Automation Performance Index
Modeling the Building Automation System's Performance

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Automation Performance Index:
Modeling the Building Automation System's Performance

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This work is dedicated to:

Maryam Riazi Sadri, my mother in whose mind I have always been a Shahriar (King)

Elahe Hessamfar, my wife who has put up with me as Shari-R (Naughty)

And to my Lord who has transformed me to ShahreYar (Kingdom of the Beloved)

“Control is impossible without measurement” *Tom Peters*

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"Man makes tools because he is rational" *Hegel*

SUMMARY

Automation is intended to improve overall building performance. Building Automation Systems (BAS) are attractive and popular due to their promise of increased operational effectiveness. BAS can be optimized and a well-designed and well-implemented BAS is expected to increase a building's overall appeal and value as a result of improvement to its performance. In order to improve the level of automation in buildings, a measurement tool in the form of a performance index is needed. The goal of this research is to quantify a building's level of automation-performance. The specific objective is to develop an Automation Performance Index (API) model for evaluating the extent of a building's automation-performance. A methodology is outlined with ten tasks to accomplish the goals of this research and a criterion for each task is described.

An extensive literature research and expert survey are performed to identify the key parameters that influence the performance of BAS. Seminars related to the building automation and commissioning fields were also attended to obtain the views of practitioners, manufacturers' experts, as well as scholars in the field of building automation and performance commissioning. A Delphi method of research approach is conducted through a series of interviews and surveys of industry and academia experts. The feedback from experts and the research from literature, industry and academic resources are combined, classified and categorized for identification of significant parameters around which Automation Performance Index (API) model can be defined.

Three modeling techniques are applied to the parameters in the illustrations of API model that are provided. The characteristics of the three models are compared with each other on various aspects, such as the effort required to set-up the model and its practical application and accuracy to quantify the building automation system's performance. The overall recommended model is tested and validated using information from existing and new facilities.

CHAPTER 1
INTRODUCTION

"Only the fittest will survive!" *a Paraphrase of Darwin's Theory*

1.1 Introduction

Buildings are dynamic and complex entities with similar needs as the living organisms that they usually house. They need to stay efficient and healthy. They need to be examined and tested to ensure all of their vital signs are within healthy ranges. Just as a physician usually orders lab tests to evaluate a patient's condition before prescribing any remedy for improvements, a facility manager needs to care for a building and assess its vital systems and the level of its performance, and then take effective steps for improvements. This research intends to develop tools for such assessments in one of the most important members of the building's anatomy, its brain, the monitoring, controls and automation structure otherwise known as Building Automation System (BAS).

Any improvement to the performance of a building, in terms of providing comfortable environment at improved energy consumption levels, should pay close attention to its automatic controls and monitoring systems. A customized BAS properly implemented is expected to improve building comfort levels and overall performance. How does one measure the performance of a customized BAS? This research will develop and introduce Automation Performance Index (API) models to evaluate BAS performance.

Current energy codes, standards and practices, such as ASHRAE 90.1 (ASHRAE 2001), Energy-Star (Energy-Star 2005) and Leadership in Energy and Environmental Design (US Green Building Council 2002) certification, are designed to provide generic prescriptions that may be tailored into proper dosage of steps for improvement of each project's energy profile. So it is important to measure the performance of vital systems and compare them with pre-determined healthy ranges, then initiate improvements and measure the effects and make corrections, as required, to stay on target. The set targets for buildings are sometimes called the prescribed codes or minimum acceptable standards.

A prescribed code, by definition sets the minimum acceptable standard. However, a minimum standard prescribed by a client becomes the maximum that the contractor will aim for delivering to that client. As a result, what was intended to be the minimum acceptable practice becomes the highest-possible performance. In final assessment, many buildings may fulfill the prescribed codes without delivering the expected performances.

The advantages of performance-based approach, as opposed to prescription-based, have been addressed by Kashiwagi (2005). Kashiwagi provides case studies and examples that clearly show how specified minimum standards in a competitive bidding environment automatically set those (minimum) levels as the maximum goals for the delivery systems. A performance-based approach, on the other hand, will remain focused on satisfying the client's requirements without limiting the level of effort. Kashiwagi demonstrates that improvement of building performance requires creativity and determination to sometimes push against all apparent limits. He explains that, to promote creativity, one should avoid constraints naturally imposed by prescribing the details of the process. API can be used to measure BAS performance against set goals without dictating the details of how BAS should be configured. Questions, such as how much automation is the right amount for a given facility, may be answered with the help of API.

1.2 Driving Forces for More Automation

The installed cost of a commercial grade Building Automation System in 1980 was approximately $500 per direct digital control point. In 2006, this cost is less than $25 per DDC point and the prices are dropping to insignificant levels (Sinclair 2005). On the other hand, the total cost of operation and maintenance of building systems, including the direct and indirect costs of building systems' environmental impacts, is increasing, and so is the desire to reduce these costs.

Regulating agencies and construction code authorities are increasingly enforcing stricter energy efficiencies and environmental policies. These drivers, coupled with the availability of low-cost controls and communication systems and access to real-time information via the Internet, all together have created a very fertile ground for building industries to move towards an integrated and global approach for operational optimization. This simply means there are both incentives and rewards for growing use of BAS, not to mention the demand of the tenants and the clients for the added features BAS can offer.

The variety of ever-increasing facility management features and options available through the evolving BAS technologies facilitate building administration and provide opportunities for more efficient and flexible operations. This prompts the owners and developers to implement increasing levels of automation in modern building construction. Continental Automated Buildings Association (CABA 2002) has documented many success cases and provided educational and informational seminars (Zimmer 2005) and many research papers have been published in this area for designers, contractors and facility managers. The evolution of BAS is depicted in Figure 1.1.

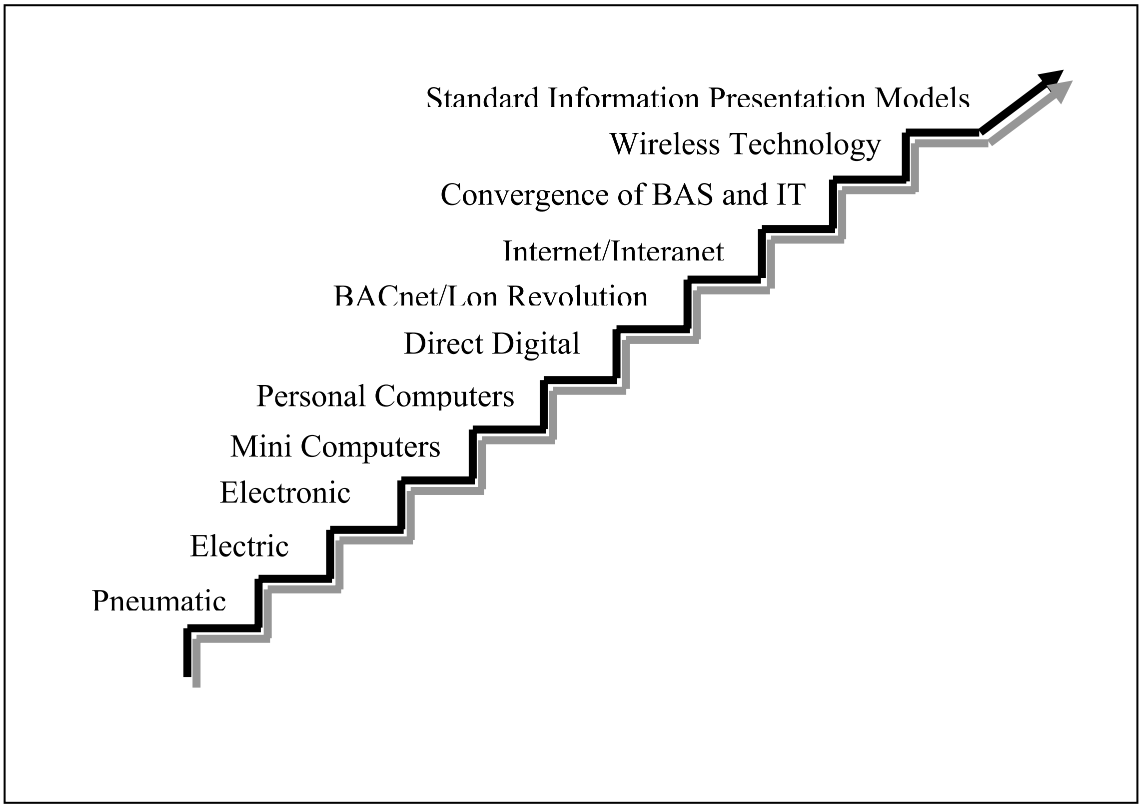

Figure 1.1 Evolution of Building Automation and Control Systems (Zimmer 2005)

1.3 Economics

Features, flexibility and added efficiency offered by more technologically advanced BAS are complemented with the economical rewards for this industry, both for the consumers and service providers. This serves as additional motivation for implementing more sophisticated automation in building construction. It is predicted that the BAS business will grow steadily into the $30 billion range by 2009 (ARC 2005).

It is therefore prudent to explore if the performance of increased BAS is proportional to the level of its use, or if such growth in building automation has predictable improved performance levels. Such information may help in deciding on the limits of BAS use.

1.4 Background

Automation is intended to improve the performance of buildings in multiple levels. Depending on one's perspective, a building's performance may be measured by its operating cost, energy use, or its net income. BAS may be designed to govern building systems according to a calendar-based and time-related sequence of operation. In commercial buildings, the BAS is either formed separately as an overriding controller, or by integration of several independent operating systems. The governed systems may include heating, ventilation, air conditioning, lighting, security, life-safety, plumbing, irrigation, fenestration, circulation, communication, transportation and janitorial systems. This list is not exhaustive and can be expanded depending on the building type and its services. For example, nurse call systems in healthcare buildings, room entertainment systems in hospitality buildings, hazardous waste containment systems in industrial buildings, and surveillance systems in institutional buildings can be added to the list.

More than three billion square feet of buildings are managed by the United States government alone, according to a recent report from the General Services Administration (GSA 2006). Studies have shown significant improvements to government buildings' performance levels through proper applications of building automation (GSA 2005). Some government studies, such as the National Institute of Standards and Technology's report on the high cost of inadequate interoperability (Michael P. Gallaher 2004), promote more integration of building systems and increased levels of building automation. However, research (Zhi-Gang Wei 1998) also indicates too much automation may actually be detrimental to a system's performance:

> In fact, too much automation results in poor operator performance caused by too-low workload, loss of skill, and loss of awareness of the system status. This raises a series of questions: How much automation should be used? What affects human use of automation? How does an increase in level of automation affect system performance and operational safety? Many such questions assume the existence of some quantitative measures for the degree of automation. To our knowledge, no such measure has been developed (Zhi-Gang Wei 1998).

Experimental studies of general automation with a simple lab-based set-up to define and test a proposed linear model has been performed (Zhi-Gang Wei 1998) to predict the optimum "Degree of Automation" (DofA) from human performance aspects. The researchers acknowledge that further studies for more complex systems, such as buildings environmental control systems, are required. The DofA research concluded that some manual intervention by human operators should be kept in the loop for improved results of an automated system which is the role of facility mangers for building automation systems.

A key indicator of building performance is its energy efficiency. Building energy standards, such as ASHRAE 90.1 (ASHRAE 2001), guidelines, such as Energy Star (Energy-Star 2005), or programs, such as LEED certification (US Green Building

Council 2002), are helpful in promoting efficient and sustainable design and practices in construction. Building codes and standards predominantly use prescriptive approaches. To verify the effectiveness of any prescriptive tools on a building, a measure of its performance is ultimately needed. Many projects built to meet codes have failed to provide the intended performance. If a performance-based approach in lieu of a prescriptive approach is followed, innovation and ingenuity is encouraged (Kashiwagi 2005). This can be illustrated by the simple example of the process of purchasing a car. If the automobile is being considered for someone else, a description of the needs and requirements of the user will lead to a purchase that minimizes the cost yet delivers the quantitative and qualitative aspects of the intended user. However, if the car is being purchased for one's own use, a more long-term view of the cost benefit and performance quality will be assessed, and higher cost and more risk of toying with the latest technology may be justified. This research contributes to BAS performance improvement by providing a scale to index the level of automation labeled Automation Performance Index (API).

Outside of detailed numerical simulations, practical scientific methods for evaluating building automation systems' performance are very scarce (Makarechi 2005). When simulation modeling tools, such as Energy Plus (Crawley, Winkelmann et al. 2002), Power DOE (Hirsch 1998) or eQuest (DOE 2005), are utilized to assess a building's energy or operating cost performance, BAS is simply treated as a set of options chosen from a list. These tools are not designed to evaluate the performance effects of the degree of automation prescribed. Automation is assumed to be at its optimum level whenever that option is selected to be available. Another misconception is in the parallel between the building's intelligence verses its performance. A presentation sponsored by the Continental Automated Buildings Association (CABA) notes:

> Intelligent Building is a building which has the inherent ability, through the design of its infrastructure and systems, to respond to the changing needs of its tenants/occupants and building owner/investor group quickly, safely and cost effectively (Katz 2005).

According to this definition, any improvement in building automation would be an improvement to its intelligence. Is it possible that after a certain point, an increase in the amount of automation (intelligence) may not necessarily offer any improvement to its performance? In 2005, CABA initiated development of a web-based utility to measure the building's level of intelligence, coined as the Building Intelligence Quotient (BIQ) (CABA 2005). The idea is to promote more building intelligence. Once BIQ is developed, tested and validated, it may become a complementary tool to API. However, the focus of API is performance level and not the intelligence level of a building.

1.5 Problem Statement

The world is facing an energy crisis and buildings are major energy consumers. Implementation of Building Automation Systems are expected to facilitate more effective and efficient building operations; effective in terms of providing more comfortable and productive environments, and efficient in energy use and cost of building operations. The question is how much building automation is needed and how to measure it.

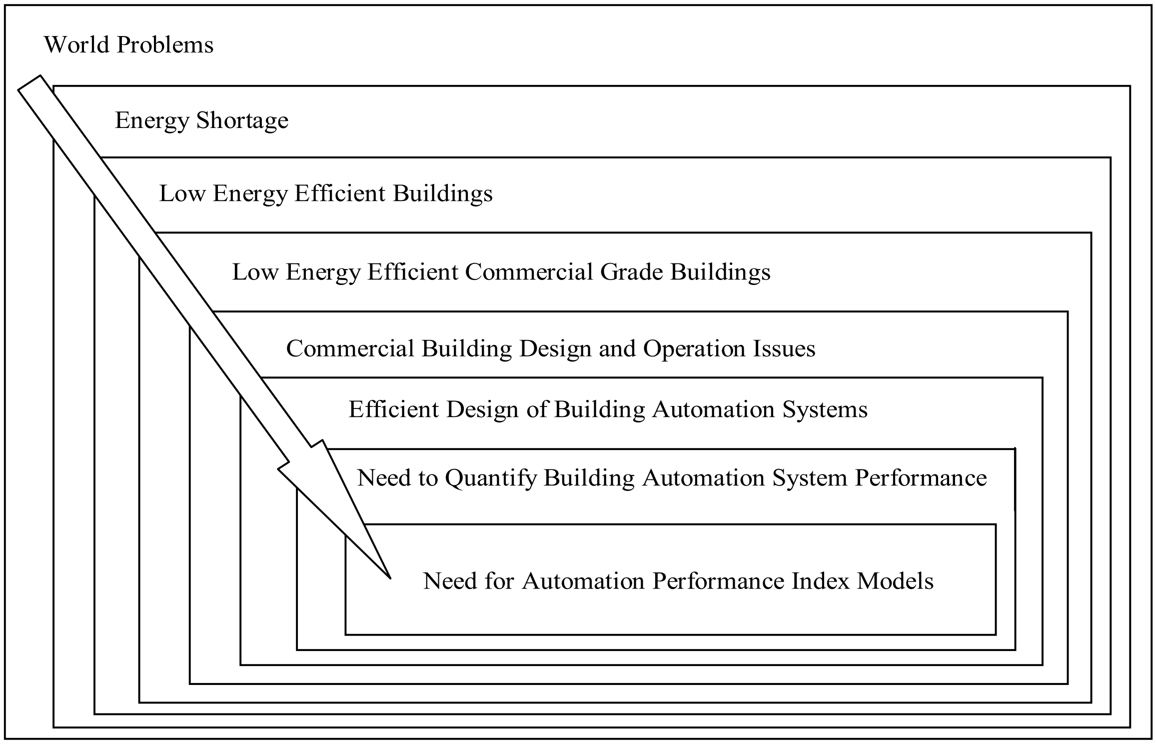

Figure 1.2 The Big Picture: Automation Performance Index (API as focus of this Research) within the Context of the Built Environment

Macwan, Wei et al. (Zhi-Gang Wei 1998) have stated that too much automation results in poor operator performance, and Michelle Addington, professor of the Architecture Program at Harvard University's Graduate School of Design, has likewise expressed concern that "the technology is coming in before we have the sophistication to know how best to deploy it" (Bowen 2005). On the other hand, implementation of technology and networking in some commercial projects have been shown to reduce the cost of building cooling system operation down to 50% level of the conventional optimized systems, as reported in I-Homes and Buildings magazine (Hartman 2006).

BAS can take unlimited forms. It can be as simple as a time-clock that operates a device, or as complex as integration and coordination of the scheduling, operation, monitoring and metering of all building systems and technologies. Table 1.1 demonstrates a few of the possibilities for BAS. In this table, some of the aspects or alternatives that may be considered for 'Building', 'Automation' and 'System' are provided for the purpose of demonstrating the numerous combination possibilities that may be considered.

Proper configuration of BAS can simplify the building operator's job, in addition to taking advantage of the operational efficiencies associated with and expected from integration of different building systems that traditionally have been controlled separately.

Table 1.1 Examples of BAS Possible Frameworks

Building	**Automation**	**System**
General	Individual	HVAC
Specific	Integral/Open	Lighting
Type	Networked	Security
Location	Closed	Life Safety
Single	Web-Based	Plumbing
Multiple	Local	Irrigation
Existing	Remote	Fenestration
New	Digital/Electronic	Circulation
Conceptual	Pneumatic	Communications
Renovated	Electric	Compactors
Use	Commercial	Transportation
In/Out Side	Industrial	Vacuum

Facility managers, owners and tenants see the value in implementing technology that will increase performance and reduce costs. Commercial facility owners, in particular, are motivated to incorporate additional levels of BAS in order to increase the appeal of their buildings in the minds of the potential tenants. The challenge is that BAS designers have no established tools to anticipate all the performance aspects among the possible BAS choices. For example, one could argue that similar spaces on the same floor should share thermostats to save on initial, as well as maintenance costs. On the other hand, running the HVAC system for a large number of similar rooms together may not be an energy-efficient solution because of the varied occupancy and use patterns in different rooms. One may also ask legitimately if a space that is not occupied should be heated or cooled as if it is. However, there is no established protocol for identifying how many thermostats, sensors or monitors would provide the best overall solution for a project. The question is, how does one quantify a building's automation-performance in order to improve it?

1.6 Objective and Scope

The goal of this research is to quantify a building's level of automation-performance. The specific objective is to develop an Automation Performance Index (API) model for evaluating the extent of a building's automation-performance. The hypothesis of this research is that a building's level of automation-performance is quantifiable.

The scope of this study is limited to commercial grade building automation systems which are manufactured with tolerance and operating limits suitable for commercial projects, such as office, retail, academic, courthouse, and light-institutional buildings. Industrial grade controls, with higher levels of accuracy, tolerance and performance (Franklin et al. 1990), are not within the scope of this research.

1.7 Assumptions and Hypothesis

International building codes (International Code Council 2003) and other international-level facility design guidelines and standards, such as those published by the US Air Force, Army, Navy and other similar design guides found listed in Whole Building Design Guide (NIBS 2006), GSA publication PQ100.1 (GSA 2004), as well as engineering guidelines of professional organizations such as (ASHRAE 2001) and (Netherlands Standardization Institute 1998), are assumed valid for defining the boundaries of the API model with API = 1 representing minimum level of satisfaction.

- All building equipment and controls are properly sized, commissioned and calibrated, and all devices and components are properly selected for their applications. Furthermore, all building systems and associated devices are assumed to meet the needs and limitations of the application for which they are used.
- Growth in user needs will prompt proportional expansion of building automation system, which means an increase in the number of control points.
- Building automation and building controls are treated synonymously.
- Terminology used by American engineering professionals and reference manuals such as (ASHRAE 2001) is valid and commonly accepted.

Above assumptions will help this research by:

- Allowing a focus on BAS performance aspects, rather than design issues.

- Simplifying the quantification of complex parameters, such as user needs.
- Providing a clear definition of terminologies used for model evaluation.

1.8 Methodology

Figure 1.3 illustrates the research methodology for this thesis and identifies the chapters that illustrate each section. The solid blocks represent "Decision Criteria" for each stage of this research process, and are described in the following section.

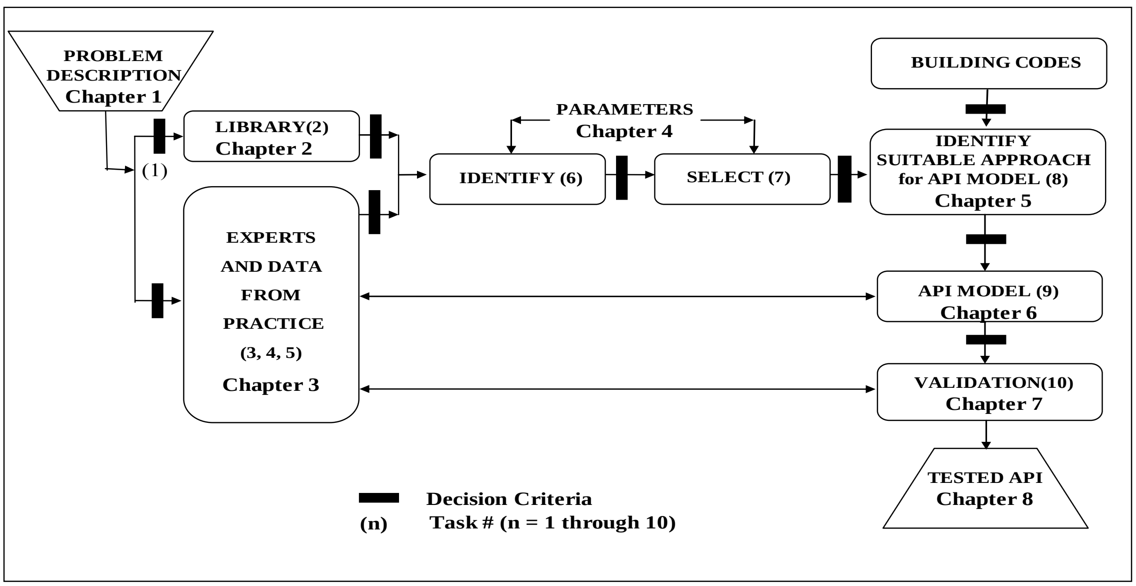

Figure 1.3 Research Methodology

Building automation can provide controls for a variety of environmental, mechanical, and security systems, and because each of these systems can separately or together form a BAS (Table 1.1), effort should be made to keep the approach for developing the API model without dependence on a specific system.

The following 10 tasks are illustrated and referenced by numbers inside the parenthesis in Figure 1.3:

1. Establishing decision criteria for each step.
2. Conducting comprehensive literature research.
3. Forming the expert panel.
4. Designing the questionnaire for the panel.
5. Receiving the required approvals for research using human subject input.
6. Identifying, Organizing, Classifying and the major building automation parameters.
7. Selecting the significant parameters.
8. Identifying suitable approach for API modeling.
9. Developing the API model.
10. Testing and validating the model.

1.8.1 Establishing Decision Criteria

The first task in the development of a methodology involved establishing the decision criteria as shown in Figure 1.3. The following part provides a guideline for establishing these important decision criteria.

a. Criteria for *Literature Research:* A keyword search for Building Automation Performance, Automation Performance Evaluation, and other combinations that are relevant was performed, and parameters that were cited with the highest frequency were identified and tabulated. Major categories for the parameters were established based on the literature search and expert knowledge as described in the following sections.

b. *Criteria for Forming a Panel of Experts:* Seminars and conference proceedings related to building controls, HVAC industry, building performance and engineering societies were identified, selected and attended to select industry experts and professionals to solicit participation in the research. Those with extensive working experience, practical and theoretical knowledge of different aspects of building operation and its automation performance but did not have published work in this area were selected for the survey in this research based on the following two major guidelines:

1. Recent professional experience in one of the aspects of building systems operations and performance.
2. Willingness to participate and provide expert knowledge to this research.

c. *Criteria for Identifying Relevant Parameters from Literature Research:* These criteria were based on collecting a comprehensive list of relevant parameters which were frequently cited in the scholarly publications. Then, these parameters were classified into groups with similar characteristics, and key parameters influencing the performance of building automation systems were identified by tabulation for the matching citations.

d. *Criteria for Identifying Relevant Parameters from the Expert Panel:* Based on the above two guidelines, a list of potential candidates for identifying relevant parameters influencing the performance of Building Automation Systems were identified. The expert panel members were asked to provide their knowledge based on their own experience at the field. Each panel member individually and without access to other members was asked to provide recommendations based on their professional practice regarding the most significant parameters that influence performance of BAS. The initial list of the parameters obtained from the panel members, were tabulated and similar items were combined into the same categories identified in the literature search. Based on how frequent each parameter category was cited, the most significant ones were identified.

e. *Criteria for Identifying the Most Significant Parameters:* Comparing the two lists of parameters and aspects with high frequency of citation, a final list of the key parameters with the highest number of recommendations and citing were produced.

f. *Criteria for Identifying a Suitable Approach for the Model:* Various modeling techniques referenced in scholarly publications in similar areas were investigated and tabulated. The criteria for model selection was based on: type of data needed (numerical or linguistic), size of data from expert panel, ease of use, relationship or correlation among the model parameters, level of accuracy, versatility and practicality.

An extensive investigation of various modeling techniques has been conducted by this author in his titled "Dynamic Decision Support Systems" (Makarechi 2004), in which appropriate decision support models are identified based on the stage of a project, whether in the early planning or design, development, construction, operation and even in latter stages of re-commissioning. The general conclusion was that in earlier stages of a project when actual data is scarce, heuristic methods and, in the latter stages, numerical methods should be utilized.

g. *Criteria for Applying Building Codes and Guidelines:* Governing building codes were utilized to define the model's boundaries. This research has used the criteria established by large organizations, such as General Services Administration (GSA), Emory Healthcare Facilities, Georgia Tech Facility Design Criteria (Yellow Book), as its criteria for model development. The criteria in these codes and guidelines were applied as boundary conditions to determine the model's constants.

h. *Criteria for Defining the Automation Performance Index:* The criteria used for indexing is based on the assumption API was a positive index defined between 1 and 5.

API equal to 1 indicated a satisfactory automation performance, API values less than one were considered lower than satisfactory performance, and API values higher than one were considered improved performances.

i. *Criteria for Testing and Validation of API:* The testing criteria were based on the validation of model by those buildings which were not included in original set used for model development. Therefore, additional information about existing buildings with known automation performance was obtained to validate and test if the model's prediction would match with the actual experience of the facility mangers.

1.8.2 Conducting Comprehensive Literature Research

For this project, extensive use of engineering and building automation journals and Internet resources, as well as a comprehensive literature search of related materials, is conducted. Attendance to seminars organized by the International Council of Research and Innovation in Building and Construction (CIB 2005), Building Futures Council (BFC 2005), and High Performance Buildings 2006 (ACG 2006), and review of these and other conference proceedings, have been a part of this research effort.

Literature research, as well as information obtained from experts in building automation, formed the basis for identifying key parameters relevant to BAS performance. As described by Chung (2004), "Domain Experts" are considered invaluable sources in practical research. Since they provide experience-based information from actual field-specific practice, their advice requires little qualification or validation.

The most-significant parameters are identified using the input from the practicing experts through a number of communications and meetings using a Delphi method of reaching consensus (Linstone and Turoff 2002). This effort, combined with information obtained through literature research, is used to screen the most-significant parameters for defining the API model. The model is further refined by application of the industry standards and guidelines (NIBS 2006) before testing and validation.

1.8.3 Forming the Expert Panel

To establish a basic understanding for the state of the industry and also to meet experts in the subject, the following seminars related to this research were attended:

1. Converging Building Systems Technologies (BuilConn 2004).
2. Performance Based Procurement (Kashiwagi 2005).
3. Building Futures Council (BFC 2005).
4. International Council of Research and Innovation in Building and Construction (CIB 2005), W92 Construction Procurement Systems Symposium.
5. High Performance Buildings (ACG 2006).

From the above seminars, and also from the list of building automation professional contacts, experts who were qualified in assisting with the research were identified. The research was done in two stages. Stage One was completed in August 2005 as an independent study titled: "A Step towards Development of Building Automation System Performance Indicators" (Makarechi 2005), in which a smaller group of 13 experts provided input. Stage Two is this research, in which a larger number of resources and experts are consulted to identify and rank the significant parameters for developing API models.

1.8.4 Designing the Questionnaire for the Panel

A questionnaire was designed and developed to capture the expert knowledge from expert panel's input. The questions were designed to be relevant to this research, short and precise without leading the experts in any direction. A total of three initial questions were sent by e-mail. The entire e-mail is reproduced in Figure 1.4:

Dear colleague,

As you may recall, I am working on a research for developing measurable Performance Indicators for Building Automation Systems. You are part of a handful of people I consider experts and practitioners that can help me in this endeavor. May I ask you please answer the following three questions in response to this e-mail?

1- Rank the performance of the following between 1-3 please. (use 1 for the best):
   a. Integration of BAS with Lighting:
   b. Integration of BAS with Security:
   c. BAS using wireless web based technology to collect information.

2- What three factors indicate a good BAS performance? Examples are comfort, operating cost, maintenance cost, simplicity of operation, integration with other systems, incorporation of occupants needs, etc.

3- How would you recommend to measure the above factors?

I would appreciate it highly if you let me have your answer before May 15, 06. I will share the results with all who participate.

Thanks
Shariar Makarechi, PE, PhD Candidate
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Building Construction Graduate TA
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Figure 1.4 Survey Questions 1-3 by E-mail

The first question was intended to get an overall view for the current trends in the BAS industry. The response to this question did not affect the process of forming the API model, but helped in validating it. Questions 2 and 3 were the key questions for the model.

1.8.5 Receiving the Required Approval for Research Using Human Subjects

Human-based research requires special review and approval from the Institutional Review Board (IRB 2005). The protocol of this research has been submitted and approved (IRB H05151) and the required training to obtain research certification was completed by this author.

1.8.6 Organizing, Classifying and Identifying the Major Building Automation Parameters

Information from literature and online research, and feedback from the expert panel is tabulated and organized separately into similar categories for the parameters cited, and the most significant parameters are chosen. Parameters cited most often were given more priority in the selection process.

1.8.7 Selecting the Significant Parameters

Parameters were selected based on the frequencies of their citations in literature search and expert knowledge. Some of the identified parameters may not be directly scalable. In order to define scalable parameters for the model, logical correlations between the parameters identified by research and other quantifiable parameters are established.

1.8.8 Identifying Suitable Approach for API Modeling

Heuristic and numerical models are considered for scaling significant parameters. Numerical analysis using value engineering techniques (Sadri 2004) and (GSA 2004), Utility Theory (Bell, Raiffa et al. 1988) and Fuzzy Logic (Zadeh 1994) modeling techniques are utilized in this research. The models are evaluated for several possible

BAS configurations and the results are plotted and analyzed for sensitivity using additional input from the panel of experts.

1.8.9 Developing the API Model

The three major models are each further refined by building design guidelines (NIBS 2006), such as GSA P-100 (GSA 2005). In each case, API is defined as an index representing the expected performance levels of BAS. This index, in general form, is the weighted average of the normalized significant automation performance parameters.

1.8.10 Testing and Validating the Models

A set of sensitivity analysis is conducted for observing the range of API and validation of its estimates and trends predicted by the numerical model. The characteristics of the three models are compared based on their strength in practical use. Definitions of the basic functions and structures of building systems and their automated controls are presented in Appendix A.

1.9 An Axiom and a Challenge

Axioms: BAS properly applied will reduce manual labor and save on building operating time and cost. The growth in user needs and demands may be addressed by proportionally expanding the building control systems, sometimes called Energy

Monitoring and Control Systems, EMCS or simply Building Automation System, BAS. An open BAS is one that can incorporate multiple building systems and disciplines and be served, monitored and serviced by multiple vendors (CABA 2002).

Challenge: BAS not properly applied will complicate maintenance and increase cost of building operation. This will cause additional effort for learning, stabilizing and securing a large building's automation system and can easily make the system cost-prohibitive due to the increase of the number of control and monitoring points.

1.10 Performance Measurement in Building Automation Systems

A quantitative model to evaluate the performance of BAS will help to assess the existing state of system in comparison with its desirable mode. Any inferior deviations may then be addressed. Structuring a decision-support system to routinely monitor and reduce deviations from set objectives is bound to improve the system performance (Makarechi 2004).

1.11 Expected Conclusions, Benefits and Contributions

A model for quantifying a building's performance index will be developed. Expected benefits of API include facilitating the evaluation of Building Automation Systems (BAS). The accuracy of the API predictions is established using data not used in developing the model and set aside for the validation of the model.

One major expected contribution of this research is defining a methodology for the development of an indicator of the net benefits of the automation applications for buildings or projects. It is expected that API will provide useful feedback to professionals during the design and construction process for improved decisions towards optimization of building automation performance.

Analysis of the API model is expected to lead to new knowledge and findings in the relationship between the Automation Performance Index and building types, sizes, locations, functions and occupants. New knowledge can also be observed in the correlation of certain aspects of building performance, such as the level of complexity of BAS in relation to the expected amount of occupant complaints, and the balance between high performance buildings, occupant satisfaction and facility management.

Improvement requires monitoring and measurement, which is made possible by having a model, such as API. As the construction industry moves towards more intelligent buildings with integrated automation systems, further discussion regarding the significant parameters for improving the building automation performance tailored for specific clients are encouraged by this research. The benefits of enhanced building intelligence, versus the challenges of a sophisticated system operation can be captured in further modeling efforts and analysis of API.

CHAPTER 2

LITERATURE REVIEW

"History is the version of past events that people have decided to agree upon"

Napoleon Bonaparte

2.1 Introduction

Previous work and research creates a foundation for this research. Although only a small and limited amount of research in the area of automation performance for the buildings is available, it is important to capture the work already done and build upon that work.

2.2 Purpose

The purpose of this chapter is to provide a review of the existing knowledge recorded in literature and published work as a background, in order to establish a point of departure for this research. This background review is comprised of two parallel efforts: 1) Literature search on scholarly work related to the subject; and, 2) Internet search for the same, as well as for the literature available through the manufacturers and service providers of the building automation industry.

2.3 Method

The search for this section included contents found under the following key topics: Building Automation Systems, Building Automation Performance, Performance of Building Technologies, Building Performance and Automation Performance.

2.4 Building Automation Background

Appendix A provides basic definition and background information on Building Automation Systems (BAS). Successful facilities management entails taking a holistic, performance-based approach to building automation and tracking key performance metrics in real time (ARC 2002). A recent study (Mark J. Stunder 2003) for the Air-conditioning and Refrigeration Technology Institute (ARTI) provides a suitable summary of the state of the industry.

As building owners strive to reduce both operating costs and occupant complaints, they are likely to utilize Building Automation Systems (BAS), sometimes called smart or intelligent building technology, to manage and save energy consumption and to increase occupant comfort.

While investment in smart-building technology has been increasing, the science or art of using real-time information in adaptive building management systems is also growing out of its relatively immature state. Automated building systems that traditionally used very limited number of local sensors due to the high initial and maintenance costs, are now looking into the new information pathways (i.e., via the Internet) that could result in considerable cost savings and greater efficiency (Mark J. Stunder 2003):

> Internet technology has now progressed to the point where it can be a source of real-time information for predictive purposes in managing buildings. Proactively managing and operating building systems in accordance with actual or anticipated conditions should increase space comfort while reducing operating costs.

Interactive connectivity of all control components, coupled with the processing power of software-based simulation engine as an optimization tool, can provide a smooth control strategy that will also optimize the cost of utilities, as well as maintenance. In an effort to design an interactive control system, attention should be paid to the need for local intelligence and not mere connection. An effort to just make all controlled components talk to each other or to a central processor will not provide the reliability and performance expectations of building owners. Electronic controls today are already capable of performing a reasonable amount of default tasks if the interconnection lines are interrupted for any reason. Additional local intelligence can be built to assigning an identification "signature" for each component, device and element in the system. A hand shake between these more intelligent items at any time should make it possible for each side to identify all the needs, capabilities and limitations of the other side, and provide action, signal or make adjustments and decisions accordingly.

2.4.1 Intelligent Buildings

The operational behavior of all mechanical, electrical and environmental equipment in a building can be automatically controlled and coordinated for improved performance. A building with BAS is sometimes called an "Intelligent Building":

> An Intelligent Building is designed and constructed based on an appropriate selection of Quality Environmental Modules to meet the User's Requirements by mapping with the appropriate building facilities to achieve a Long-Term Building Value. The Intelligent Building is a

building which has the inherent ability, through the design of its infrastructure and systems, to respond to the changing needs of its tenants/occupants and building owner/investor group quickly, safely and cost effectively (Katz 2005).

2.5 Analytical Work Background

High-level analytical research has been done towards application of simulation-assisted dynamic building strategies (Mahdavi 1997) and integration of control and building performance by open or communicating protocols (Azzedine Yahiaoui 2003). There are now validated, knowledge-based algorithms for thermal load predictions using real-time weather forecasts (Tse 2003), as well as faster simulation models, emerging. These eliminate unnecessary calculations by efficient merger of computational fluid dynamics with building simulation techniques using communicating objects method. In this method, physical components of buildings, such as walls and spaces, are modeled as computational objects that individually solve the appropriate physical equations and exchange changes of surface values, such as temperature, when necessary.

Because the object structure is derived directly from the building structure, and because generic objects are reused, simulators can be generated with very low effort. Based on object-oriented modeling and automatic code generation, new physical effects can be easily integrated. This method is fast because calculations are only generated by changes. Quick and accurate responses to external events can also be accomplished. Both features are necessary for real-time tests of the Building Automation Systems definition of object structure (Zimmermann 2001).

2.6 Economical Background

Facility owners, engineers and managers are training their staff for the evolution of the Building Automation System towards the Web (Paul Allen 2003). Economical analysis of alternative networking methods have been done to show viability of a global approach to building systems (Avaya 2003). The concept of real-time building management services or Global Optimization Systems was originally coined by (Zulfi Cumali 1989) in San Francisco and further discussed by others (Mark J. Stunder 2003) and (Makarechi 2005). Cumali installed sensors in PG&E office buildings in downtown San Francisco and used a central personal computer to collect and analyze the data gathered from various buildings' systems, such as HVAC, Lighting and Security. The set-up was also capable of tying in with national weather service forecast office for SF Bay Area, by modem and provided a feed forward positioning for pumps, fans, air and water systems serving the buildings for smooth and energy efficient operation that met the building demands with minimum overshooting and waste. Today, BAS systems can integrate and operate multiple buildings and systems via the Internet and provide remote monitoring, updating and manipulation of their operations.

It has been demonstrated, through 40-year life cycle cost studies by (Katz 2005), that building operating costs account for about 50% of its total lifetime costs. Improving the performance of the Building Automation Systems is expected to lower building operating costs.

Automation, at its root, is the replacement of human workers by technology. It is parallel to mechanization and computerization (Encarta dictionary and thesaurus). A simple time-clock to start and stop lawn irrigation is a form of automation that may be useful to reduce manual labor. Building Automation Systems are primarily attractive because of their promise of reduction in human labor required to operate building systems. A well-designed and implemented BAS will increase the building's overall appeal (value) to potential tenants and buyers by offering state-of-the-art comfort and efficiency. Lower operating costs and higher appeal with proper application of BAS in buildings is the motivation behind development of a scale for comparing BAS options, which is the focus of this study.

In a simple BAS, a set of packaged instructions (programs) are released (communicated) in time by a computer (controller) to initiate activities (functions) that modify positions or settings of elements, such as valves, window shades or dampers (controlled device), in order to increase or decrease the measured (sensed) value of a (controlled parameter), such as lighting or temperature around a desired level (set-point).

2.7 Literature Review

A thorough search of literature, from both the literature and Internet sources, has been conducted and up-to-date relevant research that helps to determine the significant parameters shaping the performance of BAS has been identified.

Jeanine Katzel (1998), in an article in Plant Engineering Magazine, defines BAS as a collection of equipment from sensor to software, blended together to achieve a seamless flow of data and control actions. Specific components may include end devices, controllers, networks from which data are transferred, and an information path to front-end operator interfaces. A BAS also embraces control and information strategies that allow it to function effectively. Katzel goes on to explain that few BASs are leveraged to full capacity. The system installed in new construction often receives only cursory attention, lost in the overwhelming volume of tasks required at start-up. Although every BAS is capable of helping make more intelligent decisions, significant savings may be lost, unless collection mechanisms are established to gather data and time is taken to analyze the data.

Katzel promotes systems integration and flexibility and emphasizes on plant engineers and facility managers to take time to audit facility performance, establish data collection mechanisms, and analyze reports. Katzel also promotes a standard protocol that lets a BAS exchange information simply and economically, avoiding complicated proprietary or third-party gateways.

Dr. Brien Prasad (1998), in a presentation titled “Change”, speaks of controlled and regulated automation that will ultimately lead to interoperability and higher productivity at lower cost. Prasad also promotes flexibility, as well as simplicity.

Zhi-Gang Wei (Zhi-Gang Wei 1998) writes in the context of human-machine systems, and demonstrates with experiments that high level of automation may have adverse effects, and increased automation does not necessarily result in increased benefits. Wei quantifies level of automation by a ratio of what is automated to full automation.

Dr. Raja Parasuraman (2000), professor of Psychology at George Mason University, has published research on the issues of human factors and cognitive neuroscience. He explores the influence of automation and computer technology on attention, memory and vigilance of human operators. His conclusion, similar to Wei, mitigates that too much automation will be harmful (Parasurman, Sheridan et al. 2000).

Similar work has been done by University of Iowa professors John Lee and Katrina See (Lee and See 2004).

George Heath (2001) documented benefits of two-way communications for monitoring and control using the Internet. He highlighted integration of Heating, Ventilation and Air Conditioning (HVAC) with lighting, security and building management systems.

Chris Johnson (2001), of Cisco, focused on the networking and integration of building systems, and, specifically, application of wireless technology in building security controls. Carlos Brazao (2004), of the same company, cited the projected benefits of the Internet-based operations in U.S. and Europe, and referred to a 2002 MIT study of Internet organization, culture and productivity.

Continental Automated Buildings Association (CABA), a professional organization dedicated to BAS issues and initiatives, started efforts in the past three years to promote development of Building Intelligence Quotient (BIQ). Intelligent buildings are those equipped with BAS, and the higher the level of automation the more intelligence is associated with the building. At the time of this writing, CABA is still in the development of a Web-based ranking system for measuring the level of the building intelligence. Once this research is complete, it may be a complement to API; however, it will not replace it. API is intended to measure the performance of the building intelligence and provide a tool to decide what level of intelligence would provide the improved performance. Complementary work to this research sponsored by (CABA 2005) on building intelligence quotient has been noted elsewhere in this thesis. Other aspects of BAS, such as life cycle cost (CABA 2004), networking and integration (CABA 2002), interoperability (CABA 2004), should also be noted here.

Zhi-Gang Wei (1998) stated that there no accepted scientific, engineering or empirical methods available in 1998 for the purpose of evaluating Building Automation Systems. Almost a decade later, this statement still holds true.

Peter Manolescue (2003) tackled the practical issues of integrating security with the rest of the building automation systems and Thomas Keel (2003) of Georgia Tech has done extensive work on life cycle cost analysis of building automation systems and financial rewards of building systems integration.

James Hirsh (1998) worked out simulation algorithms for integrated building automation systems, and Steven Rogers (2004) proposed control architecture with focus on the building as a power plant and its energy use.

Ted Smalley Bowen (2005) covers energy savings expected by incorporation of simulation techniques in intelligent buildings among the efforts to make buildings more manageable. He refers to research led by Carnegie Mellon University scientists on building monitoring and control schemes that includes HVAC, power production, lighting, elevators, safety, and security and concludes such schemes can be complex involving computer simulations tied into building control systems and updated by sensor feedback and performance data. Sensors keep tabs on virtually anything that can be monitored, whether mechanically, magnetically, electromagnetically, thermally, optically, chemically, biologically, or acoustically. And the conglomeration of sensors packed into intelligent buildings is increasingly accessed via wireless networks. Bowen also quotes Michelle Addison of Harvard, who stated that many schemes amount to overkill, deploying too many sensors and gathering too much data, rather than narrowing in on key performance measures. She is also quoted saying “I honestly think the idea of having everything networked together misses the point,” and “You can do a hell of a lot with a few discrete things.”

While its building blocks include many promising technologies, the intelligent building addresses some uniquely complex issues, according to Addington, Professor at Harvard who noted that building environments represent some of the most difficult problems in fluid dynamics, stating: “There’s a concern that the technology is coming in before we have the sophistication to know how best to deploy it,” quoted by Bowen (2005).

A Department of Energy-sponsored research done by Hansen (2005) and others provides background material on BAS and divides it into four areas: Applications, Hardware, Communications and Oversight. The paper promotes automated commissioning and diagnostic technologies for building systems and equipment to help remedy these problems and improve building operation by automatically and continuously detecting performance problems and maintenance requirements and bringing them to the attention of building operators. Aaron Hansen has also introduced the open Building Information Exchange (oBIX) Web services.

Mary Ann Piette and her colleagues at Lawrence Livermore National Lab (Piette, Watson et al. 2005) recommend the use of wireless network technology for integration of building systems and managing its electrical demand, as well as energy consumption.

Jiri Skopec (2005) summarized the benefits of Building Intelligence Quotient (BIQ) which is going to be a complementary tool to API once developed.

Ken Sinclair of Automated Buildings (Sinclair 2005) declares a renaissance type revival is happening in the world of building automation interconnectivity, and Ron Zimmer (2005) highlights the evolution and convergence of Communication Life Safety Automation (CLA).

Anwer Bashi's article, titled "Artificial Intelligence in Building Automation" (Bashi 2006), explains simple fuzzy logic modeling for BAS. Paul Ehrlich (2006) has discussed intelligent building construction and operation issues, including building management tools and tenant portals, and Thomas Hartman (2006) illustrates the potential energy savings of a network-integrated system.

2.8 Observations and Analysis

It should be noted that none of the authors noted above actually offer a systematic list of significant parameters. Yet, in the context of the research articles, important parameters from the point-of-view of the researcher can be identified; those are the results that have been summarized in Table 2.1.

Table 2.1 Summary of the Literature Research for BAS Significant Parameters and Modeling Methods

Published Paper (Author Date)	**ISSUES DISCUSSED or HIGHLIGHTED by the AUTHORS**											
	Human Factor	BAS Effect on		BAS Integration with			Suggestions for API Parameters					Modeling Method
		Power Demand	Energy Use	Lighting	Security	Wireless	Cost	User Needs	Simplicity	Integration	Service and Maintenance Availability	
(Katzel 1998)	X							X		X	X	N/A
(Prasad 1998)							X	X	X	X		N/A
(Zhi-Gang Wei 1998)	X											Ratio
(Parasurman, Sheridan et al. 2000)	X						X					Fuzzy
(Parasuraman 2000)	X						X	X				Empirical Fuzzy
(Heath 2001)				X	X	X				X		N/A
(Johnson 2001)					X	X				X		N/A
(CABA 2002)				X	X	X	X			X		BIQ Index
(Manolescue 2003)				X	X					X		N/A
(Keel 2003)							X			X		LCC
(Brazao 2004)						X				X	X	N/A
(Hirsch 2004)				X	X	X				X		N/A
(Lee and See 2004)	X							X				Conceptual Bio Medical
(Rogers 2004)			X					X			X	N/A
(Bowen 2005)		X	X	X	X				X			N/A
(Hansen 2005)				X	X	X	X	X				N/A
(Katz 2005)				X	X	X	X					BIQ Index
(Piette, Watson et al. 2005)		X	X							X		Baseline Regression
(Skopek 2005)				X	X	X	X					BIQ Index
(Sinclair 2005)		X	X							X		N/A
(Zimmer 2005)				X	X	X		X		X		CLA
(Zimmer 2005)				X	X	X	X	X		X		BIQ Index
(Bashi 2006)								X				N/A
(Ehrlich 2006)								X	X	X		N/A
(Hartman 2006)			X			X				X		N/A
Number of Citations	5	3	5	10	11	11	9	11	3	15	3	
Low, Medium or High Citation Levels	L	L	L	H	H	H	M	H	L	H	L	
Key: L = Low = 0-5, M = Meduim = 6-9, H = High = 10 or higher BIQ = Building Intelligence Quotient CLA: Communication Life Safety Automation												

In addition to suggestions or ideas for API parameters, issues such as Human Factor, BAS Effects on Power Demand, BAS Effects on Energy Use and BAS Integration with Lighting, Security and the use of Wireless Communication Networks were identified in the literature review.

2.8.1 Human Factor

There is a general body of work focused on the impacts of automation on human beings. Most of this work evolves on psychological and medical themes regarding performance predictions of man and machine interfaces. Although this body of work does not directly address building construction or building automation industry, it offers valuable additional information on parameters, such as system cost, complexity and flexibilities that have been summarized in Table 2.1.

2.8.2 BAS Effects on Power Demand

Electrical power demand, which is an indication of the peak power requirements for buildings, measured in kilowatts or kW, is metered separately from the building's energy consumption measured in kilowatt-hour or kWh. Electrical companies charge their clients for both of these components, and are generally more concerned to be able to meet the peak kW demand that is put on them. The highest electrical power demand usually occurs in the hottest days of the summer, due to the added electrical refrigeration equipment load As a result, the demand charges for commercial clients are based on time of day and month ratings, and are usually the larger component of the electrical bills. Creative ways to save on the electrical demand are usually planned in building automation systems to produce, store and dispense the building cooling energy. A few of these techniques are:

a. Alternative Refrigeration Systems: Refrigeration machines using steam-driven turbine-type compressors in lieu of electrical compressors and Absorption refrigeration machines are two examples.
b. Peak Saving: The use of local fossil fuel fired generators during peak electrical demand to reduce the kW draw from the electrical power network.
c. Ice or Chilled Water Storage: Insulated storage tanks are added to the building cooling water circulation. The tanks are charged during off and non-peak times and assist the refrigeration system during the peak demand time.
d. Battery Packs: Batteries charged at off-peak time and assist the power network during peak demand time. In addition to the conventional methods, the charging mechanisms could be:
    1. Solar Power Cells.
    2. Wind Mills.

2.8.3 BAS Effects on Energy Use

Building energy use can be monitored and managed by BAS, and it is important to realize that the amount of energy used by a building is one of the most important indicators of its performance. If all building energy systems are managed by BAS, energy use can also be an indicator of BAS performance.

2.8.4 BAS Integration with Lighting

Lighting accounts for 40-60% of building energy use (DOE 2005) and is the largest component of the energy profile of commercial building projects (Energy-Star 2005). BAS as a tool for building energy monitoring and management can coordinate the lighting system's operation with other building systems, such as HVAC and Security.

2.8.5 BAS Integration with Security

Building security systems, due to their nature, would not normally share most of their features, such as access control information, people identification and video surveillance information, with any other systems. However, some basic input regarding occupied or non-occupied spaces can be used to trigger lighting, HVAC and other utilities in each space by BAS and help in saving both energy cost and demand size.

2.8.6 BAS Integration with Wireless Technology

Integration of Building Automation Systems using data communication networking has been discussed as part of the API parameters; however, the use of wired versus wireless technology is a fairly new and highly evolving area of research and development in building technology. Wireless networking is approaching the speed, reliability and security levels that have rendered most of the currently wired data communication systems redundant because of the immense flexibility they offer at very low costs. As a result, wireless networks are already in place or being installed in commercial, industrial, and even residential building projects. The addition of wireless systems do not totally eliminate the hard wired or fiber optic wired data networking that has emerged as the fourth utility (Murchison 2005) in building construction projects. Once data and Internet connectivity is established within the structure, using the wire, cable or fiber, then wireless provides the complementary distribution coverage. Many wireless devices rely heavily on battery-powered components, and this reliance has sparked discussions about reliability and robustness of the wireless networks for uninterrupted connectivity to critical building systems that provide life safety and emergency services.

2.8.7 Suggestions for API Parameters

Significant parameters that are identified in the literature review may be classified in the following categories:

- Cost
- User Needs
- Simplicity (of learning and operating)
- Integration (or the level of openness to share information with other systems)
- Availability (of service maintenance)

The above parameters have been identified based on criteria established in chapter 1 and is recorded in Table 2.1.

An important observation may be made that the 'Integration' column in the API parameter section of Table 2.1 has the highest number of citations compared to all the other parameters that have been identified. The information gathered by this background review should be complemented with the information received from the members of the expert panel in order to finalize the selection of significant parameters.

CHAPTER 3

EXPERT KNOWLEDGE

"Expert systems are complex logical metaphors that shift the blame for misjudgment"

Irreverent Dictionary of Information Politics
By Paul Strassmann & John Klossner

3.1 Introduction

In 2005, the Heating Ventilation and Air Conditioning (HVAC) industry celebrated its 100th year in the United States. Building automation has very strong roots in the HVAC industry. Building Automation Systems (BAS) enjoy great popularity and widespread use in new construction and renovation projects, due to the digital technology revolution. The digital building technology owes its fast-paced evolution in part to the micro processor and personal computer industry's progress in recent years. The relatively young, digitally enhanced BAS industry has even newer offspring in the form of Web-based control systems, open protocol integrated automation systems, and so on. As a result, this new BAS industry is generally too young to offer foundational research that may be used as a departing platform for the work at hand. Hence, there is a need to tap into the experience of professionals and knowledge of the academics that currently work in this field by attending seminars, and conducting interviews and surveys.

The specific objective of this research is to develop an Automation Performance Index (API) model for evaluating the extent of a building's automation-performance. In order to develop the model, parameters that significantly influence BAS performance should be identified with help from the industry experts.

3.2 The Expert Panel Selection and Polling

Getting an audience with professionals and be able to create interest among industry experts to participate in research can be quite a challenge, especially when no contractual or legal obligations exists for this purpose. There are, however, opportunities to accomplish this task by participating in specific professional and academic seminars and manufacturer's trade shows. The following seminars relevant to this research were attended for the above purpose:

1. Converging Building Systems Technologies (BuilConn 2004).
2. Performance-Based Procurement (Kashiwagi 2005).
3. Building Futures (BFC 2005).

International Council of Research and Innovation in Building and Construction (CIB 2005), W92 Construction Procurement Systems Symposium.

4. High Performance Buildings (ACG 2006).

From the above seminars, and also from the list of building automation professional contacts (ASHRAE 2006), experts who could be potential members of an expert panel for this research were contacted, and those who responded positively showing interest in assisting with the research were identified.

A total of twenty nine highly qualified experts with industry and academic qualifications and a minimum of 15 years of combined recent experience with building systems, building controls, facility commissioning and facility operations were surveyed. The expert survey was conducted in two stages. In Stage One, a group of thirteen experts were surveyed in 2005. In Stage Two, involving seven members of Stage One was completed in 2006. Data from both stages are summarized and will be illustrated in the later sections. Each member of the panel of experts was treated independently and in isolation via unshared e-mail correspondence. In other words, the experts were not informed of the responses of the other members of the panel so they could not influence each other.

3.3 Survey Questions and Responses

Once an expert was admitted to the panel for this research his input was obtained by e-mail. The first survey e-mail (Figure 1.4) with Questions 1, 2 and 3 was sent with the purpose of identifying the most-significant parameters. Questions were as follows:

1. Rank Integration of BAS with lighting, security and wireless technology.
2. Name three parameters that are most relevant to the performance of BAS.
3. Explain how the named parameters may be measured.

The above questions were designed to be brief and non-leading, so the members of the panel would be encouraged to respond in a timely fashion and feel free to make any suggestion or recommendations.

3.3.1 Question 1

This question dealt with integration of building systems which revealed the highest frequency of citations in the literature and Internet search as noted in Chapter 2. Different building systems are normally provided by different suppliers and have independent controls networked by hard-wired communication or low-voltage wiring. Integration of these building systems was the subject of this question. Integration to share selected information, for harmonizing and coordinating operational set-points and schedules of activation and de-activation of different systems, is designed to help in the building operational efficiency. Also, the viability of using wireless networks in lieu of hard wired systems was a part of this survey question.

Wireless network systems started to break into the building construction and remodeling domain around 2003-2004. This has become an exciting area of BAS development and seems to be one of the most actively developing areas three years later.

Building Automation Systems originally started as a part of the HVAC trade and, in the last 30 years, evolved into what is called Energy Management and Control Systems (EMCS). The additional management and monitoring capabilities of EMCS includes trend and demand analysis, tenant billing, scheduling and maintenance record-keeping. These features and capabilities have become essential tools for facility managers to operate the buildings.

Integration of lighting controls through EMCS with the BAS was the next natural choice, especially when lighting system alone accounts for 40-60% of commercial building energy consumption (DOE 2005). Question #2 also addressed the possibility of integration of BAS with security systems.

Although security systems require exclusive protection to prevent any access compromise, some basic information produced by the security network can be safely shared with other systems to help in verify the occupied and un-occupied spaces within the building. This information may interactively be utilized for scheduling of the operation of the other systems such as lighting and HVAC that serve those spaces. Responses to Question 1 are presented in Table 3.1.

Table 3.1 Survey Results for Question 1

Name	Company	Date	Question 1: Integration with:		
			Lighting	Security	Wireless
2005 Survey Ranking Results 1 = High, 2 = Medium, 3 = Low			**1.4**	**2.1**	**2.3**
Cheol-Soo Park	SKK University	3/22/2005	3	2	1
Jim Hubert	Trane	3/22/2005	1	1	2
Timothy B Lucas	Johnson Controls	3/22/2005	1	2	3
Jeffrey A. Rees	Newcomb & Boyd	3/23/2005	1	3	3
Mark Gershman	York	4/5/2005	1	2	3
Thomas M. Keel	GA Tech	4/5/2005	2	3	1
Brian Hampton	HI Solutions Inc.	4/7/2005	1	2	3
John Cain	Circon Controls Company	4/13/2005	1	2	3
Patrick Winkelman	Distech Controls Inc.	4/13/2005	1	2	2
Tim Bedenbaugh	IEC Systems Inc.	4/13/2005	3	3	3
Mike Tennefoss	Echelon	4/14/2005	1	1	2
Steve Smith	Convergint	4/26/2005	1	2	3
Ron Bernstein	Echelon	4/28/2005	1	2	1
2006 Survey Ranking Results 1 = High, 2 = Medium, 3 = Low			**1.7**	**2.3**	**1.9**
Cheol-Soo Park	SKK University	4/27/2006	1	3	2
Joseph Biehl	IPS	4/27/2006	3	1	2
Mike Rauzi	SSR Inc.	4/27/2006	1	3	2
Shadi Makarechi	EDG2	4/27/2006	2	3	1
Thomas M. Keel	GA Tech	4/27/2006	1	1	2
Tim Bedenbaugh	IEC Ssystems	4/27/2006	2	3	1
William Walsh	Honeywell Controls	4/27/2006	2	1	3
Zuhair Hasan	GSA	4/27/2006	3	3	1
Jeffrey A. Rees	Newcomb & Boyd	5/1/2006	3	2	1
Gary Ditzler	Lumi Systems	5/4/2006	1	1	1
Timothy B Lucas	Johnson Controls	5/5/2006	1	2	3
Mike Lowry	Mckenneys	5/8/2006	1	3	2
Steve Smith	Convergint	5/9/2006	2	1	3
Atif Debs	DSI Power	5/10/2006	1	2	1
Brian Burleigh	TCCO	5/10/2006	3	3	3
Carl Lundstrom	EMC Engineers	5/10/2006	1	3	2
Jay Denny	University of Minnesota	5/10/2006	1	2	3
Mory Nabavian	GHT Lmtd.	5/10/2006	2	3	1
Patrick Winkelman	Distech Controls	5/10/2006	1	3	2
Stinson Batchelor	Batchelor and Kimball Mechanical	5/10/2006	3	2	1
Jerry Kettler	Air Engineering	5/11/2006	1	3	2
Tim Howell	Air Balance Unlimited	5/11/2006	1	1	3
Brian E. Toevs, P.E.	Beta Engineers	5/12/2006	1	3	2
Overall Survey Ranking Results 1 = High, 2 = Medium, 3 = Low			**1.5**	**2.2**	**2.1**

3.3.1.1 Table 3.1 Discussion

The main purpose for this survey question was to get information from the expert panel about key issues regarding the 'Integration' possibilities. BAS, which is an Energy Management and Control Systems (EMCS) tool for facility managers at its most-basic level, consists of a network of sensors and operators and time-clocks for the Heating Ventilating and Air Conditioning (HVAC) systems. Similar networks exist for commercial lighting controls and security systems. Each one of these network control systems can operate independently from each other; yet, by sharing a few scheduling and sensory items, they can coordinate the on-off sequencing, as well as zone indexing between each other. A zone can be indexed simply as occupied or un-occupied by security sensors, and this information may be used in conjunction with the time-clock schedule to initiate mode of operations for HVAC and lighting. The overall priorities for applying integration starts with HVAC as the basic system, then lighting as the second integrated system and then security as the third integrated system, according to the overall rankings proposed in Table 3.1 by the experts.

The last column of Table 3.1 records the responses of the expert panel regarding the use of wireless system for BAS networks. Wireless technology seems to have earned a respectable level of confidence in being recommended for BAS by experts. Issues, such as wave noise, interference and interruption of service and limitations of battery-operated wireless devices, were brought up in the body of the responses, but the overall vote of the panel on the use of wireless technology was an above-average ranking (2.1) and on the positive side.

3.3.2 Question 2

This question of the survey requested identification of the most-significant parameters, without any suggestion or direction by the researcher. The responses included the following items:

1. Maintenance Cost
2. Integration of Systems Capabilities
3. Simplicity of BAS Operation and Training
4. Accuracy of Sensor and Actuators
5. Flexibility
6. Alarms
7. Comfort
8. Local Service and Maintenance Capability
9. Ease of Data Gathering
10. First Cost
11. Reliability
12. On-Demand Service Response
13. System Self-Learning Capabilities
14. Automated Upgrade Capabilities
15. Life-Cycle Costs
16. Waiting Time for Parts

In Chapter 2, five parameters were identified from literature and background research that represent the significant parameters influencing BAS performance. A study of the list of 16 items revealed that quite a few of them may be put in similar classifications. In the above list, the items may be classified into the five categories earlier identified as follows:

1. Items 1, 10 and 15 fall under ***'Cost'***.
2. Items 4, 5, 6, 7 and 11 fall under ***'User Needs'***.
3. Items 3 and 9 fall under ***'Simplicity'***.
4. Items 2 and 13 fall under ***'Integration'.***
5. Items 8, 12, 14 and 16 fall under ***'Availability of Service and Maintenance'***.

After the above consolidation was applied the results of the survey were recorded in Tables 3.2, where the recommended parameters by each expert are indicated by symbol 'X' in the row that bears their names. The overall citation levels for all parameters are indicated in the bottom two rows of Table 3.2.

Table 3.2 Survey Results for Question 2, Classified Expert Suggestions for API Significant Parameters

Name	Company	Response Date	Classified Expert Suggestions for API Parameters				
			Cost	User Needs	Simplicity	Integration	Availability of Maintenance
2005 Citations			**4**	**11**	**8**	**8**	**7**
Cheol-Soo Park	SKK University	3/22/2005		X	X	X	
Jim Hubert	Trane	3/22/2005		X	X	X	
Timothy B Lucas	Johnson Controls	3/22/2005	X		X	X	
Jeffrey A. Rees	Newcomb & Boyd	3/23/2005		X	X		X
Mark Gershman	York	4/5/2005			X	X	X
Thomas M. Keel	GA Tech	4/5/2005	X	X		X	
Brian Hampton	HI Solutions Inc.	4/7/2005	X	X			
John Cain	Circon Controls Company	4/13/2005		X	X	X	
Patrick Winkelman	Distech Controls Inc.	4/13/2005		X	X		X
Tim Bedenbaugh	IEC Systems Inc.	4/13/2005		X	X		X
Mike Tennefoss	Echelon	4/14/2005	X	X			X
Steve Smith	Convergint	4/26/2005		X		X	X
Ron Bernstein	Echelon	4/28/2005		X		X	X
2005 Citation Levels %			11%	29%	21%	21%	18%
2006 Citations			12	14	19	15	2
Cheol-Soo Park	SKK University	4/27/2006		X	X	X	
Joseph Biehl	IPS	4/27/2006	X		X	X	
Mike Rauzi	SSR Inc.	4/27/2006		X		X	
Shadi Makarechi	EDG2	4/27/2006	X	X	X		
Thomas M. Keel	GA Tech	4/27/2006	X		X		
Tim Bedenbaugh	IEC Ssystems	4/27/2006	X		X	X	
William Walsh	Honeywell Controls	4/27/2006	X	X	X		
Zuhair Hasan	GSA	4/27/2006	X		X	X	
Jeffrey A. Rees	Newcomb & Boyd	5/1/2006	X	X		X	
Gary Ditzler	Lumi Systems	5/4/2006			X	X	X
Timothy B Lucas	Johnson Controls	5/5/2006			X	X	
Mike Lowry	Mckenneys	5/8/2006	X		X		
Steve Smith	Convergint	5/9/2006		X	X	X	
Atif Debs	DSI Power	5/10/2006		X	X	X	
Brian Burleigh	TCCO	5/10/2006	X	X	X		
Carl Lundstrom	EMC Engineers	5/10/2006		X	X		
Jay Denny	University of Minnesota	5/10/2006	X	X		X	
Mory Nabavian	GHT Lmtd.	5/10/2006	X		X	X	
Patrick Winkelman	Distech Controls	5/10/2006		X	X		
Stinson Batchelor	Batchelor and Kimball Mechanical	5/10/2006				X	X
Jerry Kettler	Air Engineering	5/11/2006		X	X	X	
Tim Howell	Air Balance Unlimited	5/11/2006	X	X	X		
Brian E. Toevs, P.E.	Beta Engineers	5/12/2006		X	X	X	
2006 Citation Levels %			**19%**	**23%**	**31%**	**24%**	**3%**
Overall Citation Levels 1-9% = Low, 10-19% = Medium, 20-31% = High			**Med**	**High**	**High**	**High**	**Low**

3.3.2.1 Table 3.2 Discussions

The major contribution of this table is confirmation of the significant parameters that influence BAS performance. These five parameters had been identified in the previous chapter through literature and Internet investigation of existing work. However, as noted earlier, these five parameters represent five classifications in which the 16 original categories suggested by the experts were placed.

It should be no surprise that each of the identified parameters is really a complex category that encompasses several items. For example, the parameter labeled 'Cost' includes the initial cost of BAS system, the maintenance and operating cost, as well as periodical replacement and upgrading cost. For a given period of time and given financing interest rates, the combined total net present value of the above costs will represent the BAS system's Life Cycle Cost (LCC). This cost, normalized for a representative unit of area such as 100 square meters, may be used for the parameter labeled 'Cost'.

The second parameter represents a classification labeled 'User Needs' which includes expert suggested items, such as accuracy, flexibility, alarms, comfort and reliability. Each one of these items in turn represents a complex performance aspect of the Building Automation System. User Needs should also be normalized and represented by a quantifiable representative variable. This is discussed further in the response to Question 3, which is explained later in this chapter and also in Chapter 6 under the numerical analysis model.

The third parameter is labeled 'Simplicity' and represents categories such as operational ease and training requirements, as well as the ease of data gathering. This parameter is also discussed further in the response to Question 3, which is explained later in this chapter and also in Chapter 6 under the numerical analysis model.

The fourth parameter covers issues related to ‘Integration’, or simply the number of systems that share data for their control operation. This was discussed earlier as part of the analysis of Question 1 and will be further discussed in Chapter 6, Model Development.

The fifth parameter deals with ‘Availability of Service and Maintenance’ covering items such as availability of repair service and replacement parts and possibility of on-demand service. It addresses issues such as desire for minimizing the facility downtime.

3.3.3 Question 3

This question deals with the challenge of quantification of the parameters suggested earlier by the experts. For the five significant parameters of Cost (C), User Needs (N), Simplicity (S), Integration (I) and Availability (A) of Service and Maintenance, the suggestions by the experts are tabulated in Table 3.3. All suggestions, except for those under the ‘User Needs’ and ‘Simplicity’, are easily normalized per unit area and applied to the modeling techniques of Chapter 6. For ‘User Needs’ and ‘Simplicity’, a representative quantifiable parameter may be defined for numerical analysis. This parameter is the number of control points per unit area, ‘P’ and its relationship with ‘N’ and ‘S’ are verified by a second survey presented in Chapter 5.

Table 3.3 Expert Suggestions for Measuring Significant Parameters (Question 3)

Name	Company	Date	Suggestion for BAS Parameter Measurement				
			Cost	Comfort/User Needs	Simplicity	Integration	Service Availability
Cheol-Soo Park	SKK University	3/22/2005	LCC	# of Complaints/M2.Yr	n	n	n
Jim Hubert	Trane	3/22/2005	LCC	Complete Commissioning	Training hrs./M2.Yr	n	Ease of Service
Timothy B Lucas	Johnson Controls	3/22/2005	LCC	n	n	# of integrated systems	n
Jeffrey A. Rees	Newcomb & Boyd	3/23/2005	LCC	# of Complaints/M2.Yr	Training hrs./M2.Yr	LCC	LCC
Mark Gershman	York	4/5/2005	LCC	# of Complaints/M2.Yr	Training hrs./M2.Yr	# of Open Systems	n
Thomas M. Keel	GA Tech	4/5/2005	LCC	# of Complaints/M2.Yr	n	n	# of Caliborations/M2.Yr
Brian Hampton	HI Solutions Inc.	4/7/2005	LCC	LCC		# of data monitored	Addaptable Reporting
John Cain	Circon Controls Company	4/13/2005	LCC	n	Training hrs./M2.Yr	n	# of Corrections/M2.Yr
Patrick Winkelman	Distech Controls Inc.	4/13/2005	LCC	# of Complaints/M2.Yr	Training hrs./M2.Yr	n	# of Service Companies
Tim Bedenbaugh	IEC Systems Inc.	4/13/2005	LCC	n	n	# of integrated systems	n
Mike Tennefoss	Echelon	4/14/2005	LCC	# of Complaints/M2.Yr	n	# of integrated systems	# of Corrections/M2.Yr
Steve Smith	Convergint	4/26/2005	LCC	# of Complaints/M2.Yr	Common Programming Tools	# of IP enabled functions	# of Corrections/M2.Yr
Ron Bernstein	Echelon	4/28/2005	LCC	n	n	# of Vendors at Bid	n
2005 Dominant Recommendations			**LCC**	**# of Complaints/M2.Yr**	**Training hrs./M2.Yr**	**# of Integrated Systems**	**# of Corrections/M2.Yr**
Cheol-Soo Park	SKK University	4/27/2006	LCC	n	Training hrs./M2.Yr	LCC	n
Joseph Biehl	IPS	4/27/2006	LCC	# of Complaints/M2.Yr	Training hrs./M2.Yr		# of Failures/M2.Yr
Mike Rauzi	SSR Inc.	4/27/2006	LCC	# of Complaints/M2.Yr	n	n	Discuss with Owner
Shadi Makarechi	EDG2	4/27/2006	LCC	n	LCC	LCC	LCC
Thomas M. Keel	GA Tech	4/27/2006	LCC	# of Complaints/M2.Yr	n	n	# of Service Companies
Tim Bedenbaugh	IEC Ssystems	4/27/2006	LCC	# of Complaints/M2.Yr	Survey the Users	n	n
William Walsh	Honeywell Controls	4/27/2006	LCC	# of Complaints/M2.Yr	n	n	n
Zuhair Hasan	GSA	4/27/2006	LCC	n	Training hrs./M2.Yr	# of integrated systems	# of Service Companies
Jeffrey A. Rees	Newcomb & Boyd	5/1/2006	LCC	# of Complaints/M2.Yr	n	n	Establish Reward System
Gary Ditzler	Lumi Systems	5/4/2006	LCC	# of Complaints/M2.Yr	Training hrs./M2.Yr	n	# of Service Companies
Timothy B Lucas	Johnson Controls	5/5/2006	LCC	# of Complaints/M2.Yr	n	n	Level of On Demand Service
Mike Lowry	Mckenneys	5/8/2006	LCC	# of Complaints/M2.Yr	n	n	Average Response Time
Steve Smith	Convergint	5/9/2006	LCC	LCC	LCC	LCC	n
Atif Debs	DSI Power	5/10/2006	LCC	# of Complaints/M2.Yr	# of Complaints/SF.Yr	n	# of Corrections/M2.Yr
Brian Burleigh	TCCO	5/10/2006	LCC	Tenant Adaptability	Training hrs./M2.Yr	# of integrated systems	Availability of Parts
Carl Lundstrom	EMC Engineers	5/10/2006	LCC	Degree of data Accuracy	# of Data Monitored/M2.Yr	# of data monitored	
Jay Denny	University of Minnesota	5/10/2006	LCC	LCC	n	Minimize Proprietary Parts	Measure Stability
Mory Nabavian	GHT Lmtd.	5/10/2006	LCC	Use GSA Normative Toolkit	n	n	n
Patrick Winkelman	Distech Controls	5/10/2006	LCC	n	n	n	# of Service Companies
Stinson Batchelor	Batchelor and Kimball Mechanical	5/10/2006	LCC	LCC	Life Cycle Cost (LCC)	n	LCC
Jerry Kettler	Air Engineering	5/11/2006	LCC	n	n	n	n
Tim Howell	Air Balance Unlimited	5/11/2006	LCC	# of Complaints/M2.Yr	Training hrs./M2.Yr	# of integrated systems	Maint hrs./M2.Yr
Brian E. Toevs, P.E.	Beta Engineers	5/12/2006	LCC	# of Complaints/M2.Yr	n	n	Trend Analysis
2006 Dominant Recommendations			**LCC**	**# of Complaints/M2.Yr**	**Training hrs./M2.Yr**	**# of Integrated Systems**	**# of Service Vendors**
Key:	n = No Specific Recommenda LCC = Life Cycle Cost, M = Meter, Similar responses have been rephrased and combined						

3.4 Discussions

Tables 3.1 through 3.3 summarize the responses from the expert panel. Each table is organized to show the responses of the expert panel members to one of the three key questions of the first survey.

3.4.1 Expertise of the Panel Members

The names of the individuals and their company names are provided with their permission on each table and the 29 individuals listed represent the following categories of expertise:

Table 3.4 Expert Panel Expertise

Expertise	Number of Experts
Control Manufacturer	5
HVAC Manufacturer	1
Building Commissioner	6
Contractor	2
Control Design Engineer	1
Control Network Engineer	4
Academia	3
Facility Manager	2
Consulting Engineer	4
Control Service and Maintenance	1

All experts are in the United States except one member of academia who moved from the United States to Korea after completion of his doctoral studies at Georgia Tech. A review of the Tables 3.1 through 3.3 indicates that similar expertise or companies have not resulted in similar responses, confirming that the data provided is not biased and each expert has shared his personal experience and not the company's stance. Also the same individual's response (recorded in 7 cases) has not remained the same between 2205 and 2006 surveys indicating a dynamic trend in response to the changes in the technology illustrated in Figure 1.1.

CHAPTER 4

IDENTIFICATION OF SIGNIFICANT PARAMETERS

"Data is raw material of the information age, useful only after prolonged digestion"

Irreverent Dictionary of Information Politics
By Paul Strassmann & John Klossner

4.1 Introduction

In the previous two chapters, the significant parameter categories from literature search (Table 2.1) created guidelines for classifying the significant items indicated by the survey of the experts (Table 3.2). In this chapter, the identified significant parameters are discussed further.

Table 4.1 summarizes the results of Tables 2.1 and 3.2, indicating the overall significant parameters identified for API modeling through literature search and expert survey.

Table 4.1 Summary of BAS Performance Parameters from Tables 2.1 and 3.2

Data Collection Method	Automation Performance Parameters				
	Cost (C)	User Needs (N)	Simplicity (S)	Integration (I)	Availability (A)
Expert Survey	M	H	H	H	L
Literature Search	M	M	L	H	L

Key: L = Low, M = Medium, H = High Citation Levels
( ) = Parameter Symbols

It should be noted that although ‘L’ indicates low citation levels in two of the parameters, they are still significant parameters. In the case of availability of service vendors, one observation regarding the low citations from both the literature and expert sources is that the BAS industry has addressed this significant issue by encouraging most service vendors to maintain and service multiple manufacturer products.

4.2 Analysis

A total of five key parameters are identified: Cost (C), User Needs (N), Simplicity (S), Integration (I) and Availability of Service and Maintenance (A). In addition to these parameters recorded also in Table 4.1, other significant aspects, such as ‘Human Factor’ addressed by facility managers and BAS effect on building power demand on energy use, were noted and discussed in Chapter 2 and summarized in Table 2.1. The effect on “energy use” (energy management) and the “power management” discussed in Chapter 2 is an inherent function of the BAS which has direct relationship with the ‘User Needs’ (N) and it proportionally affects the ‘Cost’ (C) and the level of ‘Simplicity’ (S) of the system.

‘Reliability’ and ‘Accuracy’ were also cited with low frequencies by the experts. These aspects of the various BAS alternatives can be considered compatible from one system to another, just like the different brand names in the personal computer industry that offer compatible reliability and operational accuracy. ‘Flexibility’ and ‘Accuracy’ are noted as proportional to ‘User Needs’ (N).

‘Availability of Service and Maintenance’ (A) may be represented by the number of available vendors that can provide service to the system and is readily quantifiable. In the case of a proprietary Building Automation System, ‘A’ is 1, meaning only one specific manufacturer's products and their authorized service vendors may provide service, and, in the case of "open" BAS systems with multiple vendors available to interchange parts using a common communication protocols, 'A' can be higher. The number of available vendors for some projects may be as high as 10, creating a competitive environment in which both cost and time required for service may be reduced and quality of service may be improved. So the higher the value of 'A', the better is the expected BAS performance to be.

The parameter identified as the level of 'Integration' (I) indicates the number of building systems that are integrated. In the case of integration of HVAC and lighting, 'I' is equal to 2, and, if security is also integrated along with HVAC and lighting, I = 3. The general form of API model may be expressed as follows:

$$API = f\,(C, N, S, I, A) \qquad (1)$$

Where API = Automation Performance Index with a positive value that will not exceed 5; f = function; C = Cost; N = User Needs; S = Simplicity; I = Integration and A = Availability of service and maintenance. C, N, S, I and A are non-zero integers with a minimum value of 1.

4.3 Further Discussion on Significant Parameters

4.3.1 Cost (C)

All aspects of 'Cost' may be presented with this parameter, including initial cost, operating cost, life cycle cost, and replacement cost. It should be noted that, for the purposes of modeling and in order to have a manageable range to work with, cost per unit area (square meter) or $\$/m^2$ will represent this parameter in the modeling. For the purposes of cost modeling in a scale of 1 through 5, 1 shall represent low-unit cost (for example \$2/ m^2) and 5 shall represent high-unit cost (for example \$10/m^2).

4.3.2 User Needs (N)

'User Needs' may be the requirements for human comfort, the needs of a manufacturing process, the criteria for storage environment for products, or preservation of life in otherwise critical circumstances. According to the expert survey recorded in Table 3.3, this parameter may be measured by the number of annual complaints per unit area. For the purposes of modeling in a scale of 1 through 5, 1 shall represent low satisfaction of user needs (for example, 10 annual complaints/m^2), and 5 shall represent high satisfaction of user needs (for example, 1 annual complaint/m^2).

4.3.3 Simplicity (S)

The expert panel for this research provided a consensus, recorded in Table 3.3, that the annual number of hours of facility management personnel BAS training is a suitable indicator of the measure of simplicity. For the purposes of modeling in a scale of 1 through 5, 1 shall represent low level of simplicity (for example, 10 annual training man-hours/m^2), and 5 shall represent high level of simplicity (for example, 1 annual training man-hour/m^2).

4.3.4 Integration (I)

The number of building systems that share information to trigger the automatic controls is measured by 'I'. As explained in earlier paragraphs, the level of integration in a scale of 1 through 5, for the purposes of modeling, may be as low as 1 or as high as the number of systems that share common communication protocols and use signals to coordinate their individual control systems. This survey revealed that 3 systems (HVAC, Lighting, and Security) would be a suitable average and 5 can represent high level of integration.

4.3.5 Availability of Service and Maintenance (A)

Construction industry specifications usually require a minimum of three suppliers for products and services that are specified. The control industry, however, has been traditionally a closed environment in the sense that once the products of one manufacturer were selected for a project, it would lock-in the project with the products of that manufacturer and other vendors would not be able to provide parts or services for the project without applying major changes in the system. This exclusive right to the project would create an environment where competition did not exist and both cost and timeliness of the services would be inflated. In order to remedy this situation, some clients would lock-in the unit prices for a period of time during the bid process.

The overall performance of a BAS system, according to this research, would be improved significantly if the number of vendors that are allowed to service the system is increased. For the purposes of modeling in a scale of 1 through 5, 1 shall represent low level of service availability (for example, 1 service vendor for the project BAS) and 5 shall represent high level of service and maintenance availability (for example, 5 service vendors for the project BAS).

All five significant parameters are defined over a scale of 1 through 5. Having identified the parameters, and defined their range over the scale, it is also important to be able to identify one or two boundary conditions. Building codes and design guidelines will help in this task. For example, GSA has criteria for the required number of thermostats in their office buildings. Such criteria will help in calculation of constant 'K' in general equations such as the following linear model for API:

$$API = \Sigma\,(w_i)(P_i) + K \qquad (2)$$

Where API = Automation Performance Index; P_i = value of Parameter 'i'; w_i = weight of parameter 'i' and i = 1 for Cost; 2 for User Needs; 3 for Simplicity; 4 for Integration and 5 for Availability of Service and Maintenance parameters; and K = Constant.

$$\Sigma\, w_i = 1 \qquad (3)$$

Where w = weight; and i = an integer value between 1 and 5 identifying one of the key five parameters.

CHAPTER 5

MODEL FEASIBILITY

"We are doing quite well and we are not doing any harm to anyone other than the currency manipulators. We only wish the world to know that there are many ways to skin a cat."

Malaysia Prime Minister Mahathir Mohamad,
September 29, 1999

5.1 Introduction

The goal of this chapter is to identify suitable modeling approaches for API. The model should enable analysis of BAS by providing a quantitative representation of its performance incorporating the five significant parameters identified in previous chapters.

5.2 Modeling

In general, modeling process is the application of scientific methods to complex organizational decision problems and opportunities. Modeling process provides systematic and general approaches to problem-solving for decision-making, regardless of the nature of the system, product, or service. The approaches and tools used in models are based on one or more of the following: Analytical methods; Simulation; and Qualitative or Logical. Many of these approaches depend highly on computer-based methodologies for implementation (Arsham 1994).

API model for building automation performance is a measuring tool. With such a tool during early design stages, decision-makers can predict the performance levels of Building Automation Systems. They can then point out ways to improve it. The improvement process should be engaged at all levels of planning, design, construction and operation. Application of heuristic and numerical methods should be examined.

Theoretically, modeling can be accomplished by computer-assisted simulation. However, accurate building simulation requires extensive knowledge of numerous variables and their behaviors. Building Automation Systems, even at basic levels, have many interacting components that receive inputs and provide outputs. Simulation modeling for such systems requires detailed set-up and experimentation and, sometimes, building prototypes and mock-ups. These are time-consuming and cost-prohibitive measures for most construction projects and there are always compromises associated with the results. Whether detailed simulation techniques or simplified models are utilized, one of the purposes of modeling remains to be maximization of its versatility by fine-tuning the results to be accurate and achievable at minimum cost.

In order to analyze and predict the BAS performance, experimentation with a mathematical model is more practical than detailed simulation. Mathematical models may be numerical or heuristic, and they can be utilized easier, faster and with less expense. For API, quantitative and heuristic modeling techniques are investigated.

5.2.1 Quantitative Modeling

This technique is based on measurements of quantified values. Measurements of key parameters in the form of feedback or response from the model or actual system would be used for this modeling technique. Examples of the parameters are temperature, pressure, location, and cost at various time frames. Because of the need for meaningful measurements, this decision-support technique is best applied in the later stages of design, production or construction of the projects.

5.2.2 Heuristics Modeling

This technique relies on experience, information from the past or expertise, and utilizes both qualitative and quantitative information for evaluation of the overall system, product or project for making decisions. Usually a weighted average function is used for the combination of important aspects or functions. Because of reliance on past experience with similar conditions, this technique may be applied at early stages of the design, development or construction of the project.

5.3 Framing the Objective for Modeling

Figure 1.2 in Chapter 1 provided a framework for API in relationship to the "big picture". It is prudent to illustrate the thought process in more detail, in order to narrow down the modeling objective and apply appropriate modeling techniques.

The overall or "global" building systems include a variety of possible aspects and combinations of sub-systems to work with. A smaller segment among these options should be selected as a sub-set for analysis. This can be illustrated by starting from a generic statement and narrowing down the objective of the research by identifying the sub-set that satisfies this generic statement for a specific cross-section.

One proposed generic statement can be: "Provide dynamic (time-sensitive) global building systems performance optimization modeling methods." Each word in this carefully framed instruction can be interpreted with multiple valid alternatives. This approach is illustrated in Tables 5.1a and b (Makarechi 2004).

Table 5.1a Objective Modeling Highlighted at Planning Stage

Framing Objectives and Modeling								
Dynamic (When?)	Time (When?)	Sensitive (What?)	Global (How?)	Building (What?)	Systems (What?)	Performance (What?)	Optimization (For Whom?)	Modeling Methods
Real Time	Planning	Status	Integrated	Residential	HVAC	Cost	Tenant	H1 (KB)
Re-active	Design	Positions	Isolated	Commercial	Lighting	Time	Owner	H2 (FL)
Pro-active	Construction	Quantity		Institutional	Security	Energy	Builder	H3 (NN)
	Operation			Industrial	Life Safety	Comfort	Manager	H4 (PE)
	Re-Commission			Educational	Telecom	Production	Public	Other Heuristic Models
				Healthcare	Data	Efficiency	Designer	N1 (DM)
					Media	Reliability	Environment	N2 (PM)
					Delivery	Longevity		Other Numerical Models

Key:

H: Heuristic Methods
N: Numerical Methods
H1 (KB): Knowledge-Based Expert Systems: Value Engineering, Weighted Evaluation, Function Analysis System Technique, etc.
H2 (FL): Fuzzy Logic; Linguistic based approach
H3 (NN): Neural Networks; Feed forward based on historical behavioral information
H4 (PE): Performance Evaluation methods; Game theory, Case methods, Imagination brainstorming
N1 (DM): Deterministic Methods: Operations Research, Mathematical Models
N2 (PM): Probabilistic Methods: Simulation models, Stochastic methods, Probability analysis, Sensitivity analysis
As the project progresses in time from Planning to Re-Commissioning suitable models may progress from Heuristic to Numerical.

Table 5.1b Objective Modeling Highlighted at Re-Commissioning Stage

Framing Objectives and Modeling								
Dynamic (When?)	Time (When?)	Sensitive (What?)	Global (How?)	Building (What?)	Systems (What?)	Performance (What?)	Optimization (For Whom?)	Modeling Methods
Real Time	Planning	Status	Integrated	Residential	HVAC	Cost	Tenant	H1 (KB)
Re-active	Design	Positions	Isolated	Commercial	Lighting	Time	Owner	H2 (FL)
Pro-active	Construction	Quantity		Institutional	Security	Energy	Builder	H3 (NN)
	Operation			Industrial	Life Safety	Comfort	Manager	H4 (PE)
	Re-Commission			Educational	Telecom	Production	Public	Other Heuristic Models
				Healthcare	Data	Efficiency	Designer	N1 (DM)
					Media	Reliability	Environment	N2 (PM)
					Delivery	Longevity		Other Numerical Models

Key:

H: Heuristic Methods
N: Numerical Methods
H1 (KB): Knowledge-Based Expert Systems: Value Engineering, Weighted Evaluation, Function Analysis System Technique, etc.
H2 (FL): Fuzzy Logic; Linguistic based approach
H3 (NN): Neural Networks; Feed forward based on historical behavioral information
H4 (PE): Performance Evaluation methods; Game theory, Case methods, Imagination brainstorming
N1 (DM): Deterministic Methods: Operations Research, Mathematical Models
N2 (PM): Probabilistic Methods: Simulation models, Stochastic methods, Probability analysis, Sensitivity analysis
As the project progresses in time from Planning to Re-Commissioning suitable models may progress from Heuristic to Numerical.

Tables 5.1a and 5.1b illustrate the thought process for framing the modeling objective. Depending on the alternatives chosen, suitable modeling techniques may be applied. The recommended modeling methods for two highlighted subsets 'a' and 'b' are indicated separately. The only difference between the two highlighted sections is in the timing of the framed objectives. The two tables list popular modeling techniques for different framing combinations. During the planning or early stages of the project, heuristic modeling techniques are recommended, and, during re-commissioning, which is a later stage of the project, numerical methods are recommended.

5.4 Measuring the BAS Performance

To narrow the performance improvement focus down to BAS for a commercial grade building in Table 5.2, the instructional objective is stated as: "Model the building's automation system performance."

In a similar approach to Table 5.1, a few of the possible objective options have been outlined. The heading of Table 5.1 still communicates a very general objective. Each word of the instructional objecting shown in the heading can take many possible interpretations or taxonomy in the context of modeling BAS for its performance measurement. The keyword is "performance" and one of the key questions is "For whom?" In the building construction and facility management industries, often the interests of different stakeholders are at odds with each other. A suitable performance for the tenant may be high comfort levels which may drive the operating costs up, and for the owner it may be low operating cost, which does not always buy the highest comfort levels.

Table 5.2 A Collection of BAS Modeling Objectives

Model	Building	Automation	System	Performance	Indicators
Qualitative	**General**	Individual	**HVAC**	**Tenants**	Cost
Quantitative	Specific	**Integrated**	**Lighting**	Landlords	Comfort
Comparative	Type	**Networked**	**Security**	Owners	**Value**
Normative	Location	Closed	Life Safety	Facility Managers	Longevity
Graphical	Single	Web-Based	Plumbing	Builders	Simplicity
Deterministic	Multiple	Local	Fenestration	Public	Productivity
Scholastic	Existing	Remote	Irrigation	Visitors	Safety
Heuristic	New	DDC/Electronic	Signage	Environment	Security
Time Sensitive	Conceptual	Pneumatic type	AV-TV	Designers	Appeal
Dynamic	Codes	Electric type	Phone	Equip. Needs	Flexibility
Virtual	Use	Commercial	Transports	Process Needs	Functionality
Simulation	Zone	Industrial	Vacuum	Animals	Aesthetics

As evident with the above aspects of measurement, building, systems, etc., the possibility of the combinations of interest to define for modeling is almost endless. A subset that would most likely define the starting point for this problem is highlighted in Table 5.2. Each model's application for other possibilities may be investigated once the model is developed for a focused objective.

5.5 Ranking of the Parameters

Prior to applying modeling techniques as a function of the significant parameters that were identified in previous chapters, it is necessary to determine how the panel of experts would rank the parameter's impact on BAS performance. Therefore, in a follow-up survey for this purpose, the expert panel members were asked to rank the significant parameters identified earlier, and a new important question was also presented to them. This was the fourth question following the first three questions that were presented in the earlier e-mail to the panel members.

Question 4 requested a verification regarding the correlations between the parameters representing User Needs, Cost and Simplicity and a new quantifiable parameter, suggested by this research as the number of system control points (P). A sample of the question and the responses from one individual is shown in Figure 5.1. The responses are recorded in Table 5.3.

Hi,
See ranking as marked below…
Regards,
EDG

From: Shariar Makarechi [mailto:yar@gatech.edu]
Sent: Monday, July 31, 2006 6:50 PM

Dear Colleague,

You have been most helpful in helping me to identify the most significant parameters for evaluation of the performance of building automation systems (BAS). As I noted in my last note, the most significant parameters based on your answers are:

- User Needs	(5)
- Cost (Life Cycle Cost)	(2)
- Simplicity	(3)
- Integration	(1)
- Availability of Service	(4)

May I please ask you now to rank these parameters based on your experience in the order of the least (1) to the highest (5) impact on the BAS performance?
Also please let me know if you agree that we can quantify the first tree items as a function of the total number of the system control points. (I agree)

Figure 5.1 Sample E-mail Response: Parameter Ranking and Question 4

Table 5.3 Significant Parameter Ranking

Response Number	Expert (Initials)	Organization	Significant Parameter Rankings					Response to Q4
			Cost (C)	User Needs (N)	Simplicity (S)	Integration (I)	Available Service (A)	
1	CSP	Seoul University	3	5	1	4	2	No
2	MG	Johnson Controls	5	4	2	3	1	-
3	JC	Circo Systems	2	4	1	5	3	Yes
4	RB	LonMark	4	3	2	5	1	Yes
5	BB	TCCO	5	4	3	3	4	Yes
6	GD	Ditz Controls	4	1	2	3	5	Yes
7	SM	EDG2	2	5	3	1	4	Yes
8	SS	Convergent Technologies	5	4	2	1	3	Yes
9	SB	Batchelor & Kimbal	1	3	4	2	5	Yes
10	TMK	GT/CABA/STAEFA	3	2	1	5	4	No
11	TB	IEC Systems	3	5	2	1	4	Yes
12	WW	Honeywell	2	3	5	1	4	-
13	BT	Beta Engineering	1	4	5	3	2	Yes
14	ZH	GSA	1	2	4	5	3	Yes
Total Ranking Score			41	49	37	42	45	Yes
Median Ranking Score			3	4	2	3	3.5	-
Mean			2.93	3.50	2.64	3.00	3.21	3.1 Avg. Mean
Average Relative Weight			0.19	0.23	0.17	0.20	0.21	-
Std Deviation			1.49	1.22	1.39	1.62	1.31	-

Key: Q4: Do you agree that: Increase in User Needs ~ Increase in Cost ~ Increase in Complexity? ~ = Proportional - = no feedback

5.6 Observations and Conclusions

Table 5.3 captures the responses to the second e-mail shown in Figure 5.1. At this stage, 14 members of the expert panel participated. The original panel had 23 members, and, based on their recommendations, the significant parameters for modeling were identified. Although it was challenging to secure the experts' further involvement in this research, the responses at this stage were adequate to derive conclusive and valuable information that helped in validation of the significance of the parameters as well as provide ranking information for the relative impact of each parameter on the development of API models. The following are some key observations from the information presented in Table 5.3:

- The mean ranking for all five parameters is between 2.64 and 3.5. This suggests that all significant parameters influence the BAS performance at about the same overall level, and the five identified parameters are all equally significant and none can be dismissed.
- The individual rankings are significantly different from each other. This shows that, depending on the point-of-view or interest of each expert, the importance or influence of the parameters on the performance are different and API will indicate a different performance.
- The rankings from experts with similar background (such as Academics, Manufacturers, Contractors, Design Engineers, Commissioners, etc.) are not similar, indicating that API performance is subject to the individual's preferences and perspective, and not to the individual's line of work.
- The last column records the responses to our question that Parameters 'C', 'N' and 'S' may be quantified with Parameter 'P', representing the number of control points per unit of area.
- A close average for Parameters 'A' and 'I' rankings is 3. This should not be confused with the actual value associated with these parameters. A representing the available number of vendors can, in fact, take the value 3 in most projects, since that is what the specifications call for (GSA 2005). 'I'

representing the number of integrated systems may also take a value of 3 for integration of HVAC, Lighting and Security systems. In fact, some of these values from suitable practice and design criteria will be very helpful as boundary conditions for an overall satisfactory performance (API = 1). One of such boundary conditions will be discussed further with minimum number of control points (P = 1) for lease cost and a minimum of 3 service vendors and 3 integrated systems.

CHAPTER 6

MODEL DEVELOPMENT

"Best way to predict the future is to invent it" Alan Kay

6.1 Approach to Modeling

Modeling for decision-making involves at least two parties, one is the decision-maker and the other is the model-builder, known as the analyst. The analyst is to assist the decision-maker in his/her decision-making process. Therefore, the analyst must be equipped with more than one set of analytical methods (Ashram 1994).

6.2 Multiple Models

It was illustrated in Table 5.1 that, at different stages of a project development between planning and design to construction, occupancy and remodeling when new tenants move in, different modeling techniques are suitable. Due to the very limited amount of prior scholarly work in this field, API modeling approaches, instead of starting with a strong theoretical and scholarly base, have to be expert knowledge-based.

Assessments presented in Chapter 5, based on the information presented in Table 5.3, indicated that although the five parameters identified by the research are indeed significant to the overall group, each individual's ranking for the relative influence of the parameters is different from the others, even when the individual experts represent similar or exactly the same industries. Providing a highly subjective and individually oriented API using a numerical method would not adequately address the spectrum of individual's preferences built only on numerical value for each of the parameters. Hence, the utility method of modeling, where preferences or the utility curves of the client, would more accurately represent how one would be satisfied within the range of possible values that each parameter may take. To take this approach to a more complex level, modeling with fuzzy sets and linguistic values, rather than utility values, have been investigated, since obtaining the linguistic feedback from a client for complex multi-variable performance indexing allows a user-friendly input/output system in the API modeling.

Fuzzy Logic method is utilized for decision-making in the building construction industry since most of the data are knowledge-based linguistics in the real world. Given the subjective nature of a building's performance level which could generally be phrased as low, medium or high performance for a given client, Fuzzy Logic provides a promising technique for evaluating the API model.

Applications of the three modeling techniques are illustrated using data provided by one of the panel members, Dr. Cheol-Soo Park who is designated as CSP (Table 5.3) in the tables and charts of this research. This is for the demonstration of concept only, and the model can also be used by other experts.

6.3 Numerical Method

6.3.1 Numerical Method Background Theory

Numerical modeling technique calculates the weighted sum of the normalized parameters. Based on the ranking of the parameters by a client, a weight distribution may be derived. The general form for API noted in Equation (1) can be written as a function of the weighted sum of the significant parameters:

$$API = w_1(C) + w_2(N) + w_3(S) + w_4(I) + w_5(A) + K \quad (4)$$

Where API = Automation Performance Index; w = weight factors numbered from 1 to indicating the weight for the following parameters: C = Cost; N = User Needs; S = Simplicity; I = Integration; A = Maintenance and Service Availability; K = constant and:

$$\Sigma\, w_i = 1 \quad (5)$$

Where w = weight; and i = an integer value between 1 and 5 identifying one of the key five parameters.

6.3.2 Numerical Method Illustration

One method to estimate the weight factors for the key five parameters is by applying the ranking input from the client. This has been done for Dr. Park (CSP) one of the members of the expert panel listed on Table 5.3 and using equation (5):

$w_1 = 3/(1+2+3+4+5=15) = 0.2$, $w_2 = 5/15 = 0.33$, $w_3 = 1/15 = 0.06$, $w_4 = 4/15 = 0.27$, $w_5 = 2/15 = 0.13$. The numerical model for API from (4) can now be estimated for client CSP as: $API = 0.2(C) + 0.33(N) + 0.07(S) + 0.27(I) + 0.13(A) + K$ (6)

For the parameters in (6) that are qualitative and they should be represented by a quantifiable substitute, answers to the survey Question #4 (noted on the last column of Table 5.2) is utilized. Quality parameters 'N' and 'S' have direct relationship with 'P' the number of control points. It should be noted that 'C' is also proportional to 'P'. Therefore:

$$C = a(P) + b \quad (7)$$

$$N = d - c(P) \quad (8)$$

and:

$$S = f - e(P) \quad (9)$$

Where C = Cost; N = User Needs; S = Simplicity; P = Number of control points per unit area; and a, b, c, d and e = positive constants. Substituting for "C", "N" and "S" in Equation (6):

$$API = 0.2(a(P) + b) + 0.33(d - c(P)) + 0.07(f - e(P)) + 0.27(I) + 0.13(A) + K \text{ or:}$$

$$API = 0.13(A) + K_1(P) + 0.27(I) + K_2 \quad (10)$$

Where K_1= (0.19a -0.23c-0.17e) and K_2= (0.19b+0.23d+0.17f+K). Two boundary conditions identified earlier will help in calculating K_1 and K_2 in equation (10):

- Boundary Condition 1: GSA design Criteria: API = 1 when A = 3, P = 2, I = 1, resulting in: $0.34 = 2 K_1 + K_2$
- Boundary Condition 2: Observations form Survey noted in paragraph 5.5: API = 1 (100%) when A = I = 3 resulting in: $-0.2 = K_1 + K_2$

With the above two boundary conditions, $K_1 = 0.54$ and $K_2 = -0.74$ and equation (10) will simplified to the following equation for client CSP:

$$API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74 \quad (11)$$

6.3.3 Numerical Method Discussion

For the numerical approach, a linear function of the significant parameters was defined. The parameters were identified by a combination of literature search and expert panel survey. The API was calculated based on a weighted average sum of the significant parameters, and, by using the rankings provided by a client, the weights (between 0 and 1) for each parameter were determined. The function was further simplified by substituting the qualitative parameters with another proportional and easily quantifiable parameter ‘P’. As a result, API was reduced to a linear function of Parameters ‘A’, ‘P’ and ‘I’. The range of the numerical values for ‘A’, ‘P’ and ‘I’ are described in the following sections.

For ‘A’ Availability of local vendors to provide service and maintenance for each project is limited and influenced by the number of BAS manufacturers. Most project specifications and industry-wide design guidelines specify a minimum of three manufacturers or vendors (NIBS 2006) for all systems, equipment and accessories. Therefore, it is reasonable to assume the average for A = 3 and the range for ‘A’ is between 1 and 5. Therefore, having five local service vendors available for a project will represent the high limit in the illustrations provided.

The number of Integrated systems, ‘I’, can also be between 1 and 5. Tables 5.1 and 5.2 show some of the integration possibilities. A suitable practical average for ‘I’ is also three systems, namely integration of HVAC, Lighting and Security systems. The response to Question 1 of the initial survey (Figure 1.4) provided ranking of the most-popular integration practices, indicating that Integration of Security and Lighting Controls with HVAC Controls through Wireless Systems was recommended by the experts.

To evaluate the range of the number of control points per unit area, ‘P’, existing guidelines for suitable practice can be used (GSA 2005; NIBS 2006). Based on the recommended practices (Codes and Guidelines), the number of control points for HVAC can be estimated to be an average of 2 per 100 m^2, as shown in the design criteria in Figure 6.1. This number for interior office spaces is 1 per 139 m^2 and for perimeter areas 1 per 28 m^2; adding one security sensor (motion detector) and one or two lighting controls for each office can result in "P" up to 5 per 100 m^2 on average.

Thermostatic Zoning Design Criteria

Interior thermostatic control zones must not exceed 139 m^2 (1,500 sq. ft.) per zone for open office areas or a maximum of three offices per zone for closed office areas.

Perimeter thermostatic control zones shall not exceed 28 m^2 (300 sq. ft.) and shall be no more than 4.6 m (15 ft.) from an outdoor wall along a common exposure. Corner offices shall be a dedicated zone.

If a building program shows that an office building shall have an open plan layout or if the program does not state a preference, it may be assumed that up to 40 percent of the floor plan shall be occupied by closed offices at some point in the future.

Figure 6.1 GSA Design Criteria (GSA 2005)

Based on the criteria in Figure 6.1 and analysis, the range for 'P' is between 1 and 5. However the most desirable density for control points is P=1 to minimize system cost and complexity with the condition that at P=1 user needs are satisfied.

As expected, API is 1 for GSA criteria; however, this criteria is based on less than average number of control points and does not require any system integration (P=2 and I=1). It is evident that improvement to the automation system performance can be expected once the systems integration level (I) is increased. The highest BAS performance is expected when GSA criteria is adopted for 'P' and maximum integration (I=5) is incorporated, provided that maximum service and maintenance availability (A=5) is provided. The BAS performance indicated by the values of API for this new set-up will be more than twice the normal GSA design criteria. In Figure 6.2 Buildings 1, 2 and MAX are hypothetical buildings to demonstrate the higher possible values of API.

API Values = f (A, P, I) for Given Buildings				
API	**A**	**P**	**I**	**Building**
1.00	3	2	1	GSA
1.00	3	1	3	Best P
2.08	3	3	3	Bldg 1
3.02	4	4	4	Bldg 2
3.96	5	5	5	Max
Based on rankings by CSP Table 5.3 API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

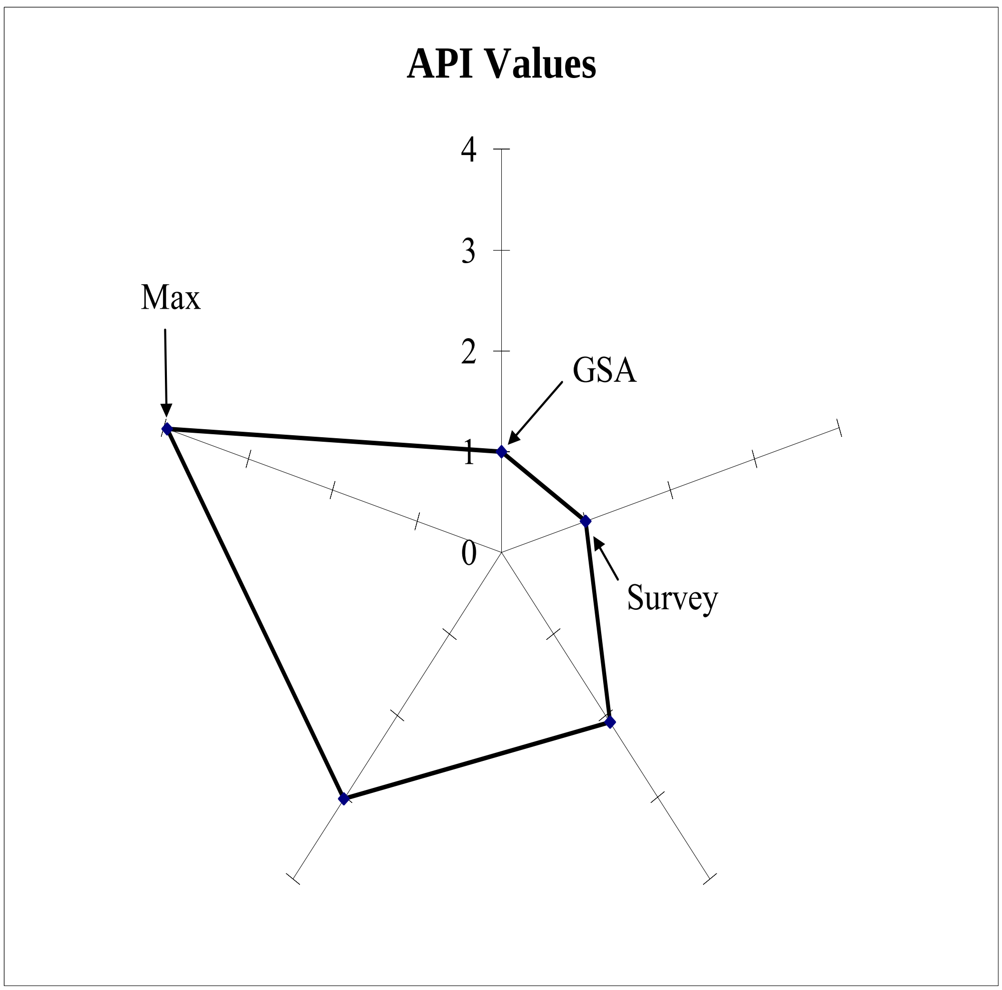


Figure 6.2 Numerical Modeling Method for API Boundary Points

API Values = f (A, P, I) for Given Buildings				
API	**A**	**P**	**I**	**Building**
1.00	3	1	3	Var. P
1.54	3	2	3	Var. P
2.08	3	3	3	Var. P
2.62	3	4	3	Var. P
3.16	3	5	3	Var. P
Based on rankings by CSP Table 5.3				
API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

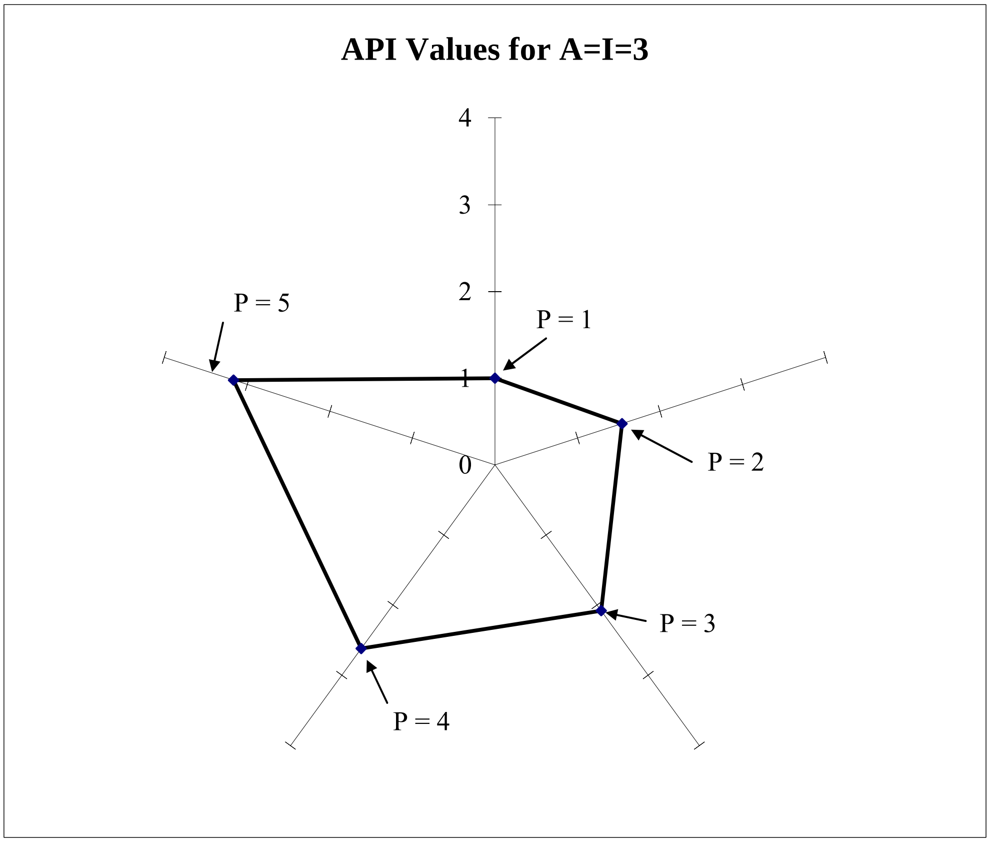


Figure 6.3 Numerical Modeling Method for API, Variable P

Figures 6.3 presents API evaluation for variable 'P' when both 'A' and 'I' are equal to 3, which indicates three service vendors and three integrated systems. Generally, design criteria requires a minimum of three vendors. This illustrates an improvements in the BAS performance with higher levels of systems integration.

API Values = f (A, P, I) for Given Buildings				
API	**A**	**P**	**I**	**Building**
2.62	3	5	1	Hi P
2.89	3	5	2	Hi P
3.03	2	5	3	Hi P
3.30	2	5	4	Hi P
3.44	1	5	5	Hi P
Based on rankings by CSP Table 5.3				
API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

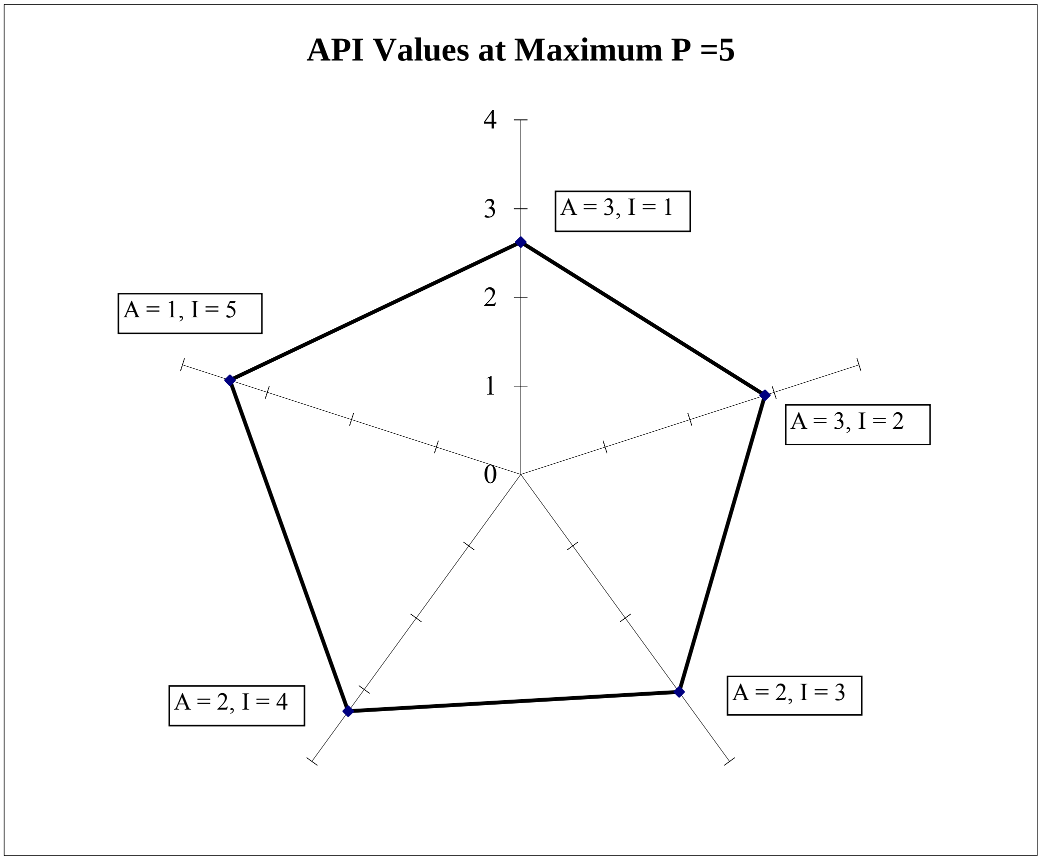


Figure 6.4 Numerical Modeling Method for API, High P

Figure 6.4 shows expected BAS performance for a combinations of 'A' and 'I' with high density of control points (P = 5).

It is assumed that a logical and sound engineering design is used, and BAS performance measured by API is independent of the actual definition of systems, design and the order of integration. Appendix A provides basic definitions of BAS and some examples of suitable practice in systems integration. For example, the assumption is that the first candidate for BAS is generally HVAC at I = 1, and for I = 2 it is HVAC plus Lighting and for I = 3 building Security will be added to the list. More system options are listed in Table 5.1, in the order of possible integration. As the value of 'I' increases to 4 or more, the order of integration of the next system candidate (Life Safety, Plumbing, Irrigation, etc.) will become less critical and it is possible to skip a few levels down to Circulation and Communication, etc. with a sound engineering design.

API Values = f (A, P, I) for Given Buildings				
API	**A**	**P**	**I**	**Building**
0.20	1	1	1	Bldg 3
0.33	2	1	1	Bldg 4
1.54	3	3	1	Bldg 5
1.81	3	3	2	Bldg 6
2.34	5	3	3	Bldg 7
Based on rankings by CSP Table 5.3 API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

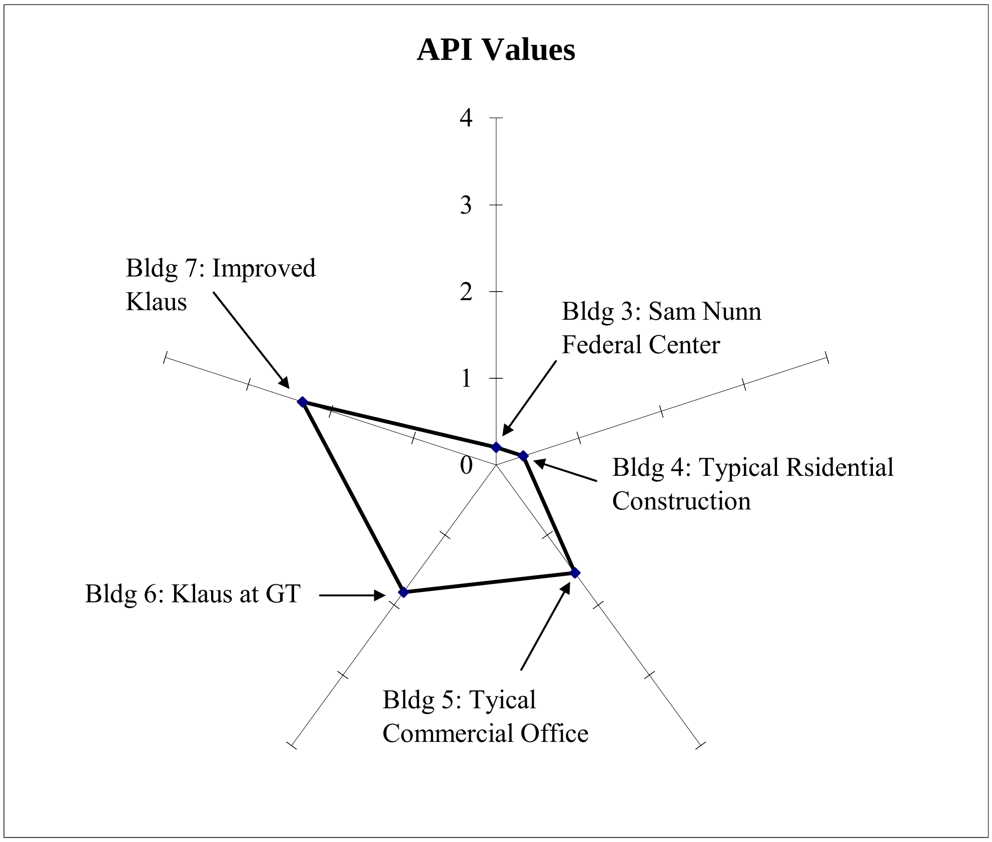


Figure 6.5 Numerical Modeling Method for API Validations

Figure 6.5 captures the performances of a few typical buildings used for model validation in Chapter 7.

6.4 Utility Method

6.4.1 Utility Method Background Theory

In this method, a utility function with values between 0 and 1 is defined for client's level of satisfaction on a key parameter's behavior. A weighted sum of these utilities is defined as the utility for API. Utility theory captures utility values (utile) from a decision-maker. Utility theory can be used in both decision-making under risk (where the probabilities are given), and in decision-making under uncertainty (where the probabilities are not provided). Utility theory may be applied with three approaches. The descriptive approach attempts to describe people's utility functions. The normative approach attempts to use utility in the construction of a rational model of decision-making. The third approach attempts to bridge the descriptive and normative approaches by considering the limitations people have with the normative goal they would like to reach; this is called the prescriptive approach (Keeney 1993).

6.4.2 Utility Method Illustration

Responses from the first member of the expert panel, Dr. Cheol-Soo Park (CSP) are listed in Table 5.3. This client's preferred utility distributions relative to each parameter are plotted in Figure 6.6. Since the survey indicated near equal overall weight for all parameters, for this example, equal weights for the parameters are used.

The utility of API can be expressed as:

$$U_{API} = \sum_{1}^{5} (w_i \times u_i) \qquad (12)$$

and $$\sum_{1}^{5} w_i = 1 \qquad (13)$$

Where U_{API} = Utility value of API; u_i = utility value of each key parameters; i = an integer number between 1 and 5 designated to a key parameter and w_i = associated weight for each parameter.

Using the overall weighted average values from survey results (Table 5.3), and equal weight factor of 0.20 is assumed for each key parameter to illustrate an example. Therefore, Equation (12) may be expressed as: Utility value of API = 0.2 (utility of cost + utility of user needs + utility of simplicity + utility of integration + utility of service and maintenance availability) or:

$$U_{API} = 0.2\,(u_1 + u_2 + u_3 + u_4 + u_5) \qquad (14)$$

Figure 6.6 captures typical results for an example of calculated Utility of API for client CSP for whom the numerical model was developed earlier.

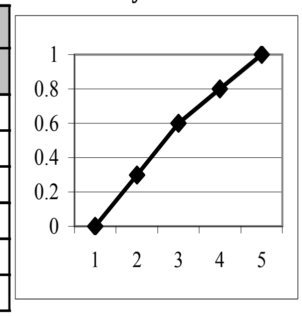
The first step is to develop a client's utility curves (u_i) for each of the parameters. Then, the utility value of the API can be calculated for a given set weight factors. In this illustration, C_2 represents the utility value of Cost shown by u_1 at i=2. In the same procedure, U_3, S_5, I_1 and A_3 have been selected for API utility calculations. The weighted sum of these points on the parameter utility curves is the value of utility of API which is between 0 and 1 and should be calculated back to a meaningful index.

In order to calculate the utility of API back to an index value for API, a reference utility converter is defined. This converter is shown as a straight line that translates values of API utility to indices of "low" to "high" performance for API. This example is presented in Figures 6.6 and 6.7. Figure 6.7 illustrates that the predicted performance level in this example for client CSP is between medium low and medium levels for Building Automation System as defined.

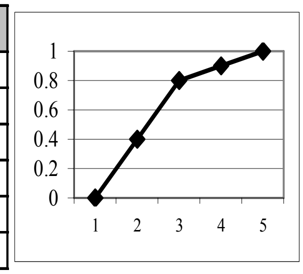
Utility Data | **Utility Curves**

Client Utility Curves for Significant Parameters

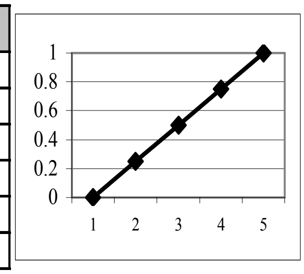
Cost per unit area (C)	Plot Scale	CSP input	u_1
Low Satisfaction	1	0.5	0
Medium Low Satisfaction	2		0.3
Medium Satisfaction	3	0.6	0.6
Medium High Satisfaction	4		0.8
High Satisfaction	5	1	1



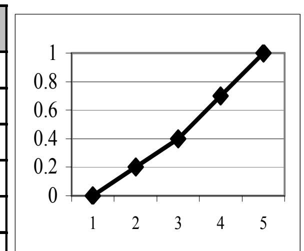
User Needs (N)	Plot Scale	CSP input	u_2
Low Cost	1	0.5	0
Medium Low Cost	2		0.4
Medium Cost	3	0.8	0.8
Medium High Cost	4		0.9
High Cost	5	1	1



Simplicity (S)	Plot Scale	CSP input	u_3
Low Simplicity	1	0.2	0
Medium Low Simplicity	2		0.25
Medium Simplicity	3	0.5	0.5
Medium High Simplicity	4		0.75
High Simplicity	5	1	1



Integration (I)	Plot Scale	CSP input	u_4
Low Integration	1	0.2	0
Medium Low Integration	2		0.2
Medium Integration	3	0.4	0.4
Medium High Integration	4		0.7
High Integration	5	1	1



Service Availability (A)	Plot Scale	CSP input	u_5
Low Availability	1	0.4	0
Medium Low Availability	2		0.4
Medium Availability	3	0.8	0.8
Medium High Availability	4		0.9
High Availability	5	1	1

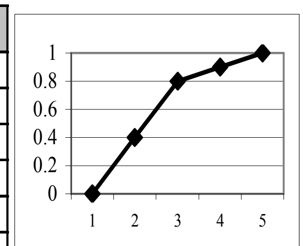
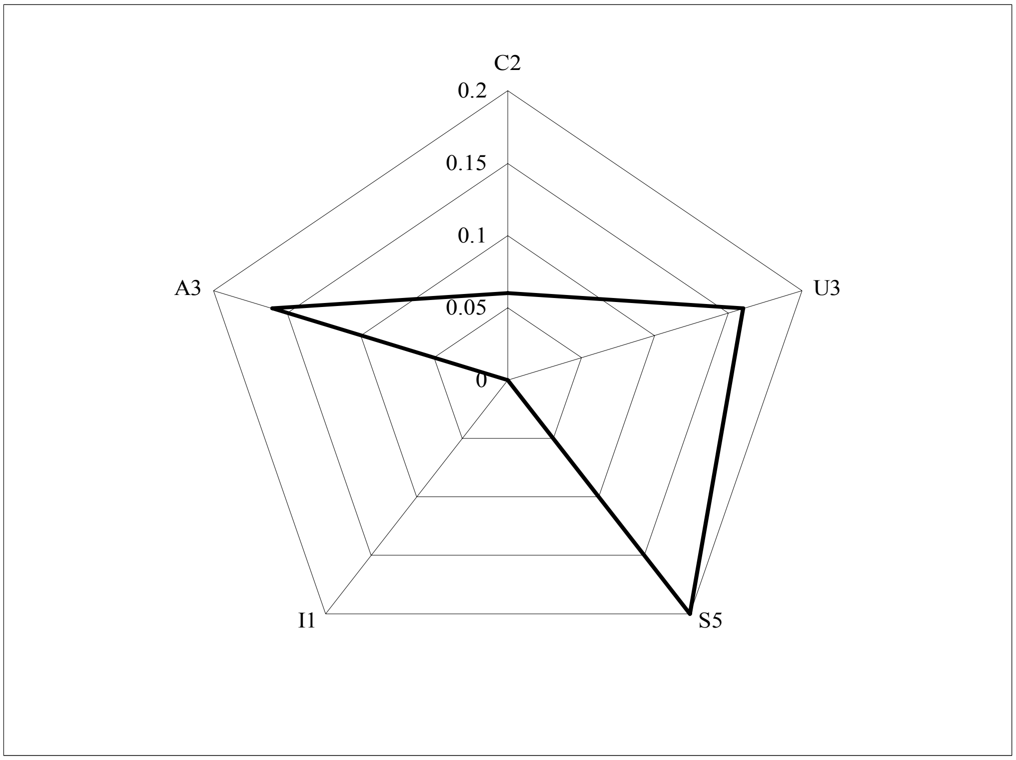


Figure 6.6 A Sample of Client Utilities for API Modeling

Reference API	Referance U_{API}
Low Performance	0.2
Medium Low Performance	0.4
Medium Performance	0.6
Medium High Performance	0.8
High Performance	1

Selected Criteria	$w_i = 0.20$
CSP Selection	**$0.2u_i$**
C_2	0.06
U_3	0.16
S_5	0.2
I_1	0
A_3	0.16
U_{API}	**0.58**



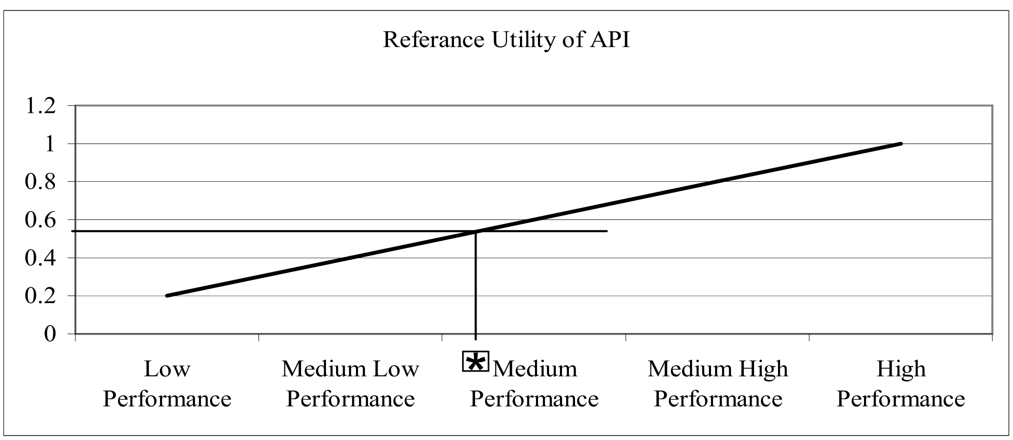


Figure 6.7 API Using Utility Method for Equal Parameter Weights

6.5 Fuzzy Logic

6.5.1 Background Theory

Fuzzy Logic was first introduced by Dr. Lotfi Zadeh in 1965, which provided the theoretical basis for Fuzzy computer chips that appeared 20 years later. Control systems, such as thermostats and cruise control, utilize Fuzzy Logic for their operation. In Appendix A, Figure A.1 shows a simple closed control loop. The following is an example of a typical control sequence:

1. If the thermostat reads temperatures 'Higher' than set-point by a 'Low' margin degree, open the damper 'Slightly' for each degree, and hold damper position for a 'Brief' time.
2. If the thermostat reads temperatures 'Lower' than thermostat set-point by a 'Low' margin of degree, the reverse of the above shall take place.
3. If the thermostat reads temperatures within 'Low' 2 degree, do not change damper position.

The above sequence of control follows a Fuzzy Logic using linguistic values to maintain a temperature set-point for the cooling process.

Fuzzy Logic simply is a structured, model-free estimator that approximates a function through linguistic input/output associations. Fuzzy set analysis allows a linguistic approach to our API analysis based on natural language. A word such as "Medium" can be assigned to portion of the study range. The same is done for "Low" and "High", thus, each category will cover a domain of variables (or sets) assigned to it.

A linguistic variable (word) can be viewed as a fuzzy set *A(x)* of a domain *U* in which *A(x)* represents the meaning of *x*. This can be expressed as follows:

$$A(x) = [x \mid m_A(x)] \tag{15}$$

Where A = fuzzy set; m_A = membership value between zero and one; x = a scale element chosen to be between zero and 5 in this study representing no performance to high performance.

Based on the Lotfi Zadeh's extension principle (Zadeh 1994), the following fuzzy addition, multiplication and division are defined for fuzzy sets *A* and *B*:

$$A(x) = [x \mid m_A(x)] \;\; and \; B(y) = [y \mid m_B(y)] \tag{16}$$

$$A \; 5 \; B = [(x + y) \mid \min(m_A(x), m_B(y))] \tag{17}$$

$$A \; U \; B = [(x \# y) \mid \min(m_A(x), m_B(y))] \tag{18}$$

$$A \; 8 \; B = [(x \, ' \, y) \mid \min(m_A(x), m_B(y))] \tag{19}$$

Where: 5 , U *and* 8 are fuzzy arithmetic operations of addition, multiplication and division of the two sets and $+$, $\#$ *and* $'$ are the normal arithmetic operations. When the result of the calculations leads to more than one membership value for a given scale, the highest membership value is selected. In most cases, the results of fuzzy division must be normalized.

Therefore, a fuzzy set of API can be calculated based on the above questions, and the fuzzy sets for key parameters and their associated fuzzy set weight factors as:

$$[API] = (!_{1}^{5} [W_i]\ U\ [U_i])\ 8\ (!_{1}^{5} [W_i]) \quad (20)$$

Where [API] = API fuzzy set; [W] = Weight factor fuzzy set; [U] = a fuzzy set representing a key parameter; *i* = an integer number between 1 and 5 representing a key parameter.

6.5.2 Fuzzy Logic Illustration and Discussion

In a similar fashion to the Utility analysis, input from Dr. Park (abbreviated as: CSP) was utilized for definition of this client's fuzzy sets for each parameter ($[U_1]$ = [Cost]; $[U_2]$ = [User Needs]; $[U_3]$ = [Simplicity]; $[U_4]$ = [Integration]; and $[U_5]$ = [Service and Maintenance Availability]). The client then was asked to provide input for API fuzzy set evaluation. One fuzzy set of weights for low, medium and high range was established to apply to all parameters as shown in Table 5.3. The weight level for each parameter was selected from the common fuzzy weight set. This information which is the basis of calculations for API fuzzy set in this example is captured in Table 6.1:

Table 6.1 Example Fuzzy Set Selection for Client's API Evaluation

Parameter	Set Level for Weight	Set Level for Parameter
Cost	High	Medium
User Needs	High	High
Simplicity	Medium	Low
Integration	Low	Medium
Service and Maintenance Availability	High	High

In addition to this, a reference fuzzy set of API performance was formed. Table 6.2 recaps the input from the client used for developing the fuzzy sets shown in Table 6.3. All added information in Table 6.3 is filled in by interpolation between the values provided in Table 6.2. Table 6.4 is the result of applying the client evaluation criteria indicated in Table 6.1.

Table 6.2 Fuzzy Sets Provided by Client CSP

[U1] = [Cost]			
Scale	**Low**	**Med**	**High**
1	x		
2	x	x	
3		x	x
4			x
5			x

[U2] = [User Needs]			
Scale	Low	Med	High
1	x	x	
2		x	
3		x	x
4			x
5			x

[U3] = [Simplicity];			
Scale	Low	Med	High
1	x		
2	x	x	
3		x	
4		x	x
5			x

[U4] = [Integration];			
Scale	Low	Med	High
1	x		
2	x		
3	x	x	
4	x	x	x
5			x

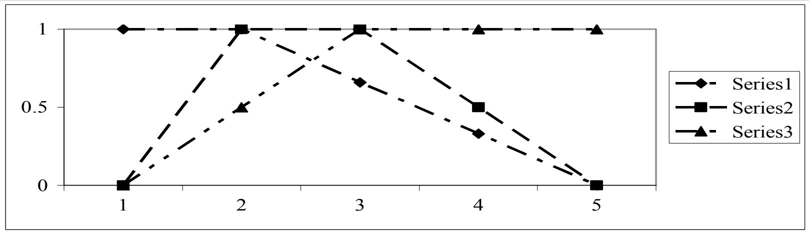
[U5] = [Service Availability]			
Scale	Low	Med	High
1	x	x	
2		x	x
3			x
4			x
5			x

[W] = Weight fuzzy set			
Scale	Low	Med	High
1	x		
2			
3		x	
4			
5			x

Table 6.3 Parameter and Weight Fuzzy Sets Provided by Expert CSP

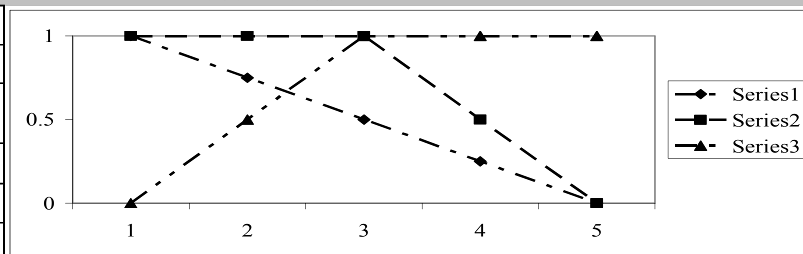
Cost

Scale	Low	Med	High
1	1	0	0
2	1	1	0.5
3	0.66	1	1
4	0.33	0.5	1
5	0	0	1



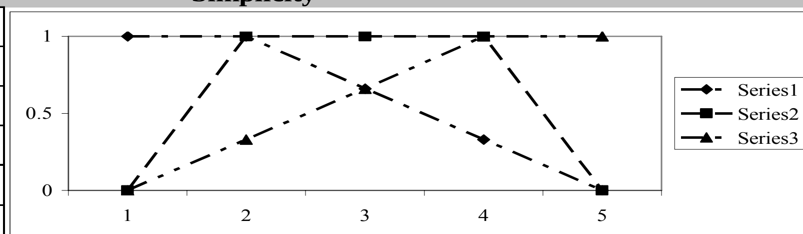
User Needs

Scale	Low	Med	High
1	1	1	0
2	0.75	1	0.5
3	0.5	1	1
4	0.25	0.5	1
5	0	0	1



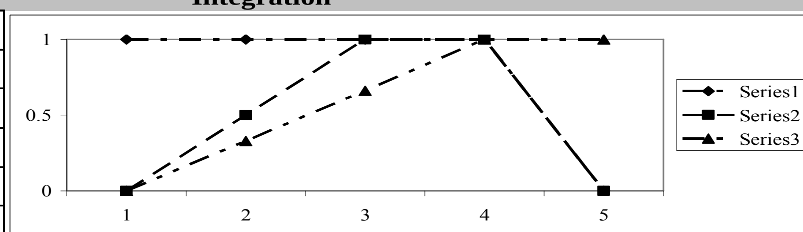
Simplicity

Scale	Low	Med	High
1	1	0	0
2	1	1	0.33
3	0.66	1	0.66
4	0.33	1	1
5	0	0	1



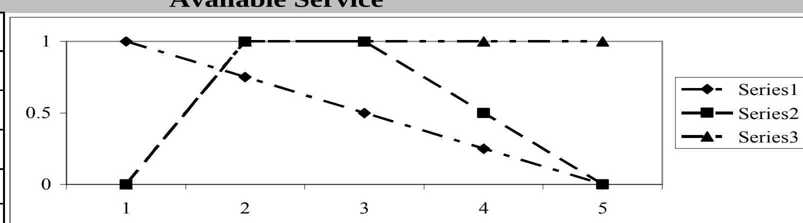
Integration

Scale	Low	Med	High
1	1	0	0
2	1	0.5	0.33
3	1	1	0.66
4	1	1	1
5	0	0	1



Available Service

Scale	Low	Med	High
1	1	0	0
2	0.75	1	1
3	0.5	1	1
4	0.25	0.5	1
5	0	0	1



Weight Sets

Scale	Low	Med	High
1	1	0	0
2	0	0	0
3	0	1	0
4	0	0	0
5	0	0	1

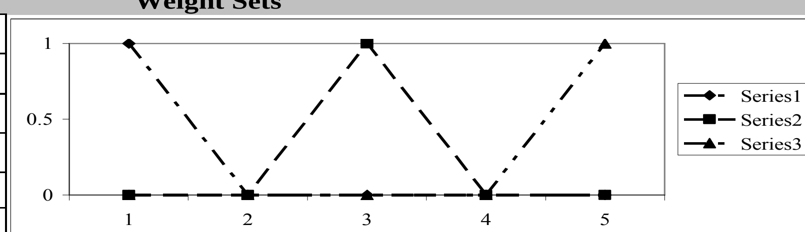
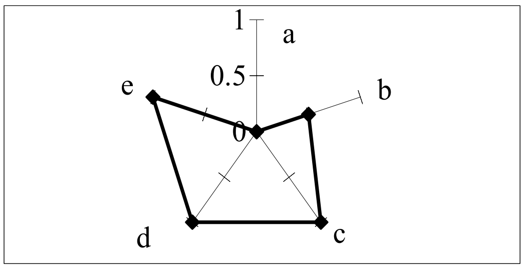
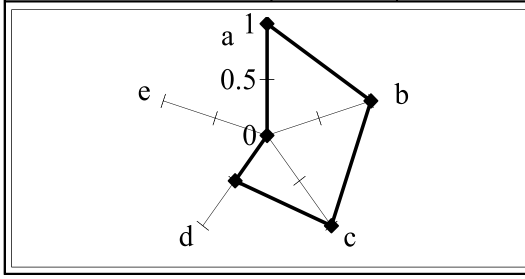


Table 6.4 Selected Fuzzy Weight and Parameter Sets for [API] Illustration

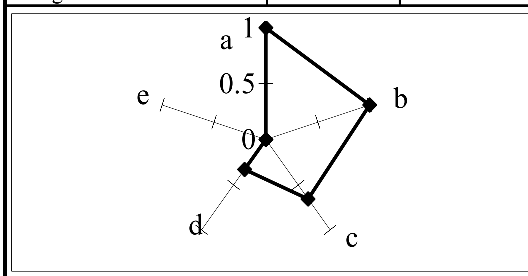
Cost (per unit area)	$[w_{High}]$	$[u_1]$ High
a: Low Satisfaction	0	0
b: Medium Low Satisfaction	0	0.5
c: Medium Satisfaction	0	1
d: Medium High Satisfaction	0	1
e: High Satisfaction	1	1



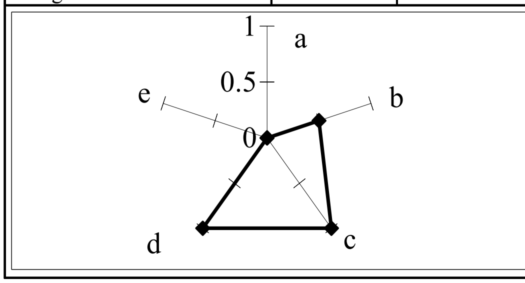
User Needs	$[w_{High}]$	$[u_2]$ Medium
a: Low Satisfaction	0	1
b: Medium Low Satisfaction	0	1
c: Medium Satisfaction	0	1
d: Medium High Satisfaction	0	0.5
e: High Satisfaction	1	0



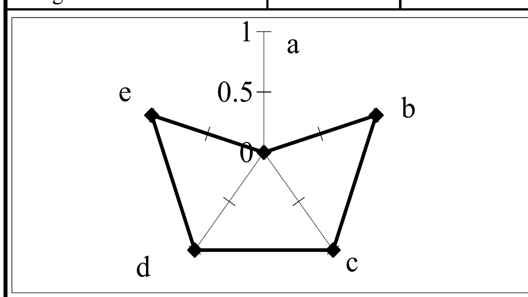
Simplicity	$[w_{Medium}]$	$[u_3]$ Low
a: Low Satisfaction	0	1
b: Medium Low Satisfaction	0	1
c: Medium Satisfaction	1	0.66
d: Medium High Satisfaction	0	0.33
e: High Satisfaction	0	0



Integration	$[w_{Low}]$	$[u_4]$ Medium
a: Low Satisfaction	1	0
b: Medium Low Satisfaction	0	0.5
c: Medium Satisfaction	0	1
d: Medium High Satisfaction	0	1
e: High Satisfaction	0	0



Service Availability	$[w_{High}]$	$[u_5]$ High
a: Low Satisfaction	0	0
b: Medium Low Satisfaction	0	1
c: Medium Satisfaction	0	1
d: Medium High Satisfaction	0	1
e: High Satisfaction	1	1



Key to Table	
Symbol	Description
$[w_{High}]$	Weight (Table 6.3)
$[u_1]$ High	Cost Set
$[u_2]$ Medium	User Needs Set
$[u_3]$ Low	Simplicity Set
$[u_4]$ Medium	Integration Set
$[u_5]$ High	Service Availability Set
Plot Axis a	Low Satisfaction
Plot Axis b	Medium Low Satisfaction
Plot Axis c	Medium Satisfaction
Plot Axis d	Medium High Satisfaction
Plot Axis e	High Satisfaction
Client	CSP

Selected sets for calculations from Table 6.3 are shown in Table 6.4.

Parameter Sets:

$[U_1]$ = Medium level fuzzy set for N = [1|1, 2|1, 3|1, 4|0.5, 5|0]

$[U_2]$ = High level fuzzy set for C = [1|0, 2|0.5, 3|1, 4|1, 5|1]

$[U_3]$ = Low level fuzzy set for S = [1|1, 2|1, 3|0.66, 4|0.33, 5|0]

$[U_4]$ = Medium level fuzzy set for I = [1|0, 2|0.5, 3|1, 4|1, 5|0]

$[U_5]$ = High level fuzzy set for A = [1|0, 2|1, 3|1, 4|1, 5|1]

Weight Sets:

$[W_{Low}]$ = [1|0, 2|0, 3|0, 4|0, 5|1]

$[W_{Meduim}]$ = [1|0, 2|0, 3|1, 4|0, 5|0]

$[W_{High}]$ = [1|0, 2|0, 3|0, 4|0, 5|1]

Based on the fuzzy set derived using equation (20), and plotted against a reference [API], the linguistic performance level may be evaluated. Calculation of the first parenthesis for [API] in equation (20):

$! {}_{1}^{5} [W_i] \cup [U_i] =$

[1|0, 2|0, 3|0, 4|0, 5|1] ∪ [1|1, 2|1, 3|1, 4|0.5, 5|0] 5

[1|0, 2|0, 3|0, 4|0, 5|1] ∪ [1|0, 2|0.5, 3|1, 4|1, 5|1] 5

[1|0, 2|0, 3|1, 4|0, 5|0] ∪ [1|1, 2|1, 3|0.66, 4|0.33, 5|0] 5

[1|0, 2|0, 3|0, 4|0, 5|1] ∪ [1|0, 2|0.5, 3|1, 4|1, 5|0] 5

[1|1, 2|0, 3|0, 4|0, 5|0] ∪ [1|0, 2|1, 3|1, 4|1, 5|1] =

Only the non-zero terms will be shown:

[10|1, 15|1, 20|0.5] 5 [10|0.5, 15|1, 25|1] 5

[3|1, 6|1, 9|0.66, 12|0.33] 5 [10|0.5, 15|1, 20|1] 5

[2|1, 3|1, 4|1, 5|1] =

[20|1, 25|1, 30|1, 35|1, 40|1, 45|0.50] 5

[13|0.5, 16|0.5, 18|1, 19|0.5, 21|1, 22|0.33, 23|1, 24|0.66, 26|1, 27|0.33, 29|0.66, 32|0.33]5

[2|1, 3|1, 4|1, 5|1] = [22|1, 23|1,24|1, 25|1, 27|1, 28|1, 29|1, 30|1, 32|1, 33|1, 34|1, 35|1, 37|1, 38|1, 39|1, 40|1, 42|1, 43|1, 44|1, 45|1, 47|0.5, 48|0.5, 49|0.5, 50|0.5] 5 [13|0.5, 16|0.5, 18|1, 19|0.5, 21|1, 22|0.33, 23|1, 24|0.66, 26|1, 27|0.33, 29|0.66, 32|0.33]

The second parenthesis is:

$!_1^5[W_i]$ = [1|0, 2|0, 3|0, 4|0, 5|1] 5 [1|0, 2|0, 3|0, 4|0, 5|1] 5 [1|0, 2|0, 3|1, 4|0, 5|0] 5

[1|1, 2|0, 3|0, 4|0, 5|0] 5 [1|0, 2|0, 3|0, 4|0, 5|1]

= [1|0, …18|0, 19|1, 20|0… 25|0] (21)

And after fuzzy division and normalization:

[API] = ($!_1^5$ $[W_i]$ U $[U_i]$) 8 ($!_1^5[W_i]$) = [1|0, 2|1, 3|0.33, 4|0, 5|0] (22)

[API] is plotted to compare with the performance reference in Figure 6.8.

Scale	Referance Set			[API]
	Low	Med	High	
1	1	0	0	0
2	1	0.5	0.25	0
3	0.66	1	0.5	1
4	0.33	1	0.75	0.33
5	0	0	1	0

[API] compared to Reference Set

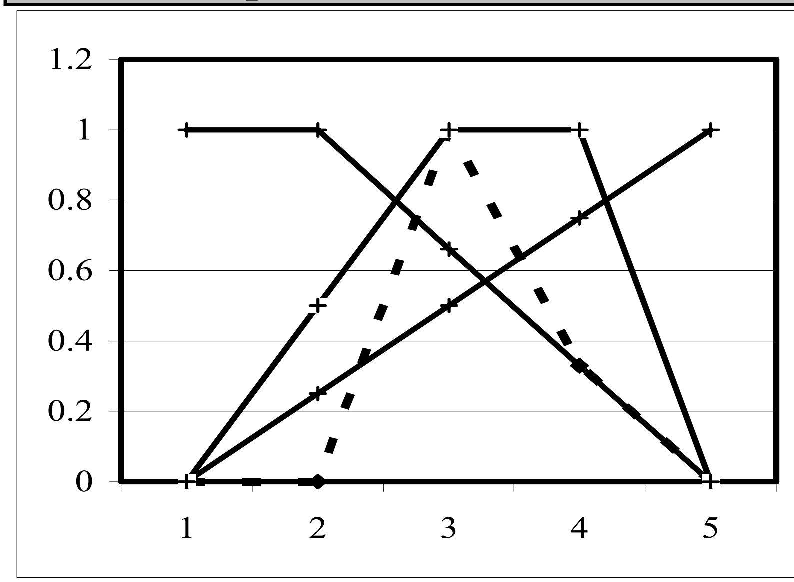


Figure 6.8 Illustration of [API] Against Reference [API]

6.5.3 Fuzzy Logic Discussion

In the above simplified analysis, the calculated values of [API] for the client CSP has been plotted and superimposed on a reference set for interpretation of the linguistic value of API, as shown in Figure 6.8.

As a result of visual comparison of [API] in Figure 6.8 with a sample reference set for linguistic, API for this example is in the low-to-medium range.

CHAPTER 7

MODEL ANALYSIS AND VALIDATION

"The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man."

George Bernard Shaw

7.1 Summary

Table 5.2 validates significance of the parameters identified, namely, Cost (C), User Needs (N), Simplicity (S), Level of Integration (I), Availability of service and maintenance (A), by providing evidence that the overall ranking weighted average of all parameters are very close to the mean with a small standard deviation. This basically means, in the aggregate, these five parameters can be equally influential in the automation performance.

API shows that, within the commercial and practical ranges of P = the number of control point per unit area, which represents the size and cost of the BAS, the building automation performance increases as 'P' increases, and higher levels of control implementation should result in better performance.

Using three different modeling techniques, examples of quantifiable Automation Performance Index have been presented. The numerical approach requires calculating weight factors for the significant parameters, and the weights are different for different clients. This agrees with the ranking survey summarized in Table 5.2. All three models applied can help in analysis of the trends and comparative values associated with BAS performance and they are all relatively easy methods; however, the numerical method requires the least amount of data input, as opposed to the fuzzy logic that requires the most input from the client amongst the three methods.

API models indicate that GSA criteria in which no integration, a minimum of three vendors and control point density of 2 per 100 square meters are specified, will provide lower-than-average performance, compared to the highest-possible levels.

7.2 Validation for Numerical Method

Information for Sam Nunn Atlanta Federal Center, along with a few other GSA office buildings, were provided to a research team at Georgia Institute of Technology for a benchmarking project in the areas of energy and lighting (Park 2002).

Figure 7.1 Sam Nunn Atlanta Federal Center (3 Buildings and Parking)

The Sam Nunn Building utilizes a BAS with control point density of P = 1 per 100 square meter and does not have integration between various systems, such as lighting an HVAC, which means I = 1. The direct digital control system installed at this project is

Johnson Controls METASYS and may be serviced only by Johnson Control authorized vendors, which means A = 1. With A = P = I = 1, the value of API may be calculated using (6). Building 3 in Figure 6.5, with an API = 0.2 is expected to provide low performance. This, in fact, represents GSA's experience with this building. GSA commissioned Georgia Tech to perform several investigative tasks to make recommendations to improve the performance of the building between 2002 and 2006 (Park and Augenbroe 2003).

Table 7.1 Information on Sam Nunn Atlanta Federal Center

Building Characteristic	Sam Nunn Atlanta Federal Center
Location	Atlanta, GA
Year of Construction	1998
Floor area (m2)	148,822 (exclusive of the parking area)
Number of occupants	4,500
HVAC system	Variable Air Volume with reheat except for computer rooms
Heat generation for space heating	Electric Reheat
Humidification	None Provided
Cold source for space cooling	Chilled water supplied from central plant
Windows	Double glazing with air space
Window wall ratio (window/wall)	40.2%
Wall type	6" Concrete with R11 except for historical Rich building with Brick veneer and R-11 insulation
Lighting	Central on/off, no day-lighting controls
Ventilation	Mechanical (80% return air + 20% outdoor air)
Energy Source	All Electric

Building 4 in Figure 6.5 is defined based on a typical residential-style building with DX cooling and gas furnace for heating, in which at least two vendors can service the system. The predicted low performance of API = 0.33 is compatible with expected performance. The table in Figure 6.5 has been reproduced as Table 7.1 for this discussion.

Table 7.2 API Validation

API Values = f (A, P, I) for Given Buildings				
API	**A**	**P**	**I**	**Building**
0.20	1	1	1	Bldg 3
0.33	2	1	1	Bldg 4
1.54	3	3	1	Bldg 5
1.81	3	3	2	Bldg 6
2.34	5	3	3	Bldg 7
Based on rankings by CSP Table 5.3 API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

Building 5 is a typical commercial office or academic building with BAS provided only for the HVAC. Building 6 is defined based on the Klaus Computing Building at Georgia Tech, currently in its final stages of construction. This building has been designed with integration of lighting and HVAC (I = 2) and, due to additional of sensors for day-lighting controls, as well as occupancy sensors for lighting, the density of control points may be estimated at P = 3. The building controls at Klaus may be serviced by at least three vendors, due the requirements of the Georgia Board of Regents, who acted as the client for this project.

Building 7 is a realistic case for improving on performance of Building 6 (Klaus) by increasing the value of some of the significant performance parameters.

Table 7.3 Basic Information for Klaus (Building 6)

Building Characteristic	Klaus advance computing building
Location	Georgia Tech campus, Atlanta, GA
Year of Construction	Completed in 2006
Floor area (m2)	17,960 (exclusive of the parking area)
Number of occupants	2,449
HVAC system	VAV with reheat except for computer rooms
Heat generation for space heating	Hot water provided by a steam-to-water heat exchanger fueled by high pressure steam from the campus central plant
Humidification	Unfired steam generator fueled by high pressure steam from the campus central plant
Cold source for space cooling	Chilled water supplied by the campus central plant
Windows	Double glazing with air space
Window wall ratio (window/wall)	37.6%
Wall type	Brick wall + steel framed curtain wall
Lighting	Occupancy sensors + daylighting sensor in the East façade
Ventilation	Mechanical (82% return air + 18% outdoor air)
Heat recovery system	Enthalpy wheel

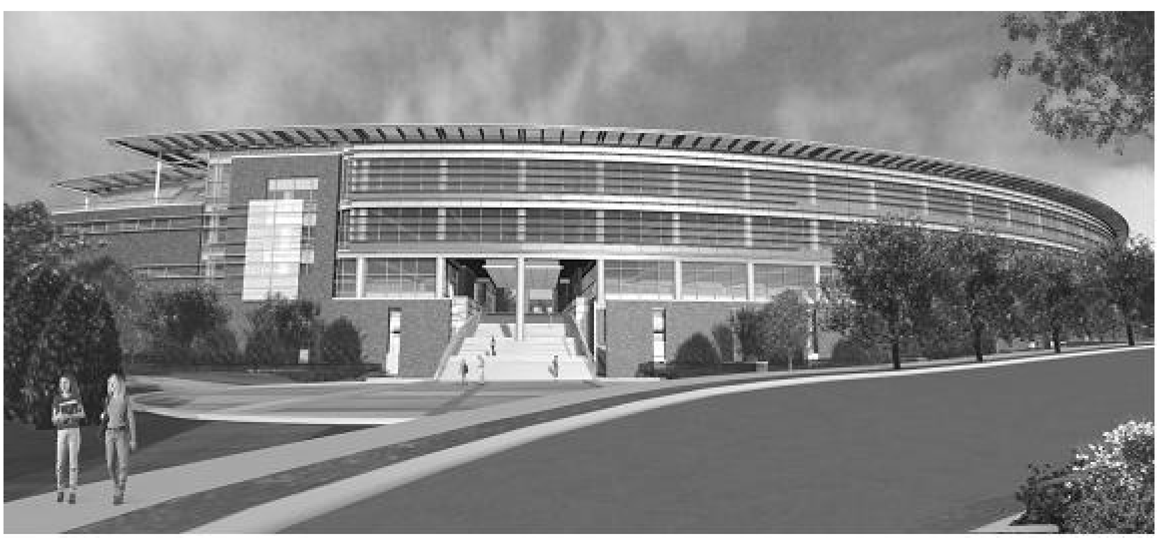


Figure 7.2 Klaus Advanced Computing Building (Building 6)

API Values = f (A, P, I) for Given Buildings				
API	**A**	**P**	**I**	**Building**
0.20	1	1	1	Sam Nunn Fed. Ctr.
0.33	2	1	1	Typical Residential
1.54	3	3	1	Typical Office Bldg.
1.81	3	3	2	Klaus at Tech
2.34	5	3	3	Improved Klaus
Based on rankings by CSP Table 5.3				
API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

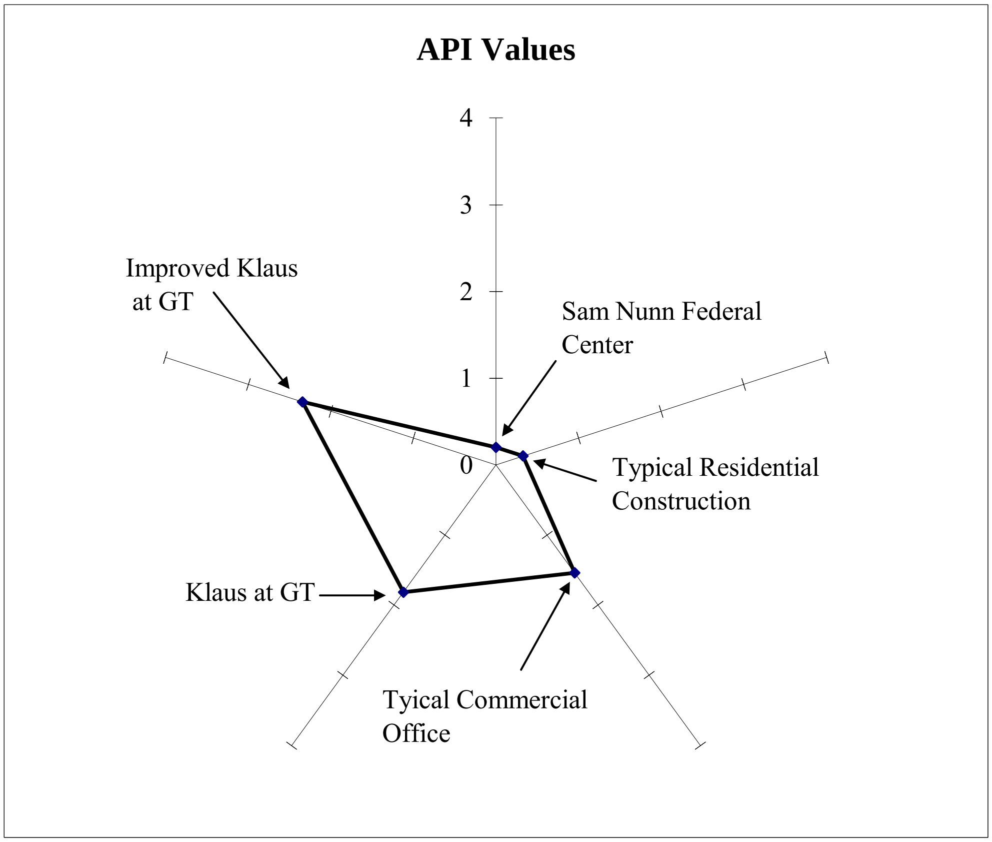


Figure 7.3 API Values for Various Projects

API	A	P	I	Criteria
1.00	3	1	3	Var. P
1.54	3	2	3	Var. P
2.08	3	3	3	Var. P
2.62	3	4	3	Var. P
3.16	3	5	3	Var. P
Based on rankings by CSP Table 5.3				
API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

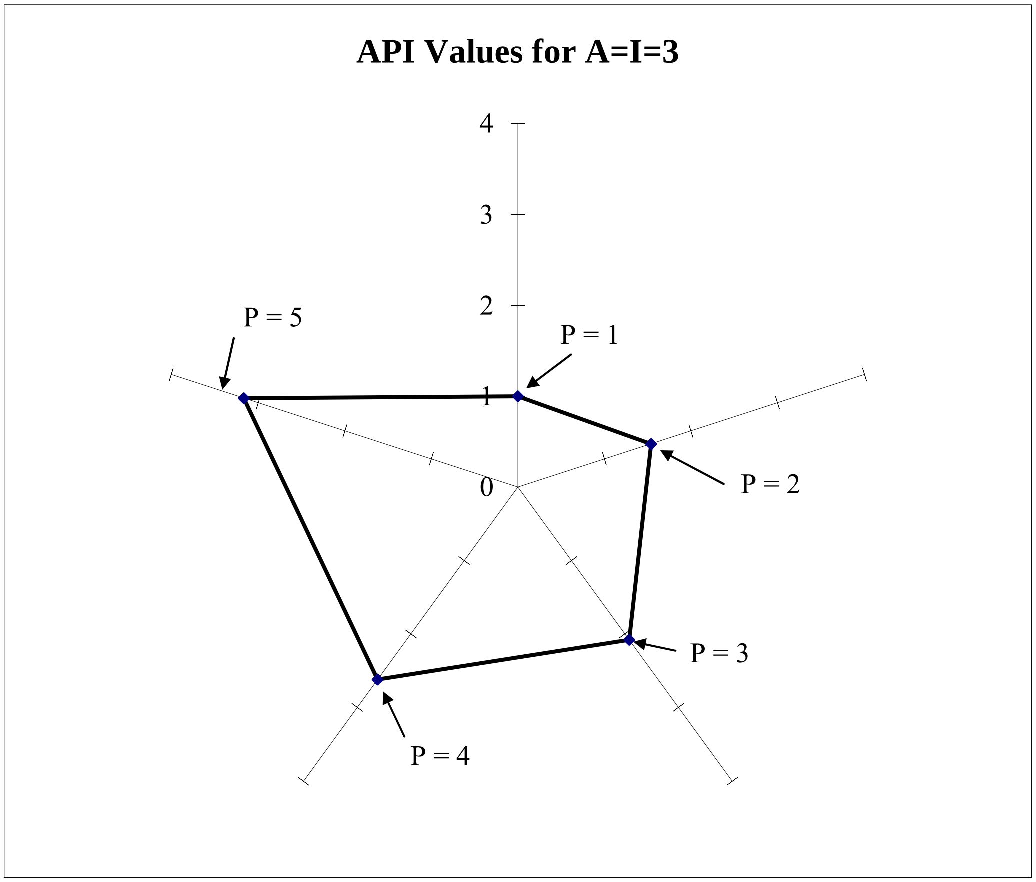


Figure 7.4 API Values for Various Control Point Densities

API	A	P	I	Criteria
2.62	3	5	1	Hi P
2.89	3	5	2	Hi P
3.03	2	5	3	Hi P
3.30	2	5	4	Hi P
3.44	1	5	5	Hi P
Based on rankings by CSP Table 5.3				
API = 0.13(A) + 0.54(P) + 0.27(I) - 0.74				

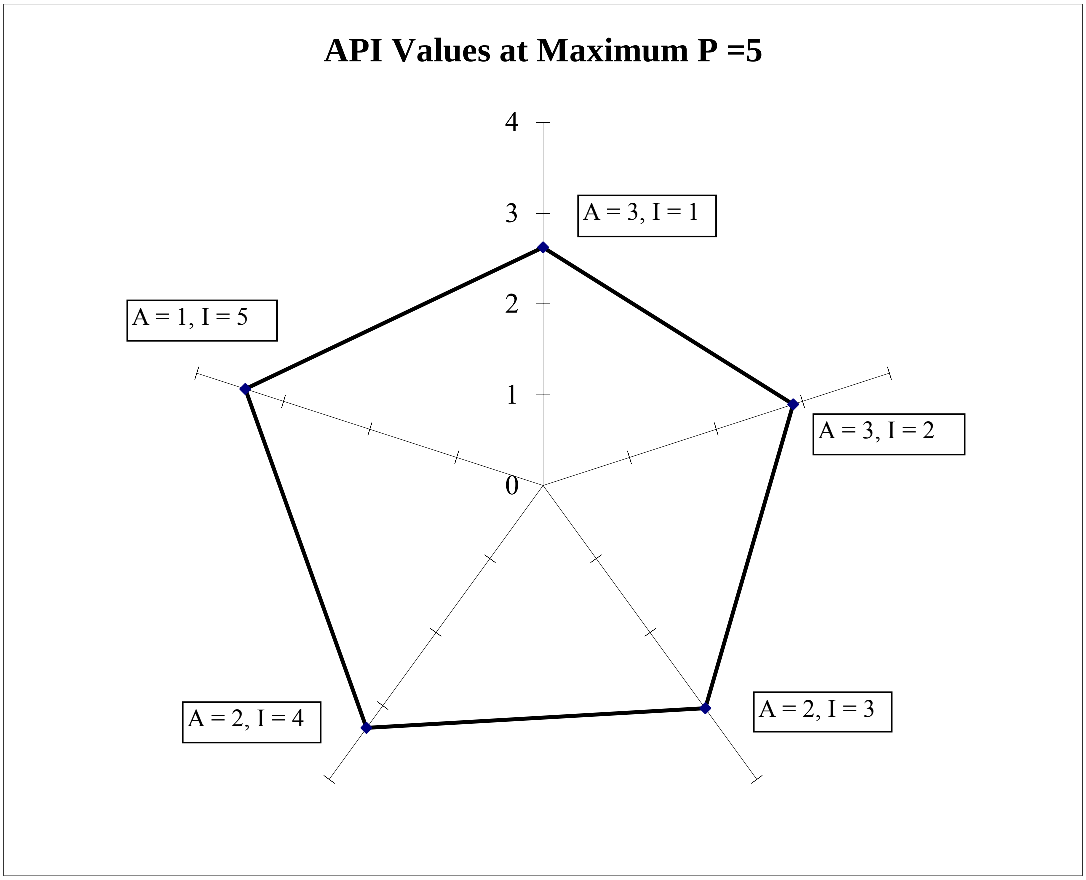


Figure 7.5 API Values for Maximum Control Point Density

7.3 Model Characteristics

Three different models for developing API were illustrated as follows:

1. Numerical Model: A linear weighted sum of individual parameters reduced our function to: API = f (A, P, I) = $w_1A + w_2P + w_3I + C$.
2. Utility Model: Utility of API which is the sum total of the weighted utility of significant parameters is presented as index.

3. Fuzzy sets for client's point-of-view of performance for each parameter through linguistic classifications are defined, and each parameter's fuzzy set is multiplied by the associated fuzzy set of the weight factor to calculate the fuzzy set for automation performance index.

The numerical model was tested and validated and the other two models were illustrated. Table 7.4 captures how the three models performed in this research in comparison to each other for measuring Automation Performance Index. The characteristics tabulated compare simplicity of set-up and use of the model, the amount of data required for arriving at the index, the level of effort required for date collection and processing, the model's ability to apply linguistic, as well as quantitative, input, and the level of practicality and versatility of the model with respect to building construction and operation scenarios.

Table 7.4 Model Characteristics

Characteristics	**Numerical Method**	**Utility Method**	**Fuzzy Method**
Set-Up Effort	X		
Processing Effort	X		
Easy to Use	X		
Data Needed	X		
Versatility		X	
Practicality	X		
Accuracy			X
Research Focus	*		

CHAPTER 8

SUMMARY, CONTRIBUTIONS, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

"I never think of the future - it comes soon enough." *Albert Einstein*

8.1 Summary

Any improvement to the performance of a building, in terms of providing comfortable environment at improved energy consumption levels, should pay close attention to its energy monitoring and comfort control systems. Improvement requires monitoring and measurement, which is made possible by quantifying relevant parameters. As the industry moves towards more intelligent buildings with integrated automation systems, this research prompted discussions regarding the automation performance. Further discussions regarding the significant parameters for improving the building automation performance tailored for specific clients were prompted by this research. The benefits of enhanced building intelligence, versus the challenges of a sophisticated system operation, are described in this study.

Automation is intended to improve overall building performance. Building Automation Systems (BAS) are attractive and popular due to their promise of increased operational effectiveness, such as energy saving. BAS can be optimized and a well-designed and well-implemented BAS is expected to increase a building's overall appeal and value as a result of improvement to its performance. In order to optimize the level of automation in buildings, a measurement tool in the form of a performance index is needed. The goal of this research was to quantify a building's level of automation-performance. The specific objective was to develop an Automation Performance Index (API) model for evaluating the extent of a building's automation-performance.

Chapter 1 described the research challenges, provided a comprehensive background study, and a new methodology to embark on for reaching a solution. This methodology provided a systematic and general approach which could be tailored to the requirements of each potential client. The methodology also provides a set of criteria which could be used in similar research work. Chapter 1 demonstrated that Building Automation System (BAS) technology is evolving rapidly and providing opportunities to add more intelligence to the buildings, making them more efficient in providing desired environments for the users. It was also demonstrated that increasing the level of building automation and intelligence does not necessarily increase the automation system's performance and, consequently, the entire building's performance. As the level of automation increases, so does the cost and complexity of the operation and maintenance, indicating that improved levels of automation for better performance can be expected. In order to improve automation, its performance levels should be measured.

In Chapter 2, a comprehensive literature and background search was conducted and five categories of parameters were identified. The results of this chapter led to the identification of a comprehensive list of key parameters. Then, these parameters were classified into five major areas: Cost, User Needs, Simplicity, Integration, and Service and Maintenance Availability. Chapter 3 has summarized expert survey results of 29 professionals in the field of Building Automation Systems (BAS), building commissioning and operation. The survey resulted in identifying 16 significant items contributing to the BAS performance. These items were then classified and categorized according to their unique characteristics into five categories that were identified in the literature and background search. Chapter 4 was dedicated to further investigation and understanding of the five significant parameters that influence the performance model.

In Chapter 5, feasibility of various modeling techniques were investigated for identifying a set of suitable techniques.

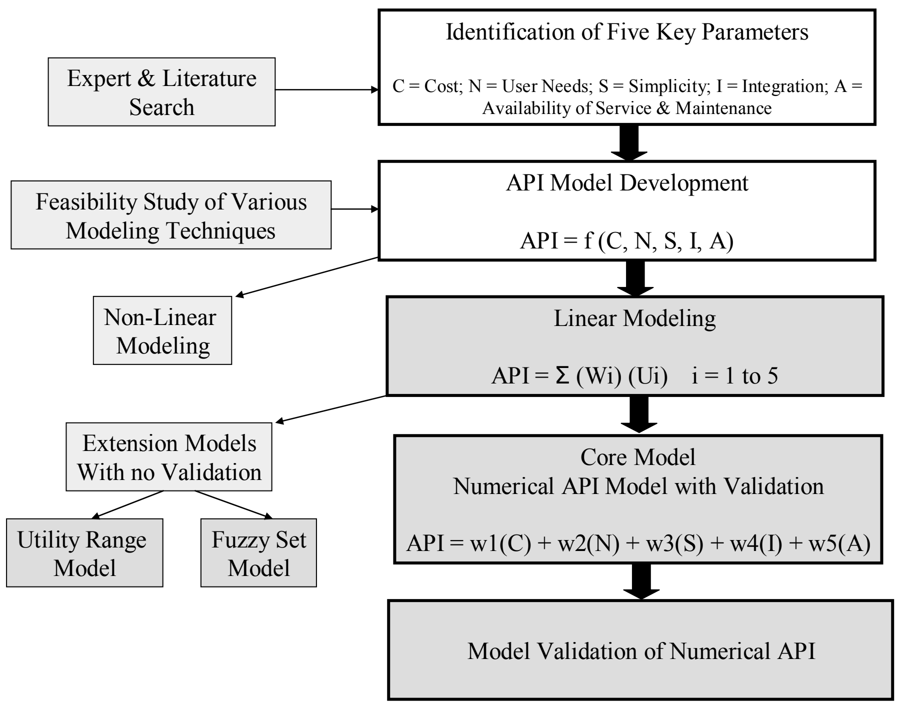


Figure 8.1 Model Development Methodology

Three modeling systems were selected to illustrate quantification of the Automation Performance Index, which included: numerical model, utility values, and fuzzy set logic. To develop the numerical model, the expert panel's survey was utilized to rank the level of significance of the five major parameters in the model. This model was later tested and validated.

The utility value model was illustrated based on the utility curves of one of the members of the expert panel. The third model utilized the fuzzy logic for evaluating API for linguistic data. Chapter 6 illustrated application of the models and illustrated procedures for estimating the API. In Chapter 7, the numerical model was tested for real cases to validate the models. Chapter 8 provides an overview of the thesis, conclusions and contributions, and a set of recommendations for future research.

8.2 Contributions and Conclusions

The primary contribution of this research is the development of a set of criteria or guidelines (road map) for quantification of a building's level of automation-performance. The secondary contribution is the identification of key or significant parameters for the development of an Automation Performance Index (API) model. The third contribution of this study is the development of a systematic approach for quantifying a building's level of automation-performance. This research developed three Automation Performance Index (API) models for numerical, utility and linguistic evaluation of a building's automation-performance level.

The above contributions led this research to the following major conclusions. It was concluded that the decision criteria or guidelines developed in this research are critical to the overall outcome of the models. For example, utilizing the criteria for building codes and guidelines by large organizations, such as General Services Administration (GSA), Emory Healthcare Facilities, Georgia Tech Facility Design Criteria, are essential in model development and validation. Without these well-defined criteria, the model can not define its practical boundaries; therefore, it will lead to a theoretical result and impractical answer.

The study revealed that five major parameters contributing to the evaluation of the Automation Performance Index are: Cost, User Needs, Simplicity, Integration and Availability of Service and Maintenance. It was concluded that these are the significant parameters influencing the performance of Building Automation Systems. The research also concluded that there was no consensus among the industry professionals for ranking the five major parameters. The results of the ranking revealed that experts did not agree with each other on the relative significance of the five parameters, and the overall ranking revealed close average and small deviation in relative impact of the five parameters. It was concluded that all five parameters are equally ranked when an average of overall survey results was evaluated.

The study concluded that quantitative models can be developed to evaluate a building's automation-performance based on numerical, utility or linguistic values. Three modeling techniques: Numerical, Utility Value, and Fuzzy Logic for evaluating the Automation Performance Index (API) were developed. The research concluded that all three models are capable of evaluating the API, however, the level of complexity significantly differ. The Fuzzy Logic model had the most-complex evaluation technique; however, it allowed a simple linguistic data input/output. The utility model required utility functions from the decision-maker, which made the model very theoretical and not practical to use. The numerical model provided a simple data input/output with less complexity. It was also concluded that building automation, which has traditionally consisted of automatic controls and scheduling of Heating Ventilation and Air Conditioning (HVAC) systems, can significantly benefit and improve if it is integrated with the lighting and security systems.

8.3 Research Discussions

As illustrated in Figure 8.1, Time, Performance and Cost are the three sides of the construction management triangle (Kerzner 2003), while Planning, Monitoring and Control are its three corners (Allinson 1997). This dynamic triangle seems to also suggest a flow of activity starting from the planning corner towards monitoring and through control that cycles back to more planning and so forth. Planning takes a small portion of the overall building life, but it sets the tone for design, construction and operation of a facility for a long time, namely its life. Monitoring the operation during this extended time is essential for proper maintenance, control and up-keeping.

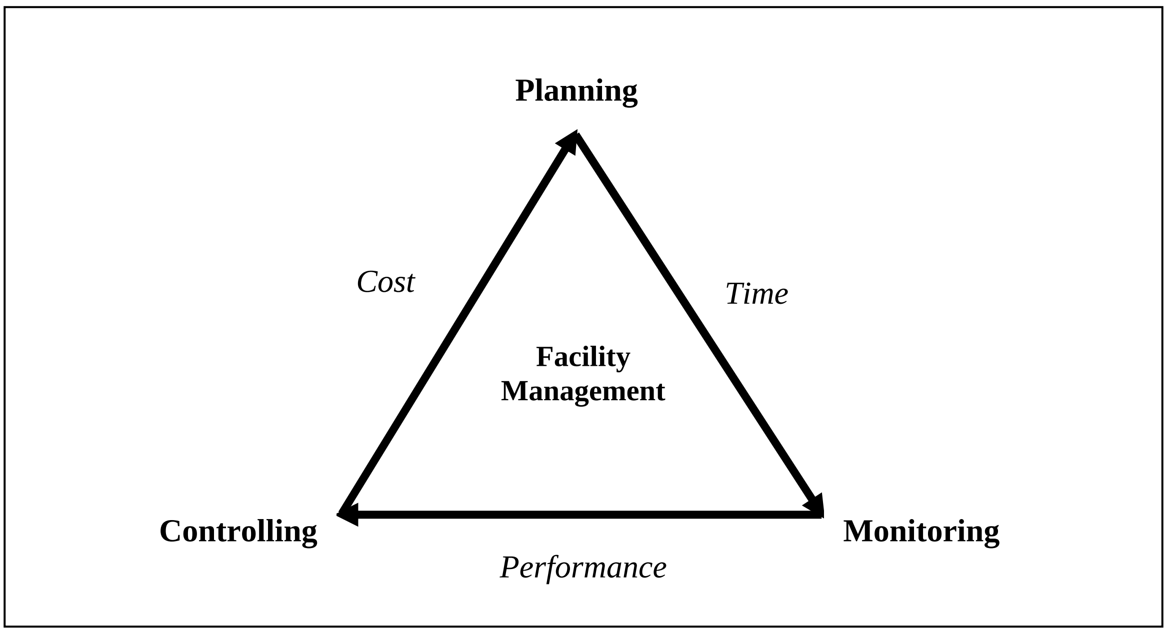


Figure 8.2 Improving Performance by Project Management

Today, with the easy access to information and communication technology the monitoring task is possible with almost no constraints and borders. Therefore, the focus is directed to methods of making decisions about the choices of Monitoring and Control to improve performance.

One major impact of this research is expected to be in the development of Six Sigma performance improvement approach for BAS design and construction, shown in Figure 8.2. Facility managers and system designers can benefit from the API model as a BAS performance measurement tool, and systematically analyze and improve the life-cycle performance of a building. The target for the desired API index may be determined from the owner's criteria, similar to GSA criteria used in this study. API may then be calculated at every project milestone to compare the current index with the desired value. This procedure can also be used to conduct sensitivity analysis (answering "what if" questions).

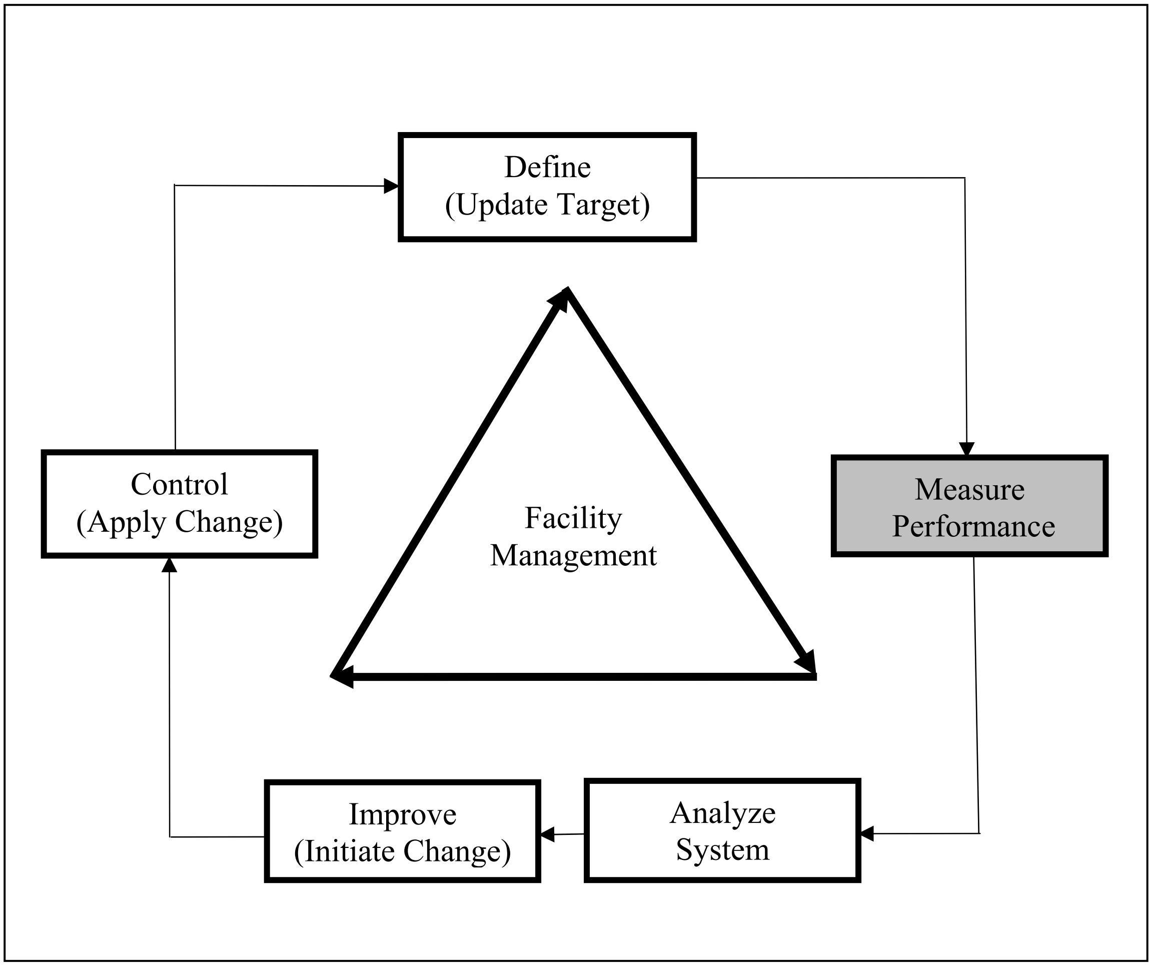


Figure 8.3 A Performance Improvement Approach In Construction

It is conceivable that project management and scheduling software commonly used in the industry can be enhanced to give feedback to professionals for energy, lighting, comfort, maintenance and BAS performance of the project at major milestones, and help to prevent deviations from the project goals. Therefore, the API can contribute to more effective decision-making system for BAS to develop a Global Optimization Service (GOS), as further described by this author (Makarechi 2005). The following part summarizes human, technological, and organizational impacts of the API model developed in this research in a GOS environment where individual cell phones can be considered as a personal BAS interface device.

8.3.1. Human Impacts

The developed API model promotes integration that will allow Building Automation Systems to incorporate the human perspective and provide additional comfort, flexibility, and active participation. The integrated building systems can follow an individual's location and provide them with the needed environmental services through wireless networking. The same network can be used by authorized individuals to alter the environmental set-points on demand, by logging into an Internet website that communicates with the Building Automation System.

Each individual can passively or actively contribute to the mode and mood of the built environment by cell phone or other wireless connection to the BAS network. Through the use of BAS integration, human needs are satisfied, as opposed to blindly meeting pre-determined rigid set-points.

8.3.2. Technological Impacts

The expected technological impact of the developed API model is great. It emphasizes integration, simplicity, service and maintenance availability, and incorporation of user needs. Building owners may not need to spend more than what they are already spending on the BAS systems to receive these benefits. In fact, some of the costs of the systems may be passed onto individual accounts, similar to personal cell phone accounts. Web-based services can be created to maintain and update personal control set-point preferences, such as the temperature and lighting levels. Many cell phones currently have GPS already, and every individual's cell phone can constantly communicate the individual's desired environmental control information. For this to be accomplished, wireless systems with higher data transfer speeds will be needed that may be accessed by personal PC, PDA and phones for faster and meaningful response from the controlled systems. A PDA can communicate to a person's destination, arrival or departure, based on the calendar scheduling functions.

8.3.3. Organizational Impacts

It is expected that the cell phone industry will expand into companies that also provide comfort and entertainment, in addition to information and communication. In this case, API will play a major role in evaluating a built environment's performance. Companies will be able to eliminate personal phone extensions and simply log their employee's cell phone into their systems. The cost of comfort, communication and Internet access will be distributed at the individual level. It can be predicted that office spaces will shrink to space for occasional conferences and physical archives. Homes will also provide virtual office and meeting spaces. The size of physical libraries of books and references will be reduced drastically, and portable PCs and wall-mounted, Internet-ready Plasma PC/TVs will provide telecommuting access for most office jobs. In all these cases, API will provide a systematic approach to incorporate a built environment's performance level into other systems.

8.4 Recommendations for Future Research

It is recommended that further study is needed to investigate the possibility of a non-linear relationship between parameters (cost, user needs, simplicity, degree of integration and level of service and maintenance availability) in the numerical method. It is also prudent to further investigate and verify the linear or polynomial correlation between the number of control points and the above key parameters.

Other methods of estimating the weight factors in lieu of using the ranking of the key parameters should be investigated.

All building systems claiming to be open for integration are not truly open, and some interface equipment is needed. A correction factor defined to adjust for the degree of a system's openness for integration may also be developed.

The responses to surveys for this project recommended the use of information, such as time required for training to measure 'Simplicity' and the number of complaints to quantify 'User Needs'. An investigation into the accuracy of linear correlation between the number of control points 'P' and the number of complaints and learning time is recommended for future study.

It is recommended to do an Investigation of the robustness of the linear model and determine its strength and weaknesses to predict the building automation's performance in different phases of the project and make provisions to incorporate the time element.

The API model presented in this research may be used for educating the clients and the designers in order to overcome the natural biases that currently exist against systems integration.

The utility method required the development of utility value curves for the client. A sample set of utility curves were plotted. It is recommended that the trends for such utility curves should be analyzed based on the client categories such as: owner, tenant, public, designer, etc. With established utility values based on client type, it is possible to generalize the utility method for client type rather than an individual.

The fuzzy logic was developed for linguistic analysis of API. This technique has promising potential. Future research may be dedicated to develop fuzzy sets for the significant parameters.

"When you are finished changing, you are finished" *Benjamin Franklyn*

APPENDIX A

Building Automation System Components

Introduction

This appendix provides definition of some of the most common terminology for Building Automation Systems. It also provides a basic understanding of the building control systems.

Building Systems: In a simple BAS, a set of packaged instructions (programs) are released (communicated) in time by a computer (controller) to initiate activities (functions) that modify positions or settings of elements, such as valves, window shades or dampers (controlled device), in order to increase or decrease the measured (sensed) value of a controlled parameter such as lighting or temperature around a desired level (set-point). Systems in the buildings traditionally categorized as mechanical and electrical may be included in BAS schemes. Heating, ventilation and air conditioning (HVAC), lighting, security, operable fenestration/shading, plumbing and life safety systems are in this category. Building power, vertical transportation, escalators, conveyors, trash compactors and irrigation systems traditionally are not included in BAS and are excluded from this study, however, the concepts that will be presented may be expanded to all systems.

HVAC Systems: M/E equipment producing and/or just distributing cooling, heating and fresh air to satisfy occupants and equipment requirements in the building are its HVAC systems. Chillers, boilers, air handling units, fans, pumps along with heat exchangers, ducting, room terminal units, diffusers, piping, valves and dampers are a few of the components of these systems.

Plumbing Systems: Water, sewer, storm, gas and waste (sanitary) system are collectively part of this system. Equipment that maintain minimum water and gas pressures as well as control water PH level also fall under this category of systems in the building.

Life Safety Systems: Fire and smoke detection and protection systems in the building along with automatic zone isolation shutters and dampers and water sprinkler or dry chemical fire suppression system are part of this system n the mechanical side. Emergency generator system, exit lighting, as well as stairwell pressurization and fire alarm and annunciation, are the electrical portions.

Security Systems: This consists of building access controls and surveillance cameras as well as occupancy detection systems. A part of the security system which is capable of monitoring the location of building occupants without specific or explicit information about them is what is considered useful for integration and coordination of the HVAC and life safety services by BAS.

Fenestration/Shading Systems: Electrically operable windows, doors, skylights and associated shading devices fall in this category. These items on one hand may be tied to building security and on the other hand to lighting and day-lighting schemes.

Lighting Systems: Both interior and exterior lighting as well as exit and signage lighting is part of this system. Lighting is responsible for 40-60% of the building's total energy and coordination of lighting operation with BAS has the potential benefits in avoiding wasteful energy. Lighting controls may include switching and dimming technologies as well as controls to take advantage of day-light autonomy.

Control Systems: Three basic elements are present is every control system (Haines 1977). A person turning a heater on-off to get the room more comfortable is an example for a simple control system: 1) Sensor (person's sense of comfort in our example), 2) Controller (the person), 3) Controlled device (heater).

At occupied and unoccupied hours of the building in each calendar day different behaviors are expected from the different systems. A time-sensitive and logical approach is required to operate the M/E devices and components. These systems require sequences of operation defined based on the user, equipment and space needs at various calendar times. The technology that governs the behavior of the components of building M/E systems is called the building control system.

A typical control system consists of computer hardware, software, relays, sensors, switches as well as actuators. Control systems have traditionally been driven by pneumatic, electric or electronic powered switches and actuators. A version of electronic controls called direct digital system (DDS) using microchip technology has emerged as the dominant choice in the in the last 20 years due to low cost of manufacturing and minimal size and ease of replacement and relative accuracy of the performance. DDS has helped the control technology to work through communication networks similar to computer network systems and with the added benefits of real time information and remote monitoring and functionality through the internet, web based control systems are becoming popular too. Large building HVAC, plumbing, life safety, security and lighting systems may have many subsystems and each subsystem may have its own hierarchical controls.

Basic Controls: This study will not declare the conventional control systems as the only form of BAS. The detailed theories of building controls are not studied either; however, it is important to understand some basic principles and definitions that may be used in the control centered automation systems. These systems happen to dominate the BAS practice in the building industry. Such understanding will help identify compatibilities in type and operational behavior of many vital components and their basic setup before attempts are made to compare such systems.

Open and Closed Loop Control Systems: An example of a closed loop or feedback control is a thermostat maintaining a room temperature by turning the heater on and off to satisfy its set-point (Figure A.1). An example of open loop controls is a room thermostat turning the heater on and off based on outside temperature. Closed loop system in Block Diagram is shown below. This diagram depicts one single control point with a single analog input and a single analog output.

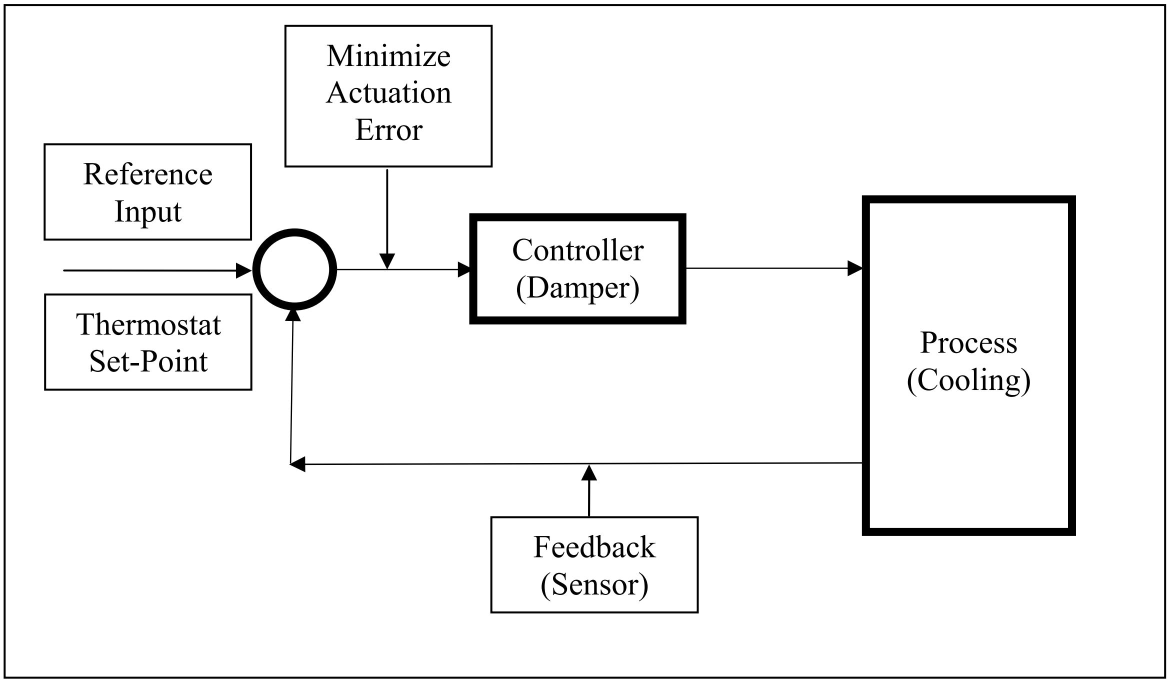


Figure A.1 Closed Loop Control Diagram (ASHRAE 2005)

Controlled devices are usually valves in case of fluid and steam control, or damper for air and gas. Dampers and Valves may be designed to have a variety of flow characteristics. Their operational performance for different positions are available in tabular or graph form. Further information on “Fundamentals of Controls” may be obtained from Chapter 15 of ASHRAE Manual of Fundamentals (ASHRAE 2005).

BAS and Control Networks: Central monitoring and control of HVAC systems are traditionally termed Building Automation System, however, combination (integration) of one, two or more of the other building systems noted above may also be called BAS. There may be restriction by some local or national building and life safety codes on combining fire protection, monitoring and alarm systems with other building systems.

A communication network will connect different components of a BAS system together. Knowledge of status of one system may be required to operate another.

Open and Closed BAS Communication Systems: An open system will allow integration between various control components (CABA 2002). The term "open" is used for BAS systems that utilize a common communication protocol and can integrate multiple manufacturer control components. The BAS systems that have proprietary communication protocols and are limited to selected compatible products are called "closed" systems. Through the uses of some interfaces or "middleware" (CABA 2002), such as BACnet (ASHRAE 2005) and LonWorks it is possible to create open systems using traditional closed system components. SOAP/XML/Web based protocols are fast becoming the communication venue of choice for BAS networks. Several projects have been successfully tested by Lawrence Berkley Lab and completed by private companies were presented at an XML Symposium in 2004 (Tiller 2004). IP enabled will make all systems act the same. Network Security and Reliability and Homeland Security aspects:

> The United States Federal Communications Commission (FCC) has quietly been taking additional steps to help industry protect the nation's communications infrastructure from terrorist threats and natural disasters. Through the Network Reliability and Interoperability Council (NRIC), the FCC has been overseeing a thorough analysis of Telecom and Datacom vulnerabilities, potential threats, and gaps in best practices that affect prevention and restoration of service outages. In 2003, the work of various NRIC committees has produced more than 200 best practice

recommendations for service providers, network operators, and equipment suppliers to implement in order to fortify U.S. critical communications infrastructure (Andover 2003).

Control/Monitoring Points and Digital/Analog Input/Outputs: In a control loop, like a thermostat turning a heater on and off, the room temperature may be referred as a controlled point. The status of the heater can be defined as a monitoring point. If a control function has only two possible choices for input or output, such as the status of the heater (on-off), that signal is called binary or digital. However, if the there is a continuous range of possible choices, such as room temperature, the signal is called analog. Reference is simply made to each basic controlled or monitoring point as Point (P). P may have one or more analog or digital inputs and one or more analog or digital outputs. The quantity of points P in a system is an indication of its scope. The larger the number, the more interfaces, processors and action devices are required. It is possible to calculate a rough order of magnitude estimate of the entire control system cost and even estimate its maintenance budget based on the number of Ps.

An accurate estimate of the quantity of control points P is important for the design of the control system and estimation of its cost as well as for calculation of API discussed in this study. Control points are usually listed on design drawings in a table that lists the control and monitoring functions with digital or analog input or outputs. If the table is not available, a survey of the system should provide information about the sequences of controls for the M/E systems to estimate the number of control points P.

Elements of a Direct Digital Control System: Electronic control systems using binary digital systems are today the most popular methods of building controls (McGowan 2001). In the following some terminology commonly used in Direct Digital Controls (DDC) are presented.

Control Points (P): The word 'points' is used to describe data storage locations within a DDC system. Data can come from sensors or from software calculations and logic. Data can also be sent to controlled devices or software calculations and logic. Each data storage location has a unique means of identification or addressing. Direct digital controls (DDC) data can be classified three different ways - by data type, data flow and data source.

Data Type: Data type is classified as digital, analog or accumulating. Digital data may also be called discrete data or binary data. The value of the data is either 0 or 1 and usually represents the state or status of a set of contacts. Analog data are numeric, decimal numbers and typically have varying electrical inputs that are a function of temperature, relative humidity, pressure or some other common HVAC sensed variable. Accumulating data are also numeric, decimal numbers, where the resulting sum is stored. This type of data is sometimes called pulse input.

Data Flow: Data flow refers to whether the data are going into or out of the DDC component/logic. Input points describe data used as input information and output points describe data that are output information.

Data Source: Points can be classified as external points if the data are received from an external device or sent to an external device. External points are sometimes referred to as hardware points. External points may be digital, analog or accumulating and they may be input or output points. Internal points represent data that are created by the logic of the control software. These points may be digital, analog or accumulating. Other terms used to describe these points are virtual points, numeric points, data points and software points.

Global or in-direct points are terms used to describe data that are transmitted on the network for use by other controllers. These points may also be digital, analog or accumulating. Analog input points typically imply an external point and represent a value that varies over time. Typical analog inputs for HVAC applications are temperature, pressure, relative humidity, carbon dioxide and airflow measurements. Typical analog outputs include control signals for modulating valve positions, damper positions and variable frequency drive speed.

Typical digital inputs for HVAC applications represent the status (example: whether or not the motor is running) of fans, pumps, motors, lighting contactors, etc. A temperature high limit is considered a digital input because, although it is monitoring an analog value (temperature), the information that is transmitted to the controller is a digital condition (whether or not the temperature has exceeded a defined value). Digital outputs are typically motors or other devices that are commanded "on" or "off." Digital outputs include fans, pumps, two-position (solenoid) valves, lighting contactors, etc. A "true" analog output (voltage or current) is a varying DC voltage or milliamp signal that is used to drive a transducer or controlled device. Another type of analog output is pulse width modulation (PWM). PWM is accomplished by monitoring a timed closure of a set of contacts. The amount of time the contacts are closed is proportional to a level of performance for the controlled device.

Software Characteristics: There are basically three common approaches used to program the logic of DDC systems. They are line programming, template or menu-based programming and graphical or block programming. Line programming-based systems use Basic or FORTRAN-like languages with HVAC subroutines. A familiarity with computer programming is helpful in understanding and writing logic for HVAC applications. Menu-driven, database or template/tabular programming involves the use of templates for common HVAC logical functions. These templates contain the detailed parameters necessary for the functioning of each logical program block. Data flow (how one block is connected to another or where its data comes from) is programmed in each template. Graphical or block programming is an extension of tabular programming in that graphical representations of the individual function blocks are depicted using graphical symbols connected by data flow lines. The process is depicted with symbols as on electrical schematics and pneumatic control diagrams. Graphical diagrams are created and the detailed data are entered in background menus or screens.

Architecture: System architecture is the term used to describe the overall local area network or LAN structure, where the operator interfaces connect to the system and how one may remotely communicate to the system. It is the map or layout of the system. The network or LAN is the medium that connects multiple intelligent devices. It allows these devices to communicate, share information, display and print information, as well as store data. The most basic task of the system architecture is to connect the DDC controllers so that information can be shared between them.

Controller: A control loop requires a sensor to measure the process variable, control logic to process data, as well as calculate an instruction, and a controlled device to execute the instruction. A controller is defined as a device that has inputs (sensors), outputs (controllable devices) and the ability to execute control logic (software).

LAN Communication: Communications between devices on a network can be characterized as peer-to-peer or polling. On a peer-to-peer LAN, each device can share information with any other device on the LAN without going through a communications manager. The controllers on the peer-to-peer LAN may be primary controllers, secondary controllers or they may be a mix of both types of controllers. The type of controllers that use the peer-to-peer LAN vary between manufacturers. These controller types are defined later in this section. In a polling controller LAN, the individual controllers can not pass information directly to each other. Instead, data flows from one controller to the interface and then from the interface to the other controller. The interface device manages communication between the polling LAN controllers and the higher levels in the system architecture. It may also supplement the capability of polling LAN controllers by providing the following functions: clock functions; buffer for trend data, alarms, messages; and higher order software support. Many systems combine the communications of a peer-to-peer network with a polling network. The interface communicates in a peer-to-peer fashion with the devices on the peer-to-peer LAN. The polling LAN-based devices can receive data from the peer-to-peer devices, but the data must flow through the interface.

Controller Classification: Controllers can be categorized by their capabilities and their methods of communicating (controller-to-controller). In general, there are two classifications of controller - primary control units and secondary control units:

Primary controllers typically have the following features:

- Real-time accurate clock function
- Full software compliment
- Larger total point capacity
- Support for global strategies
- Buffer for alarms/messages/trend & runtime data
- Freeform programming
- Downloadable database
- Higher analog/digital converter resolution
- Built-in communication interface for PC connection.

Secondary controllers typically have the following features:

- Not necessarily 100% standalone
- Limited software compliment
- Smaller total point count
- Freeform or application specific software

- Typically lower analog-to-digital converter resolution
- Trend data not typically stored at this level
- Typical application is terminal equipment or small central station equipment.

Operator Interfaces: The next critical element in the system architecture is an operator interface. Operator interfaces are required to: See data; Program the system; Exercise manual control; Store long-term data; and Provide a dynamic graphical interface.

There are five basic types of operator interfaces. They include:

1. Desktop computers which act as operator workstations
2. Notebook computers which act as portable operator workstations
3. Keypad type liquid crystal displays
4. Handheld consoles/ palmtops/ service tools
5. Smart thermostats

Desktop computers are centralized operator workstations where the main function is programming, building and visualizing system graphics; long term data collection; and alarm and message filtering. Notebook computers may connect to the LAN through a communication interface that stands alone or is built into another device. The notebook computer connected to the LAN at a particular level may not have the same capability as a computer connected to the LAN at a higher level. Keypad liquid crystal displays typically are limited to point monitoring and control. They may have some limited programming capability, such as changing a set point or time schedule. Handheld consoles, palmtops and service tools are proprietary devices that connect to primary controllers or secondary controllers. Typically they allow point monitoring and control, controller configurations (addressing and communication set-up), and calibration of inputs and outputs. Smart thermostats are sensors with additional capabilities. They connect to secondary controllers and have a service mode to allow for point monitoring, control and calibration. They also have a user mode that allows point information to be displayed, set-point adjustment and an override mode.

PC/Network Interface: The communications interface provides the path between devices that do not use the same communications protocol. This includes computers, modems and printers. It may be a stand-alone component or it may be built into another device. Each communications interface may: Translate protocol; Provide a communication buffer; and Provide temporary memory storage for information being passed between the network and the external PC, modem or printer (mailbox function)

Larger System Architectures: When systems become larger than the capacity of a single sub-network, a higher level of architecture is added to allow the use of multiple sub-networks. The site LAN wide area network or WAN is used to connect multiple sub-networks and site computers. Multiple sub-networks can be connected to a single site LAN/WAN that allows information sharing between devices on different sub-networks. There may be a limitation on the number of site computers. The site LAN/WAN may include routers if TCP/IP is used. If no routers are used, the protocol can be totally proprietary. If TCP/IP is used, the EMS site LAN/WAN can be the information system backbone within the facility or between facilities. Multiple site computers can be added to the site LAN/WAN. They can connect the site LAN/WAN via a communications interface, which may be a router. Site LAN/WAN computers can send and receive information from the entire system. Information can be received by each of the site computers, but can not be subsequently shared from one computer to another. Sub-network computers may only be able to see their own sub-network. Site LANs allow multiple computers to communicate with each other. They may use commercially available computer network software and hardware. Messages, alarms and other data can be re-routed to other computers on the primary site LAN. Information stored in other computers can be remotely accessed. This includes graphics, programming and stored trend and operational data.

Combined Components: Some vendors combine multiple functions into a single device. In some system architecture, the communication interface is built into the primary controller. A peer-to-peer LAN or sub-network is connected directly to the device. The key component in the system consists of a communication interface, a primary controller and an interface to the secondary polling network. The addition of a site LAN allows a system to gain size in terms of the number of devices that are served, but in some applications, the location of the devices, rather than the number of devices, is the bigger challenge.

Auto-Answer/Auto-Dial System Architecture: In auto-answer/auto dial systems, a specialized communication interface is substituted which introduces a modem and phone lines into the standard architecture. These communication interfaces are made with built-in modems or use external commercial modems. Auto-answer/auto-dial configurations are used to provide monitoring and access to remote buildings. They are used where traditional direct-wiring methods are impractical; and where central site monitoring is desired; or where remote access to controllers is desired. In an auto-answer/auto-dial system, the central communications interface may call the individual sites or vice versa. Information and data can be passed to and from the layer above the central communications interface. The auto-answer/auto-dial LAN architecture is typically used by installations with multiple facilities where control and monitoring needs to be centralized. Multiple LANs are used to maintain the groupings of devices, or to separate controllers into defined groups.

Multiple Dial LAN Support: In a system's architecture, the local sites have the ability to call an alternate communication interface, if the primary is not available.

One-Way Dial System Architecture: One-way dial systems are typically used to enable system owners to access their systems from a remote location, such as their home. It is used where auto-dial monitoring is not required. It can also be used by the installation and service company or by the commissioning authority to troubleshoot and program from remote locations. One-way dial can also be used to dial into remote site LANs or sub-networks. Two modems are required, one located at the remote computer and one at the system site. Typically, the DDC operating software must be installed on the remote computer.

Communication: Communication between two different devices controlling equipment, requires a common protocol, a common communication speed and known data formatting. Vendors build their devices around these criteria, so communication between devices by the same manufacturer is routine.

Third Party Interfaces: In many installations, it is desirable for a proprietary building DDC system to communicate with other proprietary DDC systems controlling pieces of equipment. Examples would include a building DDC system and a chiller DDC system or a fume hood DDC system. Communication between the two systems will require an interface or gateway, due to different proprietary protocols, communication speeds and data formatting. The gateway or interface translates protocol between the two proprietary systems. The proper operation of the gateway is dependent on the continued use of the specific revised levels of software on both systems. It typically requires the support of the manufacturer at the corporate level to implement and cooperation between the manufacturers. In addition, the costs can vary widely.

Protocols: In the DDC world, there are the three classifications of protocols: closed protocol, open protocol and standard protocol. A closed protocol is a proprietary protocol used by a specific equipment manufacturer. An open protocol system uses a protocol available to anyone, but not published by a standards organization. A standard protocol system uses a protocol available to anyone. It is created by a standards organization.

Open Systems: An open system is defined as a system that allows components from different manufacturers to co-exist on the same network. These components would not need a gateway to communicate with one another and would not require a manufacturer specific workstation to visualize data. This would allow more than one vendor's product to meet a specific application requirement. The sole use of an open or standard protocol does not guarantee that a DDC system will be an open system. A manufacturer has the ability to use open or standard protocols, yet create a closed system, thus continuing a building owner's dependence on a single manufacturer. This can be accomplished by using unique communication speeds, unique data formatting and by not adopting the full range of an open protocol.

BACNET: BACNET is a standard protocol published by a standards organization (American Society of Heating, Refrigerating and Air-conditioning Engineers or ASHRAE). It is a specification for a protocol. DDC vendors create a communication protocol that complies with this specification. BACNET is a relatively complex standard. The standard defines protocol implementation conformance statements (PICS) that define different levels of compliance. A given vendor may or may not support the level required for a given application. In other words, a vendor could meet a very low level of compliance and be BACNET-compatible. The key question is, "At what level?" The chiller control unit's DDC will communicate with the building DDC system if each has a BACNET gateway and their PICS match.

Native BACNET: If a vendor states their product is native BACNET, they are using the BACNET protocol in lieu of a proprietary protocol on their LAN. A native BACNET building system would be able to communicate to the chiller control DDC with one less gateway.

Overlay Systems: An overlay system is a high-end workstation that communicates with multiple manufacturers' proprietary EMS systems. An overlay system supplier creates drivers to "talk" to the different systems. The vendors must have a cooperative relationship and revision control is important for continued successful use. The workstation typically displays data, allows manual control and setpoint changes, and handles alarms and messaging. Any detailed editing of the control sequence will still require knowledge of the underlying proprietary software.

LON: The Echelon Corporation has created an open protocol that uses a standard processor and a set of standard transceivers, which allows components from different manufacturers to co-exist on the same LAN. The protocol is available to anyone and is called LONTALK. A unique chip is required for any device that uses LON. Standard network variable formats have been established to allow the transfer of data from one device to another regardless of origin. Presently, various vendors are competing to become the defacto standard for the network database structure. The network database is a map of the components and the relationship of the data moving between them. The operator workstation needs this structure to visualize the data. Software suppliers providing the software for the operator workstation may be independent of those providing the software for the database structure and the EMS vendors.

APPENDIX B

Overview of Delphi Technique

This section provides a detailed discussion of Delphi methodologies. The discussion will begin with an overview on the validity of group judgment over individual judgments, and the underlying theories behind this concept. Common group techniques will then be reviewed, including the Delphi method, which is discussed in further detail, as it is the methodology used in this research. Finally, this section will end with a summary of the issues involved with implementing the Delphi methodology.

The source articles and publications used for this discussion were identified through a review of existing literature. The first step of the literature survey included a search of several databases, including *EBSCOHost* and *ProQuest*. Preliminary results identified the peer-reviewed journal, *Technological Forecasting and Social Change* as the major source of Delphi publications. Most of the related articles were then identified through this journal. In addition, citations from these articles were used to find additional articles related to this subject.

Group vs. Individual Judgments

Before beginning a discussion of the concept of group judgment, it is important to make a clear distinction between the term *Judgment,* and two other states of awareness, *Knowledge* and *Guess*. Sniezek and Henry (1989) define these three concepts based on differing levels of certainty. In this view, a Judgment task can be defined as the association of "some level of uncertainty" with the "accuracy of response," as opposed to a Knowledge task, which is a result of "prefect certainty" about the "accuracy of response," or a Guess, which is basically a response with "no certainty."

Use of groups to make decisions and judgments has been an essential part of the modern era. Juries, councils, committees, task forces, and boards are all based on the widespread belief that N+1 heads are better than one (Hill 1982). The underlying assumption is that the combination of individuals in a group setting brings different perspectives together, and provides a larger knowledge source for decision-making and, therefore, can produce more-accurate judgments and better solutions. This assumption is so strong that it has been at the foundation of all decision-making systems of modern society.

However, it wasn't until the second half of the twentieth century that this assumption was tested based on scientific methodologies. Since the late 1940s and 1950s, numerous studies have focused on comparing the true performance of groups and individuals, in regard to decision-making tasks. The results have not been surprising. A number of studies provide evidence that committees or groups have an advantage over individual judgments in a variety of domains (Nisbett and Ross 1980; Hill 1982; Rowe, Wright et al. 1991). Studies also showed that even a simple aggregation of individual judgments is more accurate than the judgment of a random individual (Woudenberg 1991).

The superior ability of groups over individuals in accurate decision-making can be explained based on the "theory of errors" (Dalkey 1975). According to this theory, the median response of a group will always be at least as close to the true answer as one-half of the individuals in the group (Figure B.1a). In addition, if the group response range includes the true answer, the median group response will be more accurate than more than half of the group (Figure B.1b). As shown in the Figures, in both cases, there is always a group member whose response will be nearest to the true answer than the group mean. Empirical findings have confirmed this matter, showing the group performance to be inferior to the performance of the best individual (Davis 1969; Hill 1982). However, it should be noted that groups are virtually always used in situations where no prior knowledge of the true answer exists. In such cases, identification of the best individual whose response is the closest to the true answer is impossible. And therefore, the group response becomes more accurate.

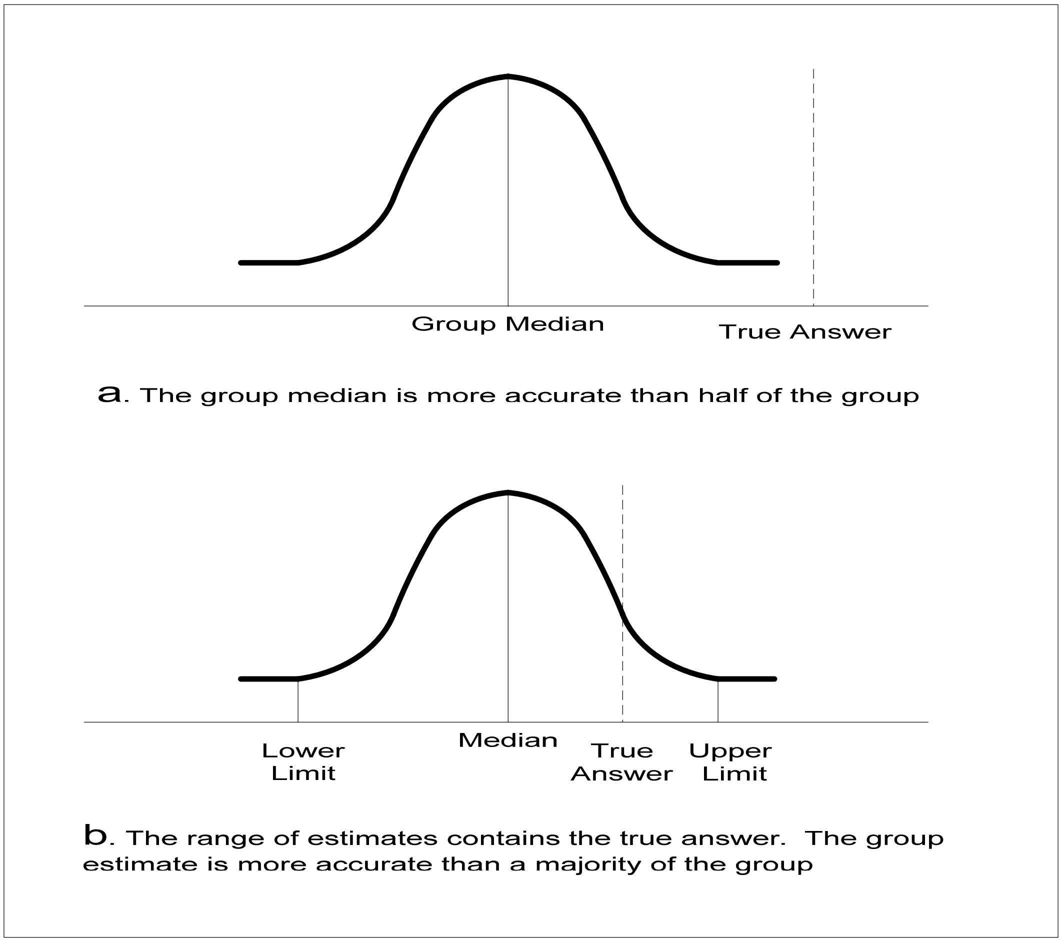


Figure B.1 'Theory of Errors' in Explaining Superiority of Groups Response over Individuals (Dalkey 1975)

Group Techniques

Staticized Groups

The simplest form of obtaining a group judgment is through use of *Staticized Groups* (Rowe, Wright et al. 1991). This method is basically a polling technique, in which the opinions of a group of individuals are gathered separately, and then summarized, based on common statistical methods, to form the group decision. Members of a staticized group are usually selected randomly to form a statistical sample of the target population. Due to their simplicity and convenience of use, staticized groups have been very popular, and they have been employed in a number of domains. Opinion surveys, or any other kind of survey, in general, are suitable examples of staticized groups. Though studies have shown that staticized groups can produce better results over individuals, use of this group technique has been largely criticized. The main reason for this criticism is that, based on their nature, staticized groups don't provide an opportunity for interaction among individuals. At the same time, a great body of research shows that interaction among a set of individuals has some usefulness, and can produce better results in the construction of subjective judgments (Armstrong 1978).

Interacting Groups

Interacting Groups are the most-common group technique. In this method, individuals are brought together to form a refined opinion after deliberate discussions (Rowe, Wright et al. 1991). Studies have shown that judgments from interacting groups are more accurate than a statistically aggregated judgment (Woudenberg 1991). This can be explained based on the increased knowledge sources available to each group member, which equals at least the sum of information available to any particular individual within that set (Rowe, Wright et al. 1991). In addition, it has been argued that being part of a group can have other advantages that will result in better performance, such as increased commitment of individuals, assistance in resolving ambiguous and conflicting knowledge, and facilitation of creativity (Lock 1987).

However, interacting groups are not without pitfalls. Lock (1987) summarizes the downsides of the group process into three categories:

1. Groupthink: This is the result of group members' access to the same knowledge base; groupthink emerges as a restriction on the range of ideas generated by a group. Groupthink can also be a result of individual's desires to conform to group norms.
2. Inhibition of contributions: This is caused by differences in the status of individuals. Most individuals are not willing to put forward ideas that are contrary to the ideas that have already been expressed in the group. It also may be caused by the presence of one dominant individual in the group.
3. Premature Closure: This results from the tendency to adopt the first alternative, which is satisfactory to all group members, rather than reaching the best alternative.

These and other additional factors, such as an individual group member's desire to "win" or avoid changing a position once they've taken it in front of the group, causes interacting groups to not perform up to their optimal level and potential (Rowe, Wright et al. 1991).

As a result, several other alternatives to interacting groups have been proposed. These alternatives attempt to reduce or totally eliminate the shortcomings of interacting groups, by changing the unstructured interaction among group members to a more structured process of feedback. In the following section, two main structured techniques (Nominal Group Techniques (NGT) and Delphi) are discussed.

Nominal Group Technique (NGT)

The *Nominal Group Technique* (NGT) is the most widely known structured group technique that provides direct interaction among individuals (Woudenberg 1991). NGT was developed by Andre L Delbecq and Andrew H. Van de Ven in 1968, as a result of their social-psychological studies in a number of different fields, including industrial engineering, and studies of NASA program design problems and of citizen participation in program-planning (Van_De_Ven and Delbecq 1974; Delbecq, Van_De_Ven et al. 1975).

A NGT study starts with individuals seated around a table writing down ideas related to a problem on a pad paper. Each individual then presents one of the ideas to the group. Ideas are recorded and discussion does not start until all of the ideas are presented. After all ideas are presented, the group begins to discuss them one-by-one. After the discussion, each individual writes down his/her own evaluation of the ideas separately. The final stage is to aggregate all the individual evaluations to come up with a group decision. NGT attempts to eliminate some of the negative aspects of interacting groups by separating out the processes of independent idea generation, structured feedback, and evaluation and aggregation of opinions (Lock 1987).

Delphi Technique

Delphi Technique is a structured process which utilizes a series of questionnaires or rounds to gather and to provide information (Keeney, Hassan et al. 2001). A Delphi can be seen as a virtual group meeting, which aims to make use of the positive aspects of interacting groups, while removing the negative aspects largely attributed to the social difficulties within such groups (Rowe, Wright et al. 1991; Okoli and Pawlowski 2004).

History

Delphi Technique was developed by Dalkey and Kaplan and their associates at the RAND Corporation (Van_De_Ven and Delbecq 1974). Kaplan headed a research effort directed at improving the use of expert predictions in policy-making (Dalkey 1968). He found that unstructured, direct interaction did not provide more accurate predictions than aggregation of individual predictions (Kaplan, A. et al. 1949; Woudenberg 1991). They associated this low performance with the negative aspects of face-to-face meetings and developed Delphi as a way to reduce these negative aspects. Kaplan coined the name "Delphi" after the site of the ancient Greek oracle at Delphi where necromancers foretold the future (Dalkey 1968; Gordon 1994).

Methodology

Dalkey and Helmer (1963) describe Delphi as a procedure to *"obtain the most reliable consensus of opinion of a group of experts… by a series of intensive questionnaires interspersed with controlled opinion feedback."* In a Delphi study, the participants are asked individually, through a questionnaire, to provide their estimates for a variable in question. Then, the feedbacks are collected and summarized in a way to conceal the origin of original estimates. The results are then circulated, and participants are asked if they wish to refine their previous answers based on the summary results. This iteration process continues until estimates stabilize (Lock 1987). A Delphi study has three major characteristics: anonymity; iteration with controlled feedback; and statistical aggregation (Dickey and Watts 1978):

1. Anonymity: In a Delphi study, the identity of respondents stays concealed throughout all the rounds. This anonymity and isolation helps to largely

eliminate most of the social pressures to conform that arise in interacting groups, such as domination of a single individual, or avoiding change of a position once one is made (Van_De_Ven and Delbecq 1974).

2. Iteration with Controlled Feedback: This takes place between different rounds, and allows members to review and change their response in light of additional information and opinions provided by other group members (Rowe and Wright 1999).
3. Statistical Aggregation: In the final stage of a Delphi study, the group response is obtained through statistical aggregation of the final individual responses. Statistical techniques may also be used to provide the level of consensus strength (Rowe and Wright 1999).

Theory

Like other group techniques, the underlying mechanics of Delphi can be explained based on the "theory of errors," which was described earlier in this chapter. In addition, Dalkey (1975) hypothesized that a Delphi will have a superior performance to unstructured group techniques as a result of the iteration process. According to Dalkey, the iteration and feedback built into the Delphi process, provides an opportunity for the less-knowledgeable panelists (whom he called "swingers") to move towards more-accurate panelists (known as "hold outs") and, therefore, results in a more-accurate response for the whole group (Figure B.2). This is based on the assumption that experts on a subject are less likely to change their response during the iteration and feedback process than people who have less knowledge on the subject. Some empirical evidence has supported this assumption. For example, Rowe and Wright (1996) found that the most-accurate Delphi panelists in the first rounds changed their estimates less frequently over rounds than those who were initially less accurate.

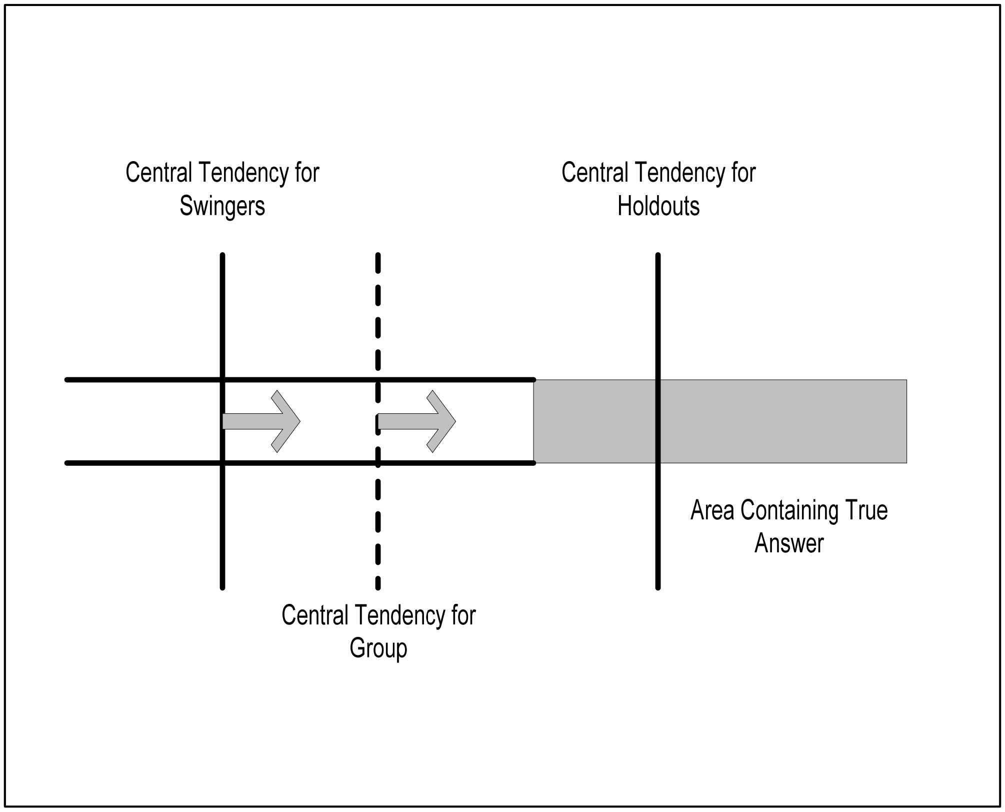


Figure B.2 Shift of Average Group Response during Iteration and Feedback Process (Dalkey 1975)

Delphi and Inquiry Systems

Inquiry systems (IS) are philosophical systems, which underlie different methods used for analyzing a phenomenon (Lock 1987). According to Mitroff and Turoff (1975), an inquiry process is compromised of four major steps. First, an individual is faced with some assumed "external event" or "raw data set" which is considered to be a characteristic property of the "real world." Second, this individual transforms or filters this "raw data" into the "right form," so it can be inputted into a model. Next, the model transforms the "input data" to "output information." Finally, this "output information" can be passed to another filter, so it can be used by the "decision-maker." Mitroff and Turoff describe five main inquiry systems, which can be used as the philosophical basis for the Delphi technique:

- Lockean IS: This states that truth is *experimental*. Based on this inquiry system, the truth of a model is measured in terms of its ability to: 1) Reduce every complex proposition down to its simplest referents; and, 2) Ensure the validity of simple referents, by means of widespread, freely obtained agreements between different observers.
- Leibnizian IS: Truth is *analytic*. Based on this IS, the truth of a model is measured in terms of: 1) Its ability to offer a theoretical explanation of a wide range of general phenomena; and, 2) Our ability to state clearly the formal conditions under which the model holds.
- Kantian IS: This has a *synthetic* view of the truth. In other words, in a Kantian IS, truth has both empirical and theoretical natures. Truth of a model is measured in terms of the model's ability to: 1) Associate every theoretical term of the model with some empirical referent; and, 2) Show how underlying every empirical observation is a theoretical referent.
- Hegelian IS: Truth is *conflictual*. In other words, truth of is a result of a complicated process, which depends on the existence of a plan and a counter plan.
- Singerian IS: Truth is *pragmatic*. Truth of a system is relative to the overall goals and objectives of the inquiry, and is measured with respect to its ability

to: 1) Define certain objectives; 2) Propose several alternative means for securing these objectives; and, 3) Specify new goals to be accomplished by some future inquiry.

Delphi is a classic example of Lockean IS, since its main purpose is to get consensus from expert judgments (Mitroff and Turoff 1975; Parente and Anderson-Parente 1987). However, Mitroff and Turoff argue that some applications of Delphi are based on a different inquiry basis. For example, policy Delphis, which function as a result of causing experts to debate on mostly unstructured issues, can be best described from a Hegelian viewpoint. Or in problems, in which the purpose is to elicit different alternatives, a Kantian Delphi can be more appropriate than pure Lockean or Leibnizian approaches (Mitroff and Turoff 1975).

As a result, we can conclude that, for a researcher who is intending to perform a study, knowledge of the inquiry base used in the method is very important, because it defines the merits and boundaries of the studies, and can help identify the limitations of the technique.

Applications

The first application of Delphi was used in 1948 to improve the betting scores at horse races (Woudenberg 1991). However, the first major application of this method did not occur until the 1950s, when it was used on a U.S. Air Force-sponsored project. The goal of the project was to gather expert opinions on the selection of an optimal U.S. industrial target system, from the point-of-view of a Soviet strategic planner (Rowe and Wright 1999). Application of Delphi during the 1950s was, however, limited to the army-sponsored projects in the Rand Corporation. Use of the Delphi technique became popularized in the 1960s, after it was first described in a published article in 1963 (Gupta and Clarke 1996).

Since its development, one of the major applications of the Delphi has been in technological forecasting. Today, it is estimated that 90% of all technological forecasts studies are based on Delphi (Yuxiang, Donguha et al. 1990). In addition to forecasting, Delphi has been used extensively for other applications, such as policy formation and decision-making (Rowe and Wright 1999). Currently, Delphi is applied to a number of different problems, such as project evaluation, short- and long-range forecasting, science and technology planning, policy formulation, energy generation, urban analysis, bank automation, risk management, market research, curriculum development, and others. (Gupta and Clarke 1996). Delphi studies are used in various areas, such as education, business, health care, information systems, engineering and transportation (Rowe and Wright 1999). Interest in Delphi has grown from non-profit organizations and government, as well as industry and academia (Linstone and Turoff 1975).

In the construction industry, Delphi has been applied to a number of professional and academic problems including: development of residential areas (Anatharajan and Anataraman 1982); bridge condition rating and effects of improvements (Saito and Sinha 1991); construction process quality (Arditi and Gunaydin 1999); procurement selection (Chan, Yung et al. 2001); project risk management (Cano and Cruz 2002); identifying factors affecting international construction (Gunhan and Arditi 2005); and determining the standard of care for structural engineers (Kardon, Bea et al. 2005).

Delphi Critique

Despite its extensive use in both industry and academia, application of Delphi technique has not been without criticism. The first major criticism of the Delphi technique was proposed by Sackman (1974). Referring to a number of studies that were conducted based on the Delphi method, Sackman strongly criticized the use of Delphi to obtain any scientific results. In response, several authors questioned Sackman's findings. Linstone (1978) argued that most of Sackman's criticism is pointed toward poor executions of Delphi, rather than the method itself, and he had ignored significant supportive evidence. Coates (1975) argued that the criteria in evaluating a Delphi is not so much that it is *right*, but that it is *useful*: "*If one believes that the Delphi technique is of value not in the search for public knowledge, but in the search for public wisdom, not in the search for individual data, but in the search for deliberative judgment, one can only conclude that Sackman missed the point.*" Furthermore, Mitroff and Turoff (1975) noted that much of the accusation that the Delphi technique is nonscientific, arises from the misconception in equating what is "scientific" to what is "Leibnizian."

In recent years, as a result of growing application of Delphi, especially in the scientific field, a number of studies have been performed on the validity of this technique. Following is a summary of the Delphi method's major shortcomings, as cited in these studies:

- Accuracy: Accuracy of a Delphi study can be expressed in terms of the correspondence between the obtained group judgment and the true value (Woudenberg 1991). Since most of Delphi studies are on unknown issues, such as forecasting an event in the far future, accuracy of Delphi studies is hard to measure. Strauss and Ziegler (1975) argue that the claim that Delphi represents valid expert opinion is scientifically untenable and overstated. In response, Goodman (1987) argues that, if the panel members in the study are representative of a group or area of knowledge, then content validity can be assumed. In addition, there have been studies that show the result of Delphi have been accurate in terms of forecasting (Ono and Wedemeyer 1994). A study by Rowe et al (2004) shows that the accuracy of judgmental probability forecasts increases over Delphi rounds.

- Reliability: Reliability is defined as the certainty with which an instrument produces the same results over time (Woudenberg 1991). The Delphi technique has been heavily criticized as having no evidence of reliability; meaning, there is no guarantee that the same results will be obtained if the same Delphi study is repeated with another panel (Keeney, Hassan et al. 2001).
- Anonymity: Another criticism of Delphi has been the issue of anonymity. It has been argued that complete anonymity may lead to lack of accountability, and will encourage ill-considered judgments (Goodman 1987). It has also been argued that anonymity of Delphi will hinder the positive effects of unstructured group interactions, such as flexibility and richness of non-verbal communication (Woudenberg 1991). In addition, Dijk (1990) claims that this anonymity prevents a meaningful discussion.
- Consensus: Consensus resulting from a Delphi study has also been a subject of criticism. Keeney notes that the existence of consensus from a Delphi process does not mean that the correct answer has been found (Keeney, Hassan et al. 2001). Also, the Delphi technique has been criticized as a method which forces

consensus (Goodman 1987). Some study findings suggest that the consensus gained over several rounds may be a result of panelists simply altering their estimates, in order to conform to the group without actually changing their opinion (Woudenberg 1991; Rowe and Wright 1999). Empirical evidence supports this argument by showing that a majority opinion exerts a strong pull on minority opinion, even when the majority favors an incorrect answer (Rowe, Wright et al. 2004). It is also argued that social pressures, such as the impact of a dominant individual, are still felt even though they are not as immediate and threatening as in an unstructured group (Rowe, Wright et al. 1991).

In considering the varying criticism of the Delphi method, it should be emphasized that it is a technique of "last resort," to be used when no adequate models exist upon which some statistical predictions or judgment might be based (Coates 1975). Although criticism of the Delphi method have been countered by studies in the favor of the technique, consideration of its criticism is useful in recognizing this method's shortcomings as a valid research methodology and in recognizing opportunities for improvement. Therefore, the "Delphi Method" has largely escaped examination (Rowe, Wright et al. 1991). Delphi is not a procedure intended to challenge statistical or model-based procedures, against which human judgment is generally shown to be inferior; rather, it is intended to be used in judgment and forecasting situations in which pure, model-based statistical methods are not practical or possible. This is due to a lack of appropriate data, and, thus, some form of human judgment input is necessary (Rowe and Wright 1999). The Delphi method is especially effective in difficult areas that can benefit from subjective judgments on a collective basis, but for which there may be no definitive answer (Lindeman 1975). As Rowe et al. (1991) conclude, Delphi is a valuable technique in judgment-aiding, but improvements are needed.

Delphi vs. Nominal Group Techniques

Delphi and NGT are both well-known structural techniques, and each has their own characteristics. The prime difference between them goes back to the level of anonymity, specifically at the feedback stage. NGT provides an opportunity for direct communication among participants at the feedback stage. Although this direct communication has been cited as an advantage of NGT over Delphi, it also gives NGT the normal drawbacks cited for interactive groups (Lock 1987).

A number of studies have made an attempt to compare the results of Delphi and NGT group techniques. Most of these studies have compared these two methods on three main dimensions: accuracy of the technique; quantity of the ideas generated; and participant satisfaction.

The results of studies that have compared the accuracy of Delphi and NGT have not been consistent. Gustafson et al. (1973) and Miner (1979) found NGT to be more accurate than Delphi. On the other hand, Fischer (1981) Boje and Murnigham (1982) found the two techniques to be equally accurate. In addition, another study (Erffmeyer and Lane 1984), found Delphi results to have a higher quality (in terms of comparison of rankings to “correct rank”).

As for the quantity of ideas, Van De Ven and Delbecq (1974), found NGT to produce more ideas than Delphi. At the same time, a study by Hill (1982) showed that NGT and the Delphi procedure did not differ in quantity of unique ideas.

In terms of satisfaction of the participants, studies by Van de Ven and Delbecq (1974) and Hill (1982) showed a higher satisfaction among participants of NGT than Delphi. First study explained the lower satisfaction with Delphi process as a result of the lack of social-emotional rewards in the problem-solving process and unresolved conflicting or incomplete ideas. But at the same time, a more recent study (Hornsby, Smith et al. 1994) showed participants in a Delphi study to have higher satisfaction with the process than NGT.

As discussed, the results of comparisons between these two techniques have been very different. This disparity can be explained based on the fact that each study has used a different evaluation method, and each study has used a different variation of Delphi, which may account for these discrepancies.

Based on these contrasting findings, it is difficult to draw a conclusion as to which method is superior. Selection of a method can then be based purely on the specific research requirements (i.e. geographical, time, cost, etc.) and the qualitative differences of these two methods. Table B.1 summarizes these qualitative differences based on Van De Ven and Delbecq (1974).

Based on these differences, Delphi is selected as the appropriate knowledge gathering technique for this study. This technique is chosen due to its ability to provide an environment of discussion among a panel of experts and gain a level of consensus among them, while minimizing the difficulties involved with face-to-face meetings such as the limited amount of time and availability of experts and geographical considerations. Delphi also helps to remove the negative impacts of the face-to-face meetings and keep the independency of individuals in analyzing the situation.

Table B.1 Qualitative Differences between Delphi and Nominal Group Technique (Van De Ven and Delbecq 1974)

Dimension	Nominal Groups	Delphi Technique
Overall Methodology	Structured face-to-face group meeting Low flexibility Low variability in behavior of groups	Structured series of questionnaires & feedback reports Low variability respondent behavior
Role of orientation of groups	Balanced focus on social maintenance and task role	Task-instrumental focus
Relative quantity of ideas	Higher: independent writing & hitch-hiking round-robin	High: isolated writing of ideas
Search Behavior	Proactive search Extended problem focus High task centeredness New social & task knowledge	Proactive search Controlled problem focus High task centeredness New task knowledge
Normative Behavior	Tolerance for non-conformity through independent search and choice activity	Freedom not to conform through isolated anonymity
Equality of participants	Member equality in search & Choice phases	Respondent equality in pooling of independent judgment
Method of problem solving	Problem-centered Confrontation and problem solving	Problem-centered Majority rule of pooled independent judgments
Closure decision process	Lower lack of closure High felt accomplishment	Low lack of closure Medium felt accomplishment
Resources utilized	Medium administrative time, cost, preparation High participant time and cost	High administrative
Time to obtain group ideas	1.5 hours	5 calendar months

Delphi Execution

Despite the extended use of the Delphi method over the past four decades, a standard procedure for implementation still does not exist. Delphi studies differ from each other in many ways, and the number of variations of Delphi is almost as many as the number of the Delphi studies that have been conducted. In this section, a more detailed discussion of the important elements of a Delphi procedure is provided. The goal is to find a more scientific base for implementation of this technique, based on a comprehensive review of the literature relating to this topic.

Unstructured vs. Structured Delphi

In conventional Delphis, the first round is always unstructured, meaning that the participants are allowed to identify and elaborate on those issues they consider as important (Rowe and Wright 1999). However, some recent applications of Delphi have used structured first rounds, in which an inventory is provided to save time and make the process simpler for the monitor and panelists. This information is established by interviewing key experts (Woudenberg 1991). This is specially useful in an industrial context, in which the experts are technical specialists who may not be aware of all the dynamics of an issue (Parente and Anderson-Parente 1987).

However, it has been argued that use of a structured first round in a Delphi study will prevent involvement of experts in expressing their beliefs as to what may be important in relation to the issues of interest. Therefore, this may deny the construction of coherent scenarios for assessment (Rowe, Wright et al. 1991). Also, Keeney et al. (Keeney, Hassan et al. 2001) argue that providing information in the first round may introduce some bias in the panelists' judgment.

Number of Rounds

One of the main differences between variations of Delphi implementation has been in the number of the rounds (Rowe et al. 1991). The original Delphis used by the Rand Corporation consisted of four rounds (Keeney, Hassan et al. 2001). However, different Delphi studies have been implemented from as low as 2 to as many as 10 rounds (Woudenberg 1991).

Selecting the number of rounds in a Delphi study is an important issue, as studies have shown that the accuracy of judgmental probability forecasts increases over Delphi rounds (Rowe, Wright et al. 2004). It has been stated that most of the change in panelists' responses occurs after one or two iterations (Rowe and Wright 1999), and consensus is almost always maximized after the second estimation round (Woudenberg 1991). Results from the Erffmeyer et al. (1984) study showed that the quality of responses increased up to fourth round, but not thereafter.

By the same token, the issue of time is also of considerable importance, as there is a higher tendency for participants to drop out during later rounds (McKenna 1994). Implementation of three Delphi rounds can take anywhere from three to four months (Gordon 1994). As a result, it seems the best outcome of the Delphi will be achieved with three or four rounds, in order to maximize the accuracy of results and minimize participation drop-outs.

Size of Expert Panel

There is little agreement about the ideal size of the expert panel in a Delphi study (Keeney, Hassan et al. 2001). Most studies have used between 15 and 35 panelists (Gordon 1994). Parente and Anderson-Parente (1987) suggested a minimum number of

10 panelists after drop-out. Okoli and Pawlowski (2004) suggested that Delphi group size does not depend on statistical power, but rather on group dynamics for arriving at consensus among experts.

Rowe et al. (1991) proposed that a Delphi can be interpreted as a two-stage process. The focus of the first stage is to limit the bias of individuals through structured interaction, while the second stage is aimed at obtaining a group opinion by using statistical methods. They argue that, as the second stage of a Delphi study is similar to a statistical group, factors that affect the performance of statistical groups (such as the number of the participants) must play an important role within the Delphi process. The impact of the number of panelists has been considered by Brockhoff (1975) (with groups of 5, 7, 9, and 11) and Boje and Murnighan (1982) (with groups of 3, 7, and 11). None of these studies found a consistent relationship between panel size and effectiveness criteria.

Hogarth (1978) proposed an analytical model which yields group validity as a function of the number of experts, their mean individual validity and the mean correlation among their judgments. Based on this model, he explains that the validity of the group is an increasing function of the number of experts and their mean validity, and a decreasing function of the average inter-correlation among the experts' opinion. Based on this, he concludes that, in the case of expert groups (such as Delphi) where there is some correlation between panelists' judgments, the maximum validity of the group is reached with 8-12 panelists under a wide range of circumstances (in certain conditions the maximum is reached with only 6 panelists). This further reinforces the findings of the Brockhoff and Boje and Murnighan studies. In addition, Ashton (1986) performed an empirical study to evaluate Hogarth's model and his findings, which further confirmed the results of Hogarth's model.

Expert Selection

Unlike statistical group techniques, a Delphi study is not based on a random sample which is a statistical representative of the target population (Keeney, Hassan et al. 2001). In contrast, Delphi is aimed at obtaining a judgment/forecast from a panel of experts. Studies have shown expertise of members does have an impact on performance within interacting groups (Bonner and Baumann 2002). Therefore, the selection of panel experts is central to the success of the Delphi method (Robinson 1991). However, this topic has been one of the most neglected aspects in Delphi studies (Okoli and Pawlowski 2004).

An expert panel has been defined as: a group of "informed individuals" (McKenna 1994) who can be "specialists" in their field (Goodman 1987), have knowledge about a specific subject (Davidson, Merritt-Gray et al. 1997; Lemmer 1998; Green, Jones et al. 1999) or are recognized by others in the field (Harman and Press 1975). At the same time, literature has warned about the drawbacks of illusory expertise (Goodman 1987), and it has been stated that simply having knowledge of a particular topic does not necessarily mean that someone is an expert (Keeney, Hassan et al. 2001). Based on this, one of the main problems of Delphi studies has been the issue of lack of criteria for distinguishing experts from laymen (Gupta and Clarke 1996).

Dalkey (1969) showed that self-rated experts provide more accurate estimates than self-rated non-experts. Based on this a number of studies used self-rating as a basis for the expert identification. At the same time, the result of a study performed by

Larreche and Moinpur (1983) showed that, although self-rated confidence does appear to discriminate between experts and non-experts, experts identified in this fashion are not likely to provide significantly better estimates than the average of the group's initial judgments, or than non-experts. Rowe et al. (2004) support this view by showing that confidence is not a suitable predictor of expertise.

Another technique suggested for identifying experts is the use of external measures (Rowe, Wright et al. 1991). A study by Larreche and Moinpur (1983) showed that use of a simple external measure of expertise appeared to provide significantly better estimates than non-experts identified by the same measure. Based on this, and based on guidelines provided by Delbecq et al. (1975), Okoli and Pawlowski (2004) suggested a five-step procedure for selecting the experts. This process is shown in Figure B.3 in which KRNW = Knowledge Resource Nomination Worksheet.

Finally, the issue of expert backgrounds will be discussed. According to Rowe et al. (1991), a key aspect of the selection process is choosing "*experts from varied backgrounds to guarantee a wise base of knowledge.*" Selection of a heterogeneous sample for the Delphi has been mentioned in many studies (Keeney, Hassan et al. 2001). This view is also supported by Hogarth's Model (described in the previous section), which shows that group validity has a negative relation with the mean inter-correlation of expert judgments (Hogarth 1978).

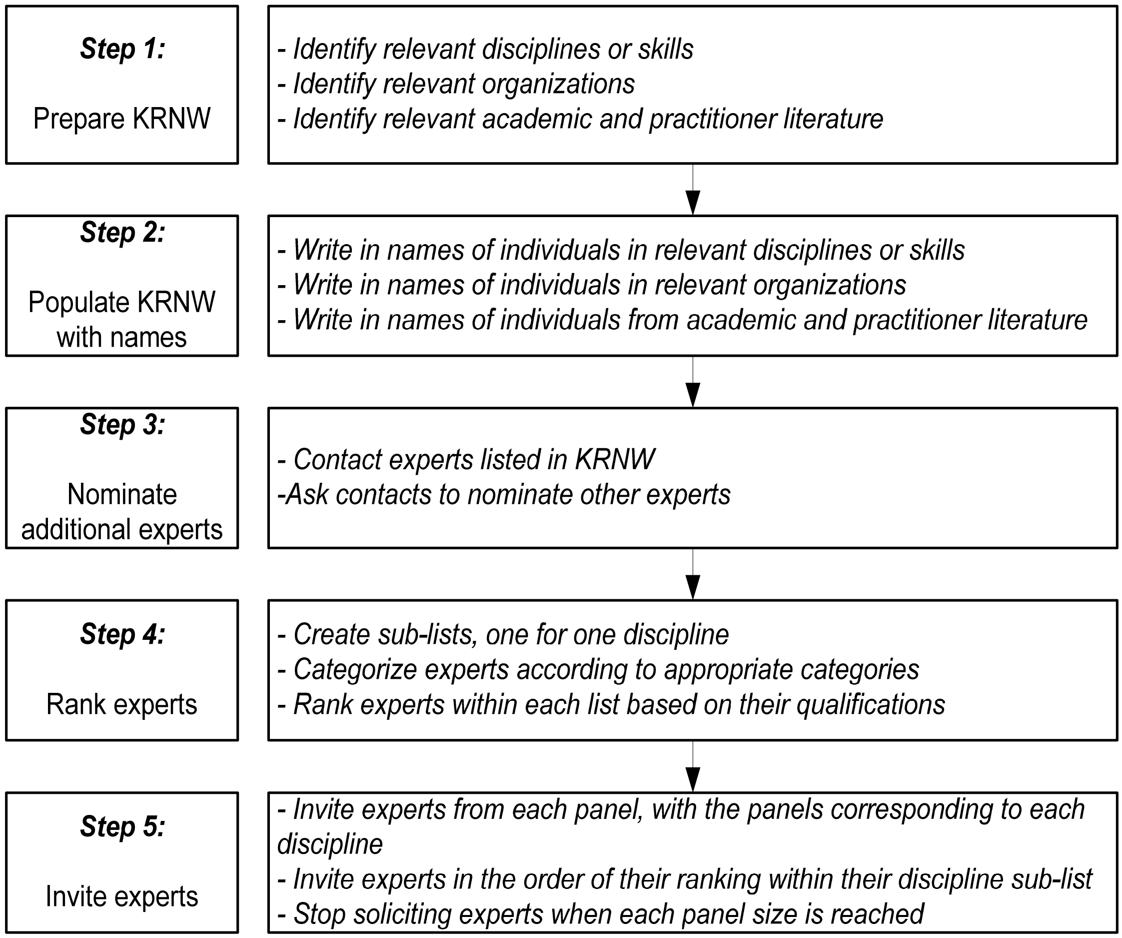


Figure B.3 Five-Step Procedure for Selection of Experts (Okoli and Pawlowski 2004)

Questions

One of the criticisms of Delphi studies has been in use of crudely designed questionnaires (Gupta and Clarke 1996). The process of writing responses to the questions forces respondents to think through the complexity of the problem, and to submit high-quality ideas (Van_De_Ven and Delbecq 1974). Therefore, an effort should be made to describe the potential event so that all respondents interpret it in exactly the same way (Salancik, Wenger et al. 1971). Several studies have given general guidelines for designing Delphi questionnaires (Robinson 1991; Gordon 1994; Okoli and Pawlowski 2004).

Salancik et al (1971) performed a study to determine the appropriate number of the words in event statements. The results of the study showed a curvilinear relationship between the amount of information one receives from respondents, and the number of the words used to describe them events Based on this, authors suggest that for the best response, wording of the questions should be between 20 to 25 words.

Feedback

Generally, it is assumed that a Delphi study provides richer data because of multiple iterations and response revisions due to feedback (Okoli and Pawlowski 2004; Rowe, Wright et al. 2004)

Studies performed by Parente et al. (1984) and Boje and Murnighan (1982) suggest the main influence leading to improved accuracy of the Delphi studies is iteration, not feedback. At the same time, Rowe and Wright (1996) argued that the feedback used in these studies has been somewhat superficial, and more informative feedback is likely to be more influential. Furthermore, in their study, Rowe and Wright (1996) compared three feedback conditions of “iteration,” “statistical” and “reasons” feedback. They found that, although subjects were less likely to change their forecasts as a result of receiving “reasons” feedback, when they did change their forecasts, this change tended to be for the better, leading to a reduction in error. This results support the findings of the Best study (1974), which showed that a Delphi group that was given “reason” feedback, in addition to median and range of estimates, was more accurate than a Delphi group that was provided with feedback that excluded reasons.

As a result, it can be concluded that Delphi works partially because of the iteration, which allows participants to reflect on their previous answers, and partially because of the feedback (Rowe, Wright et al. 2004). Additionally, in order to take advantage of the benefits of the iteration process in the Delphi study, one must make sure that the feedback is informative and provides a wide range of information, including statistical results, in addition to all the reasons participants provided for their responses.

Aggregation

The last step in a Delphi study is the aggregation of the individual response in the final round of the Delphi, in order to obtain the group judgment/forecast. To accomplish this, statistical aggregation methods, such as the mean or median of response, are employed (Larreche and Moinpur 1983; Gordon 1994).

Use of mean and median gives an equal weight to all the individuals involved in the study. An alternative to this method has been proposed in the form of using differential weights in aggregating the answers. One of the major difficulties with using differential weights is requiring prior knowledge of accuracy of responses (Lock 1987). Dalkey (1975) has suggested the use of self-ratings as a source for weights. In addition, De Groot (1974) considered processes of revision of individual judgments, in light of others' judgment. At the same time, several studies have argued that equal weighting avoids arguments about relative weighting and performs remarkably well, compared with differential weighting (Winkler and Makridakis 1983; Ashton and Ashton 1985). Overall, they conclude, "*if all the judges have positive validity and reasonably similar variability, then equal weighting will work well.*"

In concluding this section, we should mention another statistical measure that has been widely used in Delphi studies. This statistical measure is Kendall's W coefficient of concordance (Siegel and Catellan 1988). Kendall is a measure that determines the relation between several rankings of N objects or individuals. This measure is widely recognized as the best metric for measuring non-parametric rankings (Okoli and Pawlowski 2004). This metric has been used in Delphi studies as an indicator of strength of agreement among panel experts on results. The value of a Kendall's Coefficient W value ranges from 0 to 1, with 1 indicating complete 'inter-rater' agreement, and 0 indicating complete disagreement among experts.

APPENDIX C

BAS at a Crossroads

Introduction

This article was written by Shariar Makarechi and published at the *Consulting Specifying Engineer* on May 1, 2004 (Makarechi 2004). The article was the first step in the research process for dissertation on modeling the building automation system performance. It provides an overview of the state of the building automation industry in 2004, two years prior to the completion of the current dissertation.

Can our cell phones, cars and homes show us where we should taking building control?

BY SHARIAR MAKARECHI, PhD Student, with GODFRIED AUGENBROE, Professor, Georgia Institute of Technology, Atlanta

Depending on one's affinity for technology, an ideal habitat might be described as follows: the needs of occupants, and the processes in it, are monitored, assessed and evaluated continuously. Decisions for maintaining the most desirable environment for this habitat are made on a holistic and global approach where numerous possible actions and responses are quickly factored before the best choice is made. All aspects of comfort, cost, security, life safety, maintenance and environmental impact are optimized at every moment. The habitat's capabilities and its needs are matched well by an open communication of the information between all its members. The systems monitoring and controlling this habit are not closed and are supervised and updated by a dynamic world of resources available outside of it to maintain, diagnose, correct software and provide instructions for its repair, maintenance and improvement.

Sounds like the abstract some TV executive pitched in the '60s for the Jetson's or maybe Star Trek, right? While it certainly sounds futuristic, such habitats exist in the cars we drive, and in some cases, the homes we live. *New York Times* technology writer Paul Boutin recently wrote on this subject describing a computer-controlled microwave/refrigerator that allows its owner to pop a chicken in the machine before going to bed. The device automatically chills the bird overnight, warms it to room temperature the next afternoon, then calls the would-be chicken consumer's cell phone with a text message querying if it should begin. Obviously, homes or cars are but a child to the greater habitat of most commercial/institutional/industrial buildings. But what needs to happen today so we can enjoy the same level of performance found in new cars and homes in our offices and factories as well?

Driving forces toward change

Of course, we must acknowledge there is a major difference between buildings and cars, as the latter is just a small subset of habitats. Second, we need to identify what causes the gap between applied technologies in these two habitats. Cost, complexity, size, life span, mobility and diversity in function are just a few differences. These issues can explain the time lag of technology implementation to buildings at the same level as in the automobile industry. At the same time, it is this researcher's opinion that the automobile industry has been the laboratory for developing, testing and implementing technology that will eventually revolutionize building automation technology.

But before going there, a brief examination of the state of building automation industry is necessary. Commercially used building automation systems (BAS) today can offer electronic control systems that integrate a variety of building systems such as HVAC, lighting, security, fire alarm and process controls into a central control system. These controls are predominantly designed to react to feedback from the controlled environment.

A recent study by Mark J. Stunder for the Air-conditioning and Refrigeration Technology Institute provides a suitable summary of the state of the industry: "As building owners strive to reduce operating costs while avoiding occupant complaints, they are likely to increasingly utilize BAS to save energy and to increase occupant comfort. While investment in smart-building technology has been increasing, the science or art of using real-time information in adaptive building management systems is in a relatively immature state."

Automated building systems, he goes on to say, traditionally, have utilized either no local sensors or only a limited number of such sensors. But in our continuing effort to design interactive control systems, we should pay attention to the need for local intelligence and not mere connection. An effort to make all controlled components talk to each other or to a central processor, will not provide the reliability and performance expectations of building owners. Current electronic controls are capable of performing a reasonable default task if the interconnection lines are interrupted for any reason. But additional intelligence can be built in by assigning a "signature" for each parameter, device and element so figuratively, when devices or systems shake hands for whatever reason, the BAS will be able to identify all the needs, capabilities and limitations involved.

Granted, local sensors require routine maintenance, however, this information can be gathered by other means, such as the Internet, resulting in considerable cost savings and efficiencies. Furthermore, the cost of adding a control point for a BAS system is less than $30 per point compared to $500 per point in 1980 and these prices are dropping. The total cost of operation and maintenance of building systems including their environmental impacts on the other hand are increasing and so is the desire to reduce these costs. Regulating agencies and construction code authorities are increasingly enforcing stricter energy efficiencies and environmental policies. These forces, coupled with the availability of low cost communication systems and access to real-time information via the Internet, have created a fertile ground for building industries to move toward integrated and global approach for operational optimizations. (see figure-Auto Blgs.com)

Such an approach might be dubbed "predictive feed forward control using real-time global optimization (GOS)." Part of this solution involves the application of building simulation tools to real-time information. A body of documented practice and research by Zulfi Cumali of CCB/Cumali Assocs., San Francisco, addresses the use of simulation tools and techniques in an integrated and global setting where real-time decision making for control strategy of system components can be applied in a proactive and predictive way. Actual commitments to such systems, however, are currently limited to research, educational and industrial applications.

But the technology is available. Again quoting Stunder: "Internet technology has now progressed to the point where it can be a source of real-time information for predictive purposes in managing buildings. Proactively managing and operating building systems in accordance with actual or anticipated conditions should increase space comfort while reducing operating costs."

Interactive connectivity of all control components coupled with the processing power of a simulation engine as an optimization tool can provide a smoother control strategy that will also reduce the cost of utilities as well as maintenance.

And high level analytical research has been done toward application of simulation assisted dynamic building strategies (Mahdavi, 1997) and integration of control and building performance by open or communicating protocols (Azzedine Yahiaoui, 2003). There are now validated knowledge-based algorithms for thermal load predictions using real-time weather forecasts (Tse, 2003). Faster simulation models are also emerging that eliminate unnecessary calculations by efficiently merging computational fluid dynamics with building simulation techniques. For example, via the communicating objects method physical components of buildings, such as walls and spaces, are modeled as computational objects that individually solve the appropriate physical equations and exchange changes of surface values, such as temperature, when necessary. Because the object structure is derived directly from the building structure, and because generic objects are reused, simulators can be generated with very low effort. Based on object-oriented modeling and automatic code generation, new physical effects can be easily integrated. This method is fast because calculations are only generated by changes. Fast and accurate responses to external events can also be accomplished. Both features are necessary for real-time tests of BAS definition of object structure (Zimmermann, 2001).

What the BAS industry is up to?

So where are we at? As the basis for this study, we conducted a survey of existing scientific research in computer-assisted modeling and interviewed or researched the offerings of some of the major control manufacturers.

Meetings with the industry representatives (Makarechi, Crockett et al. 2002) confirmed that commercial and residential construction industry has not yet taken advantage of technology with feed-forward real-time GOS concepts. Some isolated basic tasks, such as morning warm-up cycle, have been developed with built-in intelligence to learn from its historical start time, as well as the building's response to optimize start up times. Most manufacturers now offer wireless thermostats and controllers. Almost all manufacturers are offering some Internet-based real-time data gathering.

Johnson Controls (JCI) and Trane are involved in developing their products for further networking and web accessibility. Trane, specifically, offers building and HVAC system simulation tools with limited capabilities (Trace 700, System Analyzer) that can accept real-time weather data. Trane has also started using PDA-based diagnosis devices with success. For this company, fan energy in building HVAC systems is the dominant load and Trane has focused on low temperature air distribution to reduce fan sizes.

JCI, last year, introduced its web-based services. The company has already installed a predictive HVAC and lighting control system at John F. Kennedy Airport in New York that receives information from flight data system management and prepares the appropriate gates for passengers before they arrive while simultaneously informing the janitorial crew request for service accordingly.

Other interesting JCI developments include the use of a wireless Blue Tooth-capable control system that is used for integrated controls in the automotive industry; JCI has also done work with security systems where a proximity card-access system can power up lighting and HVAC system for individual workstations.

Carrier is now offering a web-user interface to its own network for monitoring and control of systems over the Internet ss thermostats and receiver controllers for both commercial and residential (visit http://ccnweb.homeip.net/demo/waterLoop. htm). The company also offers wirele lines. Over the last 5-10 years, the company notes the use of Ethernet-based controls, using TCP/IP protocol, has been growing steadily. But one of the most popular control systems it currently offers is a demand-controlled ventilation module that responds to CO_2 sensor feedback and pays for itself in two to three years by optimizing the amount of outside air introduced to the system.

At the *Association of Energy Engineers (*AEE) conference, last fall, Honeywell showcased a PDA based diagnosis tools for its rooftop units. KMC's featured product was a programmable black box with input and output ports designed to collect and process information in a LAN setting. Their flagship "iControl" system provides a host of energy status and monitoring as well as control features.

(Please note the sidebars for links to many other useful links to products and developments).

What's next?

Despite the possibilities, market demand is ultimately what will prompt the major BAS players to push forward with GOS technology. That being said, it is also beneficial to look at our future buildings from human, technological and organizational perspective.

Human perspective: This criteria factors additional comfort, flexibility, active participation and contribution of each individual to the mode and mood of his or her environment. It's not so hard to conceive that everyone will carry their own electronic signature that constantly will be communicated through some wireless system be it a cell phone, pager or what not. This information, of course, can be altered at demand by simply logging into a web page. With this data, a building's GOS can serve people without having to work blindly to meet some pre-determined and rigid set-up.

Technology: Components and services for GOS are already in place. And this is good news because building owners do not necessarily want to spend more than what they are already spending on the BAS systems. In fact, in the near future, some costs may be passed on to individuals similar to personal cell phone accounts. Web-based services will be created to maintain and update personal preferences. Most cell phones currently are capable of web browsing already and every individual's cell phone will also be his or her environmental controller. This requires development of higher speed wireless web access systems by personal PC, PDA and phones for faster response. A PDA can communicate to a person's destination his or her arrival or departure time based on the calendar scheduling functions.

Organizational changes: It may be expected that the cell phone industry will expand to companies that also provide comfort and entertainment services in addition to information and communication. Companies may be able to eliminate personal phone extensions and simply log their employee's cell into their systems. The cost of comfort, communication and Internet access will be distributed on an individual basis. Offices themselves, will shrink to spaces mostly used for occasional conferences and physical archives, as homes can provide virtual office and meeting spaces.

It's a World-Wide-Web World

Research supports the feasibility of real-time global automation systems (Mahdavi, 1997), (Azzedine Yahiaoui, 2003) to achieve optimization, and the industry is rapidly moving toward the convergence of technology and science for building automation with closer to its most desirable operations. Today's easy access to bi-directional web-based solutions, coupled with strong desire to minimize financial and environmental exposures is driving buildings toward implementing the technology that has been evolving in the last 20 years. This technology exists presently and can be made available via the web to all members of a building environment for communicating needs and active contributing to decision-making and operation in real time.

APPENDIX D

Glossary of Acronyms

ACG: American (*Air Balancing Council*) Commissioning Group

AEE: American Energy Engineers

API: Automation Performance Index

ARC: Automated Buildings Advisory Group

ARTI: American Refrigeration Technology Institute

ASHRAE: American Society of Heating Ventilation and Air Conditioning

AV-TV: Audio Visual and TV

BAS: Building Automation System

BFC: Building Futures Council

BIQ: Building Intelligence Quotient

Builconn: Building Connectivity and Control Seminar

CABA: Continental Automated Building Association

CIB: International Council of Research and Innovation in Building and Construction

CLA: Communication Life Safety Automation

CO2: Carbon Dioxide

DOE: Department of Energy

DofA: Degree of Automation

EMCS: Energy Management and Control Systems

eQuest: A Public Domain Detailed Building Energy Simulation Program

GOS: Global Optimization Systems

GSA: General Services Administration

HVAC: Heating Ventilating and Air Conditioning

HTML: Hypertext Markup Language

IBC: International Building Codes

IMC: International Mechanical Codes

IRB: Institutional Research Board

JCI: Johnson Controls Inc.

JFK: John F. Kennedy

KMC: Kreuter controls Manufacturing Company

kW: Kilo Watts, a measure of electrical demand

kWh: Kilo Watt Hours, a measure of electrical energy use

LAN: Local Area Network

LCC: Life Cycle Cost

LEED: Leadership in Environmental Engineering Design

NIBS: National institute of Building Sciences

NTPT: National Target Performance Tool

oBIX: open Building Information Exchange

PC: Personal Computer

PDA: Personal Digital Assistant

PG&E: Pacific gas and Electric Company

Set-Point: The desired setting of a controlled parameter.

TCP/IP: Transmission Control Protocol /Internet Protocol

XML: Extensible Markup Language

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VITA

Shariar Makarechi was born in Shiraz, Iran on August 2, 1953. He now lives in Atlanta with his wife Elahe Hessamfar and daughters Helia and Tara.

Shariar received his BS degree in Mechanical Engineering from Aryameher (Sharif) University of Technology in 1976. He and his family immigrated to United States in 1978 and he completed his MS degree in Operations Research at the George Washington University in 1981. He is currently a PhD candidate at the Georgia Institute of Technology and a full time faculty at Southern Polytechnic State University.

Shariar is a licensed professional engineer with 30 years of engineering design and management practice in Georgia, California, District of Columbia, Maryland and Virginia. He is certified by National Council of Engineering Examiners and American Energy Engineers.

Mr. Makarechi’s professional career started at Carrier Corporation’s turn key design build mechanical and electrical contracting services, Sho’leh Khavar Corporation in Tehran Iran in 1972. In 1979 he joined Shefferman and Bigleson consulting engineering firm in Washington DC as project engineer. He then joined Benbassat and Sporidis as chief engineer for two years before moving to San Francisco to join Bentley Engineering in 1988. In 1992 Mr. Makarechi left his position as Vice president and director of SF office of Bentley and started Makarechi and Co. consulting engineering firm in San Francisco. Shariar and his family moved to Atlanta Georgia in 1994 and he started as a project engineer with Newcomb and Boyd Company and finally left that position to join academia at Georgia Tech in 2003.

Mr. Makarechi is a member of American Society of Heating and Refrigeration Engineers and Sharif University of Technology Association. He has also served as worship leader at Persian Community Church of Atlanta from 1994 to present.

Prior to moving to Atlanta and joining Newcomb & Boyd held positions with several companies over twenty-two year period, throughout the United States as noted above, designing mechanical systems, performing energy analyses, and managing a wide variety of project types and successfully completed projects for the California Energy Commission, Lockheed Missile and Space Company, Apple Computer, Robert Mondavi Winery, the U.S. Department of Veterans Affairs, Tiffany and Company, and the U.S. Army Corps of Engineers.

After joining Newcomb & Boyd in 1994, he was named a Senior Associate of the firm in 2002. His major works included mechanical design and project management responsibilities on numerous project types, including work for both public and private sector clients such as: Sam Nunn Federal Center, Klaus Advanced Computing Building, Bank of America Operations Center mechanical and electrical systems renovations, Battalion Headquarters, Grady Cancer Center of Excellence, IRS Customer Service Center, Emory University Hospital systems, Sixth District Bankruptcy Court design/build package, Moncrief Army Community Hospital recovery room renovations, Special Ops. Hunter Army Air Field, Scientific-Atlanta office complex, Crawford Long Hospital master plan, U.S. Federal Courthouse energy analysis, Lindbergh Center corporate office buildings and parking deck.

The brief list of his recent publications and presentations include: High Performance Building Round Table, sponsored by Johnson Controls and published by

Consulting Specifying Engineers in Jan 2002; Building Automation Systems at the Crossroads published by Consulting Specifying Engineer in May 2004; Dynamic Decision Making Applications for Buildings paper approved for presentation and publication on Feb 8, 2005 at 2005 CIB W92; Global Optimization Systems (GOS) paper presented and publication by the Building Futures Council at Las Vegas, Nevada in March 14-18, 2005.

Mr. Makarechi has taught numerous courses both at Georgia Institute of Technology, and the Southern Polytechnic State University.