AN ENERGY-AWARE, AGENT-BASED MAINTENANCE-MANAGEMENT FRAMEWORK FOR IMPROVING THE SATISFACTION OF OCCUPANTS

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Yang Cao

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AN ENERGY-AWARE, AGENT-BASED MAINTENANCE-MANAGEMENT FRAMEWORK FOR IMPROVING THE SATISFACTION OF OCCUPANTS

Approved by:

Dr. Xinyi Song, Advisor
School of Building Construction
Georgia Institute of Technology

Professor. Gary W. Merrow
School of Building Construction
Georgia Institute of Technology

Professor. Kathy O. Roper
School of Building Construction
Georgia Institute of Technology

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LIST OF SYMBOLS AND ABBREVIATIONS

ABM	Agent based model
AHU	Air handling unit
AI	Artificial Intelligence
AIM	A web-based management system
ANN	Artificial neural networks
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBR	Case-based reasoning
CMMS	Computerized maintenance management system
CoA	College of architecture
DOE	Department of energy
EMS	Energy management system
ES	Expected service
FM	Facility management
FMer	Facility manager
HTML	Hypertext markup language
HVAC	Heating Ventilation Air Conditioning
IEA	International energy agency
IEQ	Indoor environment quality
MARA	Multi-agent resource allocation
MAS-COR	Multi-agent system for construction dispute resolution
M&R	Maintenance and repair

PM	Preventive maintenance
POE	Post occupancy evaluation
RS	Received service
UML	Unified modeling language
VAV	Variable air volume

SUMMARY

Because more complicated building systems generate more diverse and complex maintenance issues, facility managers and their staffs nowadays must deal with many maintenance requests every day. Based on the empirical study on student residential buildings and campus buildings in this research, the maintenance requests can always be categorized into two types: service requests and preventative maintenance. Preventative maintenance is the pre-scheduled work to do the routine check, maintain and update for facilities. For example, the main component such as filter in big HVAC system in the campus is maintained by this scheduled work. The service requests are also called the reactive maintenance, which means facility managers take measures to solve the problem after some problem happened. For example, in a student apartment, Internet fail and abnormal indoor temperature are two of the most frequently reported service requests. This research will only focus on the service requests.

With limited budget and staff, not all maintenance requests can be dealt with immediately. This is the fact that been found through the communications with facility managers in residential, commercial and campus buildings. To schedule maintenance work, facility managers first consider the impact of each problem on system failure and life safety. In addition to those two factors, this thesis proposes to consider the occupants satisfaction as well as energy impact of service requests to prioritize work. Seldom former researches considered the occupant satisfaction but it is of great importance because creating a comfortable living environment is the final goal of building operation. In some residential buildings, the satisfaction level might also impact the economic benefit of owners through the changing occupancy rates. For the energy impact factor, this research only targets at the HVAC system because it is the biggest energy

consumption building system. Compared with a normal situation, a faulty HVAC system always wastes more energy to meet the same heating/cooling load.

Many different research methods have been attempted to quantify the occupant satisfaction and energy impact. In the first stage of research, both of them are evaluated by facility managers based on their work experience. In the later stage of research, the occupant satisfaction is determined by an empirical study with a structured questionnaire. The design of the questionnaire is based on the findings of post occupancy evaluation (POE) and many classical theories on customer satisfaction researches. The energy impact is quantified through the building energy simulation in EnergyPlus. Some faulty scenarios are simulated to calculate the total energy consumption and the result data provides useful suggestions for facility managers to prioritize their work.

After knowing how to quantify the two factors, namely occupant satisfaction and energy impact, this research further applies much computer science technology to automatically prioritize the work orders. This is one of the missing functions in the current computerized maintenance management system (CMMS). The main framework is designed by the agent based model (ABM), which is an artificial intelligence method. The agent has memory and can react to the environment based on its experience. The occupant (user) agent records information concerning occupants' evaluation for service requests. The problem agents record the required resources and impact of problem. The facility manager agent has the resources such as man hours. These three agents interact with others together to help facility managers prioritize and schedule the work orders. Moreover, the database and text-mining are also applied in this research to search the possible causes of the historical problems.

In a word, this research proposes an agent based framework to help facility managers automatically prioritize daily service requests. In this process, the research argues to consider occupant satisfaction as well as energy impact at the same time. Two main contributions will be mentioned in the following parts: first, many methods have been attempted to quantify the occupant satisfaction and energy impact. It has been a long time challenge to quantify the occupant satisfaction and this research makes a different attempt. The second contribution is the automatic program to support decision making on scheduling the service requests. The program is also able to offer suggestions on possible causes for some tested problems. In the model validation, the simulation results demonstrates that this agent based framework can not only improve the occupant satisfaction in the maintenance process, but also improve the energy efficiency by solving the more severe energy impact problem earlier.

CHAPTER 1

INTRODUCTION

Nowadays, with increasingly complex building systems the number of requests for building maintenance work is increased exponentially. In a typical medium-sized building (total area between 5,000 and 50,000 ft^2), occupants submit more than 50,000 requests for facility management (FM) service every year (Cotts et al. 2009). In most buildings, facility managers schedule work orders subjectively based on their work experience with limited budgets and human resources (Cao et al. 2014). However, this approach almost inevitably leads to inefficient operation and maintenance, which results in two significant problems: poor energy efficiency and decreased occupants' satisfaction (Wu et al. 2010).

Building Energy Efficiency

In 2013, commercial and industrial buildings consumed more than 50% of the total energy consumption in the United States (DOE 2014). More than 60% of the energy consumed by buildings was attributable to their various systems, such as electrical and HVAC systems (IEA 2012). Improving energy efficiency during the building operation phase is significant for sustainability. During the building operation procedure, facility managers have an important role in improving energy efficiency. In the *Facility Management Handbook* (Cotts et al. 2009), Cotts et al. emphasized the importance of the sustainable concept for the work of facility managers. One example is the energy audit. The FM handbook points out that one responsibility for building stakeholders is to determine the total energy consumption of a building and identify possible reduction measurements through energy audit (Cotts et al. 2009). Compared to the design and construction phase of a building's life cycle, FM has greater potential for energy savings, even from handling regular service requests. American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) estimated that the daily faults of HVAC systems account for 1-2% of the energy consumption in commercial buildings (EnergySmart 2014). This extra energy consumption is due mainly to the delay in detection of problems and the time it takes to solve the problems (Du et al. 2014).

Occupant Satisfaction

Occupants' satisfaction on their occupancy experience is another important aspect for facility managers to consider. Improved satisfaction will ultimately help to make profit for building owners. Post-occupancy evaluation (POE) is a prevalent research topic for more than 50 years. POE focused on determining the occupants' satisfaction and comfort levels with respect to the indoor environment of buildings (Lai 2013; Lai 2011; Meir et al. 2009). However, few research efforts have been conducted with the aim of determining the impact of maintenance work on occupants' satisfaction; when, in fact, the inefficient operation and maintenance of building systems waste large amount of energy and can significantly reduce occupants' overall satisfaction (Wu et al. 2010).

Meir reviewed the recent 20 years' published materials concerning POE to discuss its conceptual and methodological background. He is one of the few researchers who focused on operation phase with the purpose of determining its deficits and shortcomings (Meir et al. 2009). Cheong et al. also conducted a survey to identify the impacts of poor HVAC operation on occupants' satisfaction. They have pointed out that the maintenance of the HVAC system must be planned and conducted effectively to ensure the satisfaction of the occupants (Au and Ali, 2014).

Research Objectives

With the problem mentioned above, first of all, this research will try to quantify the occupant satisfaction and energy impact for some service requests. Second, this research will provide a useful framework to automatically prioritize the daily service requests based on these two factors. The results should not only differentiate the sequence of work orders, but also offer some suggestions on how to solve the problem.

CHAPTER 2

LITERATURE REVIEW

Agent Based Framework

This research applies the agent based model as the program framework. Although there is no consensus on the definition of agent, people agree on some characters of agent: autonomy, cooperation and learning ability (Nwana 1996). The agent is able to react to the environment and it can memorize the information based on its experience and then optimize its behavior to better fit the environment. Based on the references, one of the widely spread definitions can be understand as “a self-contained program capable of controlling its own decision-making and acting based on its perception of its environment, in pursuit of one or more objectives” (Wooldridge and Jennings 1995). It is these characters that making ABM a useful tool in FM. ABM in this paper will be the good decision support system to help facility managers in many aspects: prioritize work orders and offer useful suggestions from historical cases.

Multi-agent System Construction Industry

ABM has been applied in construction field for a long time. This phenomenon is due to the people’s awareness of the inherently complexity in construction problems and found difficulty in work on them. For example, Rinaldi mentioned that construction process is complicated for its interactivity with outer environment (Rinaldi et al. 2001). Human factor, weather condition, and design standard all increase the uncertainty and complexity of a construction project. Therefore, one of the famous research is considering the interaction between human and projects. One example is an ABM highway system which composed of pavements, bridges, signs, signals, and the decision makers (Sanford and McNeil 2008). They creatively solve the interactive process through agent model however author did not fully implement the much complex framework. Watkins applies ABM in construction site to predict and analysis the congestions which harmfully impact the efficiency of project (Watkins et al. 2009). Adaway also proposes a multi-agent system for construction dispute resolution (MAS-COR). Adaway believes that such a computer aided system is able to settle argument automatically (EL-Adaway et al. 2009).

Although ABM is already a prevailing method in construction management, its application in infrastructure management and facility management is limited (Osman 2012). Only a few researches focus on the ABM in facility management. Someone presents that ABM should be an effective decision support system in infrastructure management (Sanford and McNeil 2008). Osman conducted one of the most excellent researches: an ABM framework consists of four agents including occupant, asset, operator and politician. Occupant will have different level of satisfaction towards the faulty infrastructure system and in order to minimize this dissatisfaction, the politician agent makes decision on investment, and then operator will finish the work with the given resources. It firstly deals with the FM problem with consideration of occupants' satisfaction. The level of satisfaction is solved by behavioral model in the paper. It offers a lot of inspiration for this thesis on evaluating the occupants' satisfaction. Author also applies the same theory which will be introduced later in detail to quantify the satisfaction level.

Multi-agent Resource Allocation

In the later research, people raise an interesting problem in ABM that is multi-agent resource allocation (MARA). It can solve one kind of problem concerning limited resources. This method is also adopted in this paper because as mentioned before, one of the biggest challenges for nowadays FM is how to finish much work orders within limited resources. The definition of MARA can be described as follows: "The process of distributing a number of items amongst a number of agents" (Chevaleyre 2005; Chevaleyre et al. 2005). Some scholars apply MARA in asset management because it can address the system deficiencies concerning limited resources (Sanford and McNeil 2008). Obviously, this method is also suitable for construction industry because of sharing entities in it and their competence for limited resources. Besides, how to allocate the resources greatly affects the cost the projects (Liu and Mohamed). One of the best papers is finished by Liu and Mohamed, who construct a MARA model to allocate the bay to ships. However this model is more like a static one because allocation process is finished one time. In reality, this process should go continuously and in this thesis author will remedy this deficit through the dynamic simulation.

Multi-agent Resource Allocation in FM

Based on the above analysis, this paper will raise a MARA model for FM. FM is also a complicated activity which needs a dynamic decision support system. Although there are many available software systems to support the decision process of FM such as Computerized Maintenance Management Systems (CMMS) (Halfawy and Froese 2007; Cotts et al 2009), they cannot realize the interaction between occupants and facility managers. The function of current software is limited to a database without the decision support function. Facility managers can find the information in a better manner from these tools but they also need to do the analysis by themselves. The occupants are service receiver so facility managers must meet their requirements rather than only considering building requirements. The model in this paper will refer the advantages of the above papers and solve the mentioned problem. The decision support system can automatically produce a schedule for facility managers and occupants' feedback is considered in the decision process. Later parts of paper will implement the model and do a simulation with a simple case study. The model is feasible to work well in different situations.

Application of Artificial Intelligence (AI) in Facility Management

ABM constructs the basic framework of the program. To implement the framework, some artificial intelligence algorithms are served as the brain to take actions. To solve a new problem, facility managers need to consider many factors such as how to solve it and when is better. The evaluation of the problems should come from the historical similar case, which provided the solid impact result on every factor. Few methods are able to assist facility managers to optimize their work schedule while considering many factors including the energy efficiency until artificial intelligence was brought in this field.

Twenty years ago, some scientists in computer science defined the artificial intelligence (AI): "The study of the computations that make it possible to perceive, reason, and act'" (Winston, 1992). It aimed at endowing the computer system with capability to think and act as human beings. This character attracted the attention of scholars to regard this method as an efficient way to manage the building while meeting multiple goals: "artificial intelligence (AI) methods (e.g. artificial neural networks (ANN) and case-based reasoning (CBR)), create opportunities for the development of novel attitudes towards a more integrated approach to built asset management" (Shohet and Lavy, 2004).

Many useful methodologies, such as constraint-based programming, fuzzy logic, genetic algorithms, logic programming, ANN, and CBR have been widely applied in construction industry (Watson, 1999; Alsugair and Qudrah 1998). The CBR is the most suitable one in FM because the information concerning how a building component is served and deteriorated can offer much useful guidance for the new problem (Motawa and Almarshad, 2013). However, the application of AI in FM is limited due to many difficulties. One of them is the fact that it requires comprehensive and structured as-built databases (Yu et al., 2000). For this problem, this research solved it in the first stage research through a keyword retrieving CBR model based on the existed database of the computerized facility management system.

Occupant Satisfaction

Considering the occupant satisfaction affected by service requests is one of the innovative attempts in this research. With more focus on the operation phases of building's life cycle management, many researchers proposed the idea of determining the factors that affect service quality and occupants' satisfaction with FM. Derren and Barry suggested that facility managers use service quality concepts originated in the external consumer market to learn how occupants feel about their service. The approach is called SERVQUAL. It uses a multi-item （such as communication, credibility and security） scale for evaluating the perception of occupants towards a service. The results will help facility managers improve the performance of the existing management methods and provide better delivery of the appropriate services to meet customers' specific requirements (Shaw and Haynes, 2004). Siu conducted research to assess the quality of mechanical and engineering services in building maintenance. He posited that service providers with a clear sense of clients' expectations are in a better position to provide service that meets those expectations, which in turn results in a higher level of service quality (Siu et al. 2001).

The above research demonstrated the importance of improving the quality of service in FM. Lai did further research using an analytical hierarchy process to define high quality and cost-effective FM from five aspects, i.e., security, leisure and landscape, repair and maintenance, general management, and cleaning. The results showed that good service in repair and maintenance has a significant impact on occupants' satisfaction (Lai 2011). In addition, Meir et al. are interested in determining the factors that are related directly to occupants' satisfaction. The most well-known research in this area is the post-occupancy evaluation (POE), which is a platform for the systematic study of occupied buildings to determine the buildings' functioning and performance concerning indoor environment quality (IEQ), thermal performance, as well as subjective factors, such as users' satisfaction. The purpose of POE is to improve the buildings' current conditions and guide the design of future buildings (Meir et al. 2009). For the POE and IEQ, five aspects are included, namely, thermal, lighting, acoustic, space and indoor air quality, and comfort. These aspects are summarized from empirical studies of occupants' comfort requirements in buildings such as the work in Wang and Zamri's work (Wang and Zamri, 2014). The service quality of FM affects the indoor environment and thus it can be evaluated based on above factors to quantify the occupants' satisfaction.

<u>Disconfirmation Theory and Zone of Tolerance</u>

In this paper, the disconfirmation theory was used to explain the relationship between FM schedule and occupants' satisfaction. Based on the literature on consumer behavior, satisfaction is related closely to the size of the disconfirmation experience, with disconfirmation being related to the person's initial expectations (Churchill and Surprenant, 1982). Satisfaction, S, can be expressed by the following equation:

$$S = \sum (RS - ES), \qquad \text{Eq.1}$$

where S is the customer's satisfaction, RS is the received service, and ES is the expected service. For example, the FM service in this paper will be affected by the response time, skill and knowledge of manager and so on. More details will be clarified in the next chapter. This equation indicates that the total satisfaction level, S, of a consumer is the sum of all the service experiences over a given period of time. For every service encounter, the satisfaction is determined by the difference between RS and ES.

This theory is the most accepted satisfaction theory to explain the satisfaction level with service quality. Since FM is one of the fields in the service industry, FM-related staff members provide various services, including maintenance, for occupants or tenants who live in the building. The service that is provided by FM staffs influences the occupants' satisfaction level`.

Another important construct used in this paper is called the zone of tolerance, which emerged from the literature dealing with both service management and consumers' behaviors (Johnston 1995). Poiesz and Bloemer first argued the need to connect the expectation of customers and the outcome of service. This construct is a graphical representation of the disconfirmation theory.

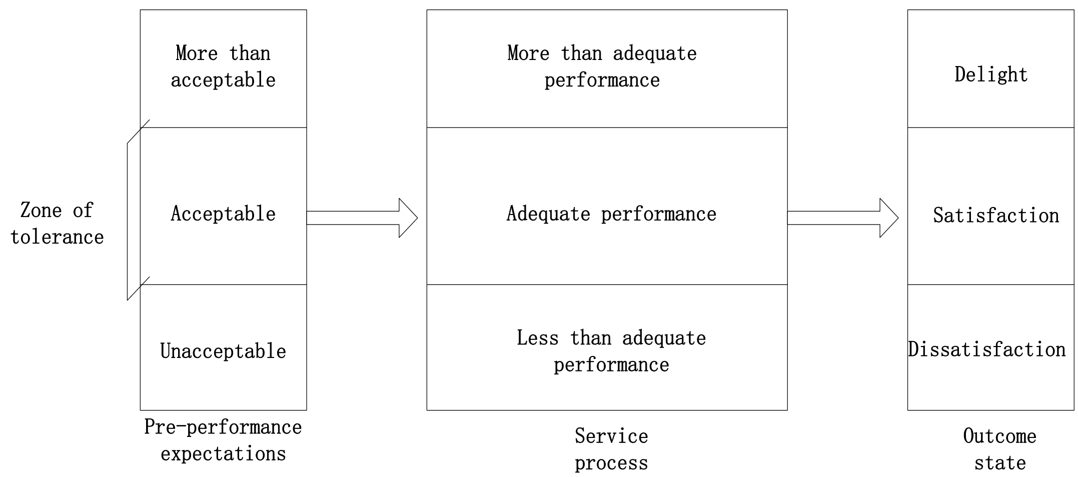

Figure 1. Zone of tolerance (Johnston 1995)

In Figure 1, the left part is the expectation of a consumer. Normally, people have three different expectations, i.e., more than acceptable, acceptable, and unacceptable. The zone of tolerance is the width of the acceptable field. In the service process, if the customer receives adequate performance, the feeling will be satisfied; if the customer receives more than adequate performance, the feeling will be delight, and if the customer receives less than adequate performance, the feeling will be unsatisfied. For a long-term process, the overall satisfaction feeling is the outcome of the accumulated experiences.

<u>The Impact of Schedule on Occupants' Satisfaction</u>

The disconfirmation theory lays the foundation for quantitative research of occupants' satisfaction. As stated before, FM maintenance is also an activity in service industry therefore the theory is applicable for it. To build a quantitative model, we must determine its unique, influential factors on occupants' satisfaction.

FM covers all of the aspects of service required to keep the building performing well. Maintenance is one of the most important aspects that can remedy problematic building systems. Delays in performing maintenance work impair occupants' comfort level and productivity. Recent research was conducted to determine how to improve occupants' satisfaction while finishing the required maintenance work (Au and Ali, 2014). The goal of the research was to determine the factors that affect the occupants' satisfaction during the performance of maintenance.

Table 1. Statistical data for maintenance characteristics (Au and Ali, 2014)

Maintenance characteristics	Occupants' satisfaction	
	Correlation coefficient	Significance Value
Skill and knowledge of laborer	0.634	0
Number of laborer	0.192	0.035
Stock of spare parts and materials	0.108	0.239
Quality of spare parts and materials	0.608	0
Length of predetermined maintenance interval	0.02	0.83
Response towards failure and downtime	0.617	0
Skill and knowledge of manager	0.697	0
Availability of maintenance equipment and technique	0.152	0.099
Capability to adopt maintenance equipment and technique	0.553	0
Accuracy of maintenance data and information	0.589	0
Frequency of monitoring and inspection	0.189	0.039

The statistical results in Table 1 demonstrated that four factors dominate the satisfaction level, i.e., the skill and knowledge of laborer, quality of spare parts and materials, response to failure and downtime, and accuracy of maintenance data and information. The response to failure and downtime is the factor considered in this paper because it is determined by the schedule of maintenance work. If the problem is solved prior to the expected time, the occupants will be delighted with the result. If the problem is solved on time, the occupants will be satisfied with the result, but, if the problem is solved after the expected time, the occupants will be dissatisfied.

Energy Impact of Fault HVAC in FM

In 2014, half of the energy consumption of the United States was attributable to buildings, and more than half of this energy consumption was due to the HVAC systems (DOE 2014). In the past, research was focused on the design of the HVAC system to minimize energy consumption. Later, it was determined that different maintenance practices associated with HVAC systems can result in substantial differences in a building's use of energy, maintenance costs, and also lifecycles of the equipment (Brandt and Reffett, 1989). To know more about improving the energy efficiency, people started to evaluate the energy change for daily HVAC faults. Several sources of information regarding commonly occurring HVAC faults were identified. The most useful source was a report produced by International energy agency (IEA)'s document "IEA Annex 25", a collection of reports on fault detection and diagnosis from researchers in a number of different countries such as Canada, France and Germany. In addition to the IEA Annex documents, useful information also was found in doctoral theses (Shun 2009; Siegel 2002; Lee et al. 2010), which documented the energy penalty associated with various air-side system faults. Their findings suggested that a single Variable air volume [VAV] box damper being stuck open on every floor could increase the use of energy for cooling by 36%. As part of their fault detection and diagnosis studies, Katimapula have highlighted the waste of energy caused by HVAC faults in buildings. (Katimapula and Brambley, 2005) determined that poorly maintained, degraded, and improperly controlled equipment wastes an estimated 15 to 30% of the energy used in commercial buildings.

The problem then came into how to measure the increased energy consumption resulted from the fault HVAC system. Much effort has been spent on assessing the energy efficiency. For example, a framework was proposed to characterize the energy efficiency by 5 categories and with 17 attributes (Trianni et al. 2013). Another research established an innovative building energy efficiency rating system and proposed an incentive and penalty framework to improve the energy efficiency (Koo et al. 2013). The research carried by Roger Woods and Bill Smith did some related evaluation on the problem of HVAC system. The research was carried in N.C. University Hall and some key data are demonstrated as follows.

Table 2. Energy consumption increase for some HVAC problems (Woods and Smith, 2011)

Problems	Energy Consumption Increase
Dirty filters in AHU's (add 1" static pressure)	4.10%
Fan Speed Malfunction	8.40%
Pump Speed Malfunction	10.60%
Dirty Cooling Tower"	1.30%
Fouled Tubes	2.20%
Poor Refrigerant Charge	3.70%

The above evaluation is significant for facility managers to reconsider a new problem. However, due to the time and fund restriction, author cannot finish the quantitative assessment of all HVAC problems.

The above method is measuring the data directly from the real system, however, due to the difficulty of collecting the data directly, from the 1960s, researchers have resorted to simulating the use of energy in buildings to learn more about the energy impacts. Although this new method was very convenient for simulating the systems in large buildings, most programs available today that simulate the energy consumed by a building have limited capabilities of directly modeling HVAC operational faults or maintenance issues, which occur in almost every building (Basarkar 2013).

The researchers at the Lawrance Berkeley Laboratory recently have proposed new ways to evaluate the energy impacts of individual maintenance issues as well as combined scenarios for an office building with central VAV systems and a central plant by EnergyPlus simulations using three approaches, 1) direct modeling with EnergyPlus, 2) using the energy management system feature of EnergyPlus, and 3) modifying the source code of EnergyPlus (Wang 2014). Their approach can be summarized in two steps, 1) collect the changed mechanical data for HVAC faults from an empirical study and 2) use the collected data to adjust the database in the simulation model. The detail procedure and the simulation will be introduced in the following part. This paper applies the same methods and refers to the data from their research.

Building Energy Simulation

Building energy simulation is also named with the building energy modeling. This is a computer aided technology to support the dynamic simulation of the operation of a building. Modelers highly replicate the real building into the computer program by inputting a large number of parameters: weather file, building envelop, heating/cooling load, building system, occupancy schedule and so on. The building simulation helps people to see the operation of the buildings in any phase with any possible modifications. Although there are deviation between the predicted data and the real data, it can give people a broad view of the operation status and offer many useful suggestions on design and building retrofit. In this research, the needed data is the energy impact resulted from the HVAC faults. It is difficult to collect sufficient real data and the simulation is able to produce it.

There are so many good simulation software such as EQuest, EcoTest, DesignBuilder, TRNSYS, EnergyPlus… In this research, the EnergyPlus is chosen as the simulation tool. Because there was a similar research from Lawrance Berkeley Lab to quantify the energy impact of HVAC fault. This research will use the same methods proposed by the researchers and last refer part of their data.

EnergyPlus is a fourth generation tools tend to be fully integrated with respect to different building performance aspects, with new developments concerned with intelligent knowledge-based user interfaces, application quality control and user training.

The following picture is the interface of the EnergyPlus. Users are required to define the weather report and input the EnergyPlus input file (IDF file) to do the simulation. IDF file includes all the building related information and data required for simulation. It can be edited by the DesignBuilder. To change some parameters, users can be either modify the parameters in DesignBuildler but also in the IDF editor

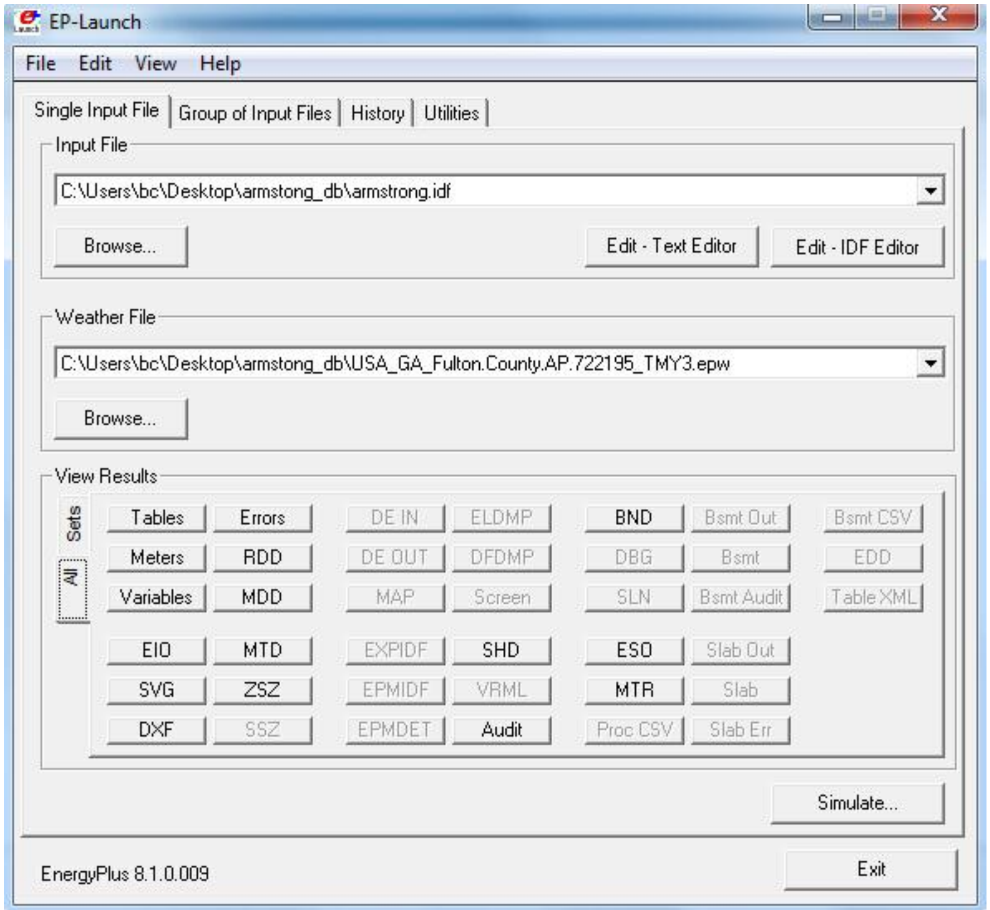

Figure 2. Interface of EnergyPlus

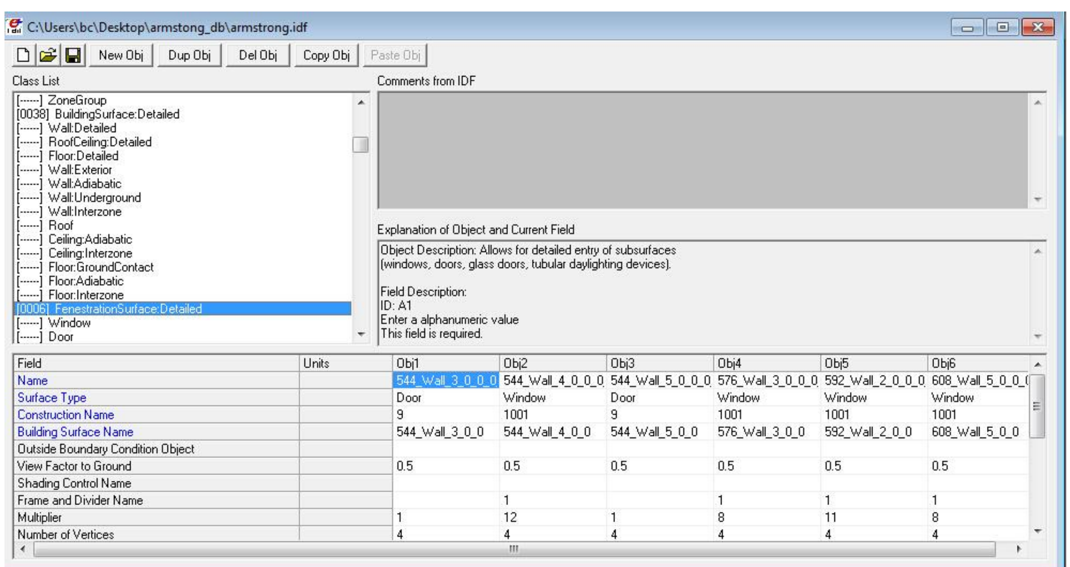

Figure 3. Interface of IDF editor

Most building energy simulation programs available today have limited capabilities of directly modeling HVAC operational faults. However Basarkar et al.

(2012) implemented four types of equipment faults in a development version of EnergyPlus to simulate common faulty operation in building systems. Lipin and Tianzhen (2013) did a further research on fault modeling, develop modeling and simulation methods for maintenance issues and assess the impacts of common maintenance issues on building performance.

In their research, three different approaches using EnergyPlus, in order of difficulty, are used to model HVAC maintenance issues:

1. Direct modeling with EnergyPlus (Direct Modeling)

In this approach, the user directly change the parameters in the EnergyPlus if they already know how the parameters change in fault scenarios. Based on the introduction of Lipin and Tianzhen, this modeling approach can be applied to such maintenance issues as supply air sensor offset, zone thermostat offset and outdoor air damper leakage. This approach is also applied to model simplified maintenance issues such as chiller or boiler fouling by introducing a degradation factor to the chiller or boiler efficiency inputs to the EnergyPlus models. The advantage of this approach is easy implementation.

2. Using the energy management system (EMS) in EnergyPlus

EMS is an advanced feature of EnergyPlus and designed for users to develop customized high-level, supervisory control routines to override specified aspects of EnergyPlus modeling in the EMS program. Users need to put much effort on programming and design the customized algorithms to let the building operate as scheduled. EMS is used to model maintenance issues like dirty filters which increase pressure drop across the filter with operating hours.

3. Modifying EnergyPlus source code (Modified Code)

This is the most difficult method because it needs users fully understand the source code of EnergyPlus and modify it based on the private requirements. Due to the time limitation, this method cannot be finished so this research will directly refer the related data simulated from this approach. Such HVAC maintenance issues as cooling coil fouling, outdoor air and return air temperature sensors offset adopt the third approach.

Text Mining in Construction Industry

Text mining is a famous data mining method specialized in solving text data analysis. This method involves the knowledge in computer science, machine learning, statistics and so on. It has a long history dating back to 1980s since it was been firstly proposed. Some researchers proposed this concept in a computer science conference in 1982 (Hobbs et al. 1982). Up to now, this data mining technology has been applied in construction industry in some areas. Mohammed and Amr designed an automatic clustering of construction project documents based on textual similarity. Their contribution is that they attempted the unsupervised text mining algorithm to cluster the new construction file into an existed category. The deficiency of supervised text mining, as mentioned by the authors, is that sufficient different documents should be provided to train the model and then the new file can be categorized. However in the practice, every project has its own characteristics and thus it is difficult to have a lot of similar projects before a new one happens (Al Qady and Kandi, 2014). Hongqin and Heng applied the text mining in retrieving similar cases for alternative resolution in construction accidents. The happening of construction accidents is normal in real life so how to resolve the dispute resolution is a trouble for project stakeholders. Authors proposed to use text mining to find the similar accidents occurring in the past in the same jurisdiction and then offer the suggestions to solve the dispute based on the historical case (Fan and li, 2013). Another interesting application of text mining is from Williams and Gong. They used the method to predict the construction cost based on the construction documents. Some important text information that might affect the cost such as area and materials was used to compare the similarity of two projects. Authors tried five different algorithms and then combined them together to minimize the error. The results showed that the text mining based methods provide an average accuracy of 44% (Fan and Li, 2013). In a word, text mining is useful for information searching among a lot of text documents. Construction as well as FM processes always produce a lot of documents. Therefore text mining offers an automatic and time-saving information retrieving method.

CHAPTER 3

METHODOLOGY

Research Process

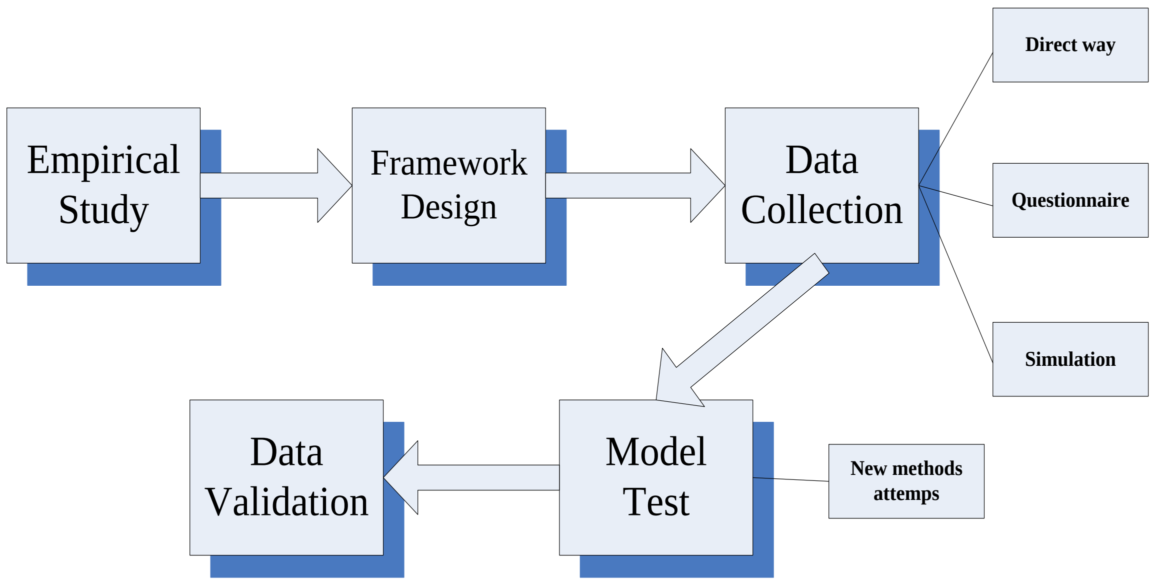

Figure 4. Research Process

In the past two years the research was conducted in the above five main steps: empirical study, framework design, data collection, model test and data validation.

The first step is the empirical study, it lasted for a semester. Author tried to know the current situation on how facility managers deal with the numerous work orders. Author first worked with the facility managers in two student residential apartments near Georgia Tech: 100 midtown student apartment and Westmar student apartment to know their work process. The reason for choosing these two buildings is the occupants type are simple (majority of occupants are graduate students) which minimize the difficulty on quantifying their satisfaction level. Besides, in the student residential apartment the typical problems are in a wide category which might be useful for solving more problems. Except for working in the student residential apartments, author also cooperated with the facility managers and energy conservation team in Georgia Tech. They have a mature computerized maintenance management system which can not only offer data for this research but also reflects the deficit part which can be optimized.

The second step is the framework design. This step is the programming work and "indoor" research. Author needs to design an automatic framework to realize the proposed functions. Here author uses the Java language and also tried the software Anylogic, which is a professional simulation software for agent based model design. The designed framework does not mean it is perfect. The update of the framework is a continuous process in the whole research.

The third step is the data collection. After having the framework, data can be inputted into the framework to test the model. However the data collection is not an easy job in this research. As demonstrated in the figure, author tried three different ways to collect the data. First one is the direct ways that is by talking with facility managers and get the data directly from their CMMS. However, in the former part we have discussed that there is few data concerning occupant satisfaction and energy impact so for these two factors this research also adopts two other methods. The structured questionnaire was designed to know both the occupants satisfaction and energy impact. In the further research, the building energy simulation is used to get the more reliable data concerning the energy increase of fault HVAC system.

The fourth step is the model test. In this step, the program was run to test the feasibility of the model. This step focuses on the technical side of the program. In the process, author also tried many different methods and algorithms to find the most suitable one to support the maintenance management in this research.

The fifth step is the data validation. In this step, the data validation is done through the simulated scenarios to conclude the effectiveness of the proposed framework. The reason by using simulation is that it is difficult to first apply the model into real life.

Another thing that needs to be clarified is that the whole research process can be divided into two part, that is stage one and stage two. In the following part, detail work which has been done in each stage will be introduced.

Stage One of Research

Model Working Procedure

In the first stage of research, the case study aims at producing a FM tasks schedule automatically for the two facility managers in a residential building. The following figure explains how our model works in the situation.

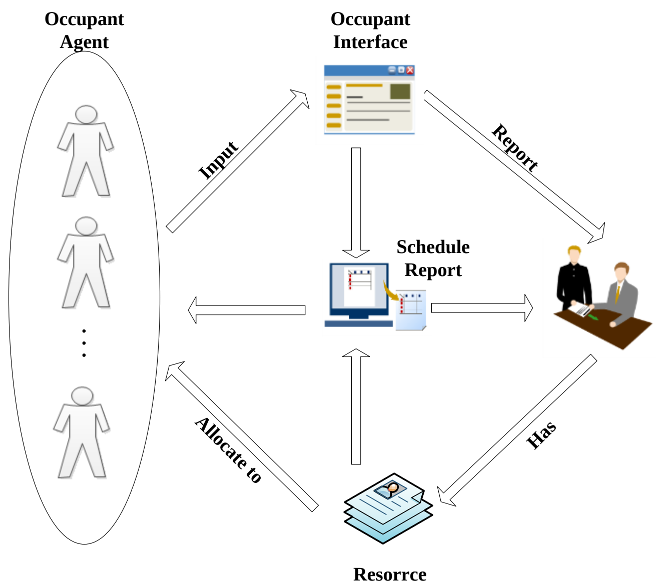

Figure 5. Framework of the Maintenance Support System

1. The occupant agent system contains all the occupants in this building, who encounter daily problems of facilities. Whenever a problem happens, people can log into a occupant-oriented interface to input the specific details of problem. At the same time,

occupant is able to choose their preferred date and evaluation on the emergent degree of the problem.

2. Problem database contains all the real time problems reported by occupants. Then system will automatically convert all the current troubles into a visible file to facility manager. In this way, facility manager will have a general view on what need to do.
3. The most important attribute of facility manager agent (FMer agent) is the resource. Facility manager has a limited budget and human resource to fulfill the work of facility management. Therefore, after received the tasks FMer agent need to allocate the limited resource to solve tasks according to priorities.
4. Once FMer agent makes an allocation plan, occupant agent will evaluate it based on their own situation, which is connected to the preferred processing time.
5. When the evaluation outcome of occupant agent is not satisfied (negative feedback can be sent manually to FMer), FMer agent will receive a negative feedback and proceed to change its allocation plan. Until the occupant agent is agreed with the schedule, FMer agent will decide the result.
6. The last resource allocation plan corresponds to a schedule. Because if we know when will the task begin and how much resource will be put into it, we can calculate the exact start time and end time of the task. The schedule report covering all the future plan is available to both occupants and facility manager. Occupants can know the start time of their own reported problem. While facility manager will have a detailed work schedule.

This model can be also explained by three main functions: input, data analysis and output:

1. Input

The input of the system is the user interface for collecting daily service rquests (SR) in buildings. Normally, occupants can use telephone, email and online system to input their problems. After receiving all the requests, facility managers need to input the collect request into their FM system. The key information may include location of the building, building components that have the problem, features of the problem.

2. Data Analysis

The data analysis module is the core of the system. All of its function is based on the knowledge database, which contains the old cases concerning FM work. Three main functions are CBR, impact on energy and impact on occupants. The system provides the CBR for every new task to find the similar cases happened in the same parts or similar ones. The historical information is useful to help facility managers evaluate the possible finish time and cost on the new problem. Also it can help facility managers predicate what causes the problem and how to solve it. Contrarily, the current case is that worker needs to first go to the site the check what causes the problem and then decide how to solve it. Sometimes they will go back and get the required equipment and materials and then solve the problem. This system can change this situation.

The innovation part of the system is prioritizing the FM work based on their impact on energy efficiency and other related factors. The current case is that when one worker has many tasks on hand at one time, he will choose one of them based on work experience. This may cause potential problem on impairing the energy performance because some problems cause severe energy loss such as abnormal strong air flow from the air-conditioner and water leak.

To deal with the above problems, this system considers different factors of the SR based on their characteristics. The energy impact factor is an innovative consideration. The analysis result will help facility manager to make a specific schedule for every worker including the sequence of their future work.

3. Output

Based on the above introduction, the output of the system is the priority of SR according to their impact on energy as well as other concerning factors. It can help facility manager to decide which work needs to be finished first scientifically, not just base on their work experiences.

How to Provide the Suggestions for New Work Orders

In the first stage of research, author attempted both database technology and text mining to search the possible causes for some service requests. The possible causes are coming from the old case database. In the current CMMS, facility managers did not record the root cause of solved problems. Author here analyzes some problems and talks with facility managers on the causes and store them into database. The process of retrieving old cases is called case based reasoning (CBR).

Case based reasoning (CBR) is a problem-solving approach in AI. It is a technique utilizing the previously experienced concrete cases to solve the new cases (Kim and Han, 2001). Some former researches have recognized the five steps of CBR: retrieve, reuse, revise, review and retain (Aha, 1998). The most difficult part is the first one: retrieve. Algorithms need to be designed for computer system to find the "similar" cases.

Motawa and Almarshad (2013) did a related research to apply the CBR in FM. In his research, every historical case has 10 attributes to determine the uniqueness. The nearest neighbor algorithm was adopted to search for the most similar case. His model covers all different problems in FM. However, this research is focusing on the HVAC system. For the large number of HVAC cases in the database, some relation determines the fact that not every case is unique. In another words, normal HVAC problems are categorized for some types. Solution for one type of problem might be similar. For this reason, it is unreasonable to retrieve the case from all the historical problems. Instead, the retrieving result should be one type of problem. Moreover, the normal CBR needs much subjective evaluation of the people, which impairs the accuracy of case retrieving.

To solve this problem, the text mining in AI and cluster algorithms are the best solutions. Text mining does not require the quantitative evaluation of a problem; it is based on the text similarity to search the cases. It has been attempted to apply in finding construction document (Mohammed and Amr, 2014). For HVAC problem, if reporter can provide sufficient text descriptions of a problem, then the mining process can be easily conducted. The data system is designed as following two steps:

- Cluster

The historical cases are used for machine learning to categorize them into different types. For text mining, the standard of differentiation is the words frequency of problems, which can be found by different cluster algorithms.

- Retrieve

The text of a new problem will be used for finding the most similar category.

Multi-agent Modeling in Facility Management

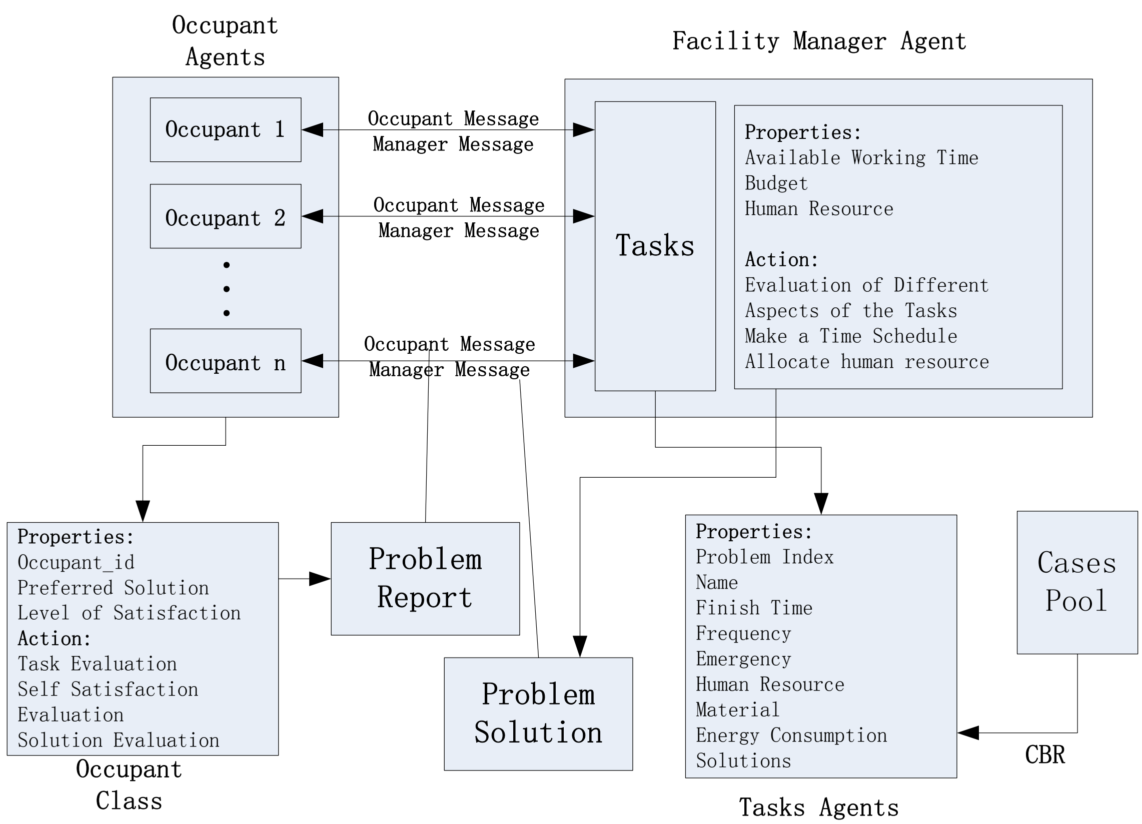

Figure 6. Agent-Based Framework in Stage 1

In the first stage of research, author proposes a multi-agent resource allocation system for the FM. There are three kinds of agent in FM system: occupants, facility manager and tasks. We assume that in a single project the facility manager is an integrated entity so there is only one facility manager agent who is responsible for all the FM tasks. However every occupant is independent so n occupant agents are different entities. Both occupant agents and facility manager agent are the standard types which are capable of taking actions respond to other information. They have different properties and are capable of taking many actions. The tasks agent is a static one without action or behavior in the communication process. They have many properties which may largely affect the behavior of occupants and facility manager. Most of the properties of tasks agent are based on case based reasoning when required and therefore the properties may change at different time.

1. Occupant Agent

The main properties of occupant agents are preferred solution as well as level of satisfaction. To every task, occupants have their own preferred solution such as schedule time. Occupants' feedback to a solution produces the level of satisfaction, which affects the behavior of facility managers. Occupant agents can evaluate the problem and solution sent by facility managers. Problem evaluation may concerns the emergent degree in a certain situation and so on. Occupant agents connect to the facility manager agent by sending problem report message to facility manager agent and receiving problem solution message from it.

2. Facility Manager Agent

Similar to occupant agents, facility manager agent behaves differently according to different situation. The properties of it are mainly concerning resource limitation. Facility manager has limited schedule working time, budget and human resource. Naturally the action or behavior is focusing on how to effectively allocate the resource to solve the tasks. Furthermore, facility manager needs to evaluate the factor of tasks and make a time schedule for dealing with tasks.

3. Tasks Agent

As mentioned before, task agent is the only static agent without active actions but it affects other agents' behavior. Different tasks have specific properties based on historical data such as frequency and emergency. Besides, tasks have properties to demonstrate how to solve them, such as finish time, required human resource, and required material. All these properties are closely restricted by resource of facility manager agent. In an idea system, these properties are calculated based on cased based reasoning from a large cases pool. For example, by searching a most similar task in cases pool, the needed human resource can be evaluated from it.

Data Collection

In this stage of research, the normal service requests are collected from the 100 midtown student apartment, a student residential building located near the Georgia Tech. The detail data will be demonstrated in the next part. For the occupant evaluation data, it is collected from the subjective of facility managers and some occupants.

Occupant agents will input all the problems into the interface designed by HTML with their preferred data and evaluation of emergent degree.

Figure 7. Maintenance problem report interface

It can be represented as (a,b,c), in which a represents the number of problem, b represents the preferred data while c represents the evaluation of emergent degree.

When scheduling all the tasks, managers will consider two factors: the objective emergent degree ranked by them and the subjective emergent degree evaluated by occupants. The objective emergent degree is given in the above part.

Obviously, sometimes occupants may have some special need for a task for some causes, which can dramatically increase the emergent degree for one time. Therefore the total emergent degree can be represented as

$$E_{total} = \omega_{fm} \times E_{fm} + \omega_{user} \times E_{user} \qquad \text{Eq.2}$$

E_{total}: total emergency level;

ω_{fm}, ω_{user}: weight value for facility managers and users;

E_{fm}, E_{user}: emergency level evaluated by facility managers and users.

Theoretically, the above two weights can be adjusted based on manager's opinion. In some cases, manager cares more about people's satisfaction and then the weight of occupant can be larger. This is also the cause of our model can be applied to any building.

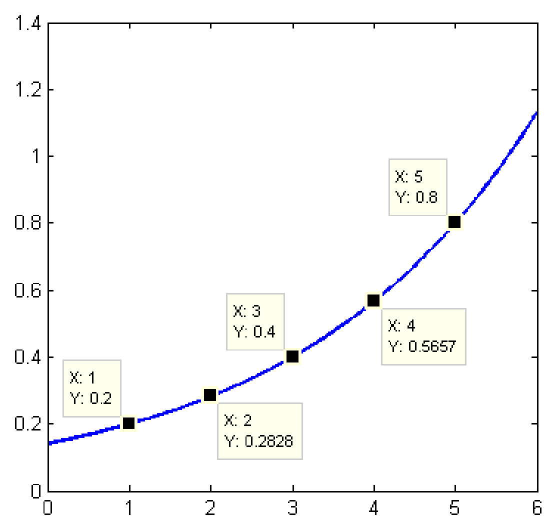

Figure 8. Exponent model for emergency evaluation

The weight of occupant ω_{user} is not a constant value even in one building. It changes with different occupants' evaluation. The function relationship can be suggested by the following chart.

In this kind of function relationship, the weight of occupant's evaluation will increase when occupant gives higher scores for a task. It can solve the situation when a normal task is extremely emergent for a occupant then the task will be addressed in advance.

For the CBR process only the HVAC related service requests are considered because they produce impact both on occupant and energy efficiency. Here the target system is in Georgia Tech for the convenience of data collection. Because this is only an illustrative example so there will be no problem that data comes from different sources.

Last, the energy data is collected through a survey in the appendix a. The results will also be demonstrated in the next chapter.

Stage Two of Research

Agent-Based, Maintenance-Management Framework

In the second stage of research, the ABM framework has been modified a little bit. Three types of agents are used in this framework, i.e., occupant agents, problem agents, and manager agent. For the purpose of considering occupants' satisfaction, every occupant represents an independent agent because everyone has different living habits and different comfort requirements. Similarly, a different problem stands for an independent problem agent. Only one manager agent is in the system to solve all the reported problems.

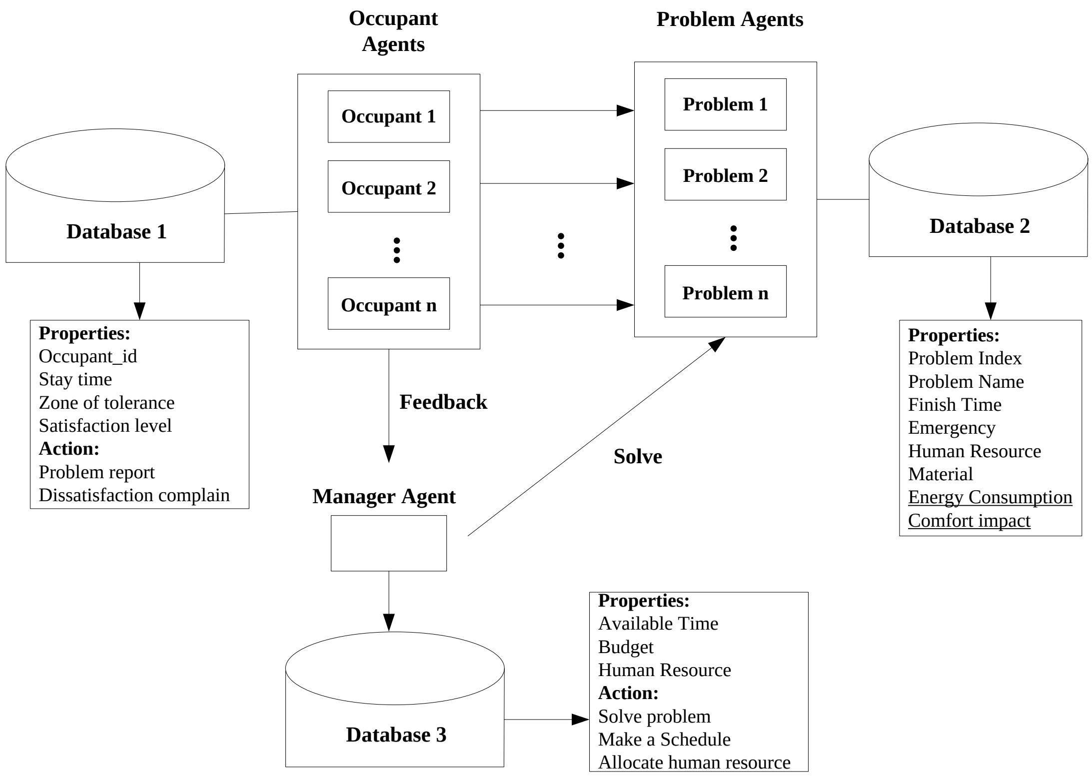

Figure 9. Improved agent-based framework

1. Occupant Agents

Occupant agents will memorize the living habits for an occupant, which has an impact on the different satisfaction evaluations. Someone who spends more time staying at home will be influenced more by a problem, such as inadequate air conditioning. Different occupants also have different evaluations for a problem based their own comfort requirement for the indoor environment. For example, someone might care more about thermal comfort, while others may care more about acoustic comfort. The occupant agents are able to report problems and express their feeling before and after the problem solution.

2. Problem Agents

Problem agents are static agents without active actions, but they affect other agents' behaviors. Different tasks have specific properties based on historical data, such as frequency and level of urgency. In addition, tasks have properties concerning how they are to be solved, such as the finish time, the human resources required, and the material required. All of these properties are closely restricted by the resources of the facility manager agent. In an ideal system, these properties would be calculated based on case-based reasoning from a large pool of cases. For example, by searching the most similar task in the pool of cases, the human resources required could be evaluated. Among all of these properties, energy consumption and impact on comfort are the two factors considered in this research. Energy consumption data can be collected from a mechanical meter or simulation software. The impact of comfort is determined by the target occupant.

3. Manager Agent

For most buildings, only one facility manager team works for the entire building system, so there is only one manager agent. Similar to occupant agents, the facility manager agent behaves differently according to different situations. Its properties are mainly concerned with resource limitations. The facility manager has a limited schedule of working time, budget, and human resources. Naturally, the action or behavior is focused on how to effectively allocate the resource to solve the tasks. Furthermore, the facility manager must evaluate the factor of tasks and make a time schedule for dealing with them.

Occupant Satisfaction Quantification

In this stage of research, the occupant satisfaction is been better quantified through a structured questionnaire based on disconfirmation theory. The questionnaire is in appendix B and the results will be showed in the next chapter. In Osman's research, the same disconfirmation theory was used to simulate consumers' satisfaction for infrastructure asset management. His simulation was based on the SERVQUAL model, which also was proposed for the entire service industry to determine the relationship between satisfaction and service (Zeithaml and Parasuraman, 1990). This thesis was based on five assumptions, some of which also can be used in maintenance work, so they are explained here.

P1: The width of the expectation zone of tolerance is inversely proportional to the degree of involvement.

This assumption was first proposed for consumers' purchase behavior (Engel et al. 1993). "Involvement" means the effort of consumers to search for the products and special interest for a purchase decision. Greater involvement results in a more narrow tolerance zone.

When applying it into this research, higher degrees of involvement were indicative of the customer's greater sensitivity to satisfaction and dissatisfaction. Therefore, we defined an attribute for occupant, i.e., 'involvement in the building.' Involvement means the daily average time the occupant spends in the building. The greater the involvement, the shorter the occupant will expect the solution time for maintenance requests to be. This means that occupants who spend more time in the building will have a more adverse reaction to delays in maintenance work because the delays will impact them to a greater extent than it will others.

P2: Performance within the zone of tolerance may not be noticed.

The zone of tolerance can be regarded as an "inertia scope" that consumer response to the disconfirmation of expectations (Liljander and Strandvik, 1993). In other words, the eligible service that meets the requirement of the consumer within a zone of tolerance will not be noticed by the consumer because he or she will take it for granted. Conversely, if the service has not been provided within the zone of tolerance, the consumer will be unsatisfied with the result and complain about the encounter.

For most maintenance work, the goal is to control the dissatisfaction rate. Therefore, solving the problem following the "first come, first serve" is not the best policy; rather, attempts should be made to solve most problems within the zone of tolerance. Positive feedback of occupants will not impact a lot on facility managers' work, but negative feedback will impair the impression for the living experience and then result in complaints for facility managers.

P3: Several satisfactory transactions are needed to compensate for a single unsatisfactory transaction.

This assumption is based on the research from Brandt and Reffett (Brandt and Reffett, 1989). Their problem-centered research program established the types and pervasiveness of customer problems and to evaluate the effect of each on customer satisfaction. It is similar to P2, which suggests that people more easily perceive the unsatisfactory service. Therefore, one unsatisfactory experience will last for a long time, or it can be compensated for by many satisfied encounters.

To avoid too much noticed unsatisfactory experiences, it is better for facility managers to make the schedule based on the expectations of occupants to minimize dissatisfaction.

P4: A failure in one transaction may raise the dissatisfaction threshold.

It has been proposed that a dissatisfying service can result in the bad evaluation of service which increases the lower limit of the zone of tolerance, and consumers will become more easily dissatisfied with the results (Johnston 1995).

Based on this assumption, problems that seldom occur can have a significant effect on occupants, thereby impairing the satisfaction level if they cannot be solved immediately. In future research, problems that have a more severe consequence for occupants' living environment will be identified so that they can be solved on a priority basis.

P5: Occupants have natural inertia towards the zone of tolerance.

Based on this proposition, we assume that facility managers cannot always leave unsolved problems from the same occupant, because doing so will cause long-term dissatisfaction, which cannot be easily compensated by some late behaviors.

CHAPTER 4

MODEL IMPLEMENTATION AND RESULTS

Stage One Research

Brief Introduction

In the stage one research, the two example models for student residential building and campus buildings are tested. In the first student residential building, the normal daily service requests are considered such as plumbing and HVAC problems. However, the criteria for prioritizing work orders are emergent degree subjectively evaluated by both facility managers and occupants. In the second example, only HVAC related problems are surveyed to know their impacts on occupants and energy impact. Except for the prioritization of work orders, this example also applies the text mining and database technology to offer possible causes for facility managers. Therefore, the second example can be regarded as the further research and supplement of the first example.

Illustrative Example one

The concerning building is a nine floors student apartment containing more than 200 residential. Two facility managers are responsible for all the daily M&R tasks in this building collected from residential. According to them, they receive a lot of works every day and find it hard to schedule a suitable plan for solving all of the problems. Even though busy all the day, they still cannot satisfy requirement of most residential. To simulate how to solve this problem, authors first list the top five frequent problems based on facility managers' experience and the corresponding finish time.

Table 3. Evaluation data for five common maintenance problems

Problem	Problem Index	Finish Time	Emergent Degree
Plumbing	1	3h	5
Locks	2	0.5h	4
HVAC	3	2h	3
Lights	4	0.5h	2
Washing Machine	5	1h	1

The emergent degree in the fourth column is determined by facility managers based on their working experience and preference. In this chart all the problems are normal ones which mean none of them are extremely urgent.

In our model, the problems are produced through random simulation every day but the total number in a week is estimated by facility managers—30 in seven days.

The working time of facility managers is 8 hours every day from 8 am to 4 pm.

The problem collection is a dynamic procedure that could happen every time of the day. However, due to the fact that problems are produced by simulation, we need to assume that problems are collected at the end of the day and the schedule will be made from the next day.

Allocation Algorithm

Step 1: The manager will calculate all the emergent degree of tasks and gives them a rank. The task with the biggest emergent degree will be addressed first.

Step 2: The manager agent will search the time based on preferred date to see if it will be enough time to finish the job. If so, the job will be inserted into the schedule. If not, the system will automatically search for the nearest time of the preferred date.

Step 3: Occupant is able to agree or reject the solution of manager agent. If they do not agree with the result they send back the info and manager agent need to keep searching time.

Step 4: The urgent problem will be inserted on the next day by replacing the scheduled tasks with minimal E. However, the replaced tasks will have a 20% bigger E when allocated next time. With this rule, one task will not be replaced all the time.

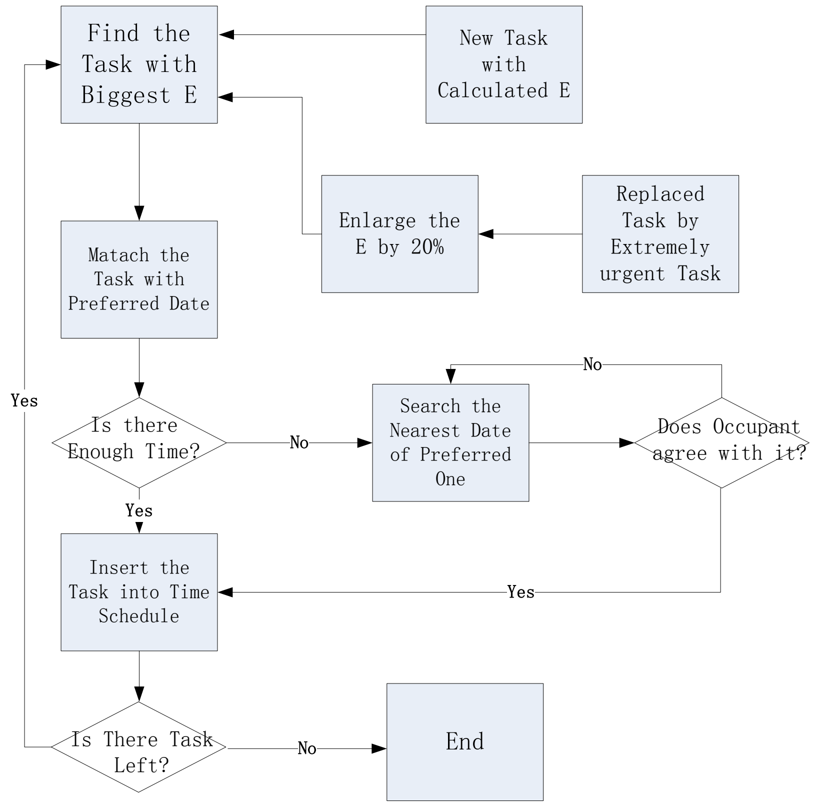

Figure 10. Process of schedule

Result Analysis

The model is simulated by Anylogic 6.9.0. First it simulates the problems in a week with the estimate of total 30 problems. The problems in every day are simulated as follows. The problems happening on Friday are not mentioned because they will be solved in next week.

Table 4. Problem simulation

Mon	Tue	Wed	Thu	Fri
3,4,2,2,1,1	4,2,0,4,4,4,3,1	2,3,4,3,3	4,2,3,4,3,0,1,1	---

The number in the second row is the index number of problems. In reality, they are reported by occupants. The main page of the program in Anylogic includes the simulation of four days because we assume that all the problems will be allocated to plan from their next days. Therefore no tasks will be solved on Monday and the problems happened in Friday will be solved in next week.

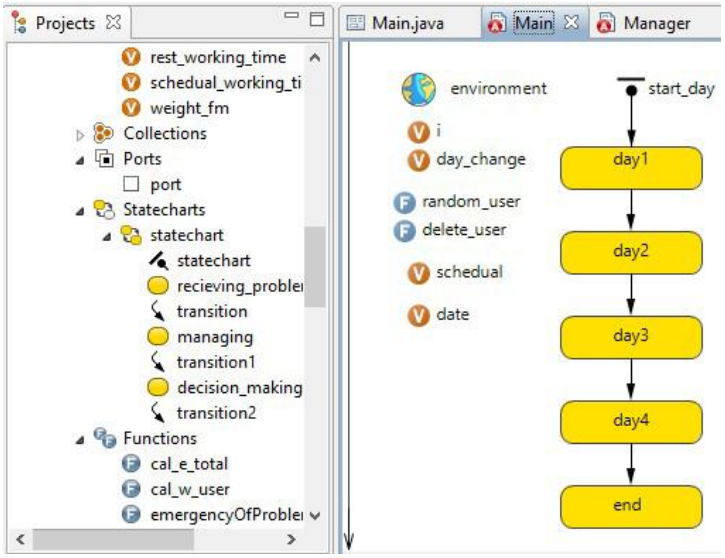

Figure 11. Interface of Software Anylogic

The simulation results are included in four time schedules and two of them are listed in the following:

Tue	Wed	Thu	Fri
4(0): 8-8.5	3(3): 8-10	3(2): 8-10	4(1): 8-8.5
			1(4): 8.8-11.5
			2(5): 11.5-12

Tue	Wed	Thu	Fri
4(0): 8-8.5	3(3): 8-10	3(2): 8-10	4(1): 8-8.5
2(7): 8.5-9	3(12): 10-12	5(11): 10-11	1(4): 8.8-11.5
	4(6): 12-12.5	1(10): 11-14	2(5): 11.5-12
		2(17): 14-14.5	1(8): 12-15
		5(21):14.5-15.5	

Figure 12. Result table after schedule

The left table is the schedule made at the end of the first day and the right one is the schedule made at the end of the fourth day. In every grid, the problem and its occupants as well as schedule time is demonstrated for facility managers. The numbers in the parentheses are index of occupants.

In this simulation process we did not consider the happening of emergent problem such as leakage, which needs to be solved immediately. But according to the algorithm, facility managers only need to directly insert the emergent problem into schedule and extract the scheduled problem with minimal E. Then the extracted problem will be allocated with a larger E.

Illustrative Example Two

In this example, the research was performed in the main campus area of Georgia Tech. The campus facility management system is responsible for operating the data for central campus area three, which contains 14 buildings including Klaus, CoA and so on. Facility managers in this department are focusing on solving daily maintenance request. Their job can be summarized as follows: receiving and scheduling maintenance request; assigning related workers to finish the work; storing the above data into the system. For the database, they apply the web-based management system called AIM to manage the data. It is developed by AssetWorks software company.

HVAC Problem Analysis

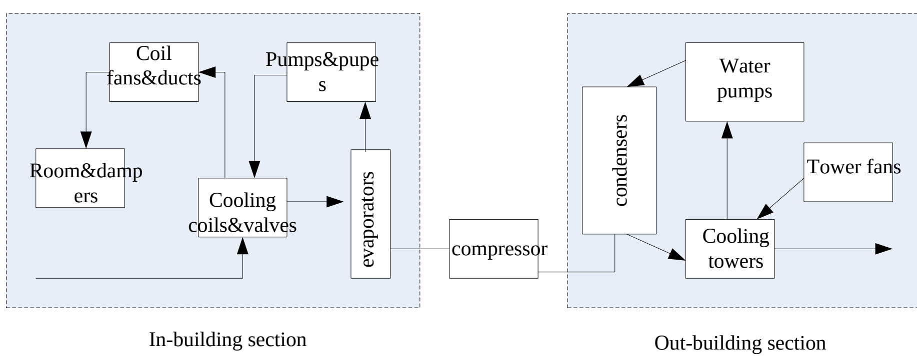

Figure 13. Overview of HVAC system

The normal HVAC system (cooling part) in Georgia Tech is designed as showed in the above picture. The water and Freon act as the medium for heat exchange among different zones.

For the system, many components need to be performed daily maintenance because they are easily out of good condition: filters; fans; pumps; cooling tower; chillers; boilers; thermostats.

Based on the statistical data, following problems are most frequently happening: temperature issues; leakage problems; noises; air-conditioning not work normally; component replacement and so on. For every problem, the normal causes could be known from the historical cases. For example, the abnormal low temperature in winter may be caused from the following reasons:

- bad compressor or reversing valves
- unit needs to be cleaned and serviced
- compressor not running
- restriction or bad metering device
- outdoor heat pump is iced up or covered in snow
- leak in the return duct, bringing in cold air

All these information will be stored in the database for the new case retrieving.

Assumption

The cluster algorithm can be classified into two types: supervised and unsupervised. Supervised cluster means people already know the number of clusters. To simplify the example, we only choose 11 normal problem types of HVAC, which means there are 11 clusters. For every retrieving process, a problem will be classified into one category which is assumed to be composed of many historical cases. So the rank index is the weighted mean of impact on occupant and energy efficiency.

Energy Impact Evaluation

To evaluate the energy impact of the HVAC SR, a survey is designed for 10 facility managers to collect the data. There are 3 categories: life safety(S); major equipment and structural failure (D); other problems are energy related ones (E).

Table 5. Survey result

Item	Category	Impact on occupant	Impact on energy efficiency
Abnormal temperature	E	3	5
Leak (valve, AC, condensation, ceiling…)	D	3	1
Noise (Indoor units, air vents…)	E	4	3
Problem on fume hood	D	4	1
AC not working	E	4	5
Air flow problem	E	4	3
Exhaust fan not working	S	5	3
Dirty vent	E	3	4
Filters	E	3	4
Repair scrubber	S	2	1
HVAC Odors	S	2	4

Facility managers also need to evaluate the impact on occupant and the increase of energy consumption based on their work experience. The impact degree ranges from 1 to 5. 1 is the least impact while the 5 means the biggest impact. The survey and the result is demonstrated in the following chart:

Result

After entering a problem description as shown in the picture, a search button will help facility managers to get the possible causes of the problem. This information are based on the real cause of historical cases. Besides, the category and priority degree will be calculated with the equal weight (0.5) for every factor.

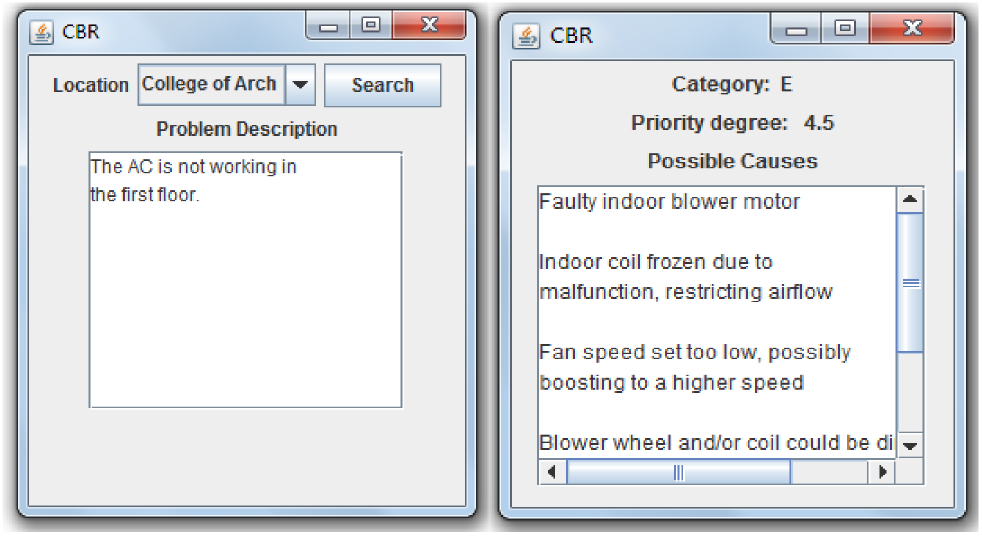

Figure 14. CBR interface

Through this system, facility managers can not only know the possible causes of the problems, but also get the priority to schedule their future work.

Stage Two Research

<u>Background</u>

In the second stage of research, in order to test the model, a simulation was conducted based on the data from two residential buildings, i.e., 100 midtown student apartment and the Westmar student apartment building. Around 50 graduate students live in these two apartment buildings. The indoor environments and equipment of these two apartment buildings are similar, and most of the apartments are designed to house four students. Therefore, the occupants of the two buildings have similar maintenance requests and experiences, which will offer adequate information for us to evaluate their satisfaction.

<u>Occupants’ Satisfaction Survey</u>

A survey was designed to collect the data. The design of the survey was adopted from POE questionnaires (Lai 2013; Lai 2011; Meir et al. 2009). The reported problem will impact the satisfaction of occupants by impairing their comfort in the building. Therefore, some evaluation criteria for the indoor environment were used to evaluate the consequence of maintenance problems.

The survey is consisted of four parts. Part 1 focuses on basic personal information including age and gender. Part 2 was used to evaluate the consequence of normal maintenance problems from six aspects, i.e., thermal comfort, acoustic comfort, visual comfort, indoor air quality, convenience, and health concerns. They were evaluated using a 5-point Likert scale (1: no impact; 2: little impact; 3: moderate impact; 4: great impact; 5: extreme impact). Based on the preliminary survey, the 10 most frequent problems were included in the final survey, i.e., stove malfunction; light bulbs broken; air conditioning not working; no or inadequate water supply; clogged drain; smoke detector alarm ringing; TV and Internet broken; washing machine broken; dishwasher broken; leaks.

Part 3 was used to evaluate the longest acceptable waiting time for each of the above problems, which was used to represent the expectation of the occupants. For every problem, the solution time was given in three categories based on the normal solution time, i.e., within one day, two days to four days, and longer than four days. Part 4 was used to determine the occupants' evaluation of the significance of each factor as it related to their comfort requirements in the building on a 5-point Likert scale (1: no importance; 2: less importance; 3: normal importance; 4: high importance; 5: extreme importance).

Fifty questionnaires were distributed randomly to the occupants of these two buildings, and 47 of them were completed and returned. Among the 47 that were returned, 44 were deemed to be useable. The other response contained obvious fake results such as totally uniform choices.

Figure 15 shows the results for part 1.

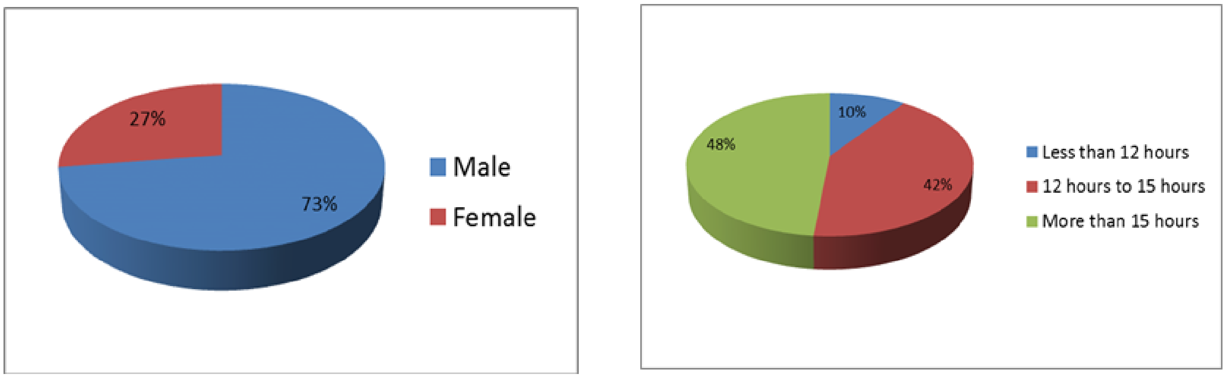

Figure 15. Statistical data for part 1

Thirty-two of the interviewees were males, and 12 were females. All of the interviewees were graduate students at Georgia Tech. regarding their daily average time at home, 48% spent more than 15 hours at home, and they were considered to be highly-involved occupants; 42% spent 12 to 15 hours at home, and they were considered to be medium-involved occupants; 10% spent less than 12 hours at home every day, and they were considered to be low-involved occupants.

The results of part 2 were used to calculate the total points of every maintenance request, which should be combined with the data in part 4.

Table 6. Statistical data for solution time expected

Problems	Estimated expectation solution time (Days)
Stove not work	1
Lighting bulb broken	1
Air conditioning not work	1
No/less water supply	2-4
Clogged drain	2-4
Smoke detector alarm	2-4
TV and Internet	1
Laundry machine	2-4
Dish-washing machine	2-4
Leak	>4

For some problems, such as air conditioning, most occupants were unwilling to wait for more than one day to have the problem solved; such problems were deemed to be urgent. Some problems could be solved in two to four days, and the leak problem was expected to be solved in more than four days, but normally it should be less than one week. Based on the interviews, the leak problem should be solved within five days to meet the occupants' requirement. Based on the inertia assumption, occupants did not notice good service but complained a lot about bad service. Therefore, this table provides the managers with a "deadline" to finish the work without complaints.

The results of part 4 were used to calculate the weights of the five factors:

Table 7. Accumulated weights for five factors

125	124	141	145	146
0.183553598	0.18208517	0.207048	0.212922	0.214391

Based on the above results, the importance scores of 10 problems were calculated as follows:

Air conditioning not working	No/ inadequate water supply	Smoke detector alarm	Clogged drain	Leaks	Light bulbs broken	Washing machine	TV and Internet	Stove not working	Dishwasher
98.96	76.24	68.42	64.23	67.55	56.96	59.11	55.14	53.89	45.75

Table 8. Comfort score for ten problems

From the table 8, it is apparent that the air conditioning problem had the most impact on the comfort of the occupants, while the dishwasher had the least impact. The score suggest the comprehensive impact of the problem. However, for the priorities of the problem, facility managers need to first consider the expectation date before consider these data, for some big impact problem, some occupants may not have urgent requirements for personal reasons.

Simulation Framework

In order to test the agent-based framework proposed in this paper, the current situation concerning solution data and frequency of problems was used to benchmark the differences. Based on documents retrieved from the FM system at Georgia Tech, the maintenance work was ordered based on the following considerations: safety and environmental concerns, major equipment or structural failure, preventative maintenance of installed equipment, minor installed equipment failure, and repair of non-installed equipment (Raytheon Polar Services Company 2014). It is no doubt that the safety problem should be solved in the first priority. In this paper, the maintenance work is in the categories of minor installed equipment failure, and repair of non-installed equipment, so the simulation was based on the assumption that there were no extremely emergent and destructive problems.

The validation was based on the comparison of two situations, i.e., the current maintenance schedule and the new schedule based on the agent-based system. Unlike a large infrastructure asset, such as a highway, there is no classical maintenance model for small daily maintenance problems. Therefore, the current situation was assumed to be "first come, first served" based on interviews with facility managers with more than 5 years of working experience. The new schedule was produced automatically by the agent-based model. The rules for prioritization used in this simulation were as follows:

1. Consider the expected solution date of each problem;
2. For problems with same accepted solution date, consider the satisfaction scores from the survey;
3. Further consider the three types of occupants (all of the occupants were either high,

medium, or low types, and the number of agents for the three types were 25, 20, and 5, based on the results of the survey); problems from the high-involvement occupants will be solved earlier based on the former assumptions because their tolerance zone is narrower;

4. Energy data were provided only for the problem of air conditioning because HVAC consumes the biggest part of energy in buildings. Therefore, for the subtype of four problems in air conditioning, the high energy consumption problem should be solved earlier;
5. Unlike the first simulation, every problem will be scheduled in limited days; this second simulation might result in a situation in which some problems cannot be scheduled with a low priority for step 1 to 4. Therefore, the model sets seven days as the longest solution time for each problem after being reported.

Based on the first two steps, the survey was used to rank the priority of the 10 problems as follows (refer the table 8):

Air conditioning not working; light bulbs broken; TV and Internet; stove not working; no or inadequate water supply; smoke detector alarm; clogged drain; washing machine; dishwasher; leaks.

For the frequency of each problem, the model will follow the Poisson distribution weekly. Based on Hosseini (Hosseini et al. 2000), maintenance work can be categorized into two types, i.e., deterioration failure and Poisson failure. Deterioration failure regards a system failure as a continuous process, while the Poisson failure is a discrete failure. The maintenance problem in this paper can be considered as a Poisson failure because there are only two conditions for each related system, i.e., it works or it doesn't. The frequency of Poisson failure was determined by a constant parameter, which is represented by lambda. The parameter was set by the average frequency of each problem: Lambda (air conditioning not working, light bulbs broken, TV and Internet, stove not working, no or inadequate water supply, smoke detector alarm, clogged drain, washing machine, dishwasher, leaks) = (4, 5, 7, 5, 2, 3, 5, 4, 1, 1). The dataset was evaluated by facility managers for a 50 apartment student building.

To make the problem focus on the energy efficiency and occupants' satisfaction, in this paper, the solution time for each problem was not considered. Unlike preventive maintenance, these problems are caused by uncertainties, so the solution time cannot be set as a constant. To demonstrate the robustness of the model, the manager agent was assumed to be able solve three to seven problems per day, also based on the evaluation of facility managers, so the number of problems finished daily is stochastic. When the finished problems exceeded five, the situation suggests that problems could be easily solved in a short time. When the problems were less than five, the situation can be explained in that solving the problems required much more time.

Table 8 (Wang 2014) lists the four most common reasons for the problem of HVAC faults and the resulting energy increases. Based on the findings of mechanical engineers, these faults occur with similar frequency, so the four problems were allocated randomly with the same probability.

Table 9. Energy increase for HVAC faults

sensor calibration	53.30%
dirty filter	3.60%
fouled cooling coil	1.10%
clogged outdoor air screen	9.36%

The problem list here is in the summer time when the HVAC is used to provide cold air. The simulation scenario was based on research from Lawrence lab (Wang 2014). The second column means the increase in energy compared to the baseline model (HVAC in good operational condition). Even though the building components might be a little different from the referenced component, it is adequate for validating the effectiveness of the model, because the data are comparative figures, not the absolute measured data.

The output of the simulation is the increase in energy consumption and the increase in occupants' satisfaction. When the problem cannot be solved within its expectation dates, one time of dissatisfaction was counted. The energy consumption was calculated based on the increase percentage of the baseline model.

Program Design

The program can be demonstrated as the following unified modeling language (UML) graph. It is written in Java and there are seven classes in this program: result, task, client, facility manager, task comparator, problem and the main class. The main class is the start of the program. All the data are stored in this class. For example there are three types of occupants in the simulation and ten types of problems in it. One of the most difficult parts in this class is the application of Poisson distribution algorithm to simulate the happening of service requests. The result class is responsible for calculating the total energy increase and the total dissatisfaction level based on the given formula. Task class stores the problem produced by Poisson distribution in the main class and then assign the attributes to them: the date and the best suggested finish date. The problem class is closely connected with this class to store the energy consumption data for HVAC problems. For the facility manager class, it schedules the service requests in two set of rules and thus produces two schedules: one and two.

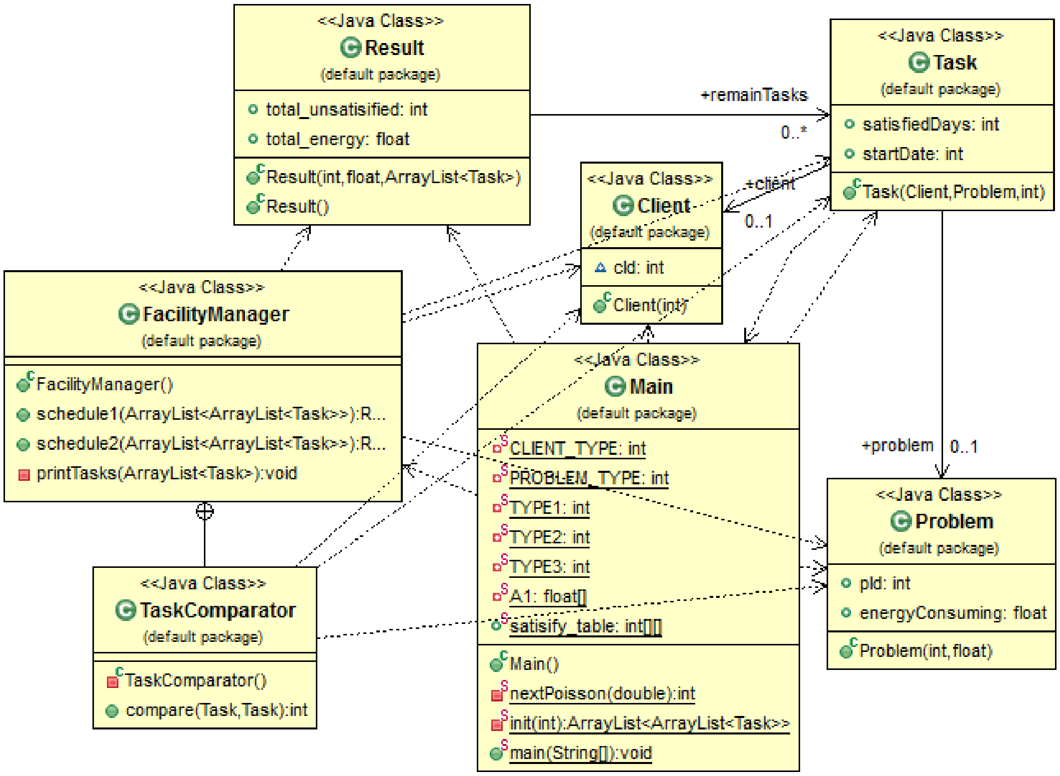

Figure 16. UML graph of the program

Simulation Results

In the simulation, the time was changed from four weeks to 52 weeks with the span of four weeks to see the optimization effect. For every four weeks, the simulation runs 100 times and calculates the average number of each item in the following table 6. Some equations must be clarified for the following results:

Rate of dissatisfaction = Dissatisfaction/total number of problems Eq.3

Increase of satisfaction = Rate of dissatisfaction 1- Rate of dissatisfaction 2 Eq.4

Decrease in energy consumption =

(Energy increase 1-Energy increase 2)/Energy increase 1 Eq.5

Table 10. Simulation results

Time (Week	Number of probler	Dissatisfaction	Energy Increase	Rate of dissatisfaction	Dissatisfaction	Energy Increase	Rate of dissatisfaction	Increase of satisfactio	Decrease of energy
4	**168**	**41**	**1719**	**24.4%**	**22**	**307**	**13.1%**	**11.3%**	**82.1%**
	146	**62**	**1554**	**42.5%**	**15**	**270**	**10.3%**	**32.2%**	**82.6%**
	145	**41**	**270**	**28.3%**	**15**	**190**	**10.3%**	**17.9%**	**29.6%**
	150	**29**	**153**	**19.3%**	**17**	**110**	**11.3%**	**8.0%**	**28.1%**
	…								
8	**282**	**73**	**1071**	**25.9%**	**29**	**489**	**10.3%**	**15.6%**	**54.3%**
	307	**143**	**9396**	**46.6%**	**57**	**733**	**18.6%**	**28.0%**	**92.2%**
	278	**93**	**1817**	**33.5%**	**39**	**418**	**14.0%**	**19.4%**	**77.0%**
	285	**124**	**2086**	**43.5%**	**42**	**455**	**14.7%**	**28.8%**	**78.2%**
	…								
12	**435**	**126**	**2284**	**29.0%**	**35**	**812**	**8.0%**	**20.9%**	**64.4%**
	461	**157**	**9596**	**34.1%**	**48**	**865**	**10.4%**	**23.6%**	**91.0%**
	419	**161**	**3626**	**38.4%**	**56**	**1244**	**13.4%**	**25.1%**	**65.7%**
	438	**184**	**10301**	**42.0%**	**61**	**981**	**13.9%**	**28.1%**	**90.5%**
	…								
…									
52	**1946**	**883**	**137005**	**45.4%**	**334**	**3474**	**17.2%**	**28.2%**	**97.5%**
	1893	**903**	**69135**	**47.7%**	**284**	**3431**	**15.0%**	**32.7%**	**95.0%**
	1941	**950**	**135206**	**48.9%**	**288**	**3553**	**14.8%**	**34.1%**	**97.4%**
	1891	**929**	**54132**	**49.1%**	**298**	**2701**	**15.8%**	**33.4%**	**95.0%**
	…								

For every simulation period (4, 8, 12…), program run 100 times and the number of problems are simulated. For every simulation there are two dissatisfaction numbers and an energy increase percentages. The first one is the "first come and first solve", while the second one is the result after the optimization. Rate of dissatisfaction, increase of satisfaction and the decrease of energy consumption are calculated based on the above equations.

Conclusion 1

The relationship between time and the increase in satisfaction and the decrease in energy used is shown in the following chart:

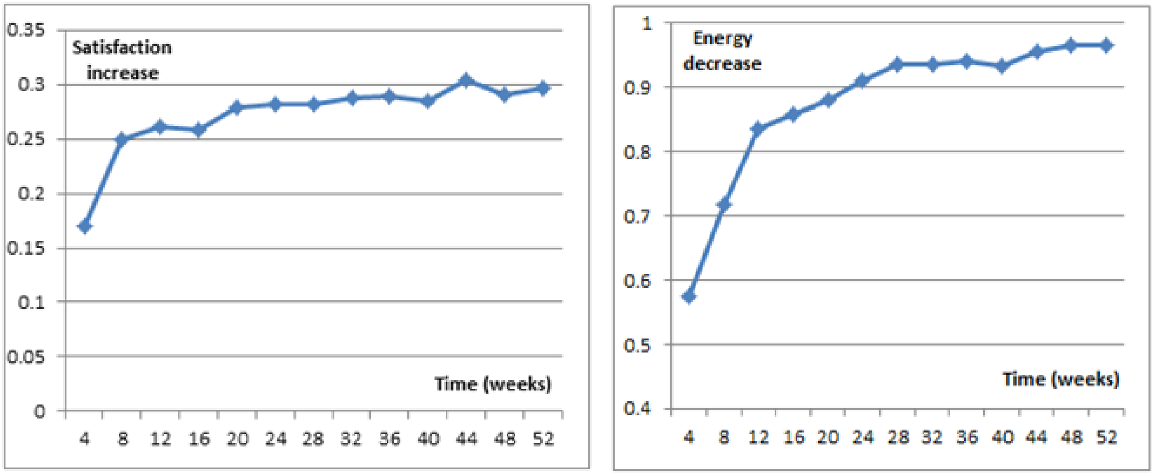

Figure 17. Improvement change

For all of the simulations, both the occupants' satisfaction and energy efficiency were improved in the proposed model. When the time period became longer, the increase in satisfaction and in energy efficiency also were improved, but the rate of increase decreased with time, which might because as the time period becomes much longer, the pressure from the limited resource becomes more obvious, and results in more dissatisfaction without applying the proposed framework. When the time was 52 weeks (approximately one year), the increase of occupants' satisfaction was about 30%, and the total satisfaction level was about 84%; the decrease of energy was about 97%.

Conclusion 2

Assuming that we set the simulation time period to be 52 weeks, when the problem number is small enough, it will not be easy to notice the optimization effect. For example, if we assume that all of the lambda values are 3, the increase of occupants' satisfaction would be 4%, and the decrease of energy would be 1%.

This can be explained easily based on the real situation, i.e., when the number of problems is small enough, facility managers have sufficient human resources to solve the problem; the majority of the problems can be solved very quickly. Therefore, the sequence of the solution will not have a significant effect on the ultimate results (satisfaction and energy).

Conclusion 3

When the expectation solution data were increased by one day for each problem for each type of occupant and the simulation time was still 52 weeks, the optimization effect also will be reduced, i.e., there will be less than a 1% increase in occupants' satisfaction. The increase expectation data mean that the facility managers have sufficient time to solve the same problem, so it is similar to an increase in human resources for managers, so the optimization effects will be decreased.

CHAPTER 5

CONCLUSION

The conclusion can be discussed from the different steps of the research. In the first stage of research, it makes the first attempt to apply the agent based modeling in facility management due to its complexity and dynamic characteristics. The proposed decision system is able to help facility manager to solve M&R problems with consideration of preference of occupants. Through this system, the facility manager not only finishes the problem based on a clear schedule but also largely satisfies the needs of occupants. The framework is flexible for many cases because of changeable variables in the model. In the model implementation, it turns out that the system works well to produce the problems schedule. To fully apply this framework into practice, there is an intrigue problem needs be solved: getting the work finish time based on case based reasoning (CBR), which was not completed in this step. Therefore in the later stage, research will focus on if CBR is feasible for estimating the finishing time and suggestive methods for facility managers based on a case pool. This work can also save a lot of time for facility managers and lay a solid foundation for the application of artificial intelligence in facility management decision process. Besides, the research only considers the subjective preference of occupants and facility managers to schedule the work, and there is no comparison to demonstrate the benefit of this framework. Therefore, the research goes into the further step.

In the further step of research, author builds a conceptual intelligent framework for campus FM. The innovative points in this step are the energy efficiency and occupant satisfaction consideration for FM works and new ways for cases retrieve, which is one of the method of AI. Then the research deeply digs into these two aspects and tries to implement them. For the energy and occupants evaluation, the author conducted a survey based on the data collected from the case study. Facility managers helped to evaluate the energy consumption increase and their impact on occupants of 11 common HVAC problems. This result can be used to prioritize FM works and make a schedule to maximize the energy efficiency. For the cases retrieve, the research suggested to apply the text mining into searching work. This is an advanced text data searching method in construction industry. However in the example, much assumption was made to simplify it. Up to this point, author still did not verify the benefit of the framework, and more accurate ways are needed to evaluate the energy efficiency as well as the occupants satisfaction.

In the second stage of research, all the above mentioned problems have been solved. For most daily maintenance problems that are not concerning life and the safety of the system, facility managers should consider occupants' satisfaction and energy efficiency to schedule their work orders. The proposed agent-based model considered these two factors to automatically produce the work schedule. The more accurate energy data can be produced by the building energy simulation. In the research, part of the data was acquired from the research of Lawrence Laboratory because there is no need to replicate the same research work and it is difficult to get a better result than Lawrence's work. The data of occupants' satisfaction were collected from the survey of the residents of the two residential buildings. The survey is based on the further research on customer satisfaction theoretically. The simulation results showed that the proposed system can improve the occupants' satisfaction and energy efficiency by 16% and 93%, respectively. Sensitivity analysis (Conclusion 1, 2, 3) provided the suitable conditions to apply this model, i.e., when the facility managers have limited human resources and the expectation of occupants are at a relatively high level.

However, some future work is still promising. This simulation was based on some data from a one-time survey. It will be more reliable if a long-term database were to accumulate records of the required data from the feedback of occupants. The quantification of people's satisfaction is always a difficult problem, the solution for which can be based only on some classical theories. That was the case in this paper, since the solutions depended on the disconfirmation theory. Therefore, more research is needed to further determine the application effects in FM. For the energy part, data were produced from the simulation in EnergyPlus, because there was a lack of adequate measured data so this is the best way to collect the required data. The results provided by the model will be more robust if they were based on measured data.

APPENDIX A

SURVEY FOR FACILITY MANAGERS

Survey on FM Works of HVAC

This survey might take you **10 minutes** to finish it. The item is the most frequent problems of HVAC in our campus facilities. They are collected from database of FM system. Please finish the chart based on the following instructions:

Category: Some problem affects the life safety. Then the category is **"S"**. Some problem is concerning major equipment and structural failure which might damage the building system. Then the category is **"D"**. Other problems is **"E"**, which means energy related problem because all of them may cause more energy consumption.

Impact on occupant: Based on your work experience, how severe will the problem affect the occupants' work and study. **1** is for almost no impact; **2** is for little impact; **3** is for normal impact; **4** is for sometimes severe impact; **5** is for always severe impact.

Impact on energy efficiency: All of the problem will cause more energy consumption than the normal condition. **1** is for almost no increase; **2** is for little increase on energy consumption; **3** is for normal increase on energy consumption; **4** is for sometimes dramatically increase and **5** is for always dramatically energy consumption increase.

Item	Category	Impact on occupant	Impact on energy efficiency
Abnormal temperature			
Leak (valve, AC, condensation, ceiling…)			
Noise (Indoor units, air vents…)			
Special requests for some events (Temperature adjustment)			
Problem on fume hood			
AC not working			
Air flow problem			
Exhaust fan not working			
Dirty vent			
Filters			
Repair scrubber			
HVAC Odors			

APPENDIX B

STRUCTUTED QUESTIONIARE ON OCCUPANTS

Survey on Occupants' Satisfaction on Daily Maintenance Requests

Thank you for taking part into this survey. It will ask you about your evaluation on the maintenance problems based on your living experience. The survey will take you about 10 minutes.

This survey is being conducted by PhD student Yang Cao at the school of building construction in Georgia Tech. The study will help researcher understand the satisfaction level of occupants in residential buildings and thus find out the problem for current facility management.

Your response to this survey, or any individual question on the survey, is completely voluntary. You will not be individually identified and your responses will be used for statistical purposes only.

If you have questions about your rights as a participant in this survey, or are dissatisfied at any time with any aspect of the survey, you may contact researcher at 404-750-3398.

Part 1. Personal information

1. What is your gender?

Male Female

2. What is your academic level?

Undergraduate Graduate

3. How long are you staying at home every day in average?

Less than 3 hours 3 to 6 hours more than 9 hours

Part 2. Evaluation on the impacts of repair and maintenance work

In this part, you are going to evaluate the consequence of normal maintenance problem from six aspects: thermal comfort, acoustic comfort, visual comfort, indoor air quality, life convenience and health concern. They are evaluated by you in a 5-point scale (1: no impact; 2: little impact; 3: moderate impact; 4: great impact; 5: extreme impact)

Problems	Factors					
	Thermal comfort	Acoustic comfort	Visual comfort	Indoor air quality	Life convenience	Health concern
Stove not work	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Lighting bulb broken	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Air conditioning not work	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Air conditioning control failure	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Air conditioning noise	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Water failure in kitchen	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Water failure in bathroom	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Clooged drain in kitchen	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Clooged drain in bathroom	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Indoor alarm	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Cable connection	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Laundry machine	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Dish-washing machine	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Leak in the kitchen	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Part 3. Evaluation on the desired solution time of repair and maintenance work

What is your longest expectation time to be solved of each problem?

Problems	How long can you wait the problem to be solved?
Stove not work	Within 1 day 2days 3 days 4 days >4days
Lighting bulb broken	Within 1 day 2days 3 days 4 days >4days
Air conditioning not work	Within 1 day 2days 3 days 4 days >4days
Air conditioning control failure	Within 1 day 2days 3 days 4 days >4days
Air conditioning noise	Within 1 day 2days 3 days 4 days >4days
Water failure in kitchen	Within 1 day 2days 3 days 4 days >4days
Water failure in bathroom	Within 1 day 2days 3 days 4 days >4days
Clooged drain in kitchen	Within 1 day 2days 3 days 4 days >4days
Clooged drain in bathroom	Within 1 day 2days 3 days 4 days >4days
Indoor alarm	Within 1 day 2days 3 days 4 days >4days
Cable connection	Within 1 day 2days 3 days 4 days >4days
Laundry machine	Within 1 day 2days 3 days 4 days >4days
Dish-washing machine	Within 1 day 2days 3 days 4 days >4days
Leak in the kitchen	Within 1 day 2days 3 days 4 days >4days

Part 4. Evaluation on the significance of your comfort factors

In this part, survey need you to give your evaluation on the significance of each factor concerning your comfort in the building in a 5-point scale (1: no important; 2: less important; 3: normal important; 4: very important; 5: extreme important.)

Factors	Importance level
Thermal comfort	1 2 3 4 5
Acoustic comfort	1 2 3 4 5
Visual comfort	1 2 3 4 5
Indoor air quality	1 2 3 4 5
Life convenience	1 2 3 4 5
Health concern	1 2 3 4 5

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