Modeling, Simulation and Verification Problems in Buildings

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I declare that this written submission represents my ideas in my own words, and where ideas or words of others have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

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Abstract

Two problems concerning modeling, verification and simulation of buildings are presented in this thesis.

In the first problem, we have proposed a generalized event driven framework for the simulation of building occupancy. Building occupancy models are crucial for building energy simulation and research, however generating an occupancy model that is able to simulate real occupancy pattern is a challenging task. Humans work together in groups and their presence is affected by events. So the proposed framework incorporates the concept of events and groups. Unlike the existing building occupancy models which were based on Markov chain, the proposed framework is fully event driven and group based which makes it closer to reality. The proposed framework can be used to simulate the occupancy patterns for any building be it an office, lab or even a house. It can also capture sudden increase and decrease in the building occupancy.

In the second problem, The zero energy building design is modeled as a hybrid system and whether the design follows the specification or not is verified using Hybrid Automata. Hybrid Automata is used to model and verify the specification of a Hybrid system. In general for a building to meet the zero energy property, the amount of non renewable energy produced by the building must be greater than or equal to the amount of renewable energy consumed by the building for an entire year. There are four different types of zero energy buildings based on the definitions and all the different types of zero energy buildings can be verified using the proposed approach. A case study where a zero energy building design is modeled and verified is also presented in this thesis.

Contents

Chapter 1

Introduction

Energy conservation is a matter of primary concern, as our sources for non renewable energy are getting depleted everyday. Moreover the usage of non renewable energy has caused harmful effects to the environment such as global warming, pollution etc. Conservation of energy is done primarily by reducing the energy consumption and then by resorting to alternative renewable sources of energy. The commercial and residential buildings use approximately 40% of primary energy and 70% of electricty in US[1]. So reduction in the energy consumption of the buildings will have significant impact on the overall usage of non renewable energy.

Noteworthy efforts are made to reduce the energy consumption of the buildings by the use of Buildings Automation, low energy buildings, low energy equipments, natural ventilation, low energy cooling systems such as radiant cooling system or a evaporative cooler as an alternative to conventional air conditioning systems etc. A promising method to reduce energy consumption in buildings is Building Automation System(BAS) which has a Intelligent centralized control network over the Heating Ventilation and Air Conditioning system(HVAC), lightning, security, appliances etc. In a BAS the HVAC system and lighting system can be intelligently controlled based on the presence of occupants, outside temperature, outside light intensity etc, by the deployment of the sensors. A home equipped with a BAS is called a Smart Home and a building equipped with a BAS is called a Smart Building.

Building simulation tools are critical in designing buildings with higher energy efficiency, higher thermal comfort, higher safety, etc. In these simulations, human occupancy patterns of the building play a significant role because humans continuously interact with the building to increase their personal comfort. For instance the occupants use appliances which use various forms of energy. Humans also emit heat, water vapour, pollutants, etc. If the building occupancy model is able to generate granular and realistic data then the energy simulation tools can predict the building energy consumption with higher accuracy. Therefore, a model capable of reproducing real building occupancy pattern is of great importance.

Informally, zero energy buildings are buildings which produce energy from renewable sources equal to or more than the amount of energy which the building consumes from the non renewable sources. They are an innovative idea which reduces the energy consumption of the buildings. Many nations are creating future plans and goals which will cut the energy consumption of the buildings with the help of zero energy buildings and near zero energy buildings. US Department of Energy stresses on the development of cost effective Zero energy buildings by 2025 [1], European Union also has a target of Near zero energy buildings by 2020 [2] etc.

We present two problem in this thesis. In the first problem, we have proposed an event driven building occupancy framework. The proposed framework tries to capture more realistic components when compared with the existing building occupancy models. In the next problem, model checking techniques are applied for the verification of the design of the zero energy building. In model checking, we construct the model of the system and we verify it's specifications. In this work, we have modeled the design of the zero energy building as a Hybrid system using Hybrid Automata and the verification is done using the Hytech tool.

The thesis is arranged as follows, The second chapter discusses the building occupancy problem, our approach, algorithm and results. The occupancy of two scenarios office and computer lab are also simulated. Then the third chapter presents modeling of Zero energy buildings using Hybrid Automata. Third chapter describes four different types of zero energy buildings, formal definition of Hybrid Automata and a case study. The fourth chapter concludes the thesis and discusses the future work.

Chapter 2

An Event driven building occupancy framework

2.1 Related work

Building occupancy models are an emerging research area in the recent two decades. Building occupancy models predict the number of occupants in the building at every time instant. Initially the deterministic methods are used for simulating building occupancy in building simulation tools, some examples include schedule and diversity profile [3]. These methods can describe the building occupancy with respect to time. The daily schedule consists of 24 hourly values while a yearly schedule usually consists of 365 daily schedules, in which the hourly values can be estimated from individual experience or on site survey. These are fully deterministic methods and these methods may not be able to predict the real occupancy patterns of a building as it will also involve stochastic components.

One of the earliest works on Building occupancy done by Wang et al in [4], where they constructed a Poisson process model which simulates the occupancy of a single room office. They were able to simulate the single person offices in an accurate manner. But this model can only simulate single person office. Another important model was developed by Page et al in [5]. This is an agent based model based on Markov chain. They have also included one event which is called the long term absence event. The model also tries to incorporate the lunch event by manually adjusting one of the input parameters. The model by Page et al [5] can also simulate multiple occupants in the building.

Another relevant model was proposed by Liao et al in [6], it is an agent based model for human occupancy and human movement in the building. This model considers each human as an agent and decides the location of the agent inside the building at every time instant through a set of rules defined by four modules. This model can also capture the movement of the occupant inside the building. It contains a module called the scheduled activity module, which is able to simulate some events. This model is scalable up to arbitrary number of users and it can simulate occupancy for every room level or predefined zone level in the building. This model is inspired from model developed by Page et al[5].

The other reasonably good model in building occupancy and human movement is proposed by Chuang et al in [7] which is based on Markov chain. This model is able to simulate the movement of occupants at every time instant. This model also supports some events to control the movement of the occupant inside the building. Then the model is also able to simulate the movement of the humans in the office environment with a reasonable accuracy.

The disadvantages of the existing models are (a) Most of the existing models are mainly based on Markov chain or a probabilistic distribution which makes the model less realistic. Markov chain can capture the stochastic components of the building occupancy, but it will be hard to capture the deterministic components (non stochastic components) of the building occupancy using Markov chain. Therefore these models may result in non-realistic simulation. (b) Most of the existing models are developed based on the office environment and so they cannot simulate the occupancy patterns of each building uniquely (c) In the existing models, all the users are treated equally and simulated in the same fashion. But the building occupancy of humans will be different depending upon their personal profile. (d) The existing agent based models can only simulate fixed number of users. The number of users being simulated cannot be changed dynamically.

2.2 Theory

The main motivation for the development of this work is two entities which are events and groups. The presence and absence of humans in a building is affected by events which happen every day. An employee, who is working in an office environment, may come out of the building to take lunch. So, this lunch event is affecting the presence of the occupant. In a similar way, there might be other events which may occur at a lower probability such as power failure, accidents, sick leave etc, but still these events affect the presence and absence of the occupants in the building. In a similar fashion, humans interact and work together in groups. These groups have group events such as group meetings. These events affect the presence and absence of every group member at the same time. Thereby with the incorporation of groups and events the building occupancy model will be able to generate patterns closer to reality.

2.2.1 Events

An event is an activity which causes the occupant to enter or exit the building, once the event has ended the occupant will return to his previous location which can be inside or outside the building. Let consider an Lunch event who *starttime* is 12PM and *endtime* is 1PM, at 12PM the event will cause the user to exit the building. Then once the lunch event is completed at 1 PM, it will cause the user to come back to the building. There can multiple events active at the same time, but only the event with the higher priority will be active.

In all most all cases occupants enter and exit a building for some reason, which can be captured as an event e.g.: - A user goes to office at 9 AM because he has a work event. He goes out of the office at 12 PM because of a Lunch event and finally he returns home at 6 PM because the work event ended. In a similar fashion, almost all entry and exit made by the occupants can be captured as events. The occupants may also enter and exit without any reason; this can be captured by probabilistic events or by using a distribution or Markov chain as in case of the existing models.

In this framework, events are categorized as follows:

(a) Deterministic or Probabilistic: Deterministic events are events which are bound to happen in a day. e.g.:- Lunch break, meeting etc. Probabilistic events may or not may not occur in a day e.g. accident, sick leave etc.

(b) Personal or Global: Personal events affect only particular individual e.g.: - Sick leave, personal holiday, accident etc. Global events affect everyone in the building. e.g.: - Natural disasters, power failure, riots, war etc.

2.2.2 Groups

As humans interact and work together as groups, incorporation of the concept of groups into building occupancy model becomes pivotal. In this work, a set of occupants are grouped together and named as a group. Each group may have group events, the group events only affect users belonging to this particular group.

2.2.3 Users

We simulate occupants as agents so proposed framework is an agent based framework. An agent based model consists of agents, who have a set of behaviors. These agents mimic the behavior of humans. But the difference between the existing agent based models and proposed framework is that the existing agent based models always simulate constant number of agents which is given to the model in the form of initial input. But, the proposed framework can simulate additional users, whenever necessary.

One of the main advantages of the proposed model is that it can capture and trace the occupancy of every user in a different manner. Let us consider the office environment, the occupancy pattern of a CEO and an employee will never be similar because of their personal profile. But all the existing models will generate the same occupancy pattern for both the occupants. Moreover in the existing models each user cannot be simulated uniquely but that is not the case with the proposed framework where the occupancy pattern of every user can be uniquely simulated and captured thereby making the simulation closer to reality.

It supports two types of users, internal users and external users. The internal users are regular users of the building, these users are simulated at every time instant by the simulator. It is similar to the work done by Page et al [5] and Liao et al [6]. 2011. Each of the internal users may be a member of several groups. The external users are not regular users of the building but they are forced to come in the building because of an event. The events which force a non-regular user to come inside the building are the external events. E.g. A fire alarm is an external event will cause some fire fighters to come inside the building. The fire fighters are the external users who just come inside the building for the duration of the external event.

2.3 Algorithm

2.3.1 Input

There are four input lists to the algorithm:
(a) Group information list which contains the information about the groups and the number of occupants belonging to each group.
(b) User profile list which contains information about internal users who need to be simulated

uniquely; it also contains information about the events from which the user is exempted. All the users in these two above mentioned lists are simulated as internal users.
(c) Deterministic events list which contains the information about the deterministic events. It contains the following fields: event name, event id, event starting time frame, duration, whether its global or not and priority.
(d) Probabilistic events list which contains the information about the probabilistic events. It contains the following information: event name, event id, probability of occurrence, expected duration, whether its global or not and priority.

2.3.2 Output

There are two outputs from the algorithm:
(a) User log which contains the information about the events in which the user is involved. There is a separate log for every user.
(b) The building occupancy list which contains the number of users present in the building at every time instant.

2.3.3 Main Algorithm

The main algorithm in figure 2.1 on page 7 simulates the activity of every user for the current time instant and then it proceeds to do the same for the next time instant. The main algorithm also calls the event schedulers. The event schedulers schedule the events using the inputs given in the events list. More than one event can be activated at a given time instant so the event with the highest priority will be selected as the on-going event for this time instant. The other event is stored in the event stack and it will be resumed once the higher priority event has ended. The main algorithm generates the building occupancy list and it edits the user log generated by the event schedulers.

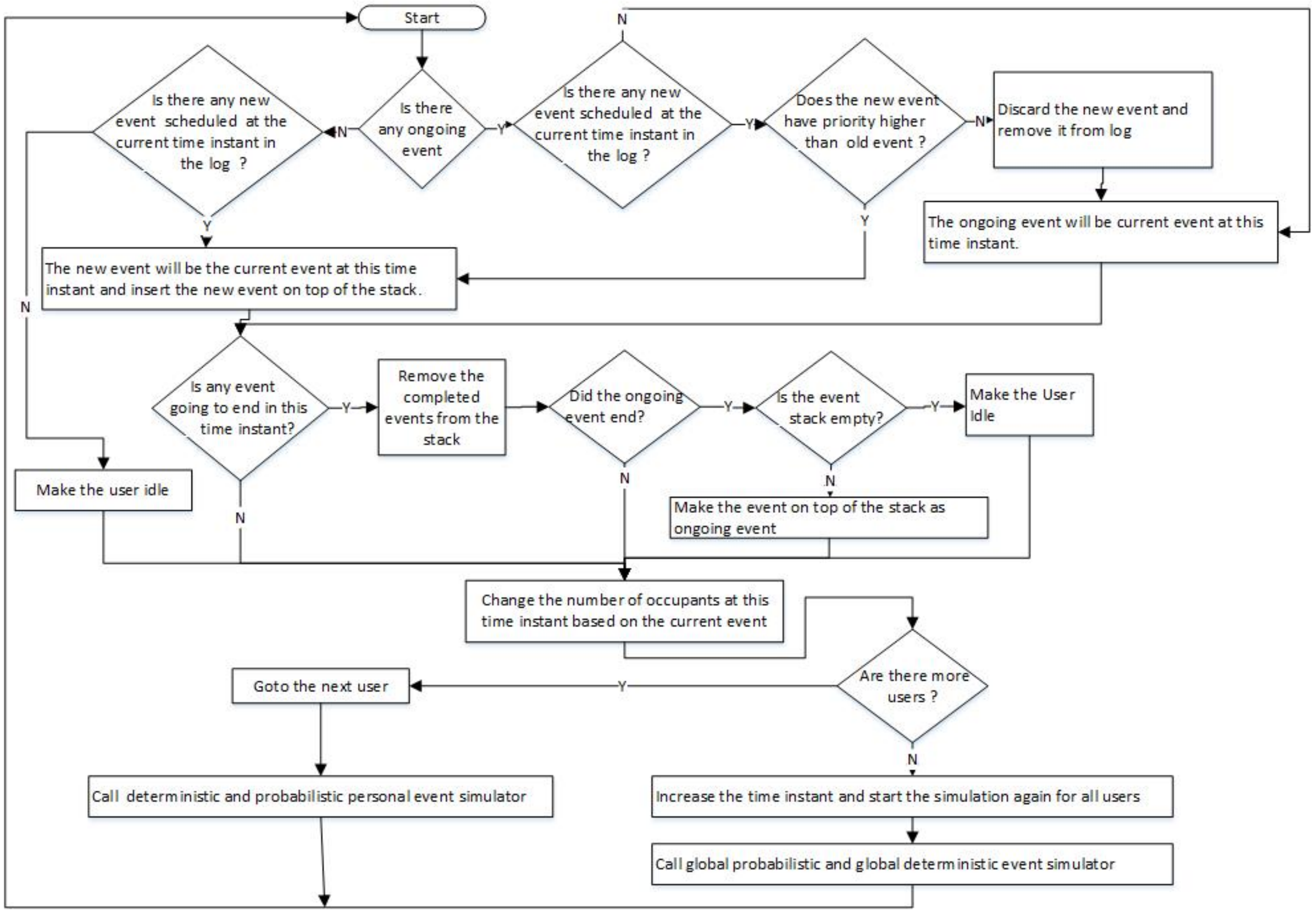


Figure 2.1: Main Algorithm

2.4 Results

A MATLAB script was used to implement the algorithm and analyze the results. We used this script to simulate the building occupancy pattern for two scenarios.
(a) Scenario 1: Office environment
Office environment had three groups. Twenty one internal users were simulated. These users were given user profile to simulate them uniquely. The deterministic events list for the office scenario is given in the table 2.1 on page 8 . The probabilistic events list for the office scenario is given in the table 2.2 on page 8. The probability of occurrance field contains the probability of occurrance of the event on every minute. The Input for ”Start time init” and ”Start time end” is given in minutes. The priorities were assigned arbitrarily based on the importance of each event.

The building occupancy is simulated for two days and they are given in figure 2.2 and figure 2.3. A fire alarm event was triggered on Day 2 from 10:30 am to 11:20 am which caused all the users to exit the building. Building was only occupied by fire fighters who were external users during this event.

Table 2.1: Deterministic Events List for Office Scenario

Event name	Event id	Start time Init	Start time end	Duration init	Duration end	In/out event	Global event flag	Priority	Group id
lunch time	e1	720	800	45	65	out	0	3	3
work	e2	540	630	480	570	in	0	22	3
tea break	e3	970	1030	10	20	out	0	4	3

Table 2.2: Probabilistic Events List for Office Scenario

Event name	Event id	Probability of occurance	Mean of duration	S.D of duration	Global flag	Probability of affecting user	Priority	In/out	Group id
Sick leave	p2	1/1440	100	10	0	NA	2	out	all
Team chitchat	p3	5/1440	10	20	1	20	3	out	1 & 2
Bio break	p4	50/1440	10	0	0	NA	2	out	alls
Fire alarm	p1	30/1440	50	0	1	100	1	out	all

(b) Scenario 2: Lab environment (Computer lab)

The computer lab consists of 9 groups such as bachelor, master, doctorate students, faculty, research groups etc. A total of thirty internal users were simulated. In that thirty users we had user profile for five to simulate them individually. (It is not necessary to have user profile for every user but if we have a user profile then we can add additional information which can simulate occupancy pattern of the user uniquely).The deterministic events list for the lab scenario is given in the table 2.3 on page 10. The probabilistic events list for the lab scenario is given in the table 2.4 on page 11.

The building occupancy is simulated for two days and they are given in figure 2.4 and figure 2.5. There is a sudden increase in the lab occupancy on day 2 from 2:30 to 4:30 pm because of the lab session. User log for a faculty is shown in figure 2.6 on page 12. We maintained a separate user profile for a faculty and using the user profile he was exempted from some events.

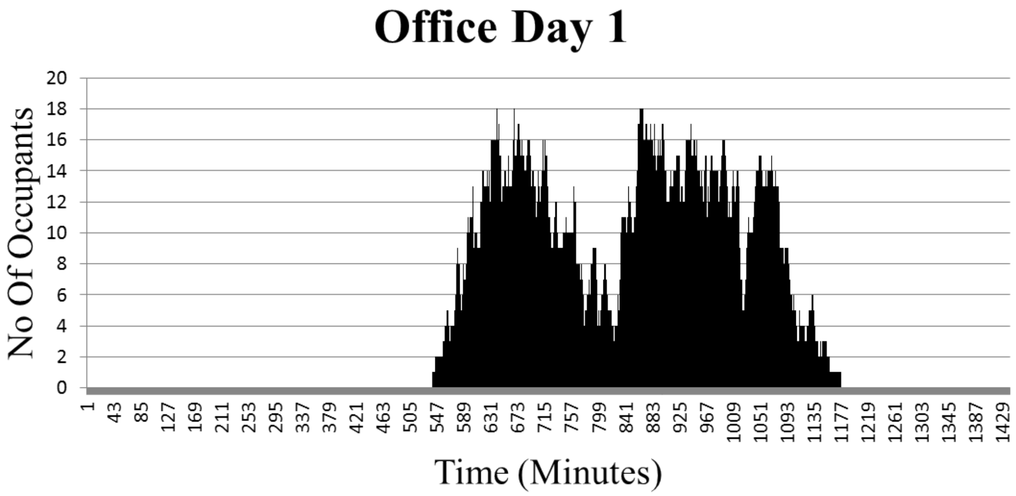


Figure 2.2: Office Environment Day 1

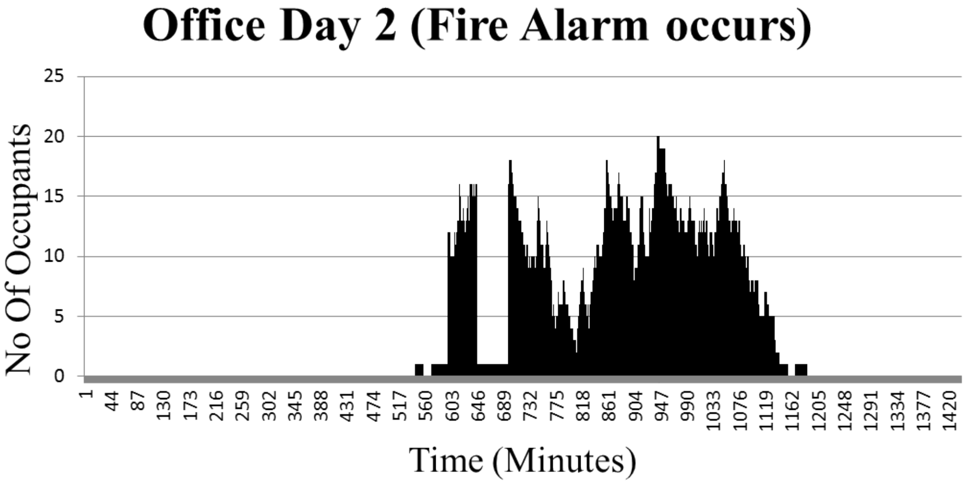


Figure 2.3: Office Environment Day 2

2.5 Conclusion

In this problem, we have proposed a generic event driven framework for building occupancy. The results of simulation of an office and a lab environment are shown. It is found that this framework can capture sudden peak in the occupancy because of the lab session in the lab environment and a sudden drop in the occupancy because of the fire alarm in the office environment. This generic framework can be used to predict the occupancy pattern of any building by providing a proper input. Also many new concepts like events, user profile management and groups are proposed in the current framework.

In the future work, we plan to compare the building occupancy patterns generated by the proposed framework with the existing models and the real occupancy pattern. Then we also plan to simulate building occupancy at a zone level, where the occupancy of users in every room or zone will

Table 2.3: Deterministic Events List for Lab Scenario

Event name	Event id	Start time Init	Start time end	Duration Init	Duration end	In/out event	Global Event flag	Priority	Group id
Network lab meeting	e1	660	690	35	65	in	1	3	2
C Programming TA work	e4	870	880	120	130	in	1	6	13
CSE faculty meeting	e5	690	695	30	35	in	1	10	7
Project staff Meeting	e6	570	595	400	420	in	1	15	16
Lunch time	e7	720	800	45	65	out	0	2	16
Tea break	e8	970	1030	10	20	out	0	4	16
Student meeting	e9	970	1030	10	20	in	0	4	10
Internal project meeting	e10	580	590	30	35	in	0	4	10

be simulated. The proposed model was presented as a work in progress paper[8] in the Symposium on Simulation for Architecture and Urban Buildings.

Table 2.4: Probabilistic Events List for Lab Scenario

Event name	Event id	Probability of occurance	Mean of duration	S.D of duration	Global flag	Probability of affecting user	Priority	In/out	Group id
XYZ server project	p1	7/1440	60	1	0	NA	8	in	15
btech 4th year students	p2	11/1440	60	1	0	NA	25	in	3
Master students	p3	10/1440	80	1	0	NA	28	in	4
Phd students	p4	30/1440	90	2	0	NA	30	in	5
lab visit	p5	20/1440	40	1	0	NA	40	in	10
Software systems project	p6	45/1440	50	2	0	NA	45	in	11
fire alarm	p8	1/1440	50	0	1	100	8	out	None
sick leave	p7	1/1440	100	10	0	NA	2	out	16
bio break	p11	50/1440	10	0	0	NA	2	out	5

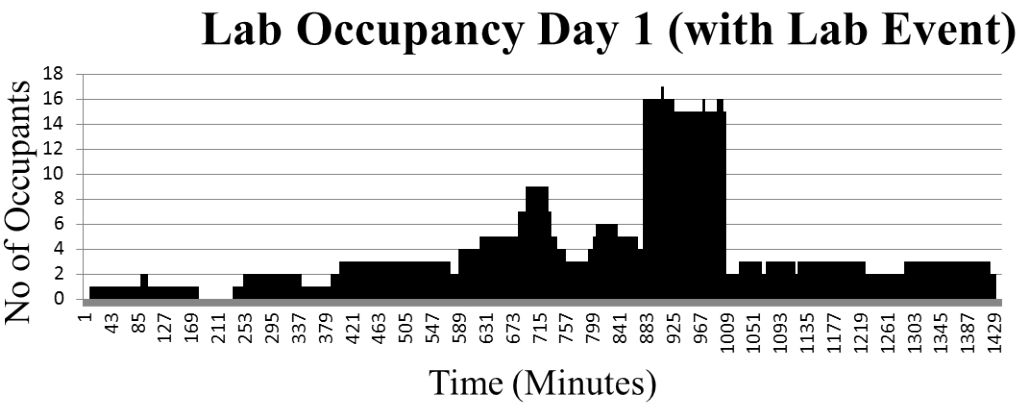


Figure 2.4: Lab Environment Day 1

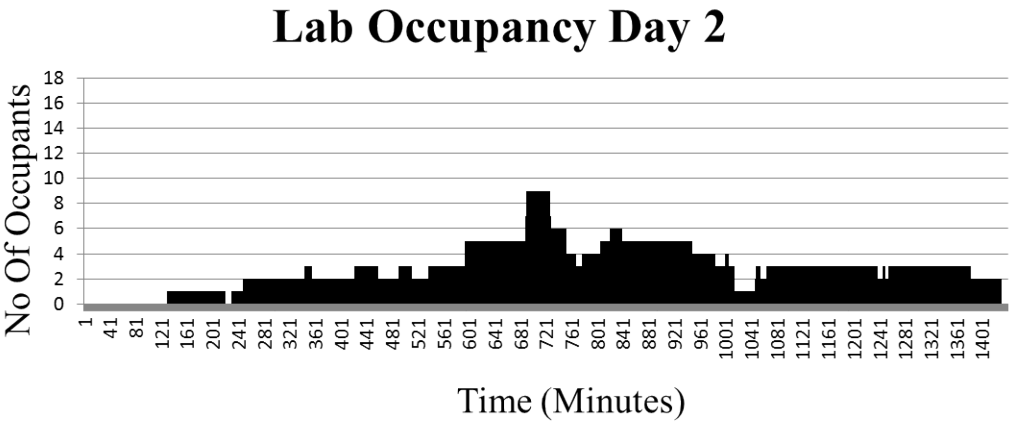
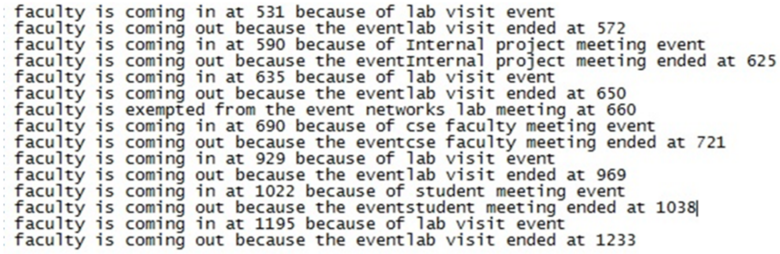


Figure 2.5: Lab Environment Day 2



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faculty is coming in at 531 because of lab visit event
faculty is coming out because the eventlab visit ended at 572
faculty is coming in at 590 because of Internal project meeting event
faculty is coming out because the eventInternal project meeting ended at 625
faculty is coming in at 635 because of lab visit event
faculty is coming out because the eventlab visit ended at 650
faculty is exempted from the event networks lab meeting at 660
faculty is coming in at 690 because of cse faculty meeting event
faculty is coming out because the eventcse faculty meeting ended at 721
faculty is coming in at 929 because of lab visit event
faculty is coming out because the eventlab visit ended at 969
faculty is coming in at 1022 because of student meeting event
faculty is coming out because the eventstudent meeting ended at 1038
faculty is coming in at 1195 because of lab visit event
faculty is coming out because the eventlab visit ended at 1233
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Figure 2.6: User Log of the Network Faculty

Chapter 3

Modeling and Verification of Zero energy buildings using Hybrid Automata

3.1 Introduction

A Zero energy building is a commercial or a residential building which produces renewable energy equal to or exceeds the amount of non renewable energy which it consumes. The zero buildings produce energy through the renewable sources like solar energy. But the renewable sources of energy may not be available throughout the year. Therefore the zero energy buildings will have to rely on the grid at times. Then there may be times when the building produces excess energy through it is renewable source, in that case the excess energy can be transferred back to the grid which can be reimbursed. As the renewable sources may not be available throughout the year the amount of energy consumed by the building in the entire year is compared with the amount of energy produced by the building in the entire year. There are very few zero energy buildings available around the world. The zero energy buildings have low energy consuming design which may include low energy equipments, natural ventilation, non-conventional cooling systems like cooling through evaporation etc. The design of the zero energy building is very important as we can not afford to waste energy. The zero energy building may have energy sources on site or off site. The energy may be produced at off site and will be bought to the building like bio mass etc. It depends upon the definition of the zero energy building on whether to consider the non-renewable resources produced off site or not.

3.2 Preliminaries

These are four different definitions of zero energy buildings as defined in [1]. The proposed methods can be used to model each type of zero energy buildings.

3.2.1 Definitions of Zero Energy Building

(a)Net Zero Site Energy: A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.
(b)Net Zero Source Energy: A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a buildings total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.
(c)Net Zero Energy Costs: In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
(d)Net Zero Energy Emissions: A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

3.2.2 Hybrid System

A Hybrid system is a dynamic system that exhibits both continuous and discrete behavior. The system has continuous flows and discrete jumps. Hybrid systems are present everywhere around us in various forms. Some examples of Hybrid systems are bouncing ball, thermostat, Automated Highway systems, Flight Control Systems, multiple vehicle coordination, computer disk drives, stepper motors etc. Hybrid systems are discussed in detail in [9]. As an example of Hybrid System consider an Intelligent Air-conditioning System which has to maintain the room temperature at a predefined temperature. If the temperature is higher than the required temperature then the air-conditioning system switches to the high power mode and tries to cool the room. When the temperature reaches the predefined temperature the air-conditioning system may turn to low power mode or switch off for some time. The discrete change of the air-conditioning system from high power to low power mode or vice versa affects the flow of the temperature. In the same way the change in the temperature causes the discrete change in the air-conditioning system. So the continuous flow influences the discrete change and vice versa.

3.2.3 Hybrid Automata

The Hybrid automaton is used to model Hybrid system. The Hybrid Automata captures the continuous flow of the hybrid system using the differential equations and then it captures the discrete changes using the discrete jumps. In this section the formal definition of Hybrid Automata is explained in an abstract manner, the detailed formal definition is present in [10]. Hybrid Automata contains these following components,
a) Variables. A finite set $X = \{x_1, x_2 .... x_n\}$ which are real valued variables. The set $\dot{X} = \{\dot{x}_1, \dot{x}_2 .... \dot{x}_n\}$ of dotted variables represent the first derivatives of the variables set X . The set $X' = \{x'_1, x'_2 .... x'_n\}$ are the set of primed variables which represent the values of the variables after a jump.
b) Control graph. A finite directed multigraph with the vertices set V and edge set E. The vertices are called locations and the edges which connect two vertices are called control switch. (A multigraph is a graph where there can be multiple edges be present between two vertices).
c) Conditions: Initial conditions are the conditions which assign initial values to the variables of

the Hybrid Automata. Invariant conditions are the conditions which the variables should follow to remain in the current location. Flow conditions are conditions which govern the continuous change of the variables using differential equations.
d)Jump conditions : Jump conditions in each location are conditions which the variables must satisfy in order to jump from one location to another.
e) Events: Each edge may be labeled as a unique event. This will help in identifying each edge and also to perform syncing in case of Parallel Composition where multiple Hybrid Automata can run parallely using synchronization between their events.

3.2.4 Verification: Forward and Backward analysis

State space:The state space of Hybrid Automata includes both the locations and the variables.
Starting state : The starting state of the Hybrid Automata is the initial state of the Hybrid Automata from which the Hybrid Automata starts to run.
Bad state : The bad state is the state in which the Hybrid Automata fails to follow the specification. So if the Hybrid Automata reaches any bad state in it's run then the verification process is failed. Given a model of a system and a specification, the problem is to verify whether the model of the system meets the specification or not. In our case modeling is done using Hybrid Automata and the task is to check whether the Hybrid Automata ever reaches a bad state or not. The verification techniques used for Hybrid Automata are presented in [11].

The Hytech tool which is a model checker for hybrid automata can only verify a subclass of Hybrid Automata called Linear Hybrid Automta which is one of the several sub class of the Hybrid Automata. The case study of the building which we modeled and verified belongs to the Linear Hybrid Automata sub class. It has to be noted that not all subclasses of Hybrid Automata are decidable. We can verify the property only if the Hybrid Automata is decidable. The detailed information of which classes are decidable is given in [12]. Hsolver is another tool for the verification of Hybrid Automata and it can handle non linear differential equations, Hsolver is based on new techniques of verification presented in [13].

Then it has to be noted that the Hybrid Automata does not capture probabilistic hybrid systems and hybrid systems which external inputs which are given on run time, there are other extension of Hybrid Automata which can model more information. Stochastic Hybrid Automata[14, 15] can capture the working of Stochastic Hybrid system. The tool Phaver[16] address some limitations of HyTech, it can verify the safety properties of hybrid systems with piece wise constant bounds on their derivatives.

3.2.5 Problem statement: Modeling of Zero energy building as a Hybrid System using Hybrid Automata

Suppose there are N sources of renewable energy in the Zero energy building let us say Source 1, Source 2, ... Source N. Each source produces energy at a different rate depending upon the time. The rate at which Source i produces energy at time t is given by the function $Produce(i, t)$.The rate at which the building consumes the energy at time t is given by the function $Consume(t)$. The sum of total energy produced by all the sources of the building between the time duration t_1 and t_2 is given by the function $Totalproduce(t_1, t_2) = \sum_{i=1}^{N} \int_{t_1}^{t_2} Produce(i, t)dt$, the total energy consumed by the building in the duration t_1 and t_2 is given by the function $Totalconsume(t_1, t_2) = \int_{t_1}^{t_2} Consume(t)dt$. Given a time duration k, there are infinite number of intervals on the time domain such as 0 to k, k to $2k$, $3k$ to $4k$ etc. The problem is to verify whether on each time interval nk to $(n+1)k$ where n is an Integer, the condition $Totalproduce(nk, (n+1)k) >= Totalconsume(nk, (n+1)k)\ \forall k$ is satisfied or not.

3.2.6 Hytech Tool

Hytech tool is a model checker for Hybrid Automata, it supports only linear Hybrid Automata. Linear Hybrid Automata is a subclass of Hybrid Automata with some additional restrictions [10]. It was developed by Tom Henzinger et al [17]. The algorithms which Hytech uses are presented in [18]. The Hytech input consists of two parts, a system description and the analysis commands. The system description is used to describe the Hybrid Automata. The analysis commands are used to give simple instructions for perfomring the verification using backward or forward analysis and generating the trace. If the verification fails which is the the model reached a bad state, the Hytech tool will provide a trace to know, how the model reached the bad state from the starting state.

3.3 Results

3.3.1 Case Study

We are considering a hypothetical zero energy building design. The amount of energy it produces and consumes at every time period is given in table 3.1 on page 17. The rate of energy production and consumption are only marginally closer to the real rates. Then the Hybrid Automata model is constructed in the figure 3.1 on page 17. The model is then written in form of Hytech input. The property to verify is whether the amount of energy produced in an year is equal to or exceeds the amount of energy consumed by the zero energy building. Finally using the Hytech tool, the property of the zero energy building is verified".

3.4 Conclusion

A case study of the hypothetical zero energy building design was performed using Hytech tool. Through these techniques we will be able to verify whether the design of building meets the zero energy criteria or not. Then there are four different definitions of the zero energy building, all the four different definitions can be modeled and verified using the presented techniques. Then it is also possible to verify whether the zero energy criteria is met every season or not.

Table 3.1: The Energy production and Consumption information of the Case study Building in Kilowatt per hour

Period	Building Load	Wind	Solar	Total Renewable energy
Summer Morning	2.5	1	1.7	2.7
Summer Afternoon	2	1	2.3	3.3
Summer Evening	3	1	1.7	2.7
Summer Night	1.7	1	0	1
Autumn Morning	2.5	1.2	1.3	2.5
Autumn Afternoon	2	1.2	1.7	2.9
Autumn Evening	2.8	1.2	1	2.2
Autumn Night	1	1.2	0	1.2
Winter Morning	2.5	0.8	0.8	1.6
Winter Afternoon	2	0.8	1	1.8
Winter Evening	3	0.8	0.6	1.4
Winter Night	1	0.8	0	0.8
Spring Morning	2.5	1.4	1.3	2.7
Spring Afternoon	2	1.4	1.8	3.2
Spring Evening	2.6	1.4	1	2.4
Spring Night	1	1.4	0	1.4

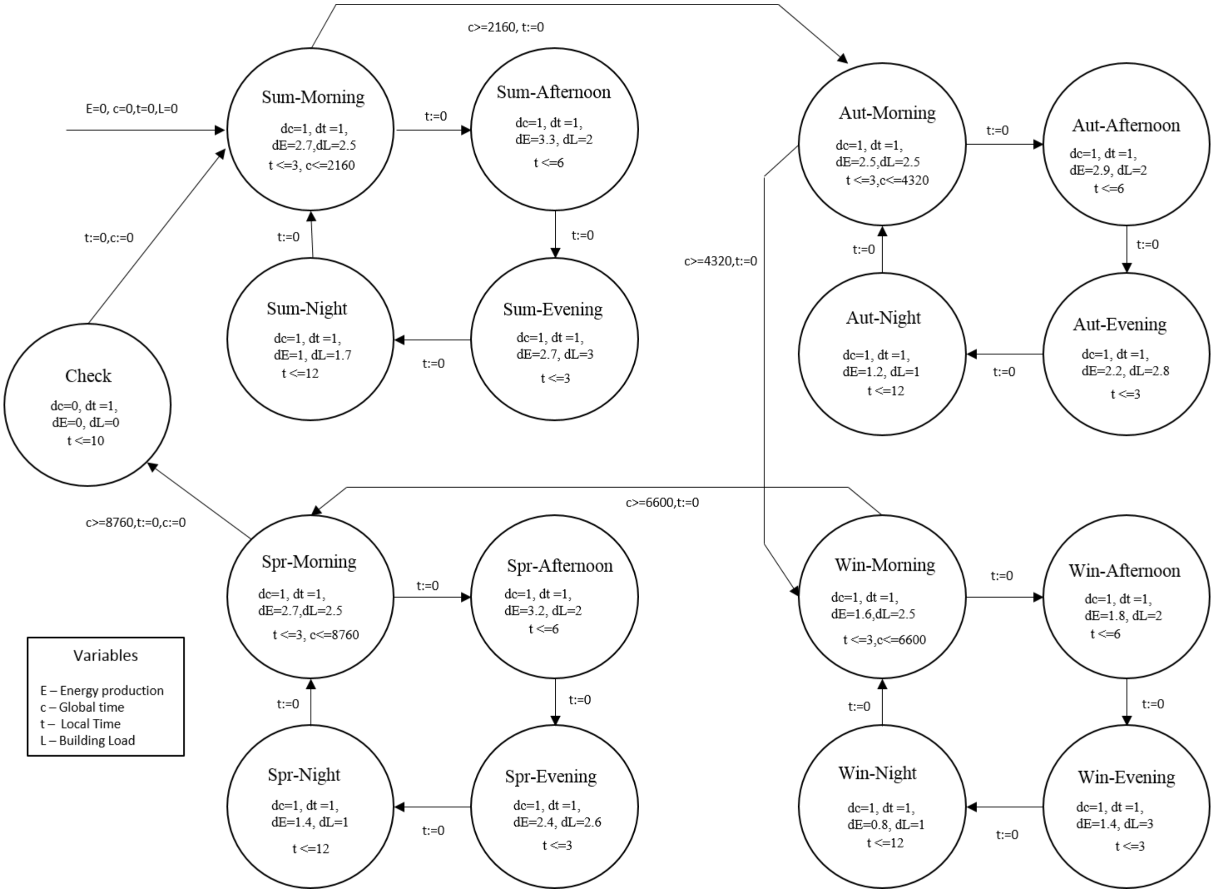

Figure 3.1: Hybrid Automata for the Zero energy building Case Study

Chapter 4

Conclusion and future work

In this thesis two problems, one concerning the occupany of a building and the modeling of the design of a zero energy building is presented. In the first problem a novel event based building occupancy framework was proposed. The framework is agent based, it models every user as an agent and simulates the occupancy of every user. The framework is based on events and groups which real world entities that affect the occupancy of a Human. Then two scenarios, Office environment and the lab environment is simulated and it's shown that the proposed framework can capture sudden increase or decrease in the building occupancy. As a future work, we plan to compare the proposed framework with the real occupancy patterns.

Then in the second problem, the design of the zero energy building is verified using Hybrid Automata. A case study where a zero energy building is modeled using Hybrid Automata and verified using the Hytech tool is also presented. On the other side it has to be noted that the model checking only verifies the abstract model of the system but not the real system but still model checking is a valuable inclusion to the testing procedures. As a future work, I intend to model and verify the design of a real zero energy building.

There are limitations for model checking, we can not model the real system precisely. When we construct a model, it is just an abstract representation of the real system. The real system may be more complex. So even if the model checking does not find any bugs, the real system may contain some error which will be caused only by the components that are abstracted in the modeling procedure. If all the necessary properties of the real system in the model, then it is possible to reveal major design flaws in the modeling checking process. On the other hand the bright side of model checking is that if any error is revealed during the model checking process, that error is surely bound to occur in the real system if the modeling process is done accurately. Unlike the other testing procedures, model checking procedures check exhaustively all possible outcomes of the design.

As defined by Baier et al in [19] Any verification using model-based techniques is only as good as the model of the system. Although the Model checking will find critical errors in the system. The design of the system must also be tested using other conventional methods of testing. If the model checking process does not revel and flaws, it should not be assumed that there is no flaw with the system. To conclude model checking procedures are not a replacement for the conventional testing methods but model checking procedure are a valuable additions to the testing process.

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