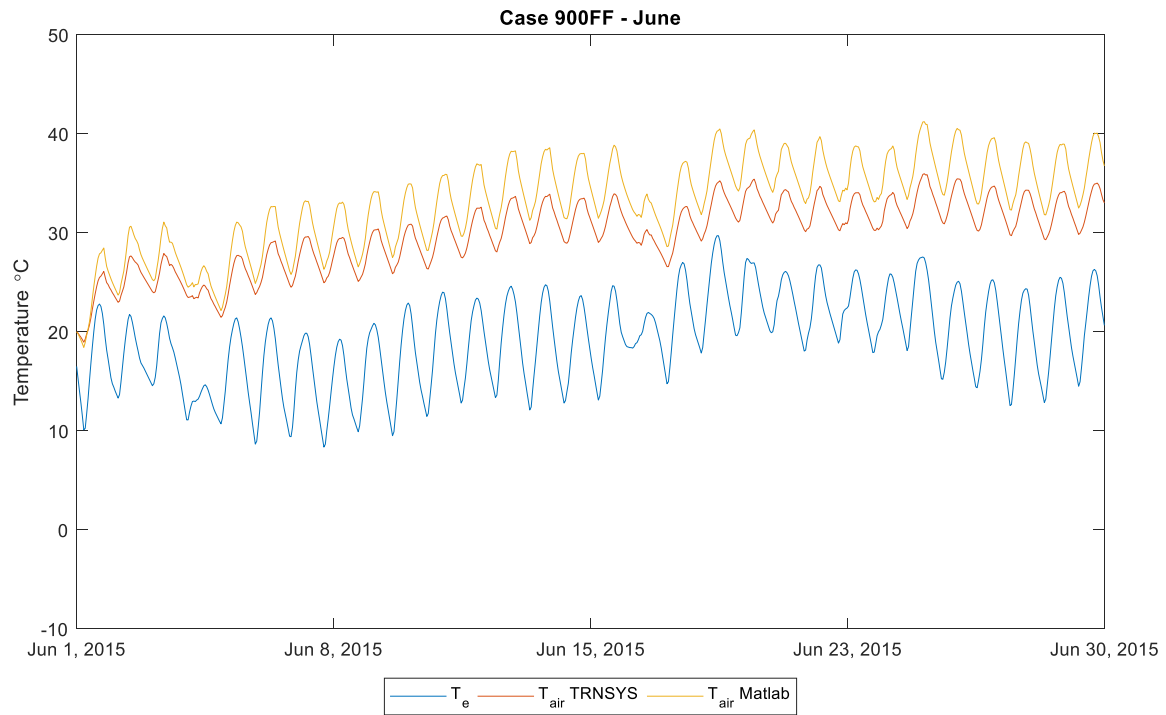
Figure 5-27: Case 900FF - Hourly internal air temperature (June) - *Milan*

5.2.2 Continuous

5.2.2.1 Lightweight opaque elements

The internal air temperature calculated using the Matlab model has almost the same behavior as of Type 56 dynamic model TRNSYS while there is just a variation of the peaks which is due to the external radiation accounted in the time step.
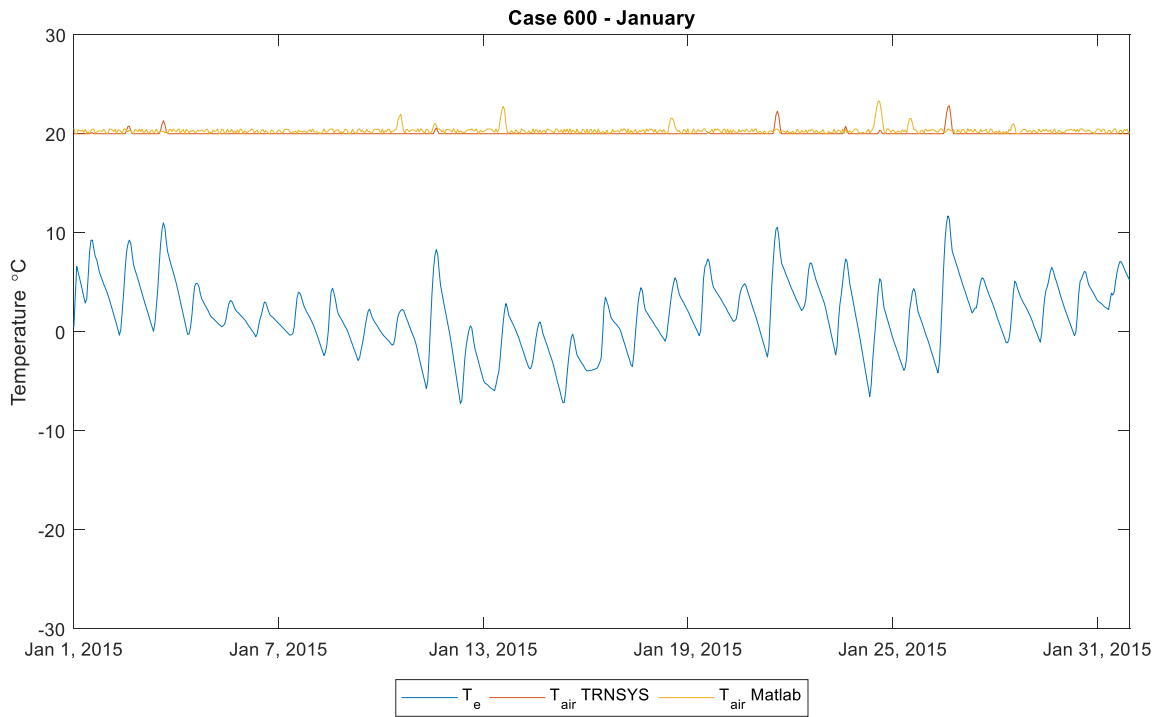
Figure 5-28: Case 600 - Hourly internal air temperature (January) - *Milan*

The Figure 5-29 shows the hourly internal air temperature for the summer and it could be seen that the system working predominantly here is the cooling system. The trend in the hourly internal air temperature is almost the same showing the validity of the model.
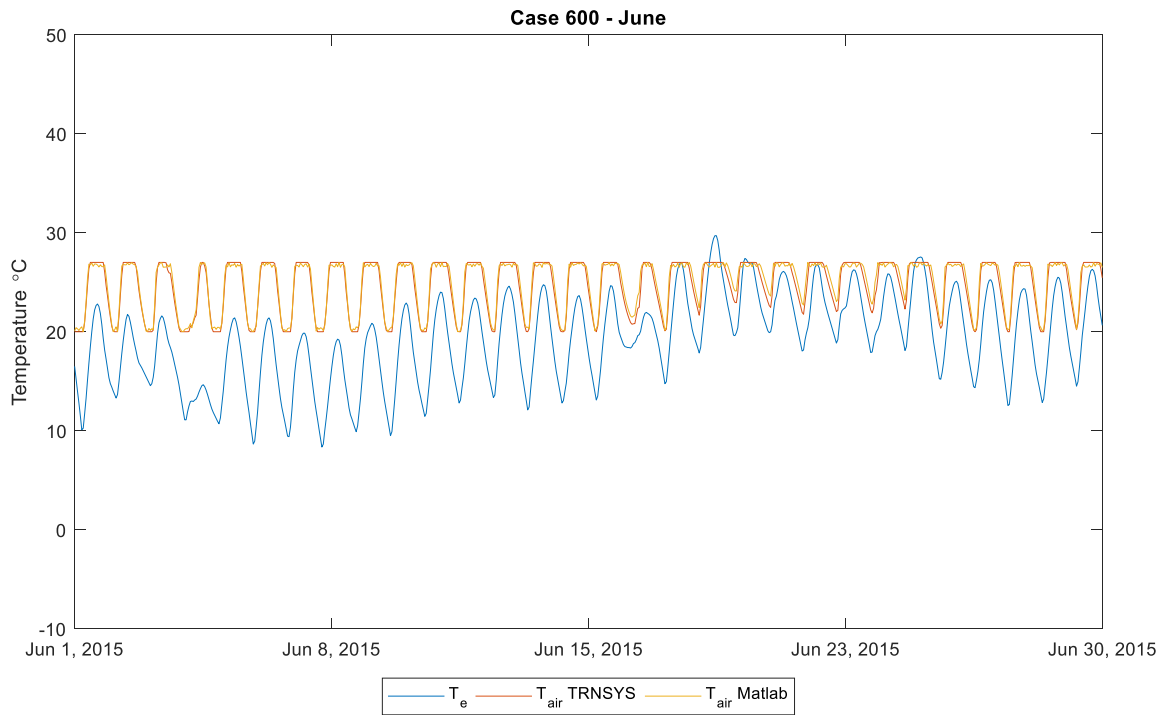
Figure 5-29: Case 600 - Hourly internal air temperature (June) - *Milan*

Figure 5-30: Case 600 - Hourly building energy demand (January) - *Milan*
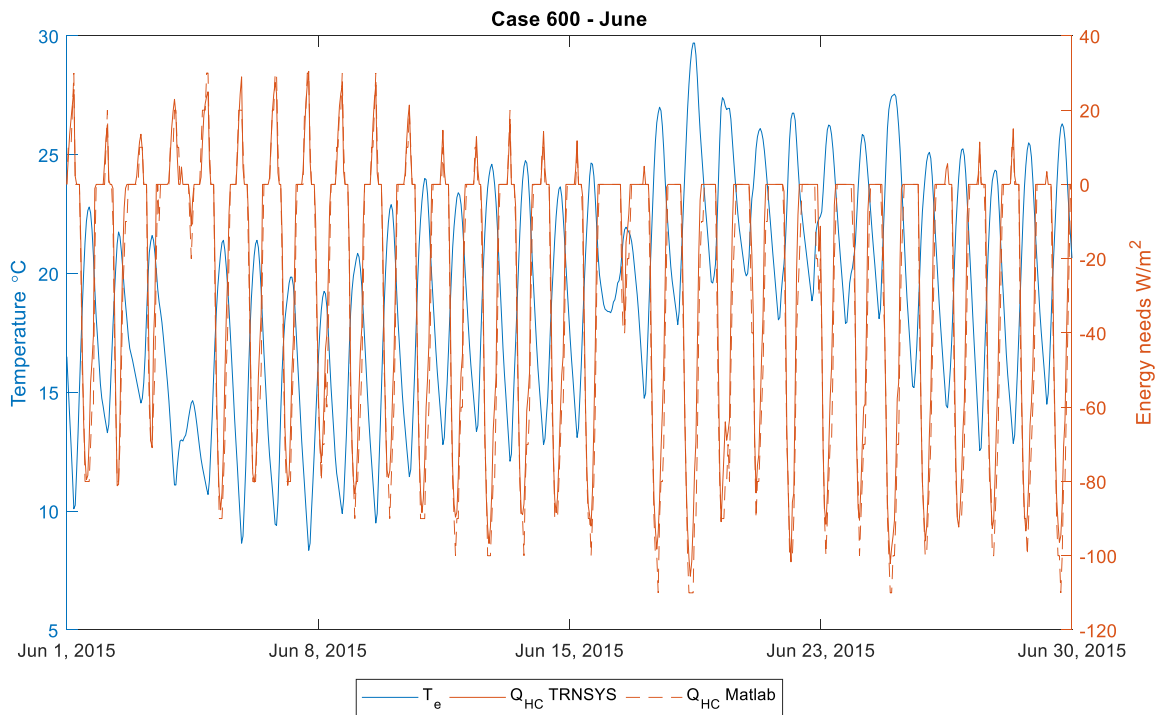
81

Figure 5-31: Case 600 - Hourly building energy demand (June) - *Milan*

The Figure 5-30 shows the hourly building energy demand calculated using the Matlab model and the Type 56 dynamic model TRNSYS. The trend of the Matlab model during the January have some issues with the peaks which is again due to the way the radiation accounted inside the thermal zone.

The Figure 5-31 shows the energy demand for the summer and here too the trends are very similar in both the models.

5.2.2.2 Heavyweight elements

The heavyweight elements have been tested again for the BESTEST cases using the Matlab model and the Type 56 model in order to test the validity in the heavyweight case.

The Figure 5-32 and Figure 5-33 represents the hourly internal air temperature of the case studies and it could be seen that the trend between both the models are similar.
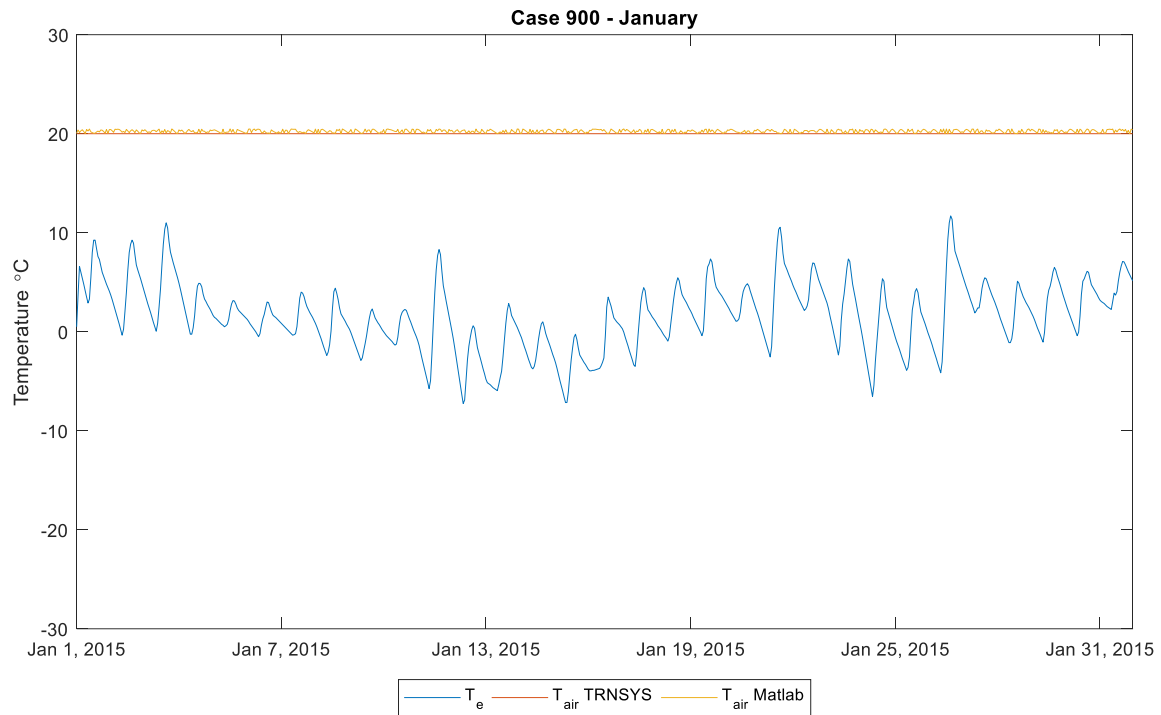

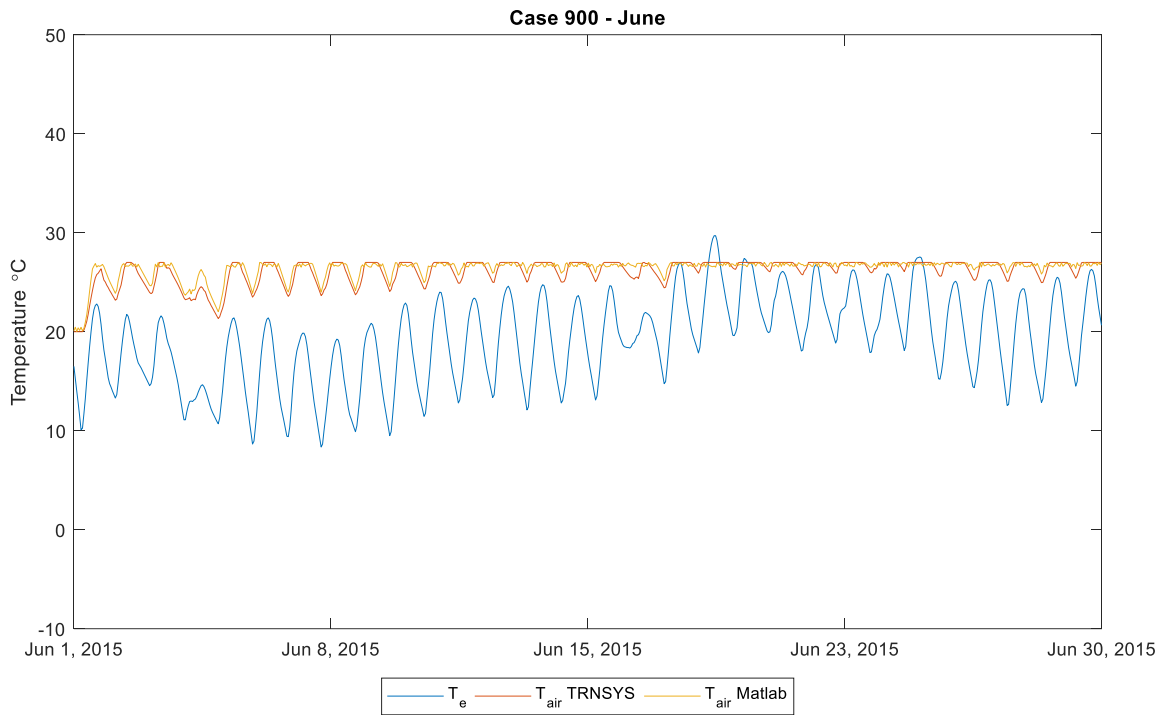Figure 5-32: Case 900 - Hourly internal air temperature (January) - *Milan*

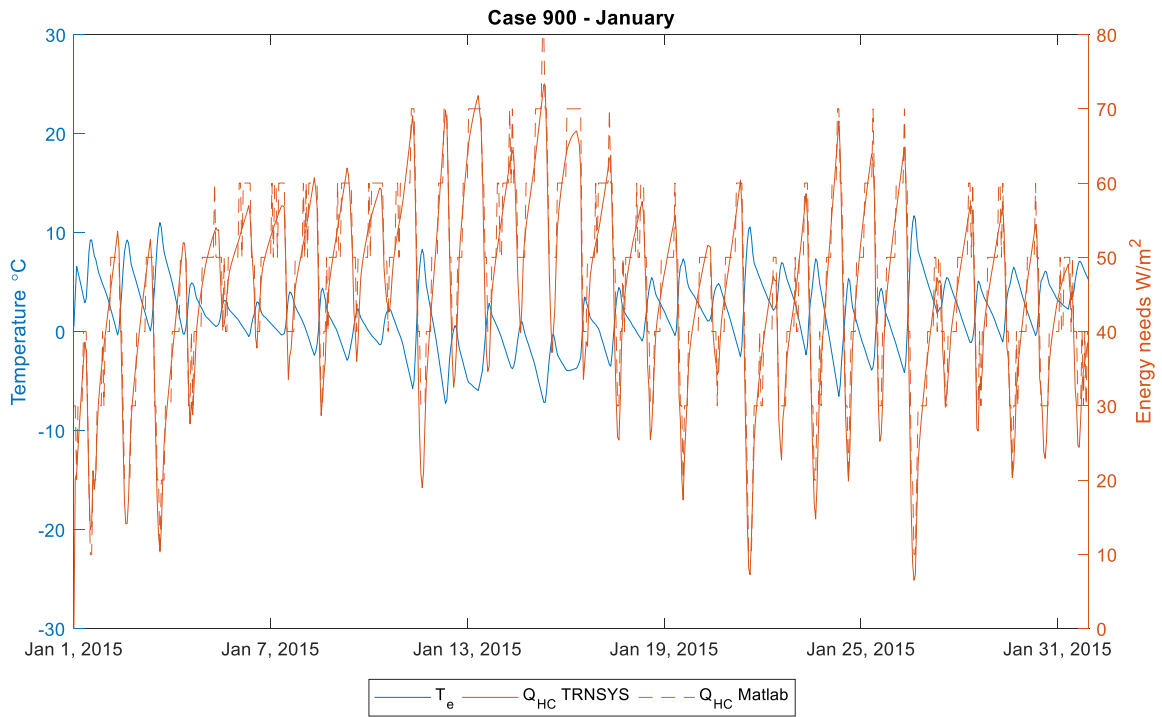Figure 5-33: Case 900 - Hourly internal air temperature (June) - *Milan*

Figure 5-34: Case 900 - Hourly building energy demand (January) - *Milan*
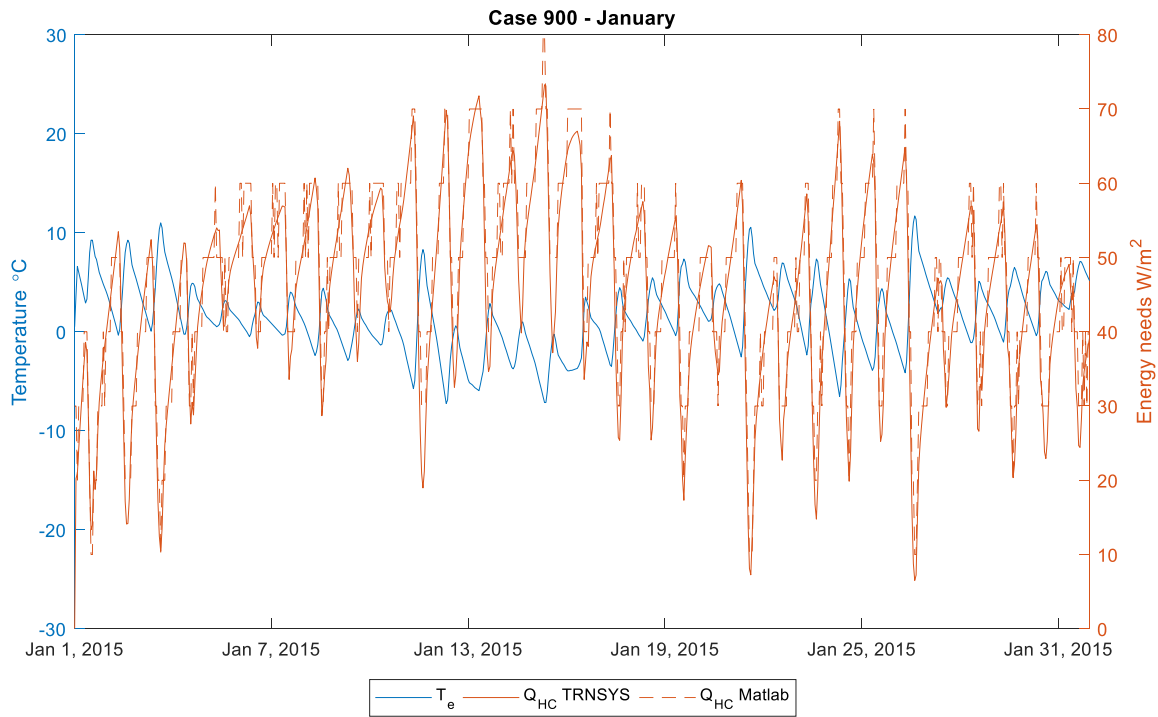
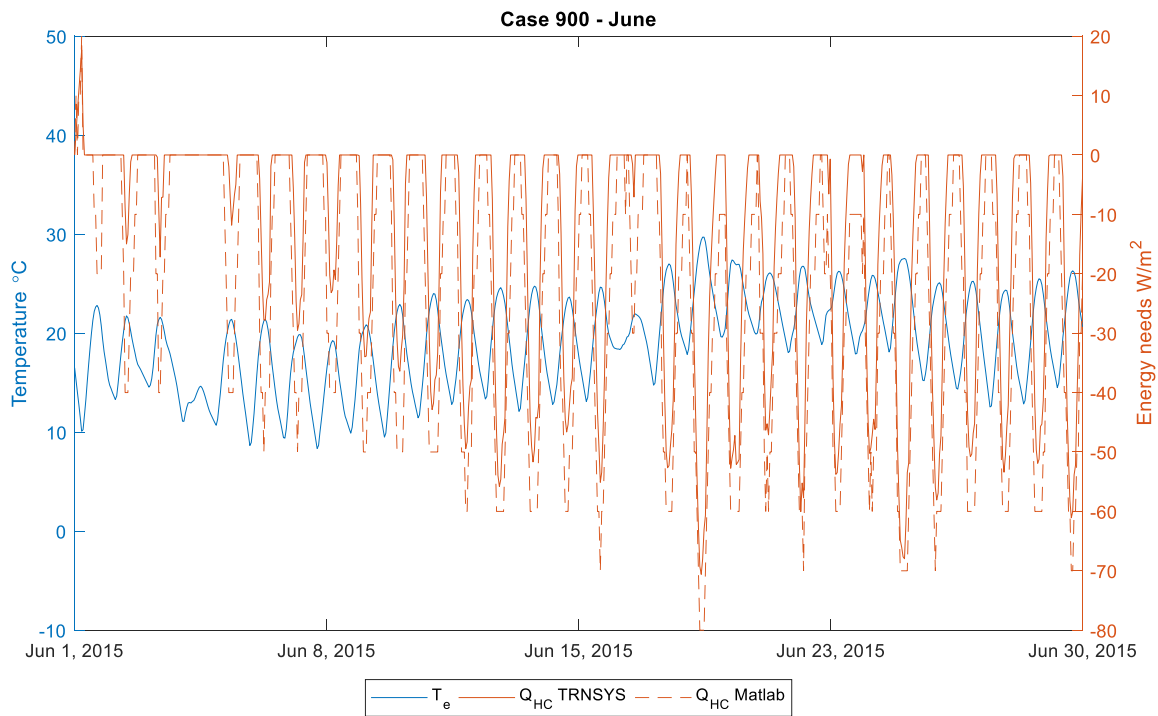Figure 5-35: Case 900 - Hourly building energy demand (January) - *Milan*

Figure 5-36: Case 900 - Hourly building energy demand (June) - *Milan*

The hourly energy demand for the January in both the models have the same trend, there is a slight variation in the peak during the summer case.

5.2.3 Intermittent

The case studies for the intermittent case has been done also for the Milan in order to study the compatibility and behavior of the Matlab model in the intermittent heating system.

5.2.3.1 Lightweight construction elements

The lightweight case for the intermittent heating system behaves identically in both the models looking at the hourly trend in the temperature. Both during the heating and cooling season the trend is more identical.

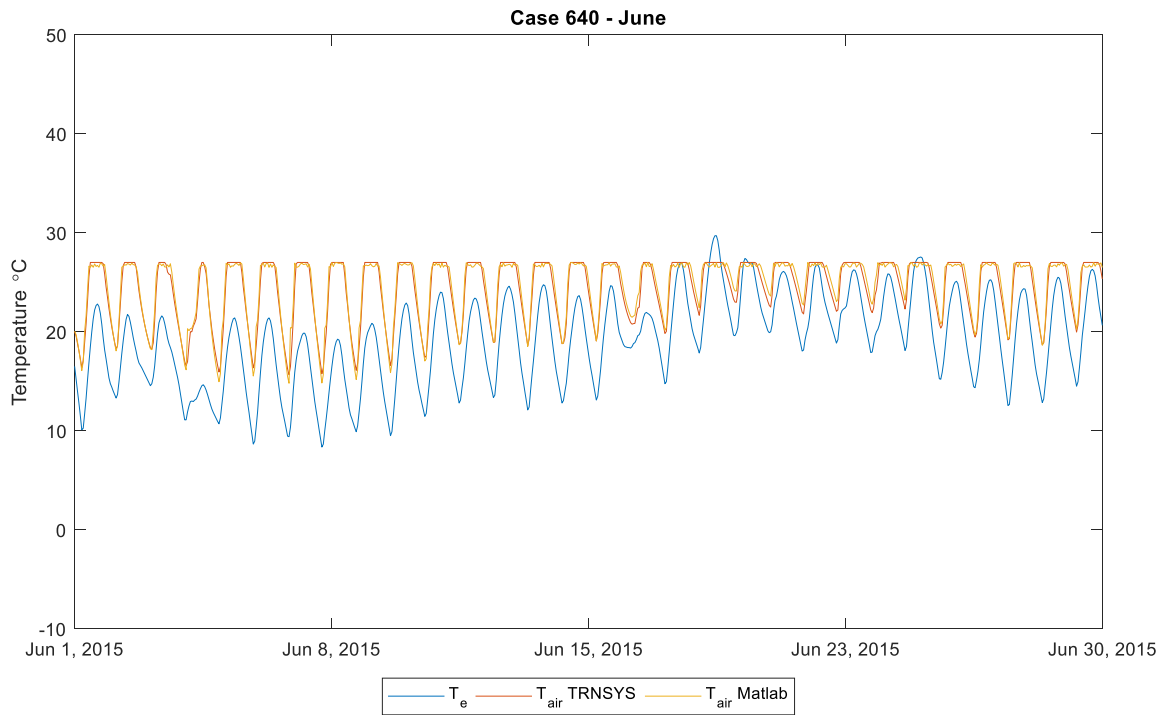Figure 5-37: Case 640 - Hourly internal air temperature (January) - *Milan*

Figure 5-38: Case 640 - Hourly internal air temperature (June) - *Milan*

Figure 5-39: Case 640 - Hourly building energy demand (January) - *Milan*
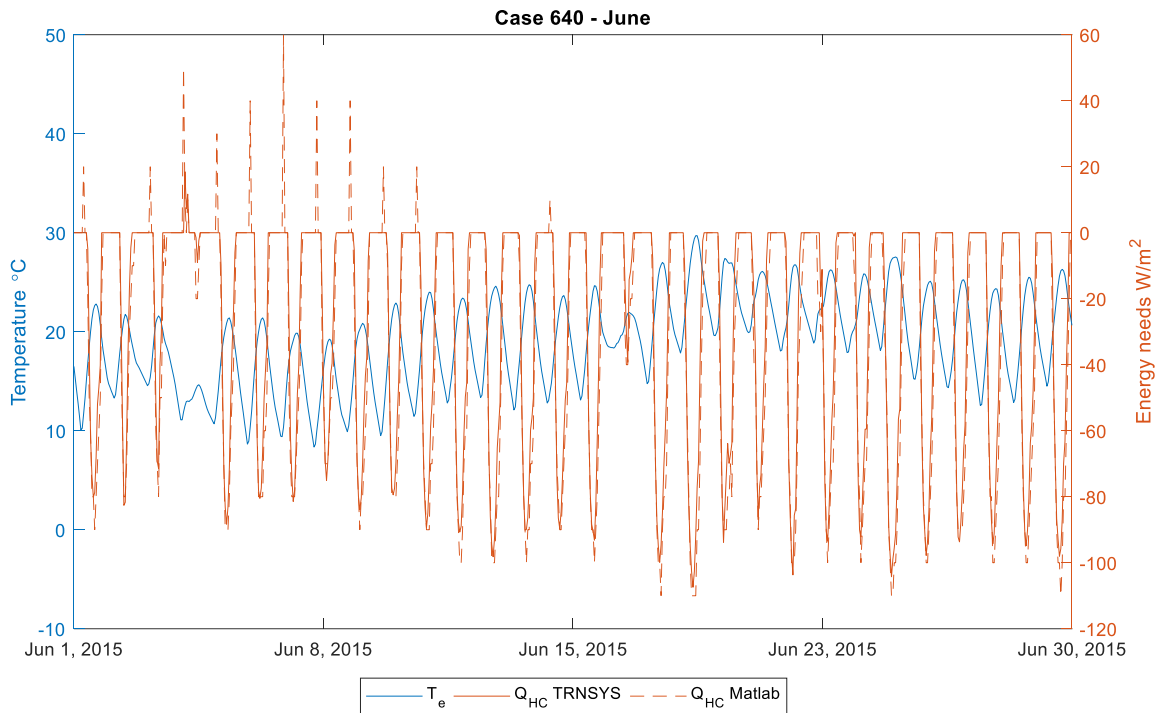
87

Figure 5-40: Case 640 - Hourly building energy demand (June) - *Milan*

The Figure 5-39 and Figure 5-40 shows the calculated energy demand for each hour for both the models in the intermittent case. It could be seen that during the summer the average hourly temperature in Milan is not high but the very high external radiation makes the system to work a lot on the cooling.

The Matlab model have some peaks unlike the TRNSYS which could be due to the accounting of more radiation contribution.

5.2.3.2 Heavyweight elements

The Figure 5-41 which shows the hourly internal air temperature for the heavy weight case for the winter have the temperature controlled according to the set-point in both the models. The Matlab model has a very good trend that is very similar to the TRNSYS.

Figure 5-41: Case 940 - Hourly internal air temperature (January) - *Milan*
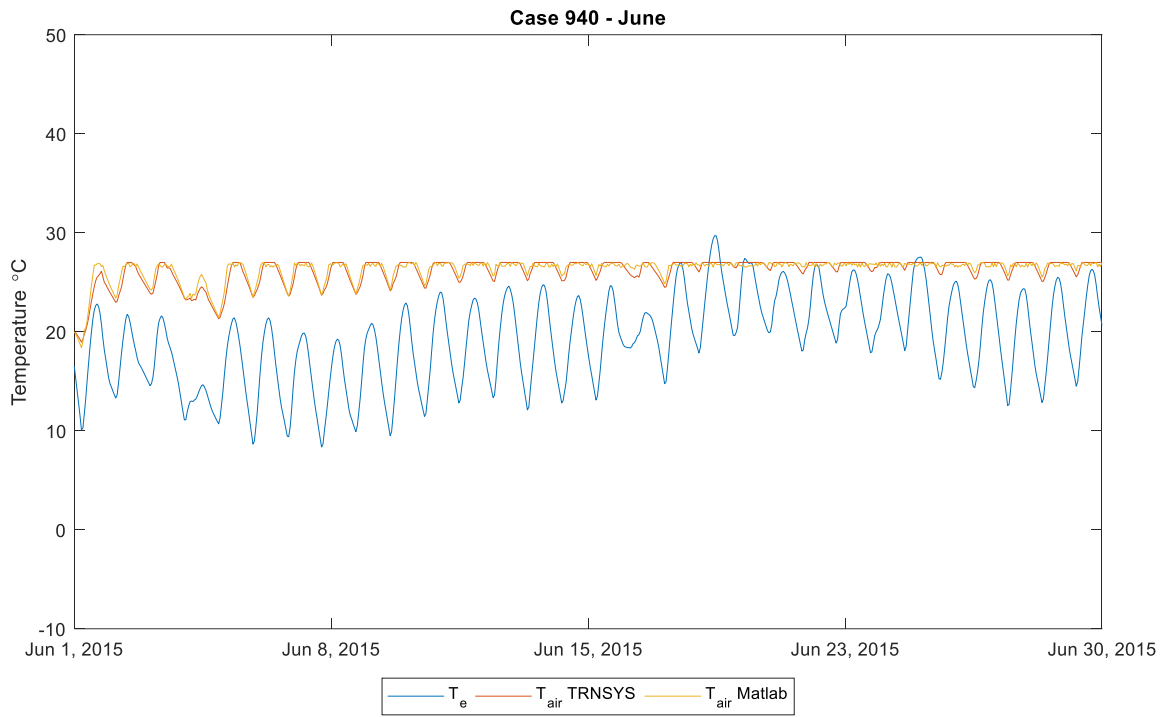
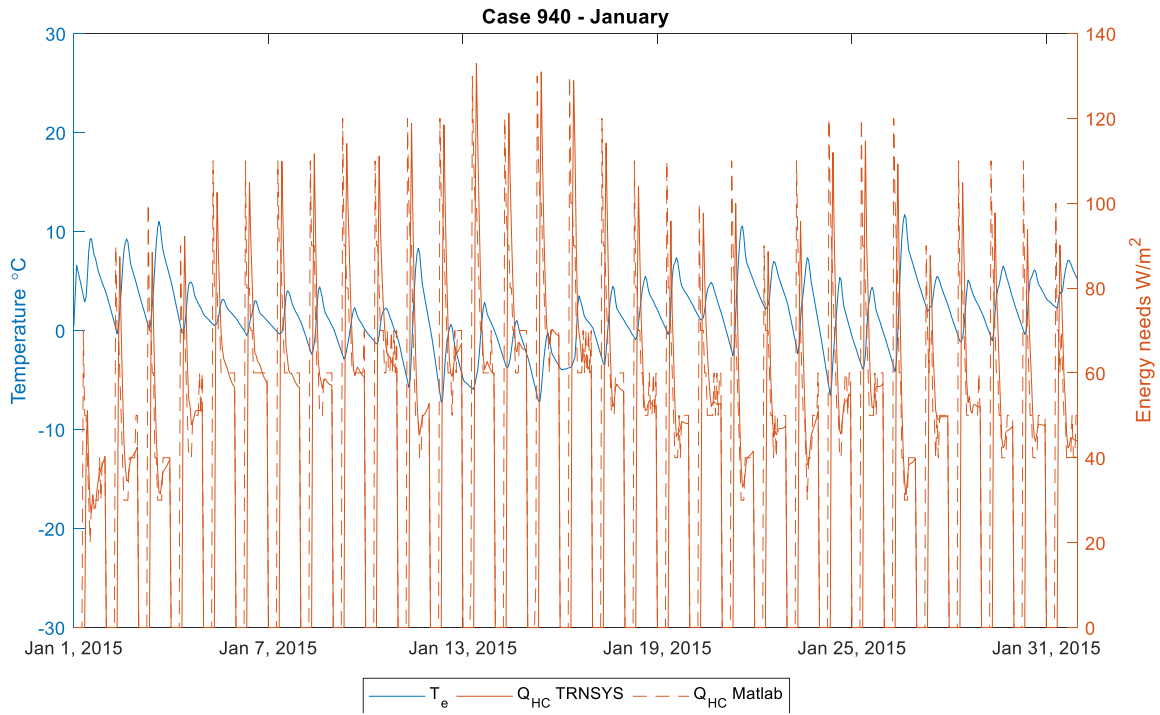Figure 5-42: Case 940 - Hourly internal air temperature (June) - *Milan*

Figure 5-43: Case 940 - Hourly building energy demand (January) - *Milan*
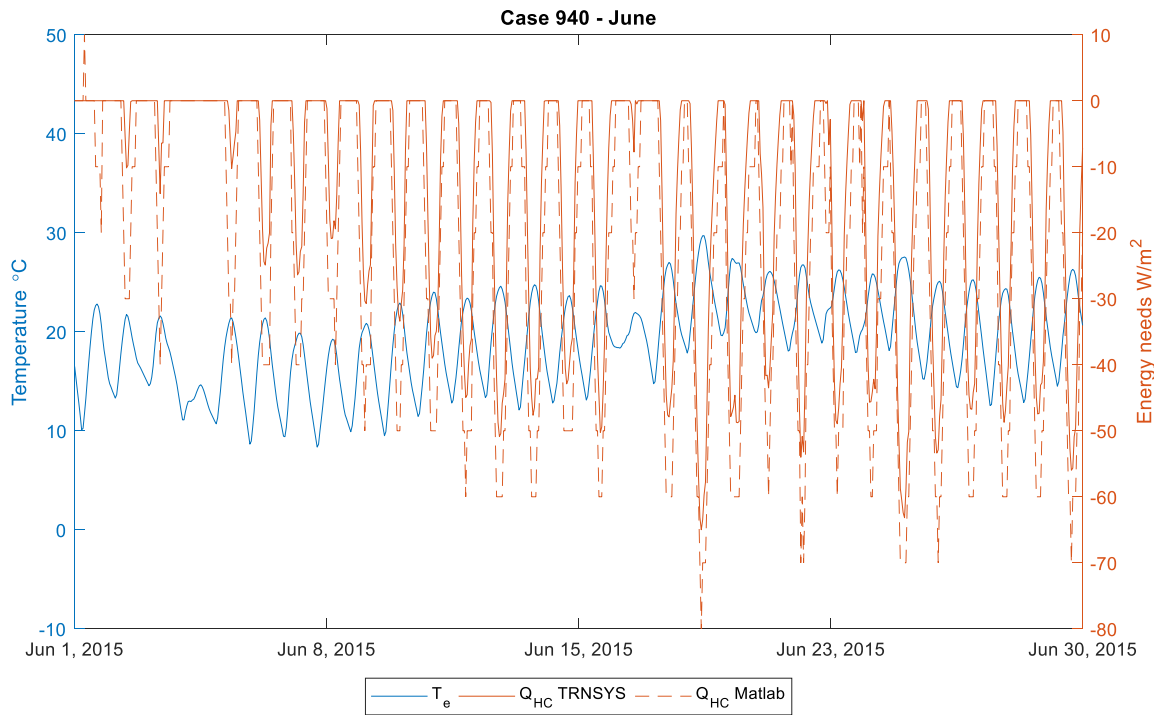
Figure 5-44: Case 940 - Hourly building energy demand (June) - *Milan*

The Figure 5-43 and Figure 5-44 which shows the hourly energy demand of the building has a bit of differences in the peaks between the two models.

5.3 Weather data 3 - Palermo (ITA)

The last climate file that we analyzed using the Matlab model is Palermo, Italy. It could be seen from 3.6.3 that the Palermo has a climate with high average monthly temperature also during the winter with higher radiation. So, it would be an interesting factor to study this climate which is different from the earlier tested cases.

5.3.1 Free-Floating

5.3.1.1 Lightweight construction elements

The Figure 5-45 shows that the internal air temperature calculated using the Matlab model has higher peaks than the TRNSYS which is due to the way the radiation has been considered in the Matlab model construction.
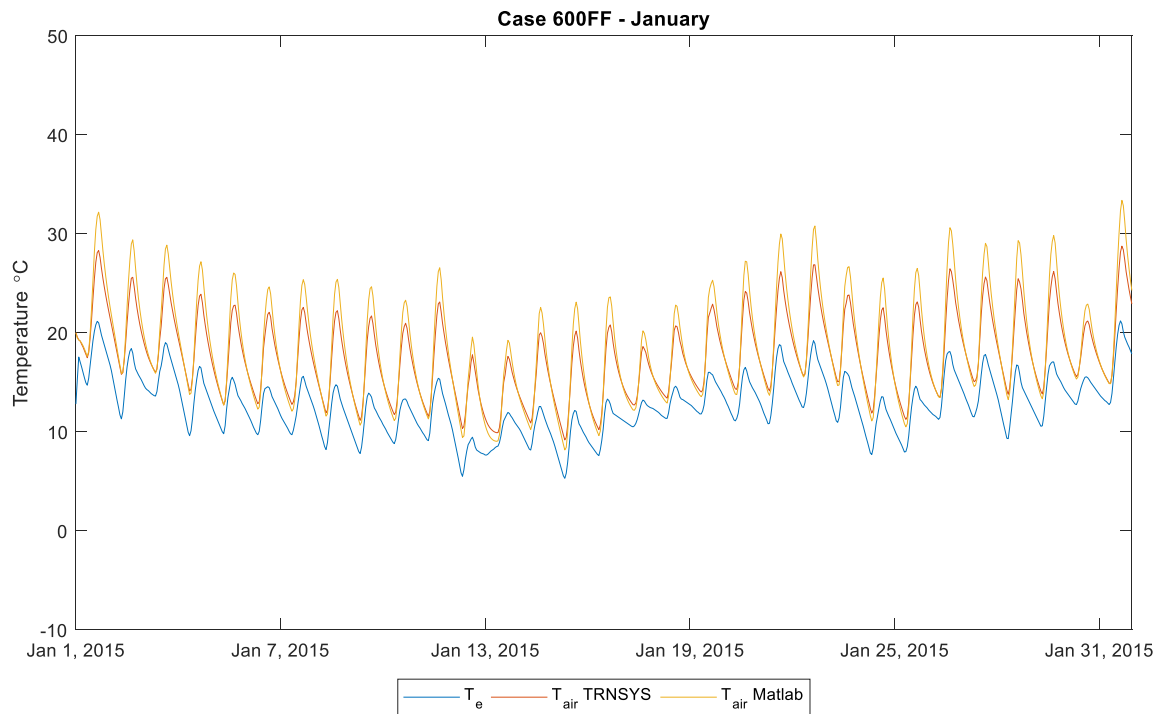

Figure 5-45: Case 600FF - Hourly internal air temperature (January) - *Palermo*

In general, the indoor air temperature is high and reaches a maximum of up to 33 °C while the reason for this trend could be due to the high amount of radiation inside the thermal zone 3.6.3.
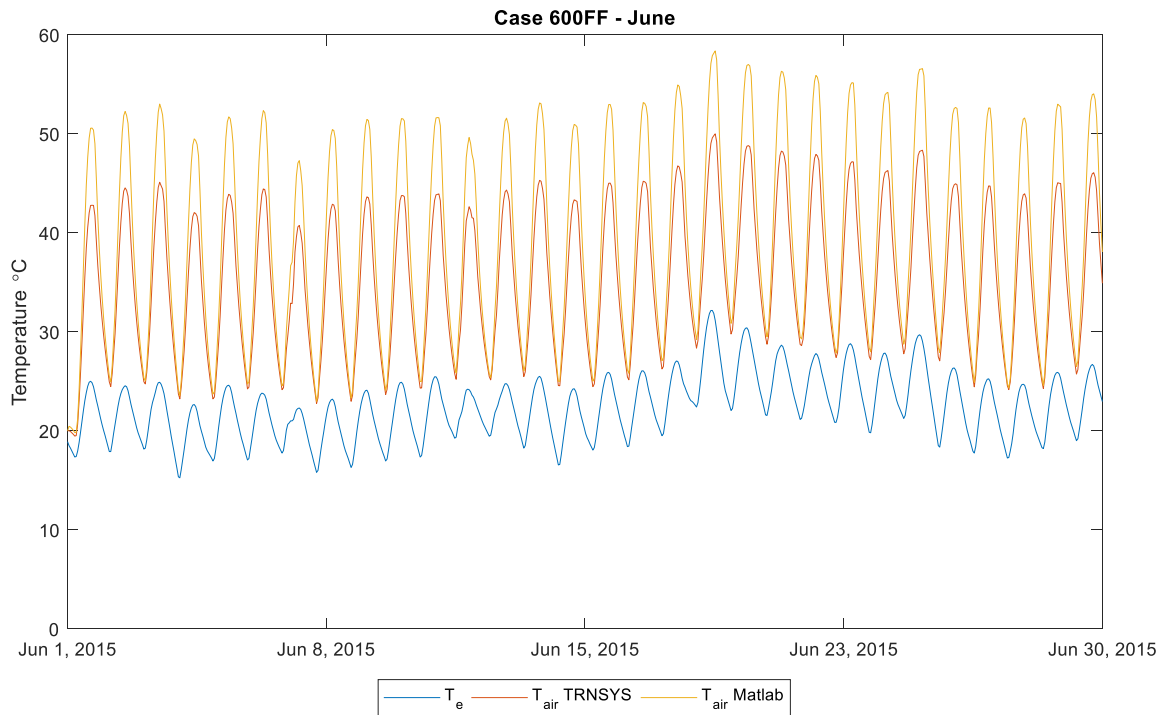
Figure 5-46: Case 600FF - Hourly internal air temperature (June) - *Palermo*

The Figure 5-46 showing the internal air temperature of the zone reaches very high temperature that is due to the moderately high external air temperature and high amount of radiation during the summer in Palermo. The difference in the way the influence of radiation considered in both the models could be clearly seen from the above results.

The R^2 value of the Matlab compared to the Type 56 dynamic model TRNSYS is 0.86 which demonstrates the consistency of the model irrespective of the climate file.

5.3.1.2 Heavyweight opaque elements

The Figure 5-47 that shows the hourly external air temperature of the heavyweight case shows that during the winter the trend is exactly the same thanks to the high thermal mass of the envelope which gives a behavior that is not exactly the external temperature but delays the response of the same.

The Figure 5-48 shows that the indoor air temperature in the heavyweight case is high but still lower than the lightweight case which could be due to the higher capacitance of the building envelope.
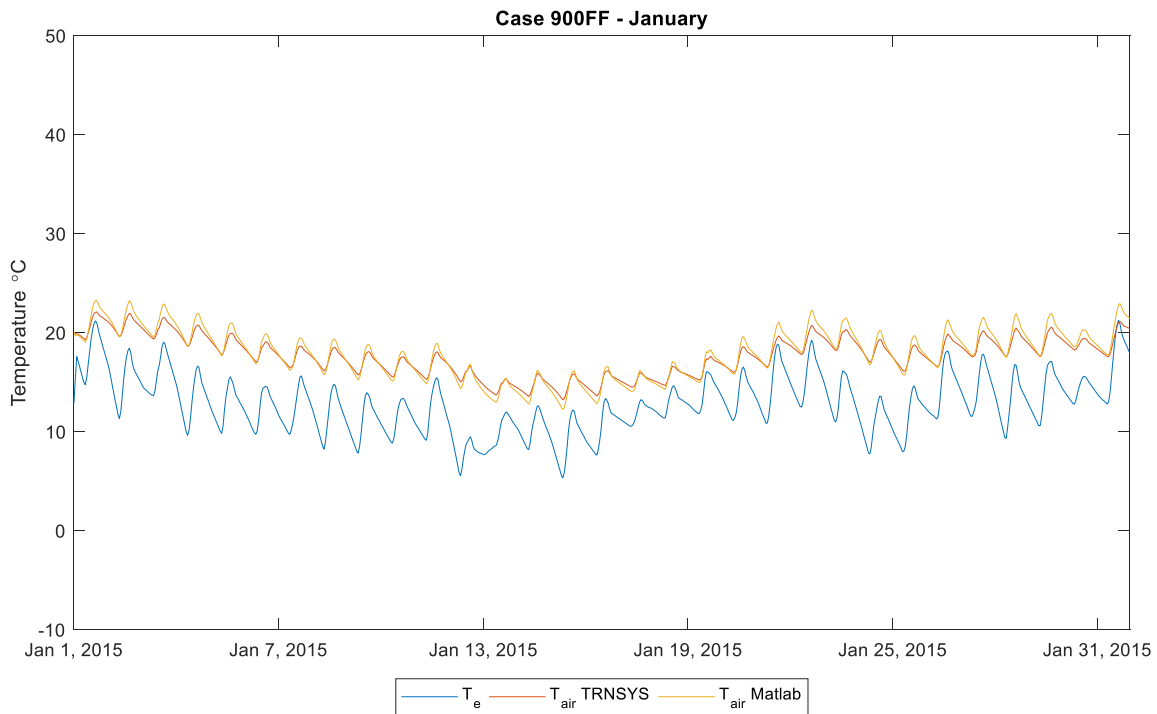

Figure 5-47: Case 900FF - Hourly internal air temperature (January) - *Palermo*
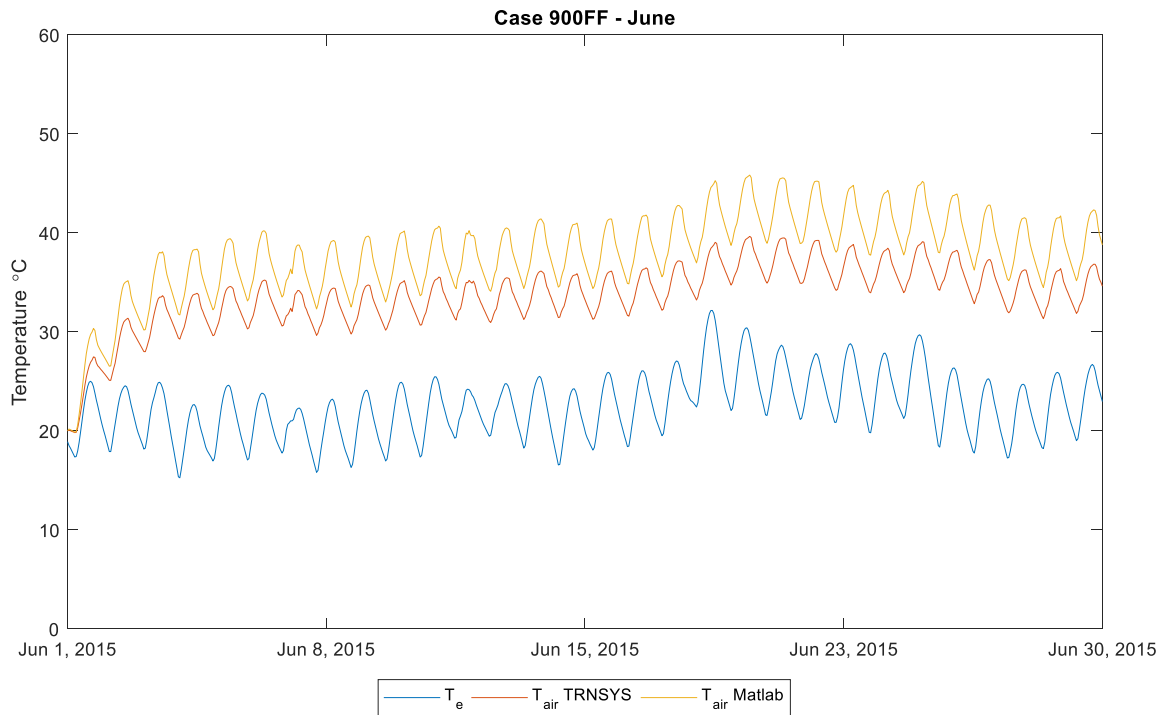
Figure 5-48: Case 900FF - Hourly internal air temperature (June) - *Palermo*

5.3.2 Continuous

The Climate file Palermo has also been tested for the contours heating/cooling system.

5.3.2.1 Lightweight construction

The study of the free-floating case clearly depicts that the Palermo has a problem with respect to the excessive heating inside the thermal zone. So, it is obvious that the predominantly used system is cooling. In Figure 5-49 it could be seen that the system works in order to keep the temperature at the cooling set-point which is 27 °C. The results obtained from both the TRNSYS and the Matlab model have the same trend.

Figure 5-49: Case 600 - Hourly internal air temperature (January) - *Palermo*
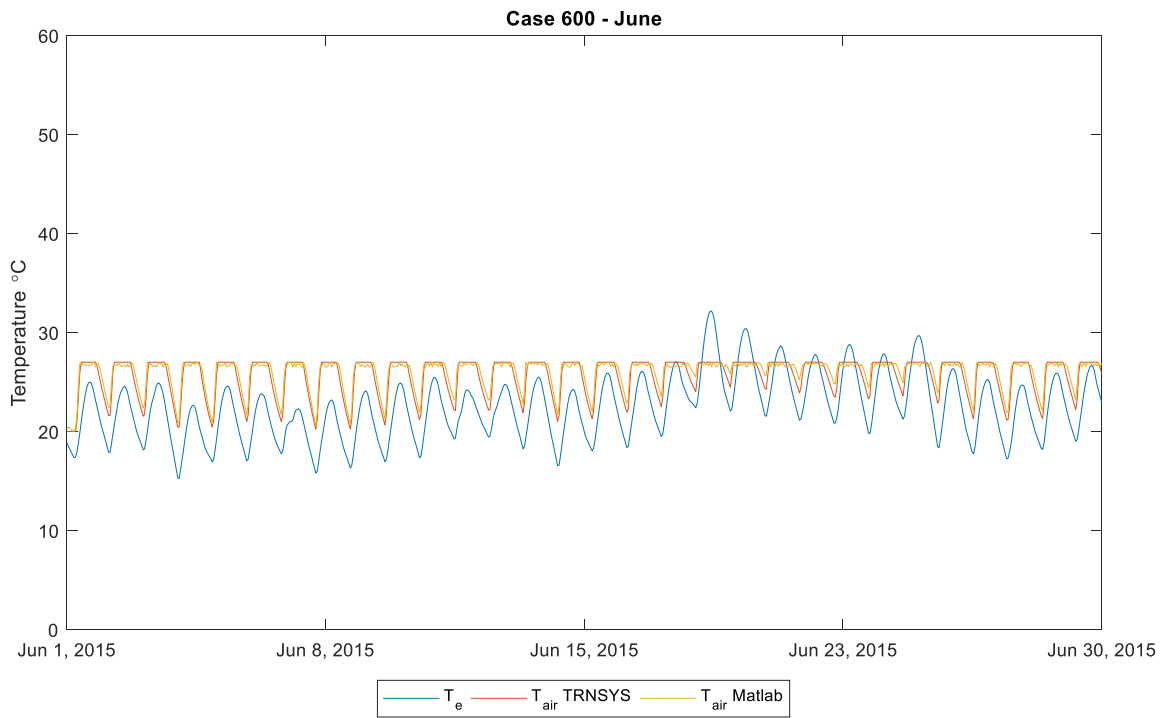
Figure 5-50: Case 600 - Hourly internal air temperature (June) - *Palermo*

The hourly temperature trend shown in Figure 5-50 shows that the during the summer it is even more of a problem for cooling and it could be seen that the external air temperature goes as high as 31 °C. Both the Matlab and TRNSYS have the same trend.

The Figure 5-51 shows that there is low heating demand during the summer in Palermo thanks to the high radiation and external air temperature.

The energy consumption during the summer is pretty high having as low as 120 W/m^2 hourly cooling energy demand.

The trends between the Matlab and TRNSYS are more exactly the same while there is still an issue with peaks in the energy demand values.
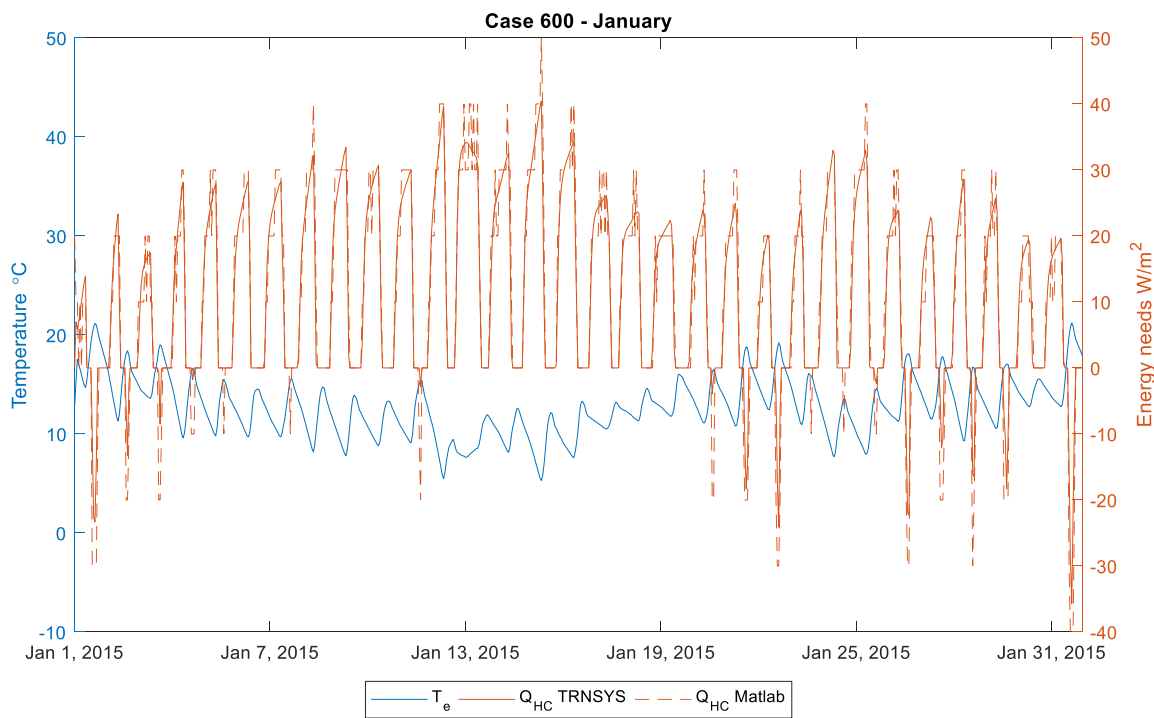
Figure 5-51: Case 600 - Hourly building energy need (January) - *Palermo*
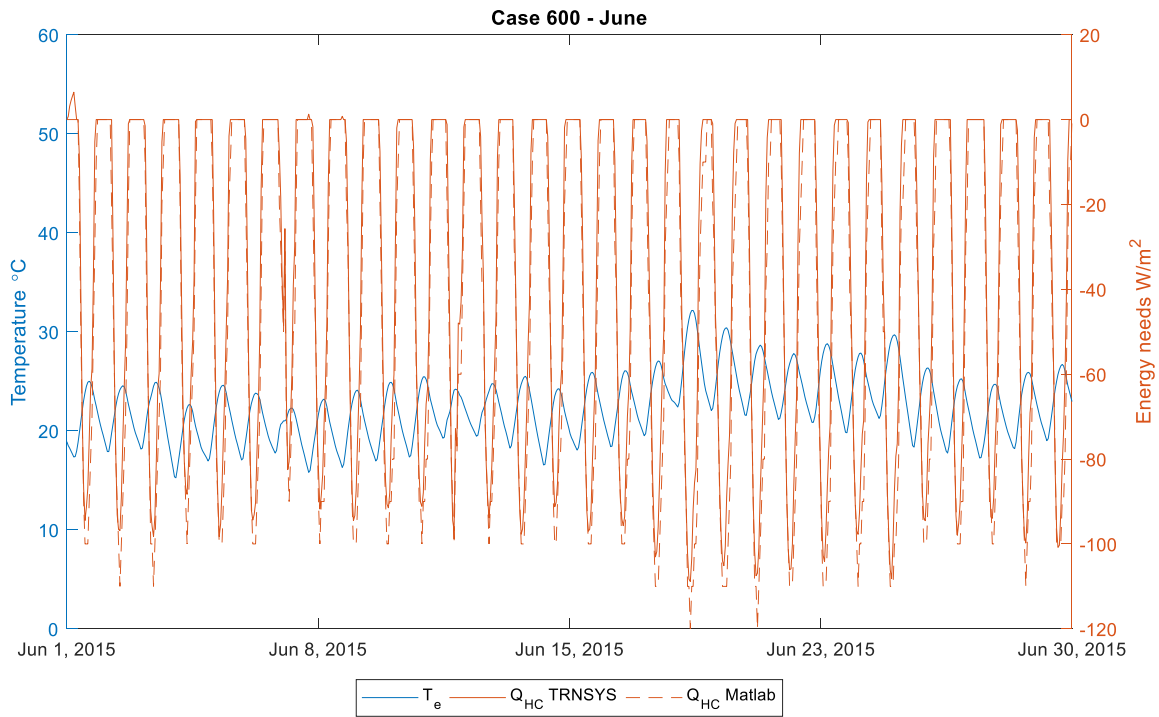
Figure 5-52: Case 600 - Hourly building energy need (June) - *Palermo*

5.3.2.2 Heavyweight opaque elements

The heavy weight elements have a lower temperature profile compared to the light weight case. Since the Palermo has a more of a diurnal temperature profile the heavyweight elements have an edge over the lightweight elements.

Since the Palermo has a higher radiation during the day time the heat is absorbed and stored by the massive elements and released later which is the reason for the trend.
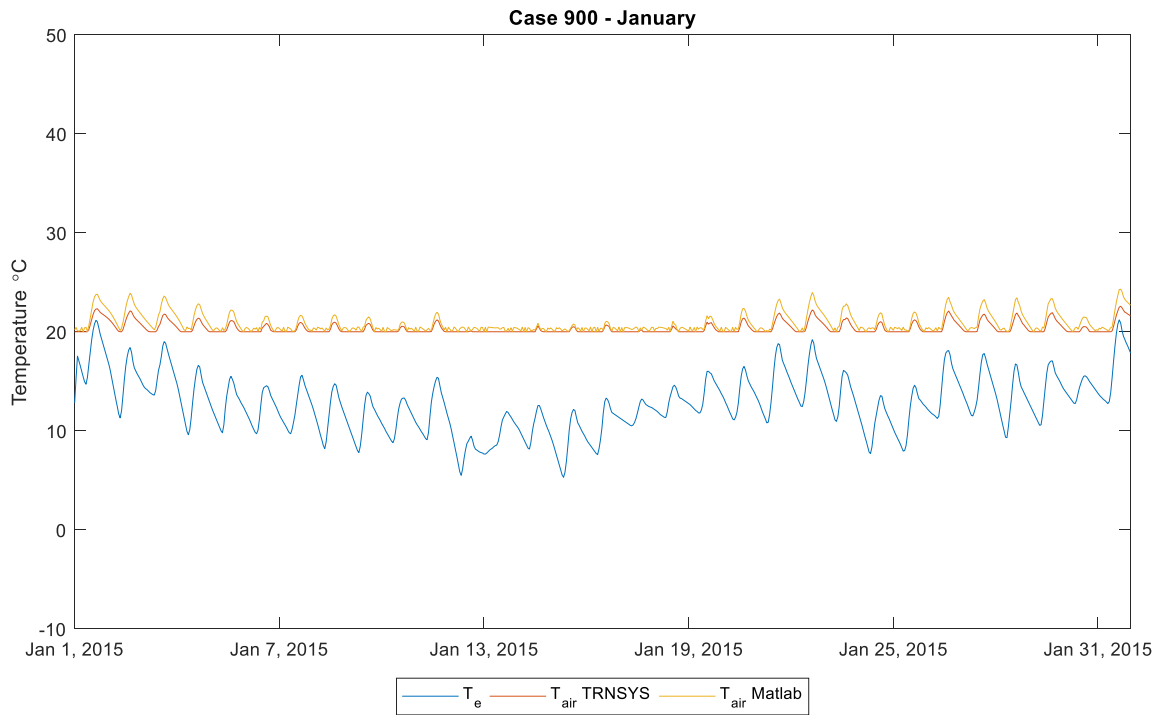
Figure 5-53: Case 900 - Hourly internal air temperature (January) - *Palermo*

The Figure 5-54 shows that the thermal zone is subjected to a very high outdoor air temperature during the June and the system works a lot to have the thermal zone under the set-point.

The Matlab model developed using the EN ISO 52016-1 and the TRNSYS model have the same hourly trend which shows the accuracy the model works.
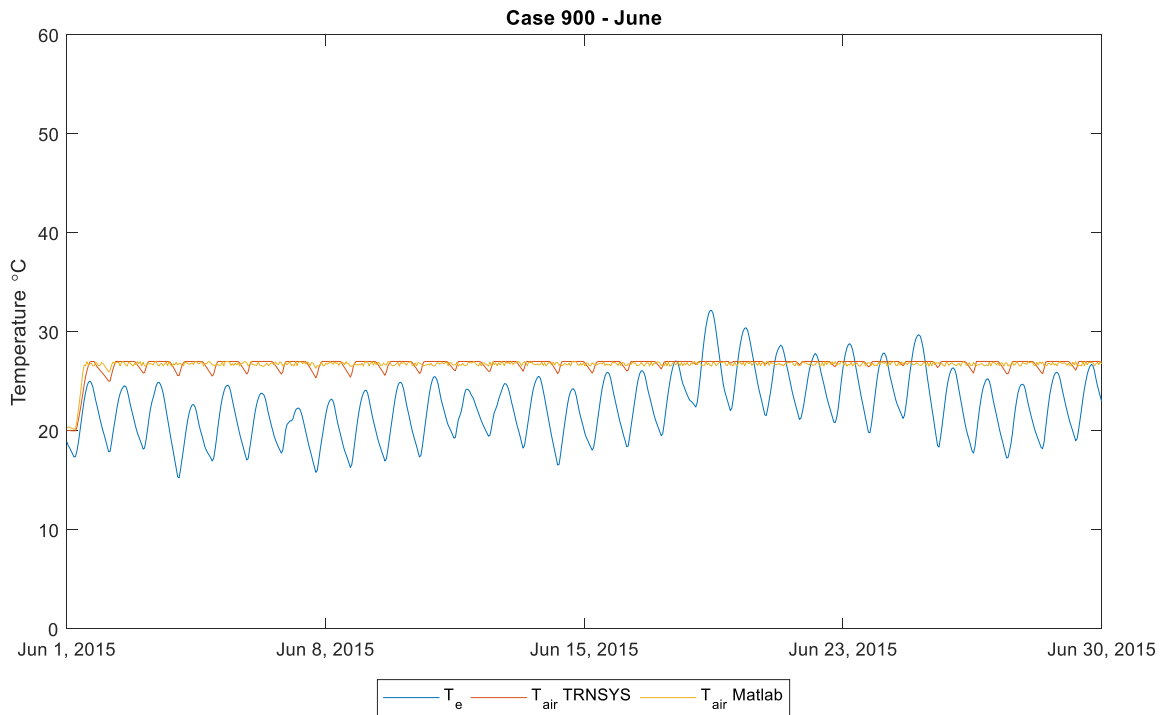
Figure 5-54: Case 900 - Hourly internal air temperature (June) - *Palermo*

The Figure 5-55 shows that the energy demand in the January is just the heating unlike the lightweight case which have very few cooling demands as well. The energy demand during the winter for the heating is not a lot like the other climate files.

The Figure 5-56 that shows the building energy demand during the summer have a very high demand as Palermo has a hot summer. The indoor air temperature is almost at the maximum set-point registering 27 °C.

The Matlab model and the TRNYS have the same trend while there are few issues with the peak demands.

Figure 5-55: Case 900 - Hourly building energy demand (January) - *Palermo*
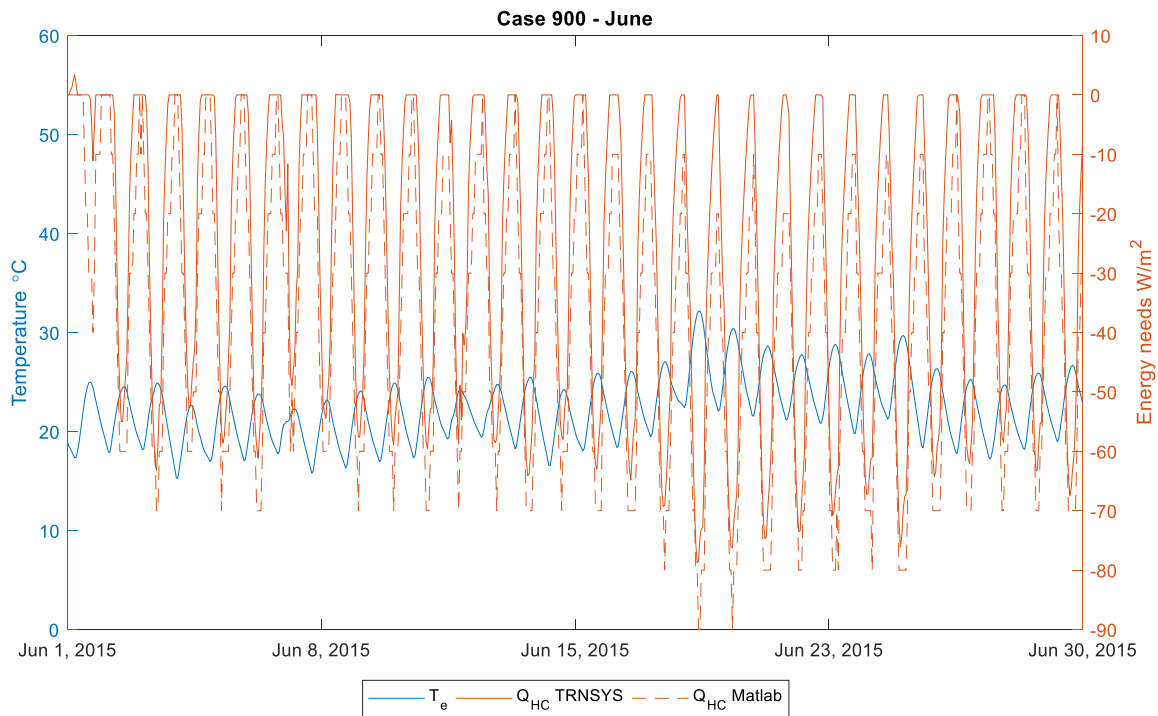
Figure 5-56: Case 900 - Hourly building energy demand (June) - *Palermo*

5.3.3 Intermittent

The Intermittent case study which has night time setback for the heating is tested for the Palermo for both the lightweight and heavyweight construction.

5.3.3.1 Lightweight construction

The Figure 5-57 shows that the system has to work and keep the temperature at its maximum set-point of 27 °C which is due to the fact of night time set-back as low as 10 °C that is the reason for the system to work at high set-point as the room reaches a temperature above the comfort range also during the winter.
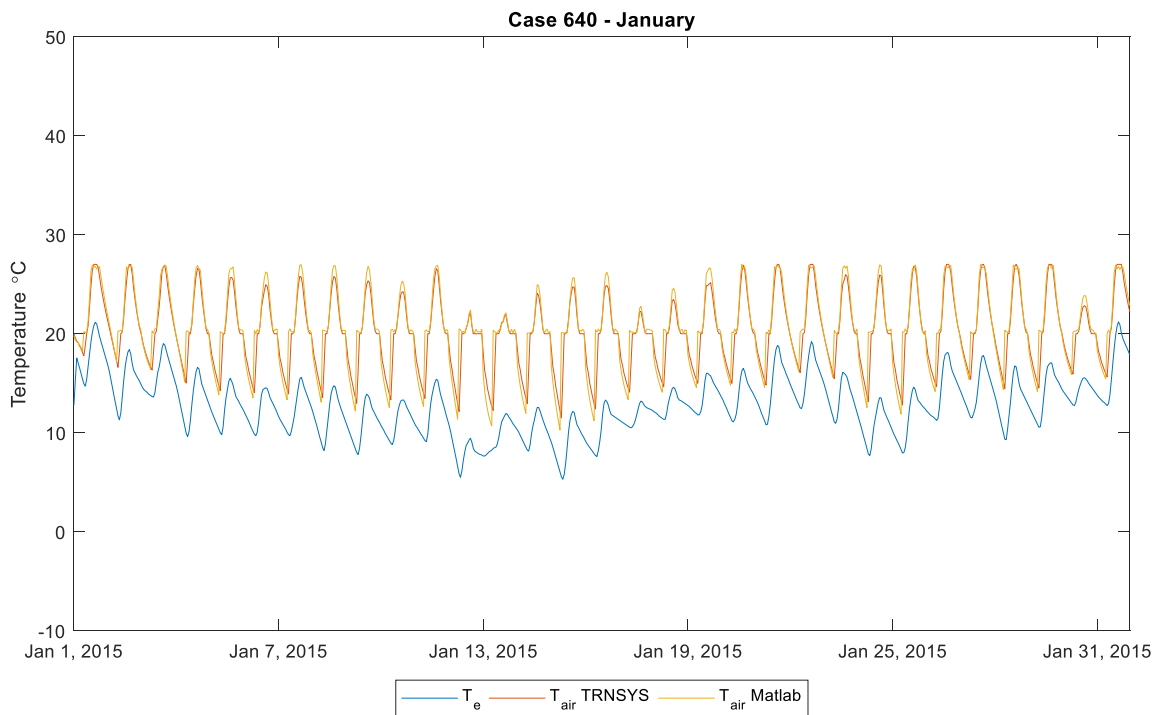
Figure 5-57: Case 640 - Hourly internal air temperature (January) - *Palermo*

The Figure 5-58 shows that the Matlab model and TRNSYS gives the same trend demonstrating the accuracy of the model developed.
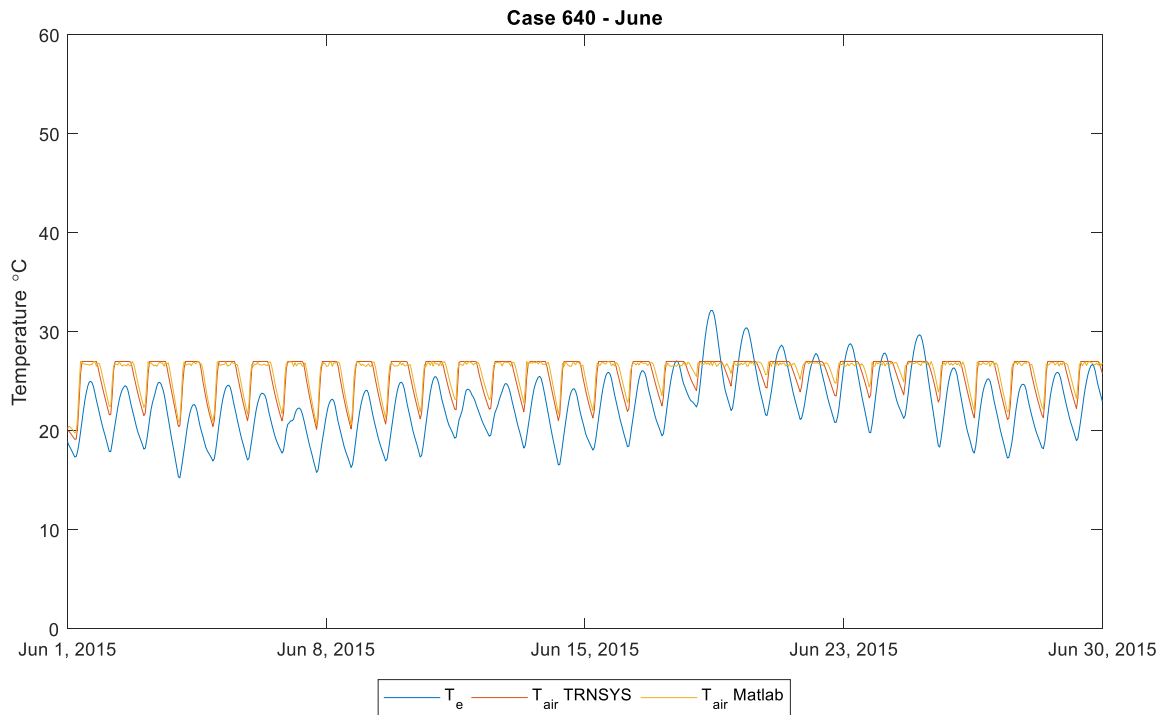
Figure 5-58: Case 640 - Hourly internal air temperature (June) - *Palermo*

The hourly energy demand has been calculated for the lightweight case and it could be seen from the graphs that the winter has higher hourly energy than the continuous system as the external air temperature worsens the situation inside the thermal zone.

The Trend in the energy demand in both the winter and summer have the same behavior while the winter have some peaks which could be due to the effect of radiation.
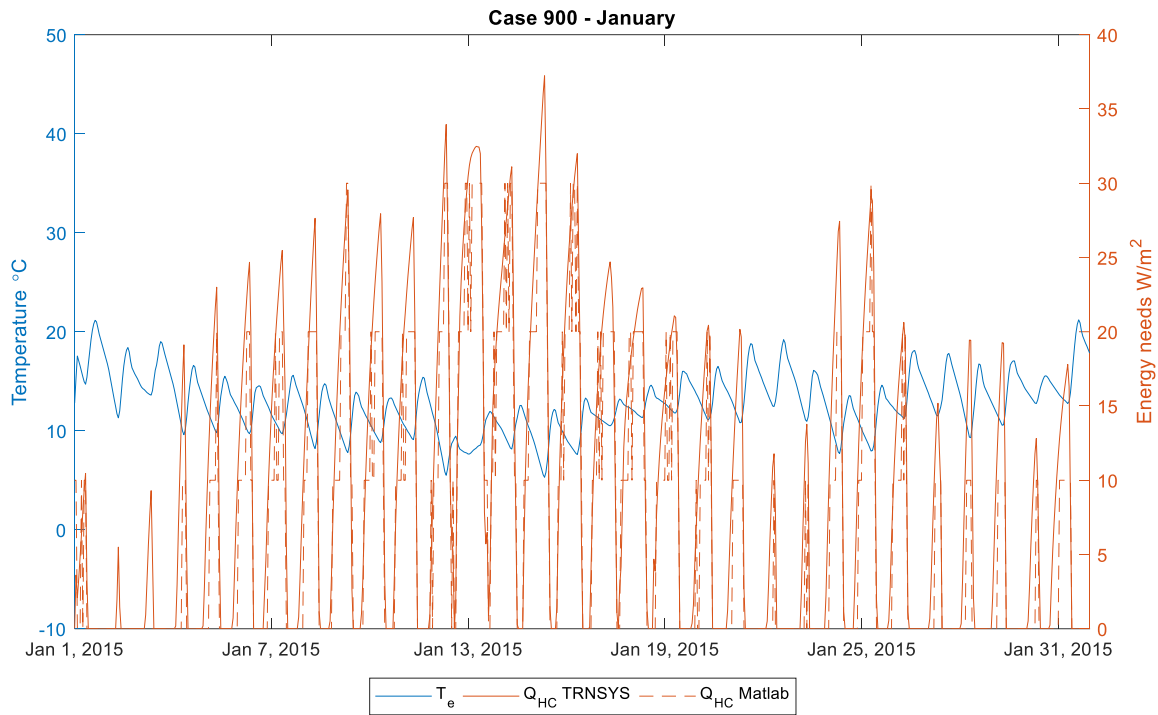
Figure 5-59: Case 640 - Hourly building energy demand (January) - *Palermo*
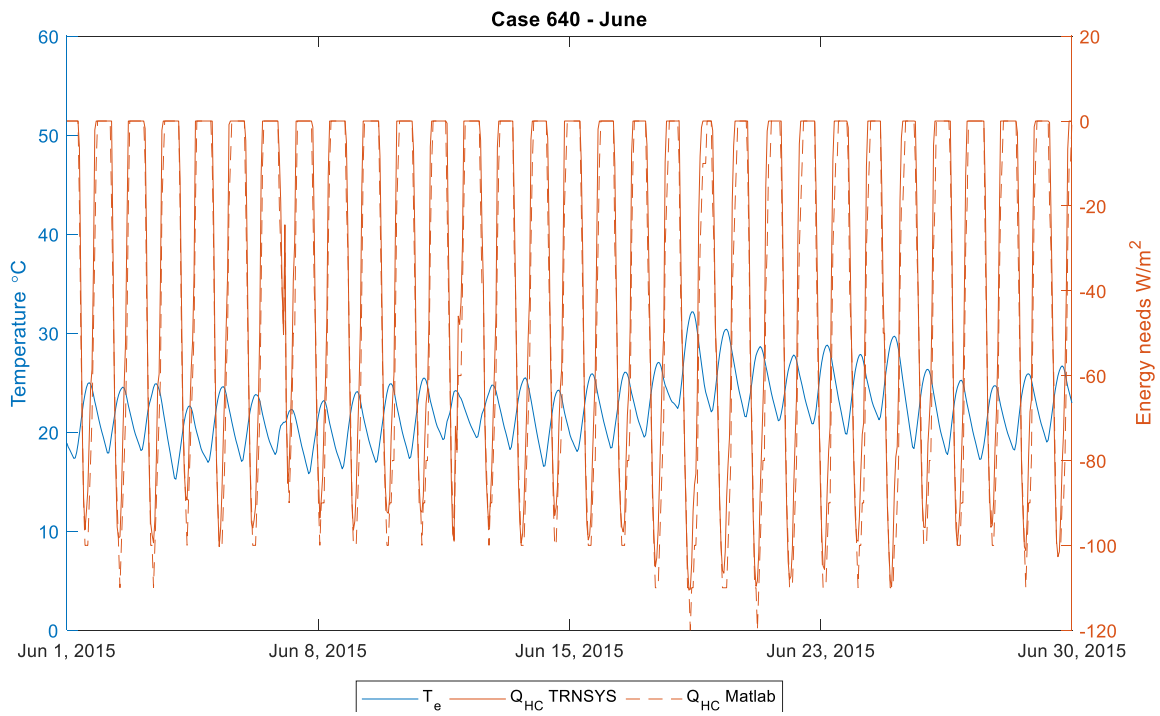
Figure 5-60: Case 640 - Hourly building energy demand (June) - *Palermo*

5.3.3.2 Heavyweight elements

The behavior in the temperature trend is better than the lightweight case thanks to the high capacitance of the envelope.
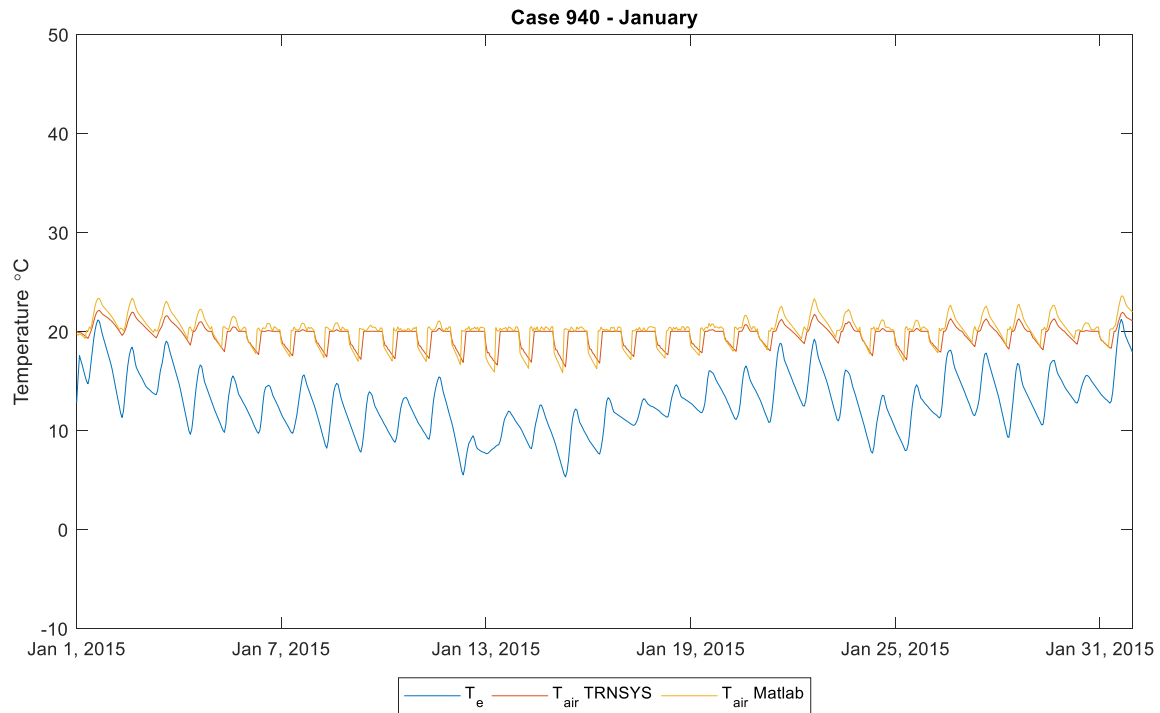
Figure 5-61: Case 940 - Hourly internal air temperature (January) - *Palermo*

The Figure 5-62 shows that the hourly trend in both the Matlab model and the TRNSYS have the same trend. The accuracy of the model in the external air temperature is really high as we get almost the same trend in both Matlab and TRNSYS.

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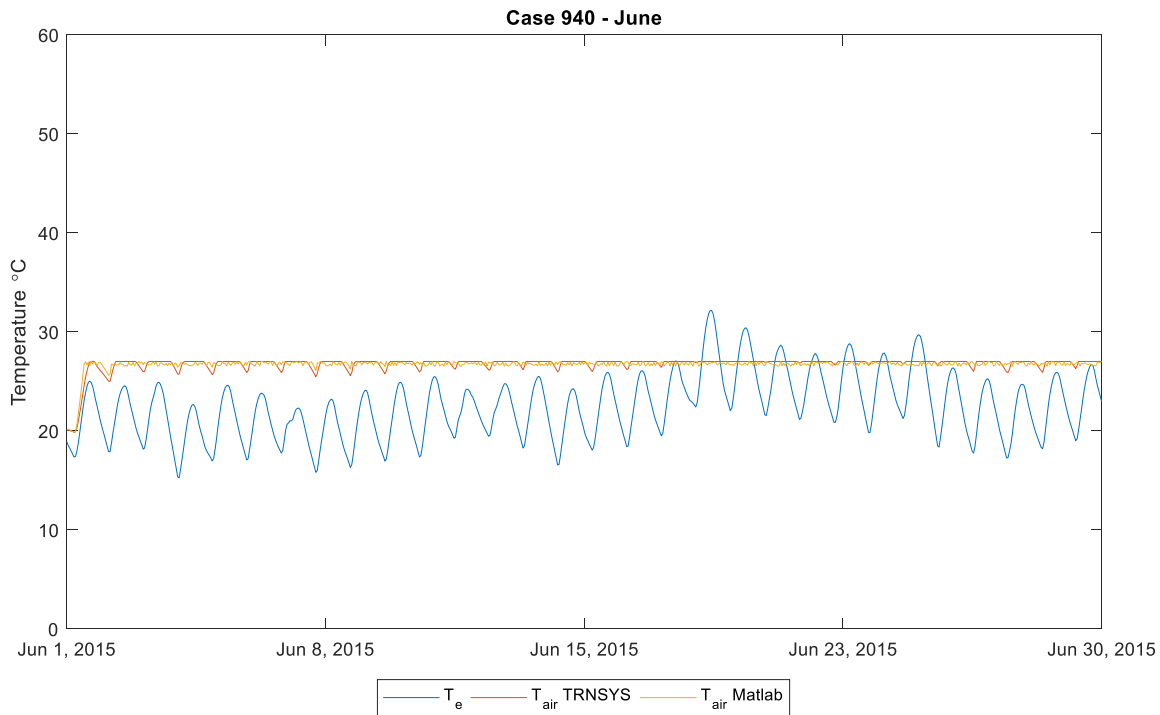
Figure 5-62: Case 940 - Hourly internal air temperature (June) - *Palermo*

The Figure 5-63 shows that the heavyweight case has a lower hourly energy demand also in the intermittent case and the pattern in both the models have the same behavior but there is always the maximum peak value higher in the Matlab model.

The Figure 5-64 shows the comparison of the hourly energy demand in the test winter case. It could be seen that the trends are similar while there is a bit of deviation in some hours which could be due to the way the model is working with the radiation.
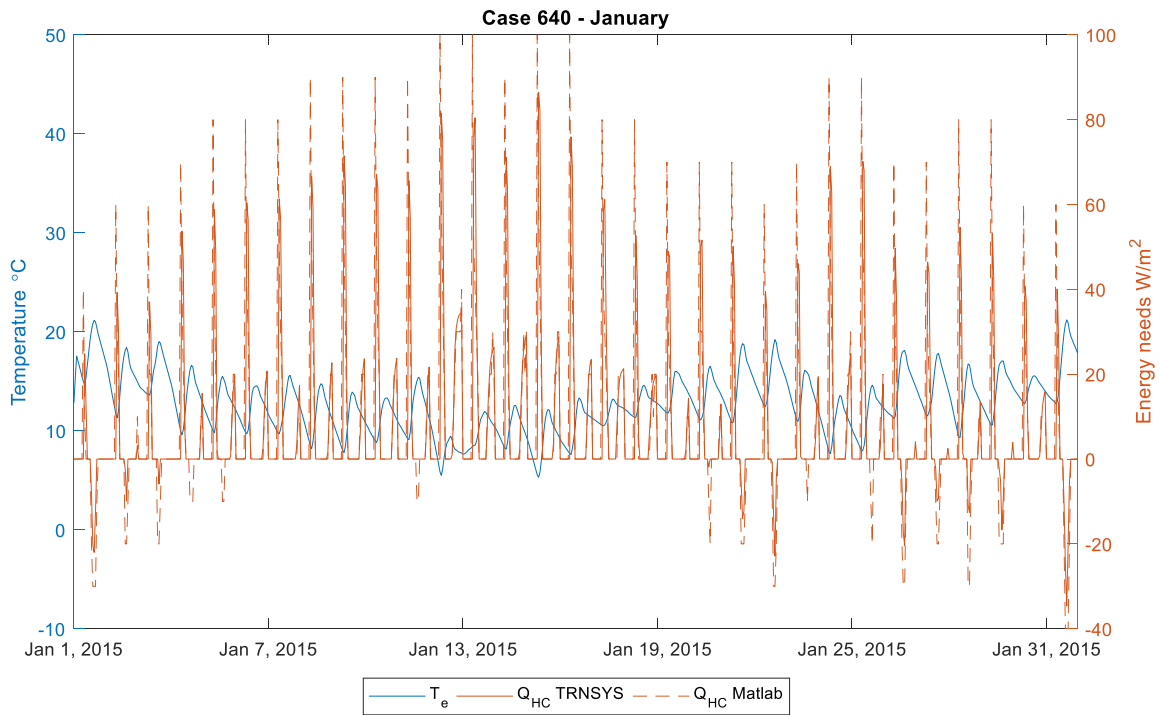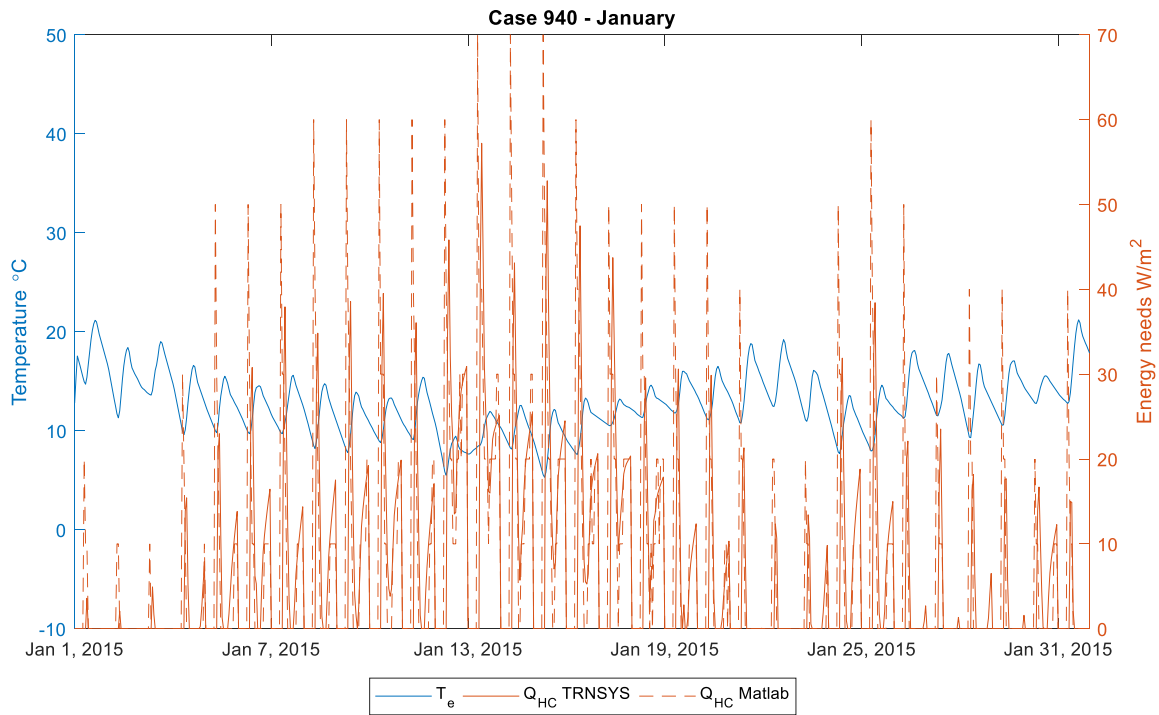
Figure 5-63: Case 940 - Hourly building energy demand (January) - *Palermo*
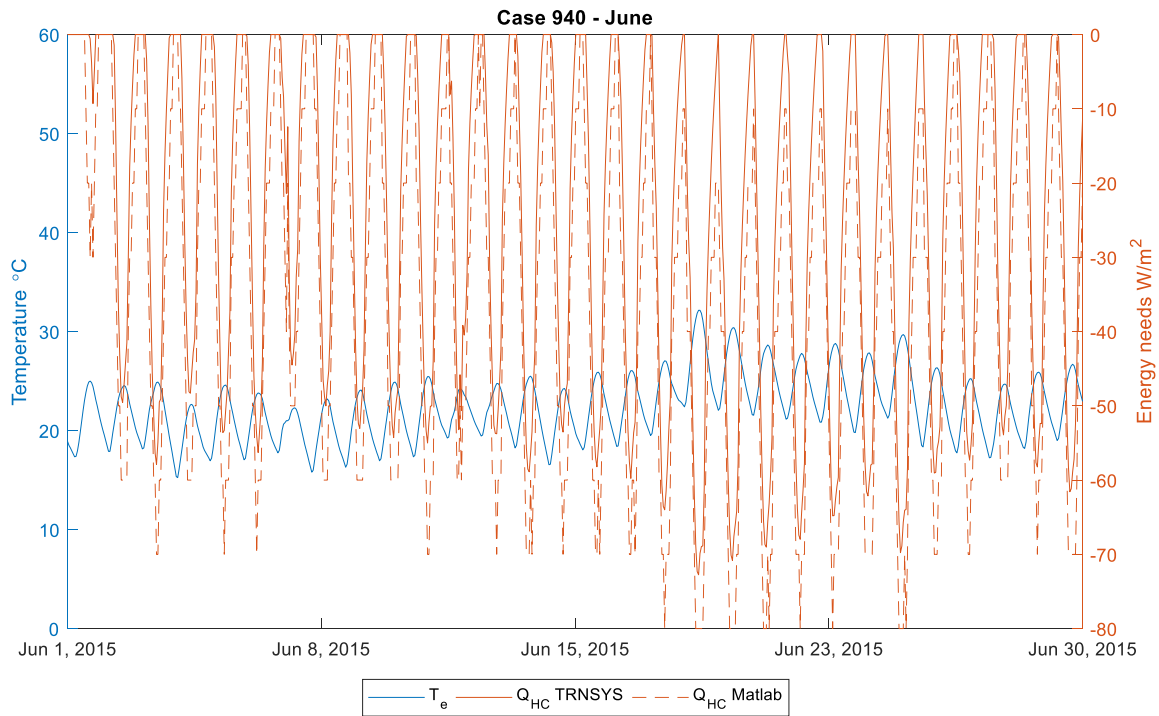
Figure 5-64: Case 940 - Hourly building energy demand (June) - *Palermo*

5.4 Energy needs comparison

The total energy needs consumed for the different climate files for the respective test winter and test summer months have been calculated for the BESTEST cases for all the three models.

5.4.1 Weather data 1 -drycold weather
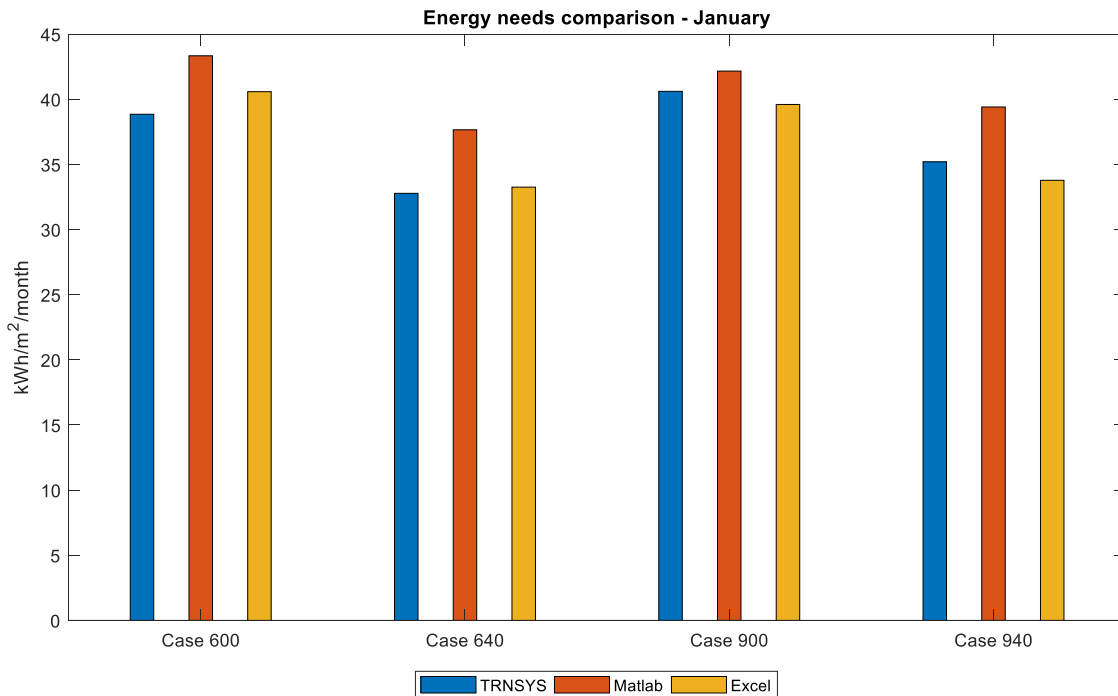
Figure 5-65: Energy needs comparison for the BESTEST (January)- *drycold weather*

The Figure 5-65 shows that for the drycold weather, the energy needs for the month of January for the lightweight case with continuous heating and cooling system (Case 600) is around 43 kWh/m^2 calculated using the Matlab model and there is a 11 percent difference in the energy needs calculated using the Type 56 dynamic model. The difference is due to the difference in the simplification done by neglecting long-wave emissivities in the Matlab model while considering the long-wave radiation in the energy balance.

The results show that the light case with intermittent heating and cooling system (Case 640) has a 14 percent savings in the energy needs compared to the case with continuous control strategy thanks to the night time reduction in the indoor air set-point temperature.

In the BESTEST series, the building elements in the heavyweight case has higher thermal mass but almost the similar U-value. Therefore, the performance of the cases is directly related to the thermal mass of the building elements. The Figure 5-65 shows that the heavyweight cases (Case 900 and 940) have equally similar energy needs in the continuous control of the HVAC system while slightly higher during the intermittent control. This is due to the fact that the high thermal mass doesn't help much in the winter climate as the outdoor air temperature is low during the whole day and the heat flow is always from the interior to the exterior.
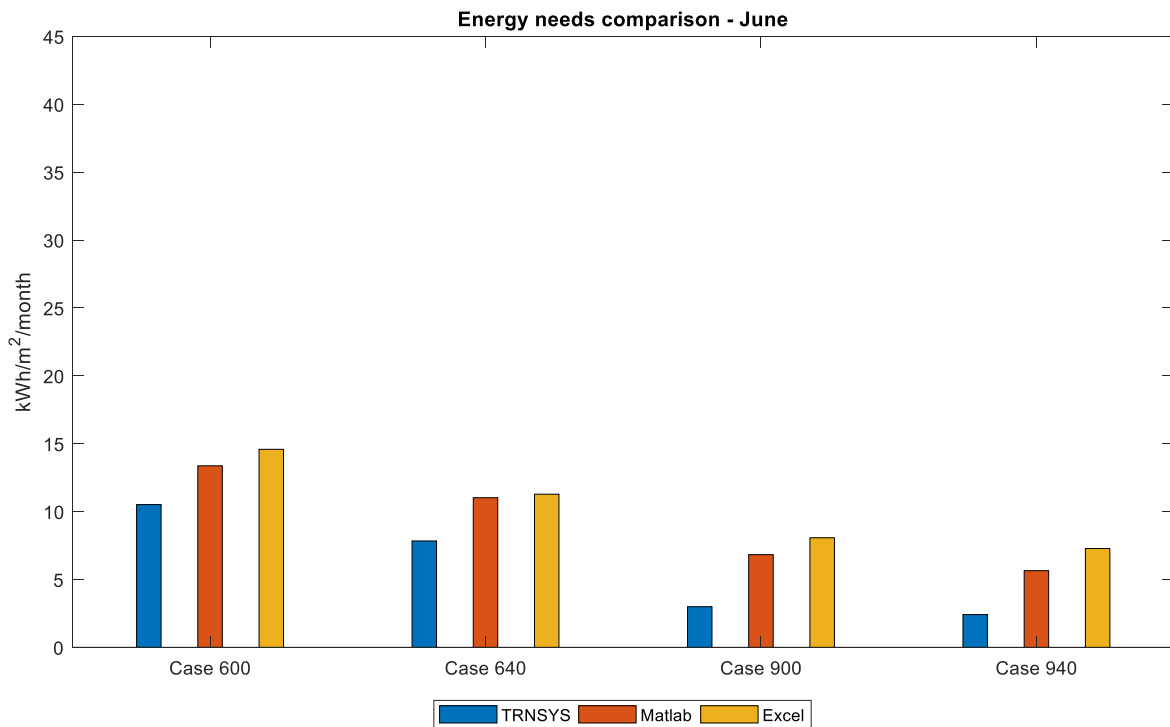
Figure 5-66: Energy needs comparison for the BESTEST (June)- *drycold weather*

The Figure 5-66 shows that the heavyweight cases have lower energy needs during the month of June when the external air temperature has a diurnal variation. This helps the heavyweight cases as the heat is absorbed and stored in the thermal mas of the building elements during the day and then released later when the external air temperature drops down. The high thermal mass works well and produce higher energy savings when there is a high diurnal variation in the temperature.

5.4.2 Weather data 2 -Milan

The Figure 5-67 shows the energy needs calculated using the Matlab model for the BESTEST series compared with the same cases calculated using the TRNSYS.
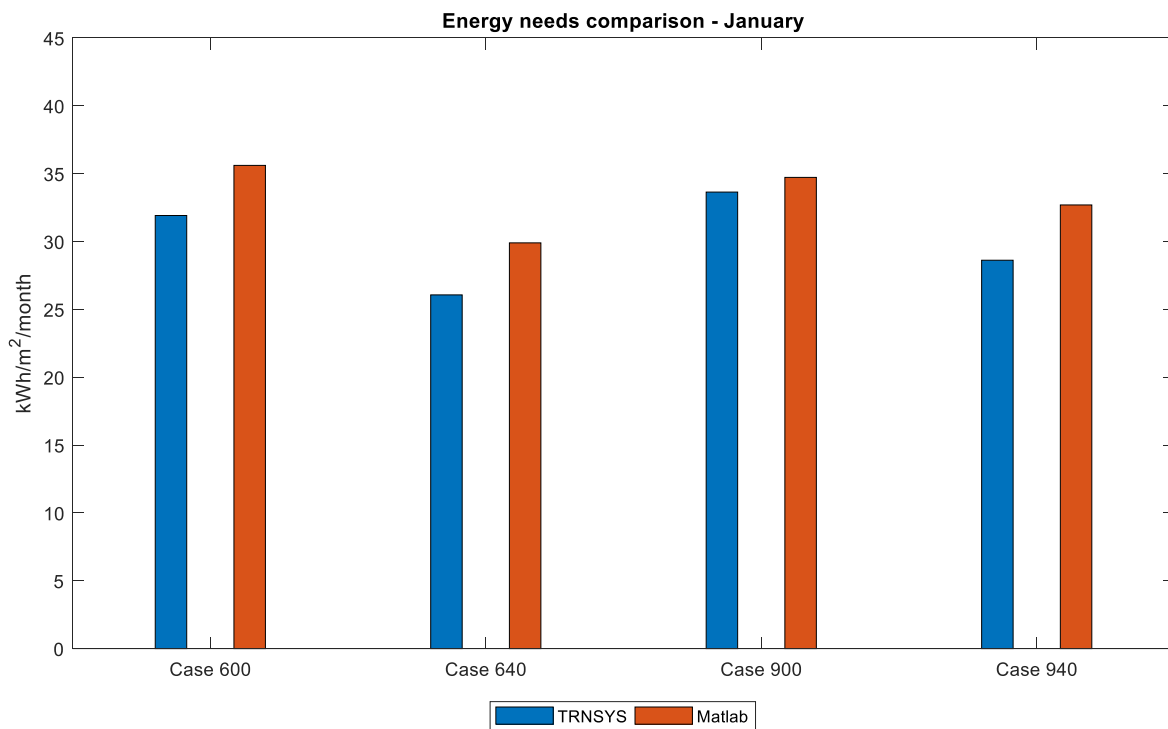
Figure 5-67: Energy needs comparison for the BESTEST (January) - *Milan*

The Figure 5-67 shows that the heavyweight cases with continuous and intermittent heating and cooling system have equally similar energy needs as the lightweight cases as the high

thermal mass does not help in the month of January in Milan as the external air temperature is below the comfort zone all throughout the day. This results in the one direction heat flow always towards the outside.

Under these climatic conditions, it is needed to have more insulation than high thermal mass as the results shows that there is not a significant effect. Since the BESTEST series have the same thermal transmittance, U-value in both the lightweight and heavyweight cases it is obvious to have similar or higher energy needs in the heavyweight case as it is a drawback.

The Figure 5-67 also shows that the heavyweight case with intermittent control strategy (Case 940) has even slight higher energy needs compared with the lightweight case which is again due to the loss of the heat due to the low outdoor air temperature.
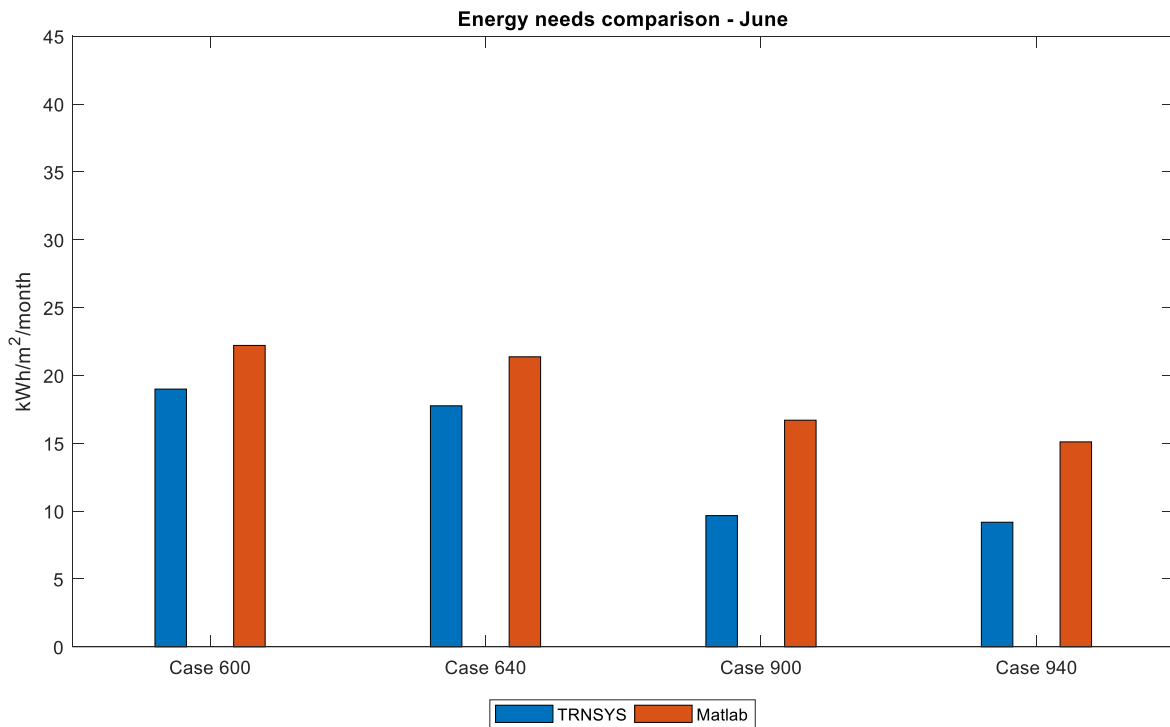
Figure 5-68: Energy needs comparison for the BESTEST (June) - *Milan*

The Figure 5-68 shows that in Milan the heavyweight cases performs better than the lightweight cases thanks the warm day and cool night outdoor air temperatures. Still the savings in the energy needs are not dramatically high between the cases with different class of construction as Milan does not have a very high outdoor air temperature above the comfort zone. The thermal mass to be most effective is its application in hot climates with high diurnal variation.

5.4.3 Weather data 3 -Palermo

The energy needs have been calculated for the Palermo using the Matlab model and then compare the same with TRNSYS.
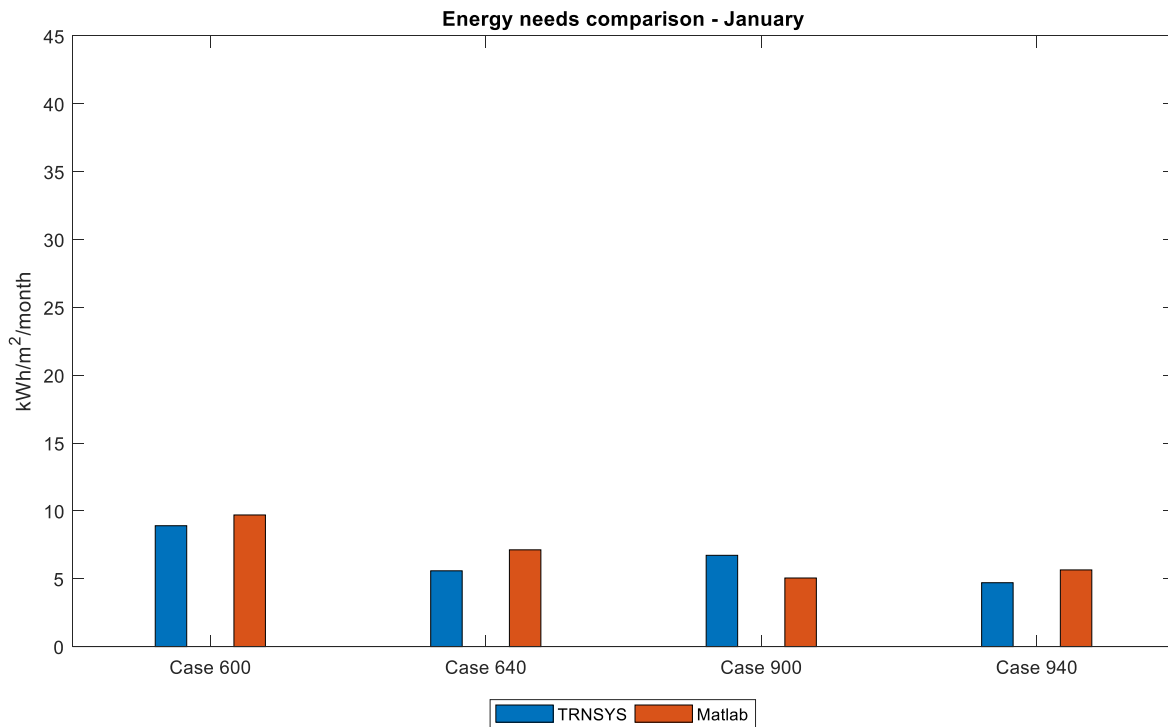
Figure 5-69: Energy needs comparison for the BESTEST (January) - *Palermo*

The Figure 5-69 shows that in Palermo the heavyweight cases unlike the other two analyzed climate files produces a minor savings in the energy needs comparing with the lightweight

cases. This is due to the fact that Palermo has not a very cold winter and there is a higher amount of radiation during the daytime which gets stored in the thermal mass of the heavyweight building element and released later helping in reducing the energy demands for heating.

The Figure 5-69 shows that the cases with the intermittent control system has a comparatively lower energy demand with the continuous control system. This is due to the night time set-back with lowered set-point temperature of 10 °C for the heating.

It is seen that in the heavyweight case with intermittent control system results in higher energy needs compared to the continuous system as it is a drawback in month of January. The heat stored in the building elements of the building is lost due to the night time set-back and this leads to a higher energy needs than the heavyweight case with the continuous system.
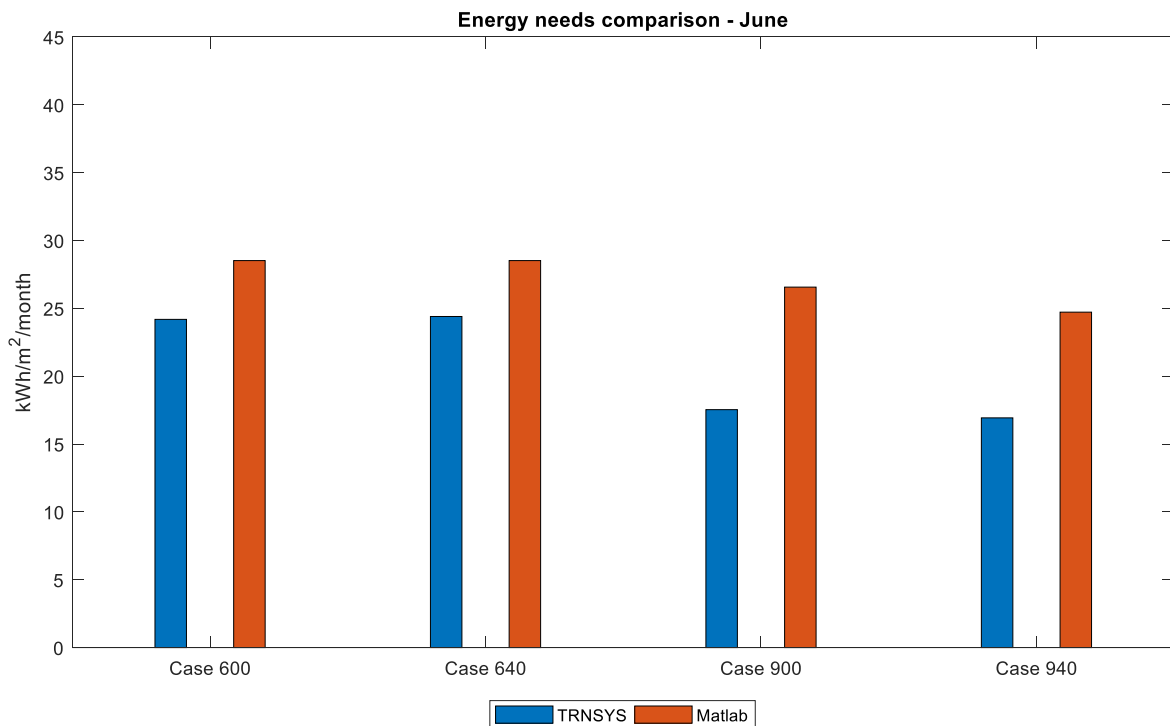

Figure 5-70: Energy needs comparison for the BESTEST (June) - *Palermo*

The Figure 5-70 that there is high variation in the energy needs during the summer which highlights again the effect of the radiation accountability in the Matlab model with respect to the TRNSYS model. In addition, the difference in the results could also be due to the control strategy used in the Matlab model to calculate the energy needs. The TRNSYS Type 56 dynamic model calculates the exact value of the energy needs required at each time step while in Matlab model is used a rule-based controller approach that increases a discrete value of the heating and cooling demand until the set-point is reached.

It is evident from Figure 5-70 that the heavyweight cases with continuous and intermittent control system has lower energy needs than their corresponding lightweight cases. This is due to the amount of heat energy stored in the high thermal mass of the building and released later as well as due to the thermal lag or time delay it produces in the heat flow through the building.

Since during the summer month of June, the outdoor temperature ranges above and below the indoor temperature set-point during a 24-hour period, the direct of the heat flow through the wall reverses. During the daytime when it is hot outdoors and cool indoors, the heat flows inward. At night, when is cool outdoors and relatively warm indoors, the heat flows outward. This reversal of the direction of the heat flow reduces the overall heat gain during a 24-hour period, which reduces the overall need for energy input from the HVAC system.

But the heavyweight cases in Palermo doesn't produce a high energy savings as the summer in Palermo does not have a high diurnal variation as the external air temperature does not lowers down enough to cool down the walls of the building elements. Since the external air temperature stays higher also in the night time, there is no way that the heat stored in the walls can be released to cool down the walls.

6 Conclusion

The main aim of this thesis work is to test the improved hourly calculation model in the EN ISO 52016-1:2017 for the energy needs and internal air temperature and compare it with the excel spreadsheet accompanied by the standard which is a mandatory provision for the testing of the developed model and then also to verify the model with a more advanced modelling software TRNSYS. The main conclusion of the work are as follows.

The inputs for the simulation of the simple hourly calculation method using 5R1C model are less when compared to the EN ISO 52016-1 as the elements are lumped to a few parameters unlike the extensive RC network model. This increases the uncertainty in the dynamic simulation of the building while using 5R1C model but not the same for an extensive RC network model.

The improved hourly calculation method adopted in EN ISO 52016-1:2017 allows to model a more advanced dynamic building model compared to the previous standard ISO 13790:2008 by considering the contributions from each nodes of the building elements.

The EN 52016-1 model considers a simplification in the contribution of long-wave radiation into the thermal zone by ignoring the long-wave emissivities and thus long-wave reflections which have created difference in the results compared to the TRNSYS Type 56 dynamic model. In fact, to highlight this point, the results show that the indoor air temperature calculated using the extensive RC network model with respect to the Type 56 dynamic model have the same trend during the winter while there is a marginal difference during the summer when there is a high influence of the radiation into the building.

In addition, the results of Palermo which has a warm winter with high radiations compared to drycold weather and Milan shows that there is a marginal difference in the indoor air temperature also during January in this case between Matlab model and Type 56 dynamic model.

The indoor air temperature (T_{air}) calculated in the Free-Floating case using the Matlab model and the TRNSYS Type 56 dynamic model for the lightweight case and heavyweight case shows that the thermal zone with the heavyweight case has a lower indoor air temperature than the lightweight case. This is due to the fact that heavyweight construction elements having high thermal mass able to store heat in the construction itself and releases it at a later time which has a positive effect in the comfort range of the thermal zone.

The energy needs calculated for the drycold weather and Milan using the Matlab model and Type 56 dynamic model have lower percentage of difference while in Palermo, there is high percentage of difference during the June. This highlights the drawback in the accuracy of the Matlab model in cooling season or when the building is exposed to higher radiation. A future refinement in the assumption of the thermal radiation in the extensive RC network model could eliminate this drawback of the model.

The running time for the case of lightweight construction in drycoldweather with free-floating condition in the Matlab model takes 0.3 seconds while it is 0.5 seconds in TRNSYS. The running time of Matlab model increases to 58 seconds in the cases with heating/cooling system which could be due to the control strategy used in the coding. Thus, future works on this part of the developed Model could increase the speed of the simulation.

The developed Matlab model based on the EN ISO 52016-1 is complex and has 27 states for the lightweight elements and 11 states for the heavyweight elements as it does not aggregate the elements into a few lumped parameters like the 5R1C simple hourly method which has only 1 state equation. Thus, the model derives accurate results and could give the dynamic behavior close to the reality.

In comparison with results obtained from TRNSYS Type 56 dynamic model, the Matlab model tested with drycold weather has a difference of 11 percent in the calculated energy needs for the lightweight case with continuous HVAC control strategy and similarly the lightweight case with free-floating condition has a R^2 value of 0.86 for indoor air

temperature. One of the reason is due to the simplifications done in the thermal radiation contribution to the thermal zone by ignoring long-wave emissivities in the Matlab model.

The Matlab model developed based on the EN ISO 52016-1 could be used for the simulation purpose to study the building energy performances and also as a smart control in the Model Predictive Control systems saving energy consumption for the HVAC systems as it could produce a dynamic behavior closes to the reality and detect the time horizon much more accurate than the simplified models.

Further research could be undertaken in reducing the complexity of the model which could lower the computational effort and a further enhancing of the control techniques used in the Matlab model for calculating the energy needs could narrow the difference between the results obtained from Matlab model and the TRNSYS Type 56 dynamic model.

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List of Symbols and Subscripts

The following tables summarizes the symbols and subscripts used in this document:

Symbols

a	Name of quantity	Unit
A	area	m^2
a_{sol}	solar absorption coefficient	-
C	heat capacity	J/K
c	specific heat capacity	J/(kg.K)
d	thickness	m
g	total solar energy transmittance	-
H	heat transfer coefficient	W/K
h	surface coefficient of heat transfer	$W/(m^2.K)$
I_{sol}	solar irradiance	W/m^2
R	thermal resistance	$m^2.K/W$
t	time	s
U	thermal transmittance	$W/(m^2.K)$
T	Celsius temperature	°C
κ	areal heat capacity	$J/(m^2.K)$
ρ	density	kg/m^3
φ	heat flow rate, heat load	W

Table 5: List of symbols

Subscripts

c	Term	Subscript	Term
a	air	HC	heating and cooling need
C	cooling, capacity	ms	conductance term[a]
c	convection, convective	mn	mean
dif	diffuse	N	north facing
dir	direct	obst	obstacles
E	east facing	op	opaque

Subscript	Term	Subscript	Term
e	External or outdoor	pl	layer
el	element	r	radiative
c	floor	roof	roof
fr	frame	i	internal (temperature)
H	heating	int	internal (heat)
i	internal (temperature)	tb	thermal bridge
int	internal (heat)	tr	transmission (heat transfer)
is	conductance term[a]	t	time
sh	shading	tot	total
sup	supply (of air)	ve	ventilation (heat transfer)
sys	system	wall	wall
S	south facing	w	west facing
sol	solar	wi	window
s	set-point	ztc	thermally conditioned zone

[a] For simple hourly method ISO 13790:2008

Table 6: List of subscripts