

Improved performance of passive heating and cooling strategies through weather forecast-based control

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Building Automation Systems (BAS) can be used to monitor and control passive buildings the same way they are used in buildings with active HVAC. However, some characteristics have to be taken into consideration. In contrast to buildings with HVAC, buildings with passive strategies capture and store heat or "coolness" rather than produce them. As a result, they experience a time lag between the time a change of the operational mode has been made and the time the required results are felt. Therefore passive buildings are more vulnerable to overheating or overcooling because they are slower in responding to sudden changes in the weather such as unexpected waves of high/low air temperatures or clear/overcast skies. This paper investigates the potential of a proposed automation system, in which a weather forecast is used to regulate the capacity of passive heating/cooling measures in a building to keep indoor temperatures within comfort limits. This approach also tries to regulate the operation mode of passive strategies to passively pre-heat or pre-cool the building thermal mass to cover periods of unfavorable weather conditions during which the passive strategy is less effective. Results of simulations indicate that the performance of forecast-based passive strategies can be higher than the performance of schedule-based passive strategies.

يمكن استخدام نظم التحكم في المباني للتحكم أداء المباني ذات التدفئة أو التبريد سواء كان ذلك بإتباع الأسلوب الفعال أو الأسلوب السلبي. ولكن يجب أخذ بعض خصائص الأسلوب السلبي في الإعتبار. فعلى عكس مباني الأسلوب الفعال تعتمد مباني الأسلوب السلبي على جمع و تخزين الحرارة أو "البرودة" لا على إنتاجها. ونتيجة لذلك فهي تعاني من وجود فترة زمنية ما بين تغيير حالتها التشغيلية و بين الإحساس بنتيجة هذا التغيير. و نتيجة لذلك هي عرضة لزيادة أو إنخفاض درجات الحرارة لأنها أكثر بطئا في التجاوب للتغيرات المفاجئة في حالة الطقس كالموجات الحارة أو الباردة أو السماء الصافية أو الملبدة بالغيوم. يتناول هذا البحث بالدراسة إمكانات نظام مقترح للتحكم في المباني ذات التدفئة أو التبريد بإتباع الأسلوب السلبي و يسعى هذا النظام بتقارير حالات الطقس المتوقعة لتعديل الحلة التشغيلية لعناصر التدفئة أو التبريد بإتباع الأسلوب السلبي للحفاظ على درجات الحرارة داخل المبنى في حدود الراحة الحرارية. ويحاول هذا النظام أيضا تعديل الحالة التشغيلية لتوفير درجة من التدفئة أو التبريد الإستباقية لكتلة المبنى الحرارية لتغطية الفترات الزمنية التي تكون فيها حالة الطقس غير مواتية وبالتالي التدفئة أو التبريد بإتباع الأسلوب السلبي أقل تأثيرا. وتشير نتائج المحاكاة باستخدام الحاسب الألي أن أداء المباني ذات التدفئة أو التبريد بإتباع الأسلوب السلبي المبني على تقارير حالات الطقس المتوقعة يمكن أن تكون أعلى من أداء المباني ذات التدفئة أو التبريد بإتباع الأسلوب السلبي المبني على الجداول الزمنية المعتادة.

Keywords: Passive heating, Passive cooling, Thermal analysis, Thermal comfort, Weather forecast

1. Background

Traditional architecture in many parts of the world had many features, which helped in creating comfortable indoor thermal environments. These climate-sensitive buildings were shaped, and different elements of the building such as windows, doors, indoor spaces, etc. were located and oriented to take the maximum advantage of the climate. In the 20th century two developments changed the way thermal comfort is achieved in modern

buildings. The first development was the use of lighter building materials such as steel, glass and reinforced concrete and lighter construction methods such as skeleton type structures. The result was deterioration in thermal comfort levels in many buildings. The second development was the total reliance on mechanical systems for lighting, heating, cooling, ventilating and air conditioning. This together with the growth in population, the increase in the living standards and the reduction in the cost of units had led to a

sharp increase in energy consumption on a national level in many industrialized countries as well as in developing countries [1, 2].

Since Heating, Ventilating, and Air-Conditioning (HVAC) equipment consume over 40% of the total energy used in buildings, the impact of improved operation of these systems can greatly affect the energy use and the cost associated with maintaining thermal comfort and indoor air quality [3]. There have been few efforts to revive some of the old concepts of climate-sensitive buildings before the 1970s. In the 1970s concerns caused by the surge in oil prices lead to a renewed interest in the topic. Principles of passive heating and cooling were studied, more sophisticated techniques were developed, experimental investigations were conducted and many books were published. But this interest faded away after the oil prices fell to an affordable level. At the turn of the millennium, environmental concerns, such as global warming and depletion of resources, are leading to renewed interest in passively heated, cooled and ventilated buildings. A new generation of buildings is emerging which is in reality a mixed-mode hybrids in which passive technologies is used to tandem with mechanical equipment to achieve a low energy solution [4]. This renewed interest appears to be more sustainable than the interest in the 1970s.

2. Aim of paper

Despite a great accumulation of empirical information on the performance of buildings with passive strategies [5- 7], very little work has been done on the potentials of using Building Automation Systems (BAS) to improve that performance. This paper investigates the potential of a proposed automation system, in which a weather forecast is used to regulate the capacity of passive heating/cooling measures in a building to keep indoor temperatures within comfort limits. This approach also tries to regulate the operation mode of passive strategies and to passively pre-heat or pre-cool the building thermal mass to cover periods of unfavorable weather conditions during which the passive strategy is less effective.

3. Passive design strategies

Two types of climate-sensitive buildings can be identified; *climate rejecting buildings* and *climate adapted buildings*. Both types use building form and envelope as elements of environmental control but in an opposite fashion.

Climate-rejecting buildings:

- Use form and envelope to diminish climate-imposed loads.
- Environmental-control strategies are handled from within by equipment such as electric lighting and HVAC.
- Form and envelope serve solely as barriers between climate and conditioned space.

Climate-adapted buildings:

- Positive and negative influences of climate are selectively filtered and balanced at the building boundary to provide internal environmental control.
- External climatic energy sources are filtered and distributed to occupied space, via the envelope, for end uses such as lighting, cooling, heating and ventilation.
- These environmental control techniques are based on age-old architectural and engineering concepts.

The climate-adapted approach has developed into what is now called passive design. A passive building can be thought of as one in which the fabric of the building behaves like a piece of equipment moving energy from one place to another. According to a well accepted definition which has evolved over the years and is thought to be more comprehensive than earlier definitions, passive design is a way of designing in which the form, fabric and systems of a building are arranged and integrated to maximize the benefits of ambient sources of energy for heating, lighting, cooling and ventilation in order to reduce dependence on building services and reduce the consumption of conventional fuels and the emission of greenhouse gases. Basic principles of passive design can be seen in table 1.

Table 1
Basic principles upon which passive strategies are built

		Conduction	Convection	Radiation	Evaporation	
Control strategy	Winter	Promote gain		Promote solar gain		
		Resist loss	Minimize conductive heat flow	Minimize external airflow		
				Minimize infiltration		
		Resist gain	Minimize conductive heat flow	Minimize infiltration	Minimize solar gain	
	Summer	Promote loss	Promote earth cooling	Promote ventilation	Promote radiant cooling	Promote evaporative cooling
		Heat sources		Atmosphere	Sun	
		Heat sinks	Earth	Atmosphere	Sky	Atmosphere

3.1. Modes of operation of passive buildings

For positive and negative influences of climate to be selectively filtered and balanced at the building boundary to provide internal environmental control, passive cooling and passive heating strategies need different day/night and winter/summer operation modes. Benefits of a passive design cannot be achieved without an active user or operator who controls vents, pumps, fans, movable, insulation, screens or shading devices to switch the building from one mode of operation to the other.

3.1.1. Passive heating

In a passive heating approach heat from an ambient heat source (the sun) is collected, stored and then distributed to occupied space. Under this category, five main strategies can be identified; a) collector systems, b) Direct-Gain Systems, c) Trombe Wall Systems, d) Sunspace systems and e) thermosyphon systems. All these strategies require movable insulation to avoid heat loss and overcooling during the night and on cloudy days. Shading is also required in summer to resist heat gain and avoid overheating. Some systems such as the Trombe wall and the thermosyphon require the use of vents or fans to control the airflow from and to the occupied space.

3.1.2. Passive cooling

In a passive cooling approach, heat from occupied space is collected, stored and then emitted to an ambient heat sink (earth, sky or atmosphere). Under this category, five main strategies can be identified; *Ventilation, Radiant cooling, Evaporative cooling, Earth cooling and Dehumidification*. Most of these strategies require some sort of control. For example, ventilation can be effective in flushing hot air out of the building and replacing it with cooler air from the outside only if it occurs at times when ambient air temperatures are lower than inner air temperatures, probably during nighttime. Radiant cooling to the sky at night can be effective only if a movable insulation is used to avoid heat gain and overheating during the day.

3.2. Automatic control

The purpose of an automatic control system is to maintain a controlled variable as close to a set point as possible. To achieve this three elements are necessary [8]: a sensor, a controller, and a controlled device (e.g., heater or chiller). The control device affects the process (e.g., heating or cooling) in a way that causes a change in the controlled variable (e.g., air temperature in the room). In a simple closed-loop control system the room occupant

can perform the function of the sensor controller, which is to measure the controlled variable and compare it with a set point (the personal sensation of comfort), and adjust the controlled device.

Because there are many reasons for a person to be not sensitive and not reliable enough as sensor/controller, automated control systems have been developed. The temperature is measured by a sensor which passes the information to the controller. The controller compares air temperature with a set point and sends a signal to open or close the heater or chiller (the controlled device) as required to maintain a correspondence between air temperature and the set point.

While this form of control is easy to achieve in an active heating/cooling system, a passive system has some characteristics in terms of capacity, accuracy and speed which make controlling a variable more difficult.

3.2.1. Automatic control in active strategies

Most electro-mechanical heating and cooling systems are designed to meet demand under the worst case conditions (hottest or coldest climate conditions) [8]. They are designed using methods with high margins of safety embedded. Designers tend to add more safety factors. As a result, many HVAC systems operate most of the time when heating or cooling requirements are far below the capacity of the heating and cooling equipment. When these systems are switched on they have enough capacity to bring the controlled variable very quickly to the required set point fig 1. Accurate and rapid measurement of the controlled variable allows the system to keep it as close as possible to the set point.

3.2.2. Automatic control in passive strategies

In contrast to buildings with active HVAC, buildings with passive strategies capture and store heat or "coolness" rather than produce them. The sun as a heat source and the clear sky, wind and cool air as heat sinks are, by their very nature, a relatively diffuse, low-intensity type of energy source available only on an irregular basis. For example, the quantity of energy collected from a solar

system at any given time rarely coincides with the building load requirements [9]. More heating is needed at night during winter while more solar energy is available during summer day. Vice versa during the summer more cooling is needed during the day while cooler air and cooler sky is available during the night and during the winter. Instead, most solar collection systems collect energy whenever there is sufficient incident radiation. Energy management principles must therefore be employed to store efficiently the collected energy for subsequent use.

In contrast to buildings with active HVAC, buildings with passive strategies do not possess enough heating/cooling capacity to cover all heating/cooling requirements of a building. This mandates that some form of auxiliary heating/cooling system be provided, so that comfort needs can be met during extended cloudy/sunny hot/cold periods when insufficient heating/cooling capacity is available fig. 2.

In contrast to buildings with active HVAC, buildings with passive strategies experience a time lag between the time a change of the operational mode has been made and the time the required results are felt. This time lag makes Passive Buildings slower in responding to sudden changes in the weather such as unexpected waves of high/low air temperatures or shiny/overcast skies. Passive buildings are therefore more vulnerable to overheating or overcooling. This makes automatic control very challenging fig. 3.

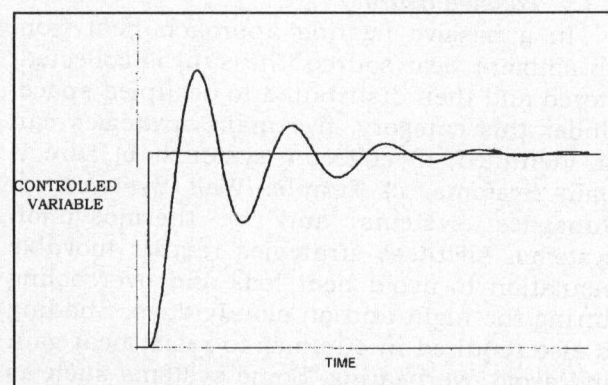


Fig. 1. Controlled variable in a mechanical HVAC system [8].

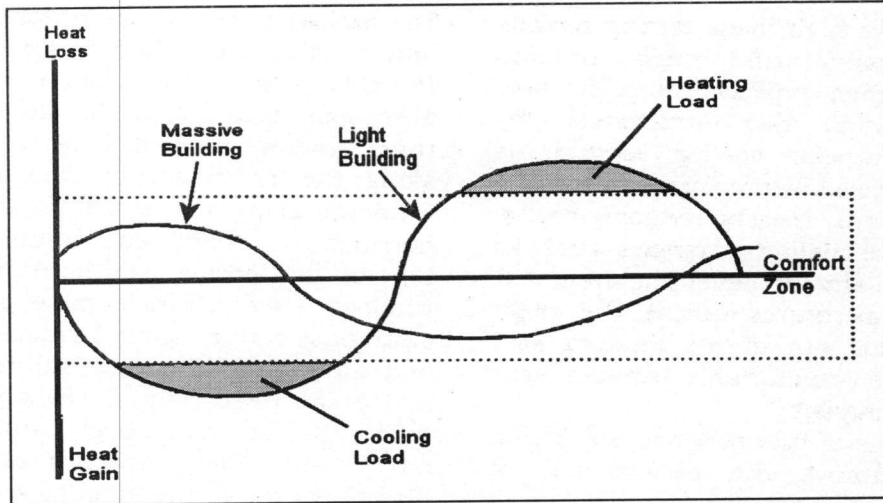


Fig. 2. Daily building heating and cooling loads for buildings of massive and light construction. Source [10].

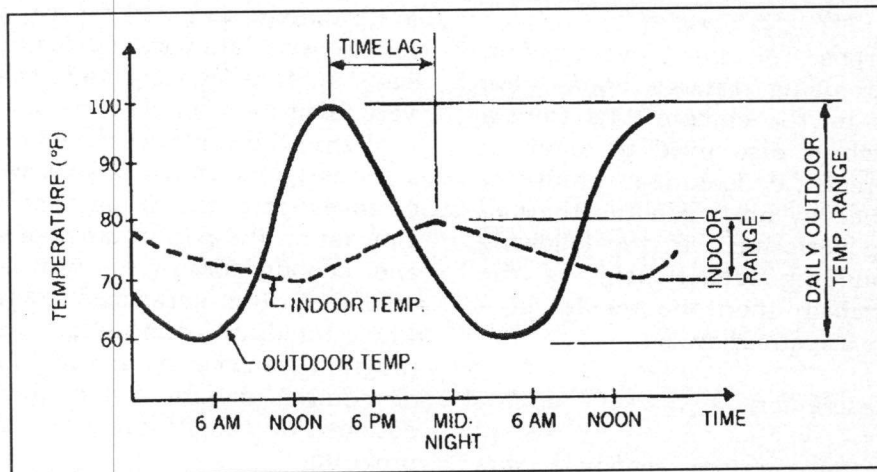


Fig. 3. Time lag between outdoor and indoor temperature peaks [11].

3.3. Building Automation Systems (BAS)

Intelligent buildings use computer-based BAS to monitor, organize, optimize, coordinate and control many building subsystems for non-energy as well as for energy related applications. Non-energy related applications include security, fire/life safety, elevators, giving directions, customized settings to meet different occupants' needs, scheduling preventive maintenance, allowing off-site building control etc. Energy related applications include: monitoring (temperature logging, energy use, equipment start times, etc) alarm reporting (notifying the operator of failed equipment, out of limit

temperature/pressure conditions or need for maintenance) equipment scheduling (turning equipment off and on as required) optimum start/stop (turning heating and cooling equipment on in advance to ensure the building is at the required temperature during occupancy) operator adjustment (accessing operator set-points that tune system to changing conditions)

BAS opens the door for the concept of pre-heating and pre-cooling of buildings. The potential of pre-cooling the building thermal mass in reducing electricity energy costs is generally well documented [3]. Active pre-cooling strategies can have a large impact

when chillers have high loads during periods of high occupancy and high outdoor temperatures (which typically coincide with on-peak periods in rate structures). By reducing the on-peak cooling load it is possible to reduce chiller energy use during these critical periods, thereby reducing energy costs. Passive pre-cooling strategies such as night ventilation aim at benefiting from low ambient air temperatures during the night time to flush heat out of the building and provide a more comfortable environment during the following day.

The hypothesis of this paper is that using a BAS can improve the performance of buildings with passive strategies.

4. Methodology

For the purpose of this investigation, simulation runs using Energy Plus were conducted based on the climate data from a weather file which is also used to obtain a quasi-weather forecast by looking a number of days ahead of the day on which the thermal analysis is being performed. In the following sections, the building model used in the analysis is described, then the results of a series of analyses are summarized.

4.1. The model description

Analysis of the thermal response was performed by means of a prototypical single-storey building having dimensions 12 m × 12 m × 3 m and consisting of one zone fig. 4.

The external walls of the model are composed of three layers: a 10 mm medium color plaster layer on the outdoor side, a 110mm thick brick layer and a 10mm thick medium color plaster layer with emulsion paint on the indoor side. The overall U-value of the external wall is 2.62 W/m² K. The internal floors consisted of a 10 mm ceramic tiles layer on a 5 mm concrete screed and a 100 mm concrete layer. The overall U-value of the floor is 0.88 W/m² K. The roof consisted of a 6 mm asphalt layer on top of a 150 mm light weight concrete layer and a 10 mm plaster layer. The overall U-value of the roof is 0.896 W/m² K. All external surfaces except the roof had a solar absorption factor of 0.45.

The roof with the thermal insulation removed had a solar absorption factor of 0.95. The movable thermal insulation had a solar absorption factor of 0.10. The building had three windows (1.20 m height × 2.00 m wide) along the north façade and three similar windows along the south façade. A 1.0 m horizontal overhang was assumed to run on top of the three southern windows. All windows used a single pane of 6mm thick clear glass with a visible transmittance of 0.92 and aluminium frames resulting in shading and Solar Heat Gain Coefficients (SHGC) of 0.94 and 0.56, respectively, and a U-value of 6.0 W/m². The properties of the various materials used in the building are summarized in table 2.

The building is assumed to be continuously occupied by five people with an activity level 500 watts/person but no internal loads such as lighting and electric equipment were taken into consideration.

Using the building model described above, a series of thermal analyses were carried out to investigate the impact of using weather forecast on the performance of passive heating and cooling strategies. Annual and annual analyses were performed using Energy-Plus whole-building simulation program. The program provides results for hourly variations of required air and surface temperatures. The options for scheduling are imbedded in the program.

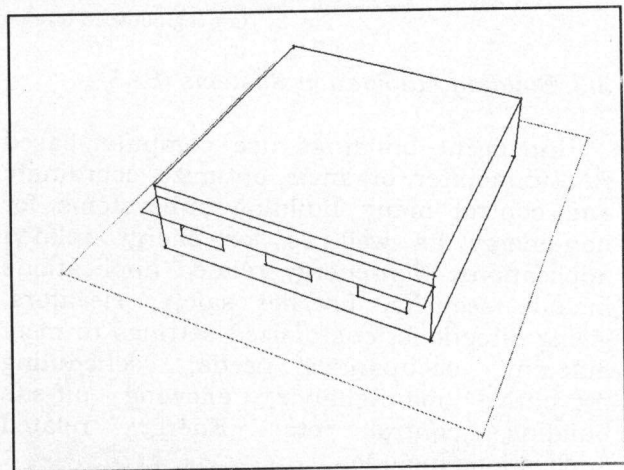


Fig. 4. Illustration of the building model (south façade with overhang).

Table 2
Characteristics of building materials used in building model

Material	Density (kg/m ³)	Specific heat (J/kg K)	Thermal conductivity (W/m K)
Plaster	1250	1088	0.431
Brick	2000	837	0.711
Ceramic tiles	1900	657	0.309
Concrete screed	2000	657	0.753
Concrete floor	3800	657	0.753
Asphalt	900	1966	0.088
Light weight concrete	950	657	0.209
Standard glass	2300	837	1.046

Two case studies are discussed in this paper. The location for the first case study was Alexandria, Egypt (latitude 29.95 N; longitude 32.20 E; altitude 7.0 m) with the focus on passive heating in the winter period. The location for second case study was Munich, Germany (latitude 48.13 N; longitude 11.7 E; altitude 529 m) with the focus on passive cooling in the summer period. Appropriate Energy Plus weather files were used in the simulation in both cases. For each of the two cases three runs were performed. In the first run no passive heating or cooling strategies were implemented. In the second run the building was controlled through normal schedules as will be described later in detail. In the third run the building was controlled through schedules which considered forecast change in weather. The change in weather information was obtained from the same weather file by looking a number of days ahead of the day on which the thermal analysis is being performed.

4.2. Case study 1: passive heating – Alexandria, Egypt

A movable 40 mm thick thermal insulation (e.g. polystyrene foam) was used for passive heating during winter. The insulation is used to cover and uncover a highly conducting flat roof and the south façade according to predefined schedules. In the winter mode of operation (November to February) both surfaces were uncovered from 9:00h to 14:00h so that they get heated by solar radiation. Both surfaces are covered the rest of the day to reduce the thermal losses to the ambient environment and to transfer heat into the building. An infiltration-related air-change rate of 3 air changes per hour is assumed throughout the whole day. The model did not

provide additional ventilation in winter or any active HVAC.

Diurnal variations in inside and outside surface temperatures of the roof and the variations in operative temperatures inside the building with schedule-based roof cooling are compared in fig. 5 to those of a similar building with fixed insulation.

The periodic analysis of hourly variations in operative indoor temperatures for the period 12 January to 20 January and the period 5 February-14 February using; a) no passive heating, b) schedule-based passive heating and c) forecast-based passive heating are presented in figs. 6 and 7. The outdoor dry bulb air temperature and the amount of total sky cover are also given in these figures to observe the basis upon which decisions are taken to regulate the capacity of passive heating applied.

From figs. 6 and 7 it is clear that, during this period, forecast-based passive heating offered more hours within comfort limits as compared to schedule-based passive heating.

4.3. Case study 2: passive cooling – Munich, Germany

A movable 40 mm thick thermal insulation (e.g. polystyrene foam) is used for passive cooling during summer. The insulation is used to cover and uncover a highly conducting flat roof according to predefined schedules. In the summer mode of operation (May to August) the roof was covered from 7:00h to 18:00h to prevent it from heating through solar radiation. Keeping the roof uncovered during the night allows it to cool by nocturnal cooling. Heat from the building is transferred through the roof to the ambient environment, and cooling is obtained.

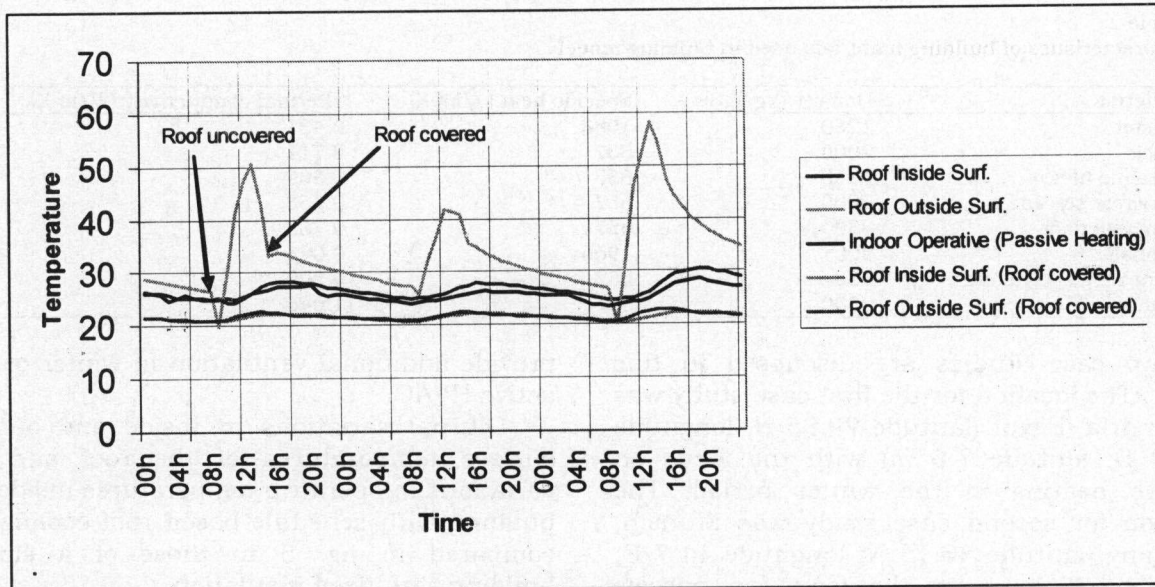


Fig. 5. Diurnal variations in inside and outside surface temperatures of the roof and the variations in operative temperatures inside the building with schedule-based roof cooling compared to those of a similar building with fixed insulation.

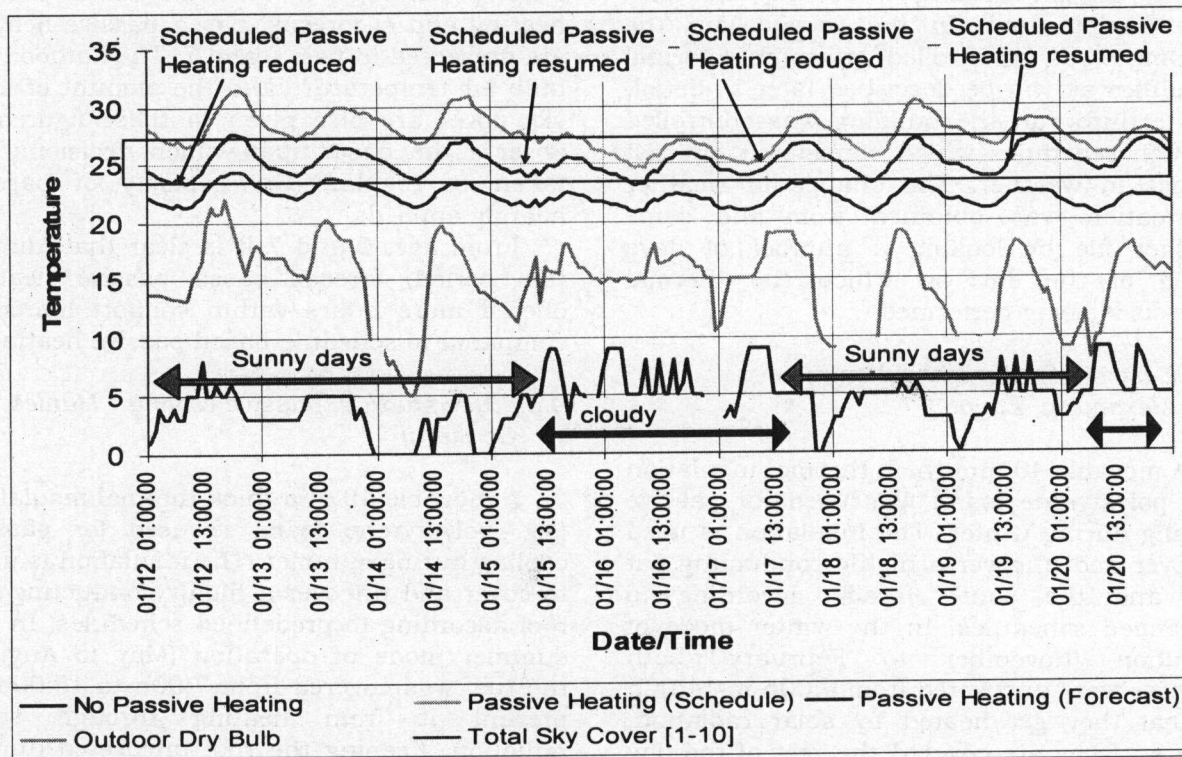


Fig. 6. Variations in hourly operative indoor temperature [C] Alexandria, Jan 12 - Jan 20.

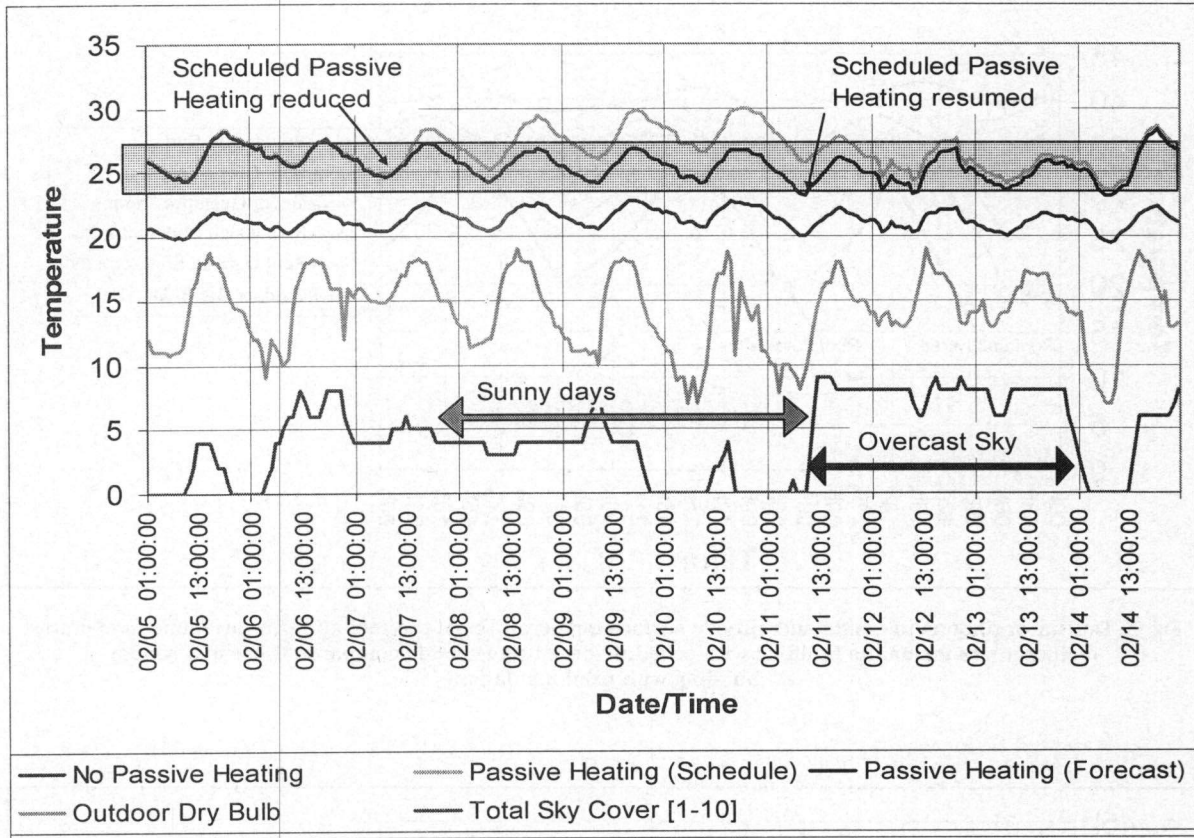


Fig. 7. Variations in hourly operative indoor temperature [C] Alexandria, Feb 05 - Feb 14.

Diurnal variations in inside and outside surface temperatures of the roof and the variations in operative temperatures inside the building with schedule-based roof cooling are compared in fig. 8 to those of a similar building with fixed insulation.

Additional cooling was obtained using lower outdoor temperatures during the night. Night ventilation was scheduled from April to September from 22:00h to 7:00h at an air-change rate of 15 air changes per hour. Night ventilation was shut off if the temperature differential between inside and outside went below 2.0 C and/or the indoor temperature went below 20 C. An infiltration-related air-change rate of 0.5 air changes per hour is assumed throughout the whole day. The model did not provide additional ventilation in winter or any active HVAC.

Diurnal variations in indoor air temperatures in the building with night ventilation are compared to outdoor air temperatures in fig. 9.

The periodic analysis of hourly operative indoor temperatures for the period 13 July-23 July using; a) no passive cooling, b) schedule-based passive cooling and c) forecast-based passive cooling are presented in fig. 10. The outdoor dry bulb air temperature and the amount of total sky cover are also given in these figures to observe the basis upon which decisions are taken to regulate the capacity of passive heating applied.

From fig. 10 it is clear that, during this period, forecast-based passive cooling offered more hours within comfort limits as compared to schedule-based passive cooling.

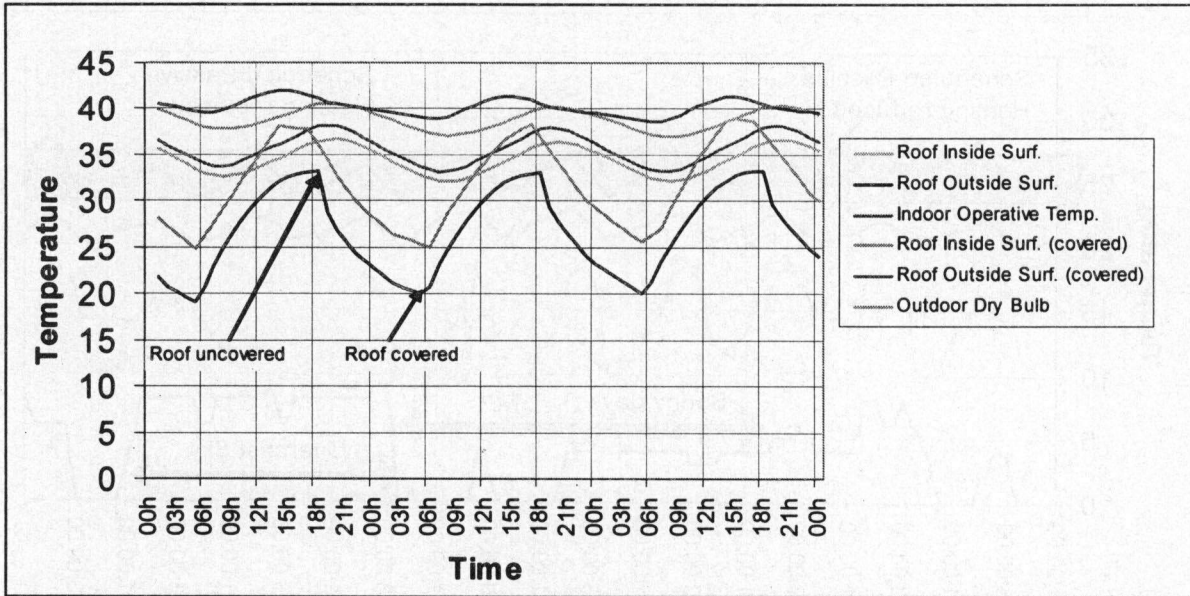


Fig. 8. Diurnal variations in inside and outside surface temperatures of the roof and the variations in operative temperatures inside the building with schedule-based roof cooling compared those of a similar building with fixed insulation.

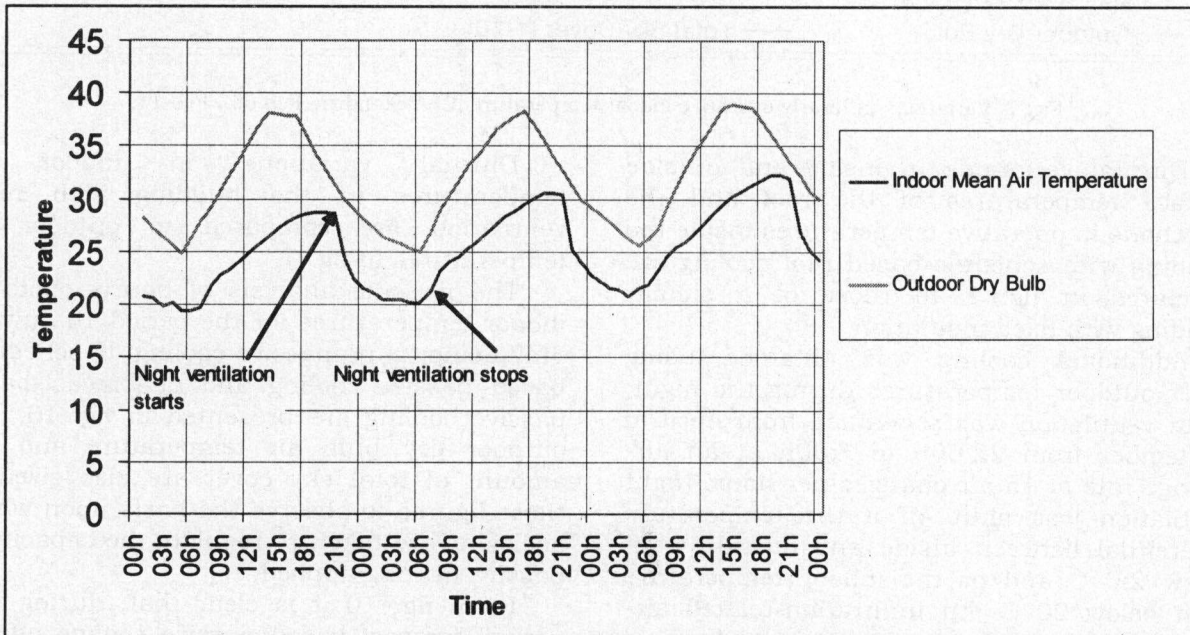


Fig. 9. Diurnal variations in indoor air temperatures with night ventilation compared to outdoor air temperatures.

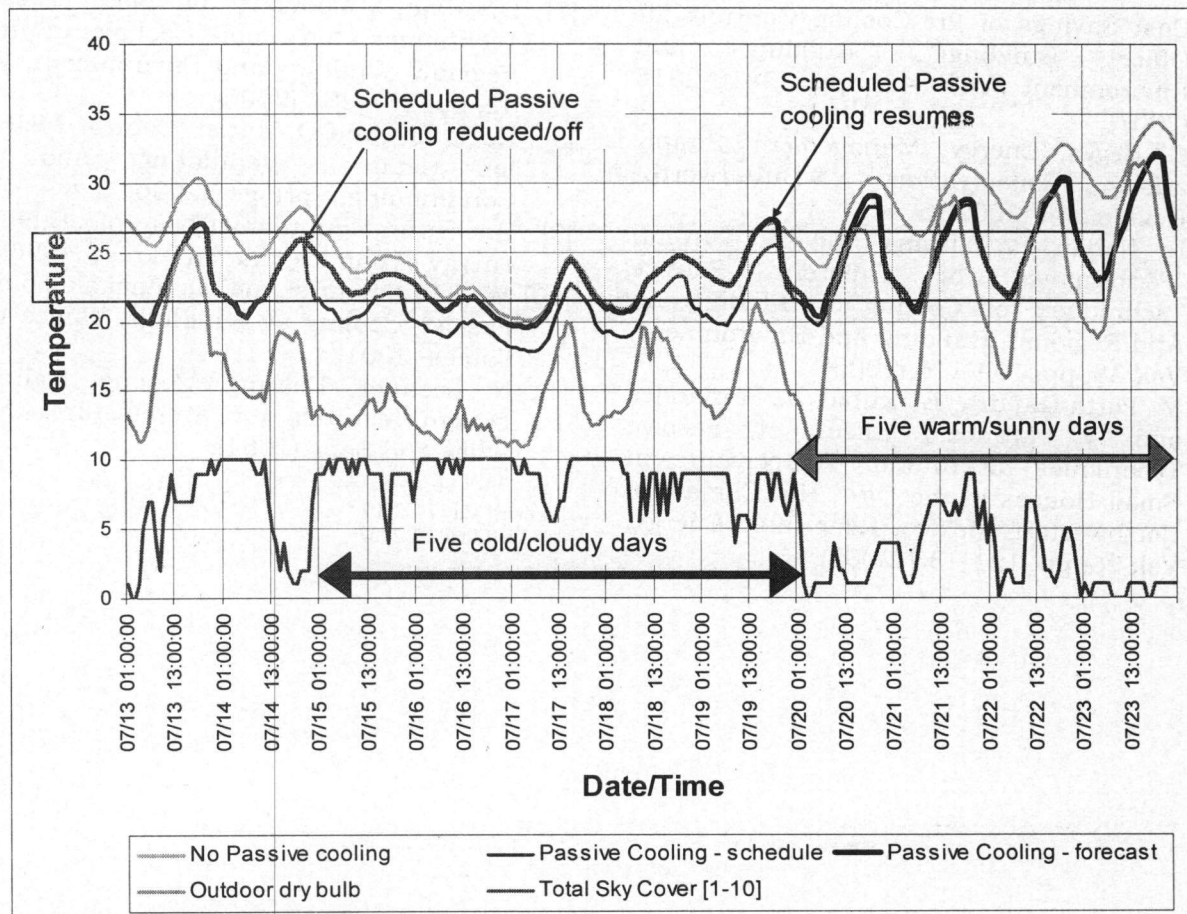


Fig. 10. Variations in hourly operative indoor temperature [C] hourly Munich July 13 - July 23.

5. Conclusions and future work

Thermal analysis of forecast-based control of passive heating in Alexandria, Egypt and passive cooling in Munich, Germany and were presented and compared to the thermal analysis of similar conditions using schedule-based control. From these two case studies it is clear that the performance of forecast-based passive strategies can be higher than the performance of schedule-based passive strategies. It is also clear that while this approach helps keeping the indoor air temperature within comfort limits, it still needs auxiliary heating/cooling to provide comfort when extreme hot/cold conditions prevail for a longer period of time.

More case studies are needed to include the effect of some characteristics such as the level of envelope thermal insulation and

thermal inertia on the amount of improvement in performance. The current investigation treats the weather forecast as 100% reliable. A future investigation could focus on the effect of reliability on the amount of improvement in performance. This could be done by using randomly generated whether change data with reduced level reliability.

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