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EVALUATION OF CONTROL STRATEGY FOR SMART AIR-CONDITIONING SYSTEM BASED ON STOCHASTIC HYBRID AUTOMATA

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Abstract. *The Internet of Things (IoT) technology has been widely used in the smart building, where the energy saving of air conditioning has attracted much more attention. Traditional manual adjustment is lag in time, while smart control is more timely, flexible, accurate and efficient for energy management. To ensure the energy efficiency of the building and the comfortable sensation of the users, the control strategies of the smart air-conditioning system should be analyzed and evaluated. In this paper, we propose a modeling and strategy evaluation framework based on Stochastic Hybrid Automata (SHA) which allows to model the behavior of smart air-conditioning system under varying environments and evaluate the performance of various control strategies in terms of energy and comfortable sensation.*

Keywords: Stochastic hybrid automata, Strategy evaluation, Smart air-conditioning system

1. **Introduction.** In recent years, the Internet of Things (IoT) technology has been widely used in the smart building, playing an important role in energy saving and emission reduction. As the largest energy consumer in the Building Automation System, the energy saving of air-conditioning system has attracted much more attention. Smart air-conditioning system can allocate energy based on use's perception on location, such as allocating more energy to more populated areas, which is more timely, flexible and efficient than traditional manual adjustment. The control strategy adopted in the system may cause significant influence on energy efficiency and comfortable sensation of the users, so it is essential for the system designer to analyze and evaluate the performance of control strategies and choose the appropriate one.

The smart control of the system is not limited to the temperature constancy, but the rational allocation based on energy requirements. While simulating the control process of the air conditioning system, we need to consider the uncertainty of user behavior, e.g., the individual user behavior affected by the uncomfortable room, as well as the time variation of the physical environment, e.g., the varying temperature in one day. The methods based on simulation [1-4] or mathematical analysis [5-7] were often adopted to analyze such cyber-physical system. In Simões and Bhattarai's work [1], an intelligent control strategy for improving energy efficiency of a commercial building using a multiagent system architecture was proposed. Chen et al. [2,3] proposed an environment-aware energy consumption evaluation framework based on the Statistical Model Checking (SMC) in their work to address the quantitative analysis problem for the energy consumption in a Cyber-Physical Energy System. In the work of [4], the authors presented the modelling formalisms of Stochastic Hybrid Automata (SHA) and proposed a framework for energy

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aware buildings allowing to evaluate the performance of the proposed control strategies. In our work, the simulation-based method Stochastic Hybrid Automata (SHA) was employed to model and simulate the air-conditioning system to evaluate the performance under various control strategies.

Up till now, a variety of academic software has been developed to implement and analyze timed automata and its extensions, such as the model checkers UPPAAL, Kronos, and TIMES [8], among which UPPAAL has now become the leader in the area. UPPAAL proposes efficient data structures and state-space reductions [9]. To allow for the efficient analysis of probabilistic performance properties, its extension UPPAAL-SMC proposes to work with Statistical Model Checking (SMC) techniques [10] which effectively avoid an exhaustive search of the state-space of the model. In early study, researchers [4,11] extended the modelling formalisms of UPPAAL-SMC to SHA. We use UPPAAL-SMC because of its good supports for modelling of SHA and analysis of probabilistic performance properties.

In this paper, we present the modeling and strategy evaluation method of smart air-conditioning system based on SHA. Firstly, the NSHA (Network of Stochastic Hybrid Automata) template of the air-conditioning system is constructed, which allows to be applied to different environments after modifying parameters. Then we transform the evaluation indices of control strategy to the specific query properties and run the model in the tool UPPAAL-SMC. The generated data are used for quantitative analysis and strategy evaluation. A case study of strategy evaluation of the air conditioner in a classroom building is conducted to support the proposed approach.

The rest of this paper is organized as follows. Section 2 introduces the notations of SHA and NSHA. Section 3 gives the details of our framework. Based on a smart air-conditioning system example in a classroom building, Section 4 presents how to construct and use the upper approaches to model the complex stochastic and continuous time behaviors of smart air-conditioning system and conduct the quantitative analysis of the proposed control strategies. Section 5 concludes the paper.

2. Preliminaries.

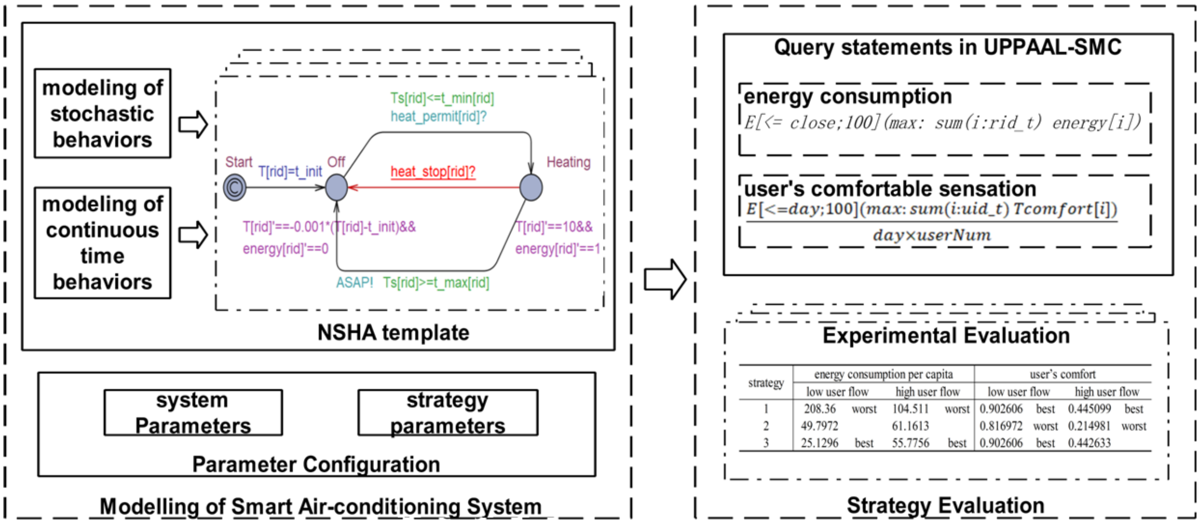
A Timed Automaton (TA) is a finite automaton extended with a finite set of real-valued clocks that can be used to model and analyze the timing behavior of real-time systems [12]. During a run of a timed automaton, all clock values increase with the same speed, i.e., increase by 1 per time unit. And the clocks can be reset. Multiple timed automatons can form a Network of (Stochastic) Timed Automata (NSTA) by synchronized channels and global variables.

Although powerful, timed automata is not expressive enough to describe the behaviors of complex cyber-physical systems, whose continuous time behaviors often rely on complex dynamics as well as stochastic behaviors [13]. The model checking problem for such systems is undecidable, and approximating those behaviors with SHA is more effective.

Definition 2.1. *Formally, a stochastic hybrid automaton is a tuple* $\boldsymbol{A} = (S, s_0, X, \tau, \Sigma, E, R, I)$*, where* S *is a finite set called the states of* A*;* $S_0 \in S$ *is the initial state of* A*;* X *is a finite set called the clocks of* A*;* $\tau \in X$ *is the system clock whose rate is 1 and cannot be reset in the run;* Σ *is a finite set called the actions of* A*;* $E \subseteq S \times S_0(X) \times \Sigma \times 2^X \times S$ *is a set of edges, called transitions of* A*;* F *is a set of clock rate functions, and* $R : S \to F^X$ *specifies a rate function vector for each state to represent the evolution of clock value in each state;* $I : S \to Up(X)$ *defines the invariants of each state.*

Unlike in timed automata, defining clock variables with various clock rates is permitted in SHA. The clock rate can be a constant or function of clocks. In the control process of the air-conditioning system, the indoor temperature varies with time and its rate is strongly related to the air-conditioning state. Such behavior can be modeled by the SHA. A Network of Stochastic Hybrid (timed) Automata (NSHA) is an NSTA with one or more SHAs. A cyber-physical system with complex continuous timing behaviors relying on stochastic events can be represented by an NSHA.

3. **Evaluation Framework of Smart Air-Conditioning System.** A modeling and strategy evaluation framework for smart air-conditioning system based on SHA was proposed in this section. The framework consists of two parts as shown in Figure 1.



strategy	energy consumption per capita				user's comfort			
	low user flow		high user flow		low user flow		high user flow	
1	208.36	worst	104.511	worst	0.902606	best	0.445099	best
2	49.7972		61.1613		0.816972	worst	0.214981	worst
3	25.1296	best	55.7756	best	0.902606	best	0.442633	

Figure 1. Evaluation framework of smart air-conditioning system

In modelling of smart air conditioner system, the automata templates of entities were constructed to generate the NSHA model of system, which allows to be instantiated to describe the behaviors of air conditioner system with customizable control strategies in a specific building environment by modifying the parameters. These automata templates are composed of five categories: (1) user: simulates stochastic behaviors of users (arriving, going to other rooms, and leaving the building, etc.); (2) sensor: responsible for the perception of building environment (user, indoor temperature, etc.) with time via various sensing and identification devices; (3) controller: the core of the system, which models the control strategy separately; (4) monitor: calculates the energy consumption and comfort indices of each room to analyze and evaluate the strategies; (5) room: describes the interaction between indoor temperature and air-conditioning control system.

The other part of our framework consists of several queries which estimates the evaluation indices by running the parameterized template in the model checker UPPAAL-SMC to quantitatively analyze the performance, i.e., energy and comfort of the proposed control strategies.

3.1. **Modeling of stochastic behaviors.** In SHA, the stochastic behavior of the system can be simulated by the probability distribution of the time-delays spent in a given state and the transitions between states.

The behaviors of the entity rely on the time factor, which indicates that the state of the entity may be transited within some time determinately or stochastically. In timed automata, the time constraint can be expressed by the time-delays spent in a state which is subject to uniform distribution, exponential distribution or user defined distribution. Figure 2 shows the transition from state s_1 to s_2, where x is a clock variable with an initial value of 0. Figure 2(a) indicates that the time-delay in state s_1 submits to the uniform distribution with parameter (t_1, t_2), where the guard formula $x >= t_1$ can be omitted when t_1 is 0. Figure 2(b) shows that the delay of the state s_1 is subject to the exponential distribution with the rate of *ep*. In addition, the probability distributions of the time-delays can also be defined by users as shown in Figure 2(c), where *distr*() is

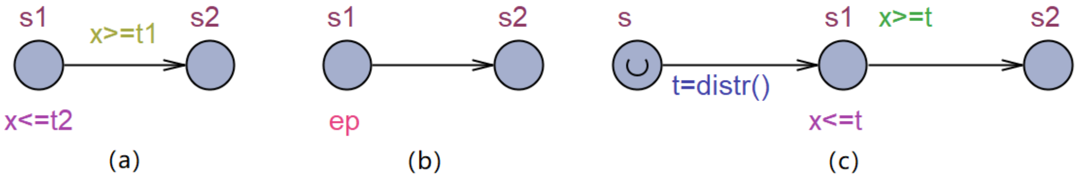


Figure 2. Modelling the stochastic behavior by the probability distribution of the time-delays in a state

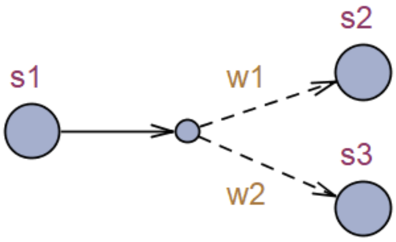


Figure 3. Modelling the stochastic behavior by the probability of the transitions between states

Figure 4. The modelling of the independent timing behavior

the distribution function defined according to the user demands and its return value is assigned to the variable t; the state with character U is an urgent state whose time delay is 0; the time-delay of state s_1 is t constrained by the guard $x >= t$ and the invariant $x <= t$.

The probability weights of the transitions are set when the entity state may be transferred to multiple states stochastically. As shown in Figure 3, w_1 is the probability weight of the transition from s_1 to s_2, and w_2 is the probability weight of the transition from s_1 to s_3. The state s_1 can be transferred to the state s_2 with the probability of $w_1/(w_1+w_2)$ or to the state s_3 with the probability of $w_2/(w_1+w_2)$.

3.2. **Modelling of continuous time behaviors.** Modelling the continuous time behaviors of environment is challenging but inevitable in most cyber-physical systems. This problem can be simplified by using clock rate in SHA. For the independent timing behavior, such as the evolution of some physical environment (e.g., outside temperature), an automaton model composed of a node with complex clock rate is constructed separately with the physical environment being regarded as an entity as shown in Figure 4, where x is the clock variable which addresses the simulated physical variable and c is a constant which tells variation rate of x. The clock rates cannot only be given by a constant but also by expressions involving other clocks, such as x_1. The $f(x, x_1)$ is a function of x and x_1. The equation $x' == c$ or $x' == f(x, x_1)$ shows evolution of x.

The dynamics of the physical world can be effectively described as stated above. However, the continuous time behaviors of cyber-physical system often rely on not only complex dynamics but also stochastic behaviors. For example, the rates of energy consumption are distinct in the working state and waiting state and state changes are commanded by the control system. The timing behavior relying on stochastic events can be expressed by an automaton with a clock that evolves with various rates and an automaton who sends the message stochastically. As shown in Figure 5, there are two automatons that A denotes the stochastic behavior where the event $e!$ must occur within t time units randomly while B models the relevant timing behavior. When the event $e!$ occurs, B gets the message by synchronized channel and moves from state s_{21} to s_{22}. The rate of its clock x changes from c_1 to c_2. The timing behavior x relies on the stochastic event e. Especially, when the rate of clock x is 1 in one state while the rate is 0 in other states, i.e., $c_1 = 1$ and $c_2 = 0$ in this case, the variable x can tell the time-delay in state s_{21}. Therefore, the time-delay in some state of an entity can be easily counted.

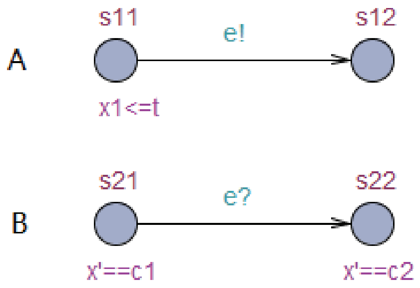


FIGURE 5. The modelling of the timing behavior relying on stochastic events

3.3. **Construction of NSHA.** To model the stochastic and continuous behaviors of system, a series of automata models were constructed. These automatons communicate via synchronized channels and global variables to generate the NSHA. The entities of the system conclude user, temperature, sensor, controller, monitor and room. The structure of NSHA can be built according to the relationships among entities as shown in Figure 6. User's location and temperature variation can be perceived by the sensor and sent to the controller and monitor. The air conditioner changes its state (on/off) according to the strategy and room temperature. The monitor calculates the energy consumption and comfort time of users dynamically. There are 4 channels where *permit* and *stop* denote the command that the controller sends while *arrive* and *leave* suggest the user's location. In addition, two automatons can share data by assigning and reading the global variable. A clock whose value is required to be queried must be stated as a global clock in UPPAAL. There are 4 important global variables, where T addresses the room temperature while Ts denotes the temperature that users feel, *energy* and *Tcomfort* are clock variables that calculate the energy consumption and user's comfort degree separately.

3.4. **Strategy evaluation in UPPAAL-SMC.** To evaluate the performance of control strategies on energy consumption and user's comfort degree, we use the tool UPPAAL-SMC to check the model properties. The query language is:

$$E[<= t; N](\max : \exp) \tag{1}$$

which estimates the average of the maximum value of exp of N runs within t time units, where t is the time bound of a random run, N gives the number of runs explicitly, exp is the expression composed of clock variables which refer to the performance indicator to evaluate.

4. **Case Study.** Taking a smart air-conditioning system in classroom building as an example, students enter the classroom to study subject to a Possion process. The students will feel cold and may go to other classrooms when the temperature gets too low. And they will get uncomfortable when the room is getting cold. There are three areas (rooms) in the building and an air conditioner in each area to keep warm in winter. The room

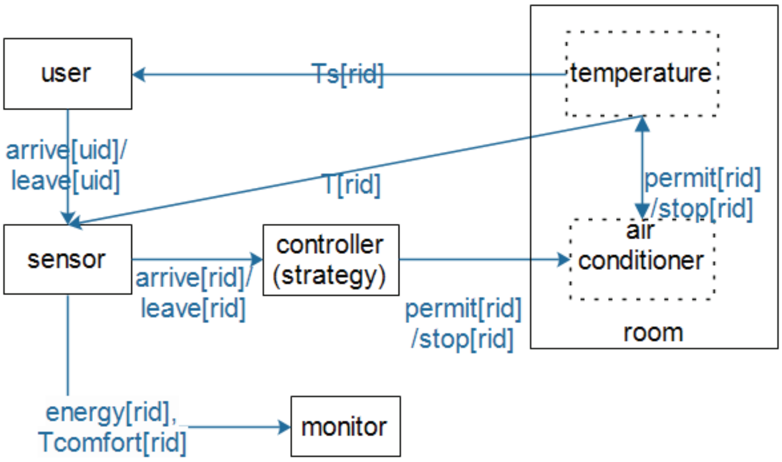


FIGURE 6. Structure of the NSHA model

TABLE 1. The experimental results of three strategies

User flow	Strategy	Energy consumption		User's comfort	
low	1	959.038	worst	0.8768	best
	2	183.394	best	0.5914	
	3	888.553		0.4529	worst
high	1	972.339	worst	0.9209	best
	2	667.483	best	0.7706	
	3	863.8		0.5209	worst

temperature is controlled ranging from 21°C to 23°C when the air conditioner in this room is turned on and the heat transfer between areas is not considered.

The system model is constructed and run under three control strategies in the tool UPPAAL4.1.19., which are: (1) turn on the air conditioner of the most crowded two rooms; (2) turn on the air conditioner in the room when the occupancy reached 20%; (3) turn on the air conditioner of the most crowded room and turn on the air conditioner in other rooms when the occupancy reached 20%. The statistical results under three strategies are shown in Table 1.

4.1. Energy consumption of three strategies.

According to the results, the energy consumption of the first strategy is the highest reaching 959.038 in low user flow and 972.339 in high user flow. Energy consumption for the second strategy is the lowest, which is 183.394 and 667.483 respectively. It can be concluded that the energy consumption of the second strategy is the lowest in both cases. In addition, the energy consumption for the second strategy is significantly lower under low user flow than high user flow, which indicates the second strategy is more suitable for low user flow.

4.2. User's comfort degree of three strategies.

The comfortable degree of users at a certain time is dependent on current temperature. The values of comfortable degree are given by $d_1 = 1$ when the temperature is higher than 21°C, $d_2 = 0.6$ when the temperature is between 18°C and 21°C, $d_3 = 0.2$ when the temperature is between 16°C and 18°C, $d_4 = 0$ when the temperature is lower than 16°C. It is expressed by clock rate in SHA. The overall comfort, ranging from 0 to 1, denoted by *cf*, is given by:

$$cf = \sum_{1}^{N} \frac{d_i \times t_i}{day} \tag{2}$$

which refers to the average comfort of users in a day, where t_i indicates the accumulated time of comfort degree of user's sensation is d_i and day is the time bound of a run. It can be transformed into query statement in UPPAAL-SMC to check the property.

The results showed that the comfort performance of the first strategy is the highest, reaching 0.8768 and 0.9209 respectively. And the third strategy is the lowest, 0.4529 and 0.5209 respectively. Therefore, the user comfortable sensation is the best for the first strategy and the worst for the third strategy regardless of the user flow.

In summary, the user's comfortable sensation for the first strategy is the best among the 3 strategies, but the performance on energy consumption is obviously inferior to the others. The energy consumption of the third strategy is lower relatively, but the user's sensation is the worst. The energy consumption of the second strategy is the lowest and user's comfortable degree is higher than the third one. It is not hart to be seen that the second strategy shows better performance than the third strategy both in high user flow and low user flow. Especially under the low user flow, the second strategy has obvious advantage in the energy consumption. Therefore, the second strategy is a better choice than the third one.

5. **Conclusions.** This paper proposed a modeling and strategy evaluation framework for smart air-conditioning system which simulates the randomness of user behavior and the time-varying nature of physical environment and analyzes the performance of control strategies. Compared to other work, our system takes user location as a major environment to input since user behaviors have significant impact on energy allocation in public buildings and we present the method for modelling stochastic and continuous time behavior based on SHA. It provides reference for the analysis, evaluation and optimization of smart air-conditioning control strategies, which is useful in the energy saving or improving efficiency of energy management of public buildings.

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REFERENCES

[1] M. G. Simões and S. Bhattarai, Improving energy efficiency of cyber physical systems using multi-agent based control, *IEEE Industry Applications Society Annual Meeting*, vol.2, pp.1-7, 2012.

[2] X. Chen, F. Gu, M. Chen, D. Du, J. Liu and H. Sun, Evaluating energy consumption for cyber-physical energy system: An environment ontology-based approach, *IEEE the 39th Annual Computer Software and Applications Conference*, 2015.

[3] C. Song, G. Fan, X. Yuan and C. Hong, Formal evaluation of scheduling strategies for smart building air-conditioning systems under uncertain environment, *Journal of Software*, 2016.

[4] D. Alexandre, K. G. Larsen, M. Marius et al., An evaluation framework for energy aware buildings using statistical model checking, *Science China (Information Sciences)*, vol.55, no.12, pp.2694-2707, 2012.

[5] J. Pinzon, P. Vergara, L. Silva et al., An MILP model for optimal management of energy consumption and comfort in smart buildings, *Power & Energy Society Innovative Smart Grid Technologies Conference*, 2017.

[6] D. Zhang, S. Li, M. Sun et al., An optimal and learning-based demand response and home energy management system, *IEEE Trans. Smart Grid*, vol.7, no.4, pp.1790-1801, 2016.

[7] E. Patti, A. Acquaviva, M. Jahn et al., Event-driven user-centric middleware for energy-efficient buildings and public spaces, *IEEE Systems Journal*, vol.10, no.3, pp.1137-1146, 2016.

[8] P. Bouyer, U. Fahrenberg, N. Markey et al., Quantitative analysis of real-time systems using priced timed automata, *Communications of the ACM*, vol.54, no.9, pp.78-87, 2011.

[9] K. G. Larsen, F. Larsson, P. Pettersson et al., Efficient verification of real-time systems: Compact data structure and state-space reduction, *IEEE Real-Time Systems Symposium*, 1997.

[10] A. David, K. G. Larsen, A. Legay et al., Statistical model checking for networks of priced timed automata, *International Conference on Formal Modeling and Analysis of Timed Systems*, pp.80-96, 2011.

[11] A. David, K. G. Larsen, A. Legay et al., UPPAAL SMC tutorial, *International Journal on Software Tools for Technology Transfer*, vol.17, no.4, pp.397-415, 2015.

[12] P. Krčál and W. Yi, Decidable and undecidable problems in schedulability analysis using timed automata, *Tools and Algorithms for the Construction and Analysis of Systems*, pp.236-250, 2006.

[13] S. N. Krishna and A. Trivedi, Hybrid automata for formal modeling and verification of cyber-physical systems, *Journal of the Indian Institute of Science*, vol.93, no.3, pp.419-440, 2015.

[14] A. David, D. Du, K. G. Larsen et al., Statistical model checking for stochastic hybrid systems, *Electronic Proceedings in Theoretical Computer Science*, vol.92, pp.187-199, 2012.

[15] A. David, K. G. Larsen, A. Legay et al., Time for statistical model checking of real-time systems, *International Conference on Computer Aided Verification*, pp.349-355, 2011.

[16] A. Fehnker and F. Ivančić, Benchmarks for hybrid systems verification, *The 7th International Workshop on Hybrid Systems: Computation and Control, Lecture Notes in Computer Science*, Philadelphia, PA, USA, vol.2993, pp.326-341, 2004.