Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 78 (2015) 2190 – 2195

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Adaptive control for building thermo-hygrometric analysis: a novel dynamic simulation code for indoor spaces with multi-enclosed thermal zones

Annamaria Buonomano[a,*], Umberto Montanaro[a], Adolfo Palombo[a], Stefania Santini[b]

[a]*Department of Industrial Engineering, University of Naples Federico II, P.le Tecchio 80, 80125 Naples, Italy*
[b]*Department of Electrical Engineering and Information Technology, University of Naples Federico II, via Claudio 21, 80125 Naples, Italy*

Abstract

A novel dynamic simulation model, called DETECt 2.3.1, purposely developed for thermo-hygrometric energy performance analyses of multi-zone buildings, is presented. Relevant novelties vs. previous implemented code releases are discussed. They regard: i) the simulation model for building spaces with multi-enclosed thermal zones; ii) a novel temperature-humidity control algorithm based on a reference adaptive control scheme. Such algorithm enables the online adaptation of the control gains, in order to overcome the well-known problems of classical fixed gain control algorithms. With the aim to show the features and the potentialities of the simulation code coupled with this new control scheme, a suitable case study related to special indoor hospitals spaces including multiple infant-incubators is developed. The robustness of the designed control approach is confirmed through the good regulation performance obtained for both the indoor air temperature and humidity, simultaneously.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: dynamic building energy performance analysis; adaptive control for indoor air temperature and humidity; enclosed thermal zones

1. Introduction

For the design and refurbishment of the next generation of buildings, a crucial role is played by Building Energy Performance Simulation (BEPS) tools. Here, the implementation of innovative building management strategies and

* Corresponding author. Tel.: +39-081-768-2299; fax: +39-081-239-0364.
E-mail address: annamaria.buonomano@unina.it

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.316

Nomenclature

Symbols

C	thermal capacitance (J/K)
h_{vs}	water latent evaporation heat (J/g)
$\dot{m}$	flow rate (g/s)
$\dot{Q}$	thermal load (W)
R	thermal resistance (K/W)
T	temperature (K)
t	time (s)
φ	air relative humidity (%)
ω	air specific humidity (g/g)
Ω	dry air mass (g)

Subscripts/Superscripts

AC	air conditioning system
conv	convection
cv	combined convection and conduction
eq	equivalent
g	internal gain
glob	global
in	indoor air
lat	latent
out	outdoor air
sp	set point
v	ventilation
w	enclosed NICU zone envelope
wg	water vapour

advanced control algorithms and systems, capable to overcome the trade-off between low energy demands and high thermo-hygrometric comfort levels, are today essential [1]. In this framework, an energy performance simulation tool for the prediction of thermo-hygrometric comfort in buildings (DETECt 2.2) which funds on a classical fixed gain PID centralized control scheme for the regulation of the thermal behaviour was previously presented in [2]. A new release (DETECt 2.3), able to guarantee and simulate rigid thermo-hygrometric constraints exploiting the features of an optimal-adaptive control scheme, has been recently described in [3]. In this paper, DETECt 2.3 has been further enhanced for simulating multiple thermal zones totally enclosed into others (release DETECt 2.3.1). The regulation of indoor air temperature and humidity, according to the different specific requirements of each zone, is guaranteed by an optimal-adaptive model reference scheme embedded into the code (namely LQ-EMRAC, Linear Quadratic Extended Model Reference Adaptive Control [4]). Such algorithm allows the control of the different indoor spaces thermo-hygrometric variables in uncertain conditions through the on-line variation of its control gains. As a result, a great control flexibility and robustness is achieved and the control action is able to automatically counteract unexpected and unknown thermo-hygrometric behaviour deviations (e.g. due to external disturbances acting on the different zones), without requiring, for its design or on-line implementation, an a priori knowledge or a detailed mathematical description of the overall dynamics. Note that, although advanced optimization and control techniques may add great benefits in achieving energy efficiency, their reliability is still not well proven for their implementation on existing commercially available digital control systems installed in very modern buildings. These observations point out the need of flexible and customizable simulation platforms, as DETECt, where different control strategies, as well as innovative building techniques, can be easily embedded and tested for the purpose of investigating the overall system efficiency in different conditions.

In order to show the effectiveness and robustness of the developed simulation model a suitable case study is here presented. It is referred to a neonatal intensive care ward where several Neonatal Intensive Care Units (NICUs) for premature and full-term newborn babies are located. In each NICU, an accurate climate control of air temperature and humidity is required for producing healthful micro-environment for the hosted babies. Although many works in literature highlighted the need of a neutral thermal environment for increasing the survival rate of preterm infants [5, 6], the adoption of accurate and advanced regulation of both the temperature and the relative humidity within the NICUs have been only recently emphasized [7].

At the best of the authors' knowledge, the presented dynamic BEPS code is the first one in literature in which: i) an innovative and optimal adaptive scheme for controlling indoor air temperature and humidity is implemented; ii) the thermo-hygrometric behaviour of multiple thermal zones totally included into larger ones can be assessed.

2. Thermodynamic model

The aim of this study is to show the features of the developed simulation model and the effectiveness and robustness of the related control algorithm for assessing the thermo-hygrometric behaviour of different building thermal zones enclosed into others. In order to properly simulate the thermo-hygrometric conditions within each modelled zone, as well as to design the indoor climate control, a suitable resistive-capacitive (*RC*) thermal network simulation model (assuming 1D transient heat transfer) for the thermo-hygrometric analysis of *Z+1* thermal zones (*Z* of them completely enclosed into a main one) is adopted [2]. Through such model, the assessment of temperatures and humidity dynamics, as well as of heating and cooling loads and demands, can be carried out. As an example, a sketch of the modelled *RC* thermal network, related to 7 thermal zones (one main zone including 6 different zones) is showed in Fig. 1. The calculation procedure takes into account the heat flows between: i) the outdoor environment and the main thermal zone (zone 1, Fig. 1); ii) the main thermal zone and the enclosed ones (zones 2 to 7 in Fig. 1).

The whole system, including the main larger zone and the enclosed ones, is modelled through a high order *RC* thermal network of: i) $M \times (N+2)$ nodes in which the building envelope of the main zone is subdivided (consisting of M envelope elements ($m = 1, \ldots, M$) and N sub-layers ($n = 1, \ldots, N$)); ii) Z nodes ($z = 2, \ldots, Z$) of the lumped envelopes of each enclosed zone; $Z + 1$ nodes related to the indoor air of each enclosed zone and the main one.

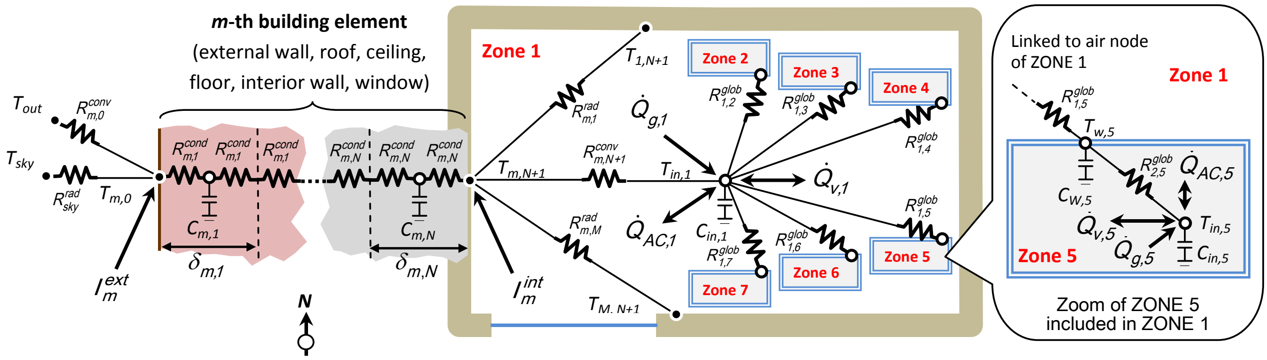

Fig. 1. Sketch of the modelled *RC* thermal network.

The thermal behaviour of the envelope nodes of zone 1 and the lumped one of each enclosed zone is described by the following eq. (1) and eq. (2), respectively. Similarly, the thermal behaviour of the main zone and of each enclosed one is described by eq. (3) and eq. (4), respectively.

$$C_{m,n}\frac{dT_{m,n}}{dt}=\sum_{j=n-1}^{n+1}\frac{T_{m,j}-T_{m,n}}{R_{m,j}^{eq}} \quad \text{and} \quad \sum_{j=n-1}^{n+1}\frac{T_{m,j}-T_{m,n}}{R_{m,j}^{cv}}+\dot{Q}_{m,n}=0 \tag{1}$$

$$C_{w,z}\frac{dT_{w,z}}{dt}=\sum_{j=1}^{2}\frac{T_{in,j}-T_{w,z}}{R_{j,z}^{glob}} \tag{2}$$

$$C_{in,1}\frac{dT_{in,1}}{dt}=\sum_{m=1}^{M}\frac{T_{m,N}-T_{in,1}}{R_{m,int}^{conv}}+\frac{T_{w,z}-T_{in,1}}{R_{1,z}^{glob}}+\frac{T_{out}-T_{in,1}}{R_{v,1}}+\sum_{z=2}^{Z}\frac{T_{in,z}-T_{in,1}}{R_{v,z}}+\dot{Q}_{g,1}\pm\dot{Q}_{AC,1} \tag{3}$$

$$C_{in,z}\frac{dT_{in,z}}{dt}=\frac{T_{w,z}-T_{in,z}}{R_{2,z}^{glob}}+\frac{T_{in,1}-T_{in,z}}{R_{v,z}}+\dot{Q}_{g,z}\pm\dot{Q}_{AC,z} \tag{4}$$

The assessment of the latent energy to be added to (or subtracted from) all the thermal zones (for preserving the selected indoor air relative humidity set-points) is carried out by adopting a decoupled approach [8]. Moreover, for each thermal zone, the moisture balance is calculated by neglecting the moisture exchange between the air node and the surrounding building surfaces. The adopted moisture balances at each simulation time step for the main zone and the enclosed ones are respectively described by means of eq. (5) and eq. (6), calculated as it follows:

$$\Omega_{in,1}\frac{d\omega_{in,1}}{dt}=\dot{m}_{v,1}\left(\omega_{out}-\omega_{in,1}\right)+\sum_{z=2}^{Z}\dot{m}_{v,z}\left(\omega_{in,z}-\omega_{in,1}\right)+\dot{m}_{wg,1}\pm\frac{\dot{Q}_{AC,1}^{lat}}{\Delta h_{vs}} \tag{5}$$

$$\Omega_{in,z}\frac{d\omega_{in,z}}{dt}=\dot{m}_{v,1}\left(\omega_{in,1}-\omega_{in,z}\right)+\dot{m}_{wg,z}\pm\frac{\dot{Q}_{AC,z}^{lat}}{\Delta h_{vs}} \tag{6}$$

The term $\dot{Q}_g$ is related to the sensible lumped heat source and $\dot{m}_{wg}$ refers to the inlet water vapour mass flow rates to the thermal zones. Such terms include the internal gains due to occupants, lights and equipment in the main larger zone and those due to eventual sources in all the related enclosed zones. Details and assumptions of the adopted model, as well as on the terms included in each equation, are reported in [2, 3].

In order to simultaneously regulate both air temperature and humidity to different specific set-points in each thermal zone, a decentralized LQ-EMRAC control approach was followed [9]. As a result, 14 different and independent adaptive controllers are synthesized. The control strategy allows the management of the indoor thermo-hygrometric conditions without requiring an a priori knowledge or an exact and detailed model of the system dynamics for the control design and its on-line implementation. The idea behind this approach is to provide control flexibility and robustness to unmodelled dynamics/parameters uncertainties while guaranteeing, at same time, optimality through the minimization of a suitable quadratic cost function, which suitably weights both the temperature/humidity tracking errors and the sensible/latent energy demand. Differently from standard fixed gains techniques (e.g. PI and MPC approach), such control is able to automatically vary its gains to counteract unexpected changing in the thermo-hygrometric behaviour due, for example, to unknown external disturbances, which are assumed to be not measured or on–line estimated. Details on the proposed approach are reported in [3].

3. Case study

The presented case study is referred to a Neonatal Intensive Care Ward (NICW) in which six Neonatal Intensive Care Units (NICUs), for premature and full-term newborn babies, are placed. In each NICU, an accurate climate control provides exact suitable conditions of air temperature and relative humidity, simultaneously. The sketch of the modelled seven-zones building is shown in Fig. 1. In order to run a dynamic simulation by means of DETECt 2.3.1, the Meteonorm hourly data file referred to the weather zone of Naples (South-Italy) is taken into account.

For the NICW, zone 1, a typical Italian building envelope, with length, width and height equal to 8, 7 and 3.5 m, respectively, is modelled. The building longitudinal axis is East-West oriented and a South facing window (4-6-4 air filled double-glazed system) of 12 m^2 is taken into account. The thickness of the building walls and floor/ceiling are 35 and 25 cm, respectively. Their stratigraphy is designed by concrete (λ = 0.51 W/mK, ρ = 1400 kg/m^3, c = 1000 J/kgK), semi-aerated bricks (λ = 0.6 W/mK, ρ = 1000 kg/m^3, c = 840 J/kgK) and thermal insulation (λ = 0.04 W/mK, ρ = 15.0 kg/m^3, c = 1400 J/kgK). The direct solar radiation transferred through the window to the inside zone is assumed to be absorbed by the floor with an absorption factor of 0.3. The absorption and emission factors of interior surfaces are assumed to be equal to 0.15 and 0.9, respectively. For such zone, a ventilation rate equal to 0.8 Vol/h and a crowding index of 0.054 person/m^2 (3 pers.) are adopted. Each NICU (zones 2 to 7 in Fig. 1) has length, width and height equal to 1.3, 0.77 and 0.60 m, respectively. In such zones, a polycarbonate envelope of 2.0 cm thickness is assumed and an occurring air infiltration of 0.5 Vol/h is modelled. In order to assess the effectiveness and robustness of the control algorithm, several accidental, heavy and intensive thermo-hygrometric disturbances were simulated. They regard: i) the opening of zone 1 windows, simulated by an additional outdoor air flow rate of 1.4 kg/s, occurring at 9:00 and 16:00 (for 1 hour); ii) the opening of the 6 NICUs, modelled as additional outdoor air flow rates of 3.5 g/s for each NICU, occurring for 10 minutes every 6 hours; iii) a steep increase of internal gains, simulated from 14:00 to 16:00 by increasing the crowding index to 0.142 person/m^2 (9 pers.).

The computer simulation model of the neonatal ward, including the incubators systems, was implemented in a MatLab/Simulink environment. The simulation starts at 0:00 on January 1st and ends at 24:00 on December 31st. In zone 1, heating and cooling are activated for indoor air temperature lower than 20°C and higher than 26°C, respectively. Simultaneously, humidification and dehumidification are required for relative humidity lower than 40% and higher than 50%, respectively. Inside the NICUs, different indoor air temperature and humidity set points are taken into account as a function of the mass of infants, gestational age and days of life (Table 2) [7].

Table 1. NICUs temperature and humidity set points as a function of the mass of infants, gestational age and days of life

	NICU1	*NICU 2*	*NICU 3*	*NICU 4*	*NICU 5*	*NICU 6*
Birthweight [kg]	0.90	1.35	1.75	2.85	2.05	2.35
Gestational age in weeks [w]	25	32	27	24	28	30
Days [d] or weeks [w] of life	3 d	10 d	8 d	13 d	4 w	6 w
Temperature set point [°C]	34	33	32	32	30	29
Humidity set point [%]	85	40	60	85	60	40

In the NICW and NICUs zones, air temperature and humidity are controlled 24/7. Sensible and latent losses of each premature infant are calculated by adopting a decoupled approach. Such physical and biological model includes conduction, convection, radiation, evaporation, breathing and heat generation from the infant, as described in [7].

3. Results and discussion

In this section some of the numerical results achieved through DETECt 2.3.1 are shown. The analysis is referred to all the investigated thermal zones, from 1 to 7. In particular, Fig. 2 (left) shows the dynamic trend of zone 1 indoor air temperature, for a sample winter day (January 25th). In the same figure the dynamic profiles of the above described sensible load disturbances in the NICW are also depicted. The heating control action (for avoiding indoor temperature lower than 20 °C) can be observed from 1:00 to 9:00 (for balancing the building heat losses) and from 16:40 to 17:00 (due to the ventilation caused by the window opening). A cooling control action (for avoiding indoor temperature higher than 26 °C) is observed from 14:30 to 16:00 (due to the raised crowding index and to the occurring high outdoor sol-air temperature). In the other time intervals, free floating temperatures are detected (comfort requirements are fulfilled). In Fig. 2 (right) the dynamic trend of zone 1 indoor air relative humidity is reported for a sample summer day (July 15th). In the same figure the dynamic profiles of the latent load disturbances are also depicted. A dehumidification control action is always observed for avoiding indoor relative humidity higher than 50 % (due to the indoor vapour sources and to the high outdoor air humidity).

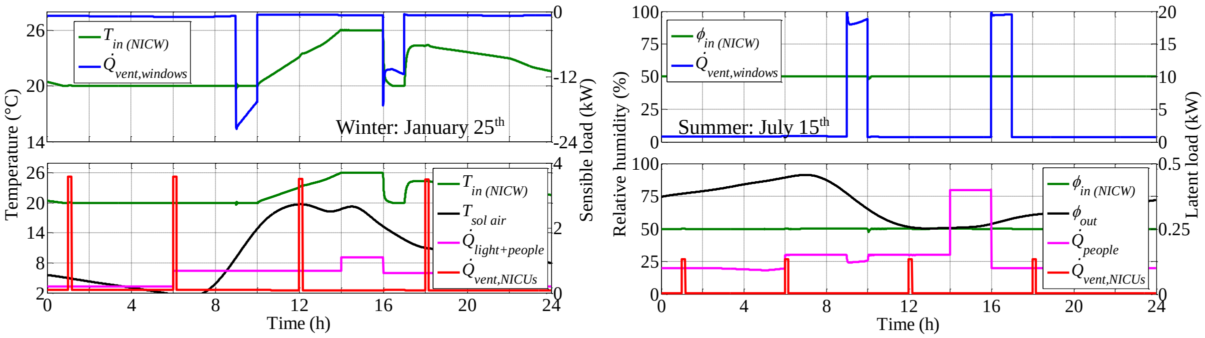

Fig. 2. Zone 1 - Controlled indoor air temperature and relative humidity and simulated disturbances.

NICUs require instead the exact regulation of both indoor air temperature and relative humidity (Table 1) for 24/7. Figure 3 (left) shows, as an illustrative example, results achieved during several hours of the same winter day (January 25th). Specifically, the profile of the heating control actions necessary to keep the NICUs 2-7 air temperatures perfectly constant and equal to their required set-points during the 24 h are depicted together with the dynamic profiles of the previously described sensible load disturbances. Obviously, the thermal loads of the zones 2-7 are much smaller than those related to zone 1.

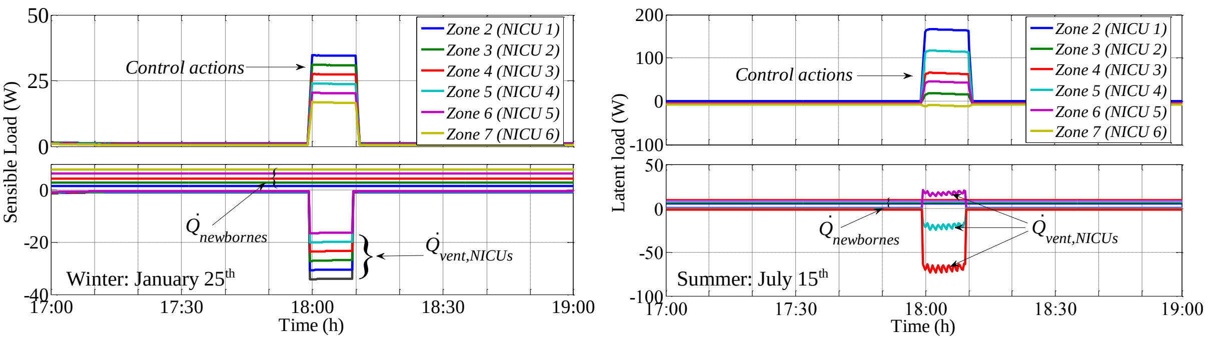

Fig. 3. NICUs – Indoor air temperature and humidity control actions and simulated disturbances.

In Fig. 3 (right) the profile of the humidification/dehumidification control actions necessary to keep the NICUs at their required relative humidity set-points for the selected summer day (July 15th) are reported together with the

occurring latent load disturbances. Note that, in several cases the NICUs disturbances overlap each other.
With the help of the obtained numerical results, some conclusions can be highlighted, such as: i) temperature and humidity set points (control targets) for both the zone 1 and the enclosed zones 2-7 are always achieved for all the investigated sensible and latent load disturbances; ii) in all the zones (where a continuous control of both the temperature and humidity is required) very low regulation errors for the indoor air temperature and relative humidity are obtained despite of the oscillation of outdoor and zone 1 climate conditions.
In Table 2, for all the investigated thermal zones the calculated heating and cooling demands (sensible and latent), are reported for two sample months. It can be observed that for the NICW (zone 1) the cooling and dehumidification demands in July are remarkably higher than the heating and humidification ones during January (according to the assumed internal gains and to the simulated weather conditions). For NICUs (zones 2-7), the obtained sensible and latent energy demands basically depends on the required indoor conditions (Table 1).

Table 2. Heating and cooling sensible and latent demands

Sensible / Latent demands [kWh/(m^2 month)]		*NICW*	*NICU 1*	*NICU 2*	*NICU 3*	*NICU 4*	*NICU 5*	*NICU 6*
January	Heating	12.9 / -	2.00 / 3.61	1.84 / -	1.68 / -	1.51 / -	1.34 / -	1.18 / -
	Cooling	0.53 / -	- / -	- / 1.88	- / 1.22	- / 2.76	- / 2.99	- / 4.65
July	Heating	- / -	1.31 / 4.22	1.14 / 0.40	0.98 / 1.47	0.81 / 2.63	0.65 / 1.01	0.49 / -
	Cooling	29.5 / 0.02	- / -	- / 3.09	- / 3.03	- / 5.18	- / 4.53	- / 5.71

4. Conclusion

In this paper, a new dynamic BEPS code, called DETECt 2.3.1, is presented. Such code, in-house developed for research purposes, allows the authors to model and analyse new prototypal technologies, non-standard operating conditions, particular system scheduling, control strategies, etc., which cannot be dealt with (or simultaneously taken into account) through commercial tools. In this paper, the regulation of indoor air temperature and humidity is obtained through an optimal-adaptive model reference scheme (LQ-EMRAC, Linear Quadratic Extended Model Reference Adaptive Control). Here, the on line adaptation of the control gains balances unexpected and unknown variations in the thermo-hygrometric behaviour, without requiring an a priori knowledge or on-line estimation of the disturbance dynamics. It is worth noting that DETEC 2.3.1 is the first BEPS code in which: i) an innovative and optimal adaptive scheme is adopted for accurate indoor air temperature and humidity control; ii) multiple thermal zones totally included into larger ones can be modelled and dynamically simulated.

The effectiveness of DETECt 2.3.1 was verified through a suitable case study where a neonatal intensive care ward is modelled. Here, a rigid temperature / humidity micro-climate control is simulated for six enclosed neonatal intensive care units for newborn babies. The analysis of the effect of different accidental, heavy and intensive thermo-hygrometric disturbances on the resulting control actions is also presented. Simulation results show very good tracking performance of air temperature and humidity, simultaneously, in all the simulated thermal zones. Numerical results also confirm the robustness of the developed control approach for unmodelled dynamics.

References

[1] Shaikh P. H. et al., *A review on optimized control systems for building energy and comfort management of smart sustainable buildings.* Renewable and Sustainable Energy Reviews, 2014. **34**(0): p. 409-429.
[2] Buonomano A. and Palombo A., *Building energy performance analysis by an in-house developed dynamic simulation code: An investigation for different case studies.* Applied Energy, 2014. **113**(0): p. 788-807.
[3] Buonomano A., Montanaro U., Palombo A., and Santini S. *Multi-zone buildings thermo-hygrometric analysis: a novel dynamic simulation code based on adaptive control*. in *Building Simulation Applications 2015 - 2nd IBPSA-Italy Conference.* 2015. Bozen, 4-6 February.
[4] Di Bernardo M., Montanaro U. and Santini S.., *Novel hybrid MRAC-LQ control schemes: synthesis, analysis and applications.* International Journal of Control, 2008. **81**(6): p. 940-961.
[5] LeBlanc, M.H., *The physics of thermal exchange between infants and their environment.* Medical Instrumentation, 1987. **21**(1): p. 11-15.
[6] Lyon A., *Applied physiology: temperature control in the newborn infant.* Current Paediatrics, 2004. **14**(2): p. 137–144.
[7] Zermani M.A., Feki E., and Mami A., *Building simulation model of infant-incubator system with decoupling predictive controller.* IRBM, 2014. **35**(4): p. 189–201.
[8] Ghiaus C., *Linear algebra solution to psychometric analysis of air-conditioning systems.* Energy, 2014. **74**(0): p. 555-566.