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The Hong Kong Polytechnic University
Department of Building and Real Estate

Development of Selection Evaluation and System Intelligence Analytic Models for the Intelligent Building Control Systems

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

With the availability of innumerable ‘intelligent’ building products and the dearth of inclusive evaluation tools, design teams are confronted with the quandary of choosing the apposite building control systems to suit the needs of a particular intelligent building project. The paucity of measures that represent the degree of system intelligence and indicate the desirable goal in intelligent building control systems design further inhibits the consumers from comparing numerous products from the viewpoint of *intelligence*. This thesis is organised respectively to develop models for facilitating the selection evaluation and the system intelligence analysis for the seven predominant building control systems in the intelligent building. To achieve these objectives, systematic research activities are conducted to first develop, test and refine the general conceptual models using consecutive surveys; then, to convert the developed conceptual frameworks to the practical models; and, finally, to evaluate the effectiveness of the practical models by means of expert validations.

The findings of this study, on one hand, suggest that there are different sets of critical selection criteria (CSC) affecting the selection decision of the intelligent building control systems. Service life, and operating and maintenance costs are perceived as two common CSC. The survey results generally reflect that an ‘intelligent’ building control system does not necessarily need to be technologically advanced. Instead, it should be the one that can ensure efficiency and enhance user comfort and cost effectiveness. On the other hand, the findings of the research on system intelligence suggest that each building control system has a distinctive set of intelligence attributes and indicators. The research findings also indicate that operational benefits of the intelligent building exert a considerable degree of influence on the relative importance of intelligence indicators of the building control systems in the models. This research not only presents a systematic and structured approach to evaluate candidate building control systems against the CSC, but it also suggests a benchmark to measure the degree of intelligence of one control system candidate against another.

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CHAPTER 1

INTRODUCTION

"Everywhere, our knowledge is incomplete and problems are waiting to be solved. We address the void in our knowledge and those unresolved problems by asking relevant questions and seeking answers to them. The role of research is to provide a method for obtaining those answers by inquiringly studying the evidence within the parameters of the scientific method."

(Leedy, 1997: 3)

1.1 OVERVIEW

There is little doubt that there has been a widespread implementation of intelligent building technologies in many contemporary building developments, and that this trend has been particularly notable in the Asian region as building developers desire to create product differentiation and to project their 'signature' building image by building highly integrated and intelligent buildings (Wan and Woo, 2004). The desire for an effective and supportive environment within which an organisation can reduce energy consumption, improve worker productivity, and promote maximum profitability for their own business has further stimulated the growth of highly adaptable and responsive buildings (Clements-Croome, 2001a). Consequently, intelligent buildings have been advocated as a building form that helps to promote an environment that maximises the effectiveness of its end-users and facilitates the efficient management of resources (Smith, 2002). Using Hong Kong as an example, an official practice note entitled 'Green and Innovative Building' was issued in 2001 outlining government incentives for environmentally friendly and intelligent buildings (Hong Kong Trade Development

Council, 2004). It facilitates the development of innovative and intelligent buildings by encouraging local industry to utilise their expertise in incorporating advanced technologies in construction.

Recent years have seen a variety of intelligent building control products developed and introduced to the market, designed to enhance building ‘intelligence’ performance and environmental sustainability, and to satisfy a variety of human needs. They are designed to provide environmental control, mobility, communications, facilities, fire protection and security in the intelligent building. Each of the building control systems plays a dominant role in the building as they act as the balance between the building’s contents, the organisations and the services that jointly determine if the value objectives of developers or end-users are accomplished (Clements-Croome, 2001b). They are being designed to enable all the individual systems to interrelate with one another in a natural way, allowing for interaction between the systems and the control of that system (Smith, 2002 and Clements-Croome, 2001a). These control systems have to be able to respond flexibly to changing conditions and user requirements throughout the whole life of the intelligent building. If the systems become unserviceable due to breakdowns, lack of control, misuse, ineffective maintenance, human discomfort and so on, it would affect the business operations, and the end-users may turn to other buildings which are able to fulfil their requirements or offer them more sophisticated services. The costs associated with system maintenance and the potential plunge in revenue arising from a loss of tenants will eventually have an adverse effect on the financial viability of the building (Clements-Croome, 2001a). As a result, the inability to match end-users’ or developers’ expectations may lead to disenchantment, and a serious decline in interest and confidence in the intelligent building (DEGW *et al.*, 1992, and Pati *et al.*, 2006). It is for this reason that a meticulous selection of building control systems is one of the most important decisions if decision makers wish to achieve an efficient and well-performing intelligent building.

A challenge to project design teams is posed by the plethora of intelligent building control products that have been made accessible over the last decade. Project design teams need to choose the optimum amalgamation of technologies and features from the available building control system packages to form an optimum configuration that meets or exceeds the expectations of developers and end-users or the unique requirements of the development projects (EIBG, 2001). The complexities of selection decisions are further exacerbated by the high aggregation of the multi-criteria and multi-dimensional perspectives of building performance, including user friendliness, international standard protocols, business and commercial needs of end-users, ability of multiple systems integration, energy-saving properties, technological advancement, scalability, future proofing, and system flexibility (Wan and Woo, 2004). As a result, design teams need to strike a balance between these considerations and the goals and expectations of the people paying for and/or intending to occupy the building (Aygün, 2000; and Pati, *et al.*, 2006). With such increasing complexities involved in the evaluation and selection of the building control systems for the intelligent buildings, the need for decision-making and selection evaluation tools is recognised. Over the past decade, a number of analytical methods and techniques have been developed that appear relevant, but they pay most attention to the financial aspects of system selection (Wong *et al.*, 2005). Models have focused on the cost performance (i.e. initial or operating and maintenance costs), which is easily quantifiable. Little attention is paid to criteria including human comfort, environmental sustainability, and building flexibility, which are not easily expressed or quantified. As a result, advanced building systems that prioritise cost savings are generally chosen, which probably leads to myopia and a biased selection process.

Existing research lacks a thorough evaluation and investigation into the building control systems selection. A review of intelligent building literature indicates that a substantial body of research has dealt with the categorisation of intelligent buildings to a definite class, in general according to their overall performance (Boyd and Jankovic, 1994; Smith, 2002; and, So and Wong, 2002). Fewer studies have been conducted to understand the factors or criteria of building control system selection in conjunction with the development of a selection evaluation model to ascertain their suitability (Wong and Li, 2006). These knowledge gaps and practical deficiencies have prevented practitioners from selecting the appropriate building control systems. They do not have a comprehensive list of criteria to evaluate building control systems, and also lack a rational and systematic approach to facilitate the selection of appropriate or suitable building control systems. Consequently, this has forced the practitioners to continuously rely on their past experience, gut-feeling, rudimentary judgements, or a combination of them, in justifying the candidate building control systems during the system design and configuration stages. The lack of research into the process of building control systems selection and the resulting inefficiency of an effective selection evaluation approach would possibly lead to an incorrect selection of building control system candidates, which might fail to satisfy the expectations of developers or end-users.

While the problem in building control system selection requires addressing, it is important that the current imbalance towards the evaluation of the system intelligence of the intelligent building control systems also be redressed. With the availability of a myriad of so-called ‘smart’ or ‘intelligent’ building control systems over the last decade, the adjective ‘intelligent’ has been widely adopted to describe the intelligent property of the building control products. However, the perspectives and understandings of ‘intelligence’ are still so abstract and ambiguous that it leads to a concern about the abuse of the term ‘intelligent’ without making any effort to clarify what the ‘intelligent’ building control system should be (Park and Kim, 2002; and Schreiner, 2000). Though the study of machine intelligence has been attempted in other closely related areas, such as in intelligent robots and machines (Bien *et al.*, 2002; and Park and Kim, 2001), there is a paucity of research that has investigated the system intelligence of intelligent building control systems and developed general analytic models. Previous intelligent evaluation models in the intelligent building research are also limited to the assessment of the overall intelligence of the intelligent building, without examining the intelligence of the building control systems inherent in it. In fact, the development of effective formal measures for what is in the ‘intelligent’ building control system or for its performance provides the discipline of building control a more formal definition and classification of what constitutes ‘intelligence’ of the building control systems. The developed intelligent measures can be also used to provide benchmarks for system performance, and to assist users and designers of systems to better understand the benefits of one control system versus another.

With the limitations and deficiencies of the current research in mind, the purpose of this research is twofold. First, it aims to investigate and develop a list of critical selection criteria (CSC) for the key building control systems in the intelligent building. Second, this research attempts to explore and identify the intelligence indicators of these building control systems. In this thesis, the research focuses on seven key building control systems in the commercial intelligent buildings (i.e. offices buildings), and is conducted within the context of intelligent buildings in Hong Kong. Seven building control systems are within the boundary in this research. They include the integrated building management system (IBMS); the telecom and data system (ITS); the addressable fire detection and alarm system (AFA); the heating, ventilation and air-conditioning (HVAC) control system; the digital addressable lighting control system (DALI); the security monitoring and access control system (SEC); and, the smart and energy efficient lift system (LS).

In essence, the understanding of the selection evaluation and intelligence analysis of the building control systems is necessary. This research provides a better tool for understanding the critical selection criteria (CSC). A systematic and structured selection approach can assist the design teams to evaluate candidate systems, with less reliance on a global impression of the system options, which would be subjective and unreliable. This further helps to minimise biased selection decisions. In addition, the development of intelligence measures provides an approach for control system developers to measure the intelligent performance of their products and to exhibit their products' intelligent superiority. This also offers a system where the consumers (for example, the design teams) can compare several building control system candidates from the viewpoint of system intelligence. From the theoretical perspectives, the general selection evaluation and system intelligence analytic models developed in this thesis also provide a good foundation for further research.

1.2 RESEARCH OBJECTIVES

The primary aim of this research is to develop models for the selection evaluation and system intelligence analysis for the seven key building control systems of the commercial intelligent building in Hong Kong. The specific objectives of this research are to perform the following:

(1) To develop general conceptual models that incorporate the critical selection factors and criteria for the optimum building control systems of the intelligent building;

(2) To formulate general theoretical frameworks that incorporate the 'suitable' intelligence attributes and indicators for evaluating and assessing the degree of intelligence of each of the key intelligent building control systems;

(3) To test and refine the general conceptual models developed in (1) and (2) by testing the level of importance of the selection criteria and intelligence indicators;

(4) To develop practical models of building control systems selection evaluation and intelligence performance analysis; and,

(5) To validate and check the robustness of the practical models developed in (4).

1.3 HYPOTHESES OF THE RESEARCH

Research objectives are translated into the following four hypotheses for testing. In general, the first two hypotheses (*H1* and *H2*) are designed to investigate the selection evaluation of the intelligent building control systems, while the latter two hypotheses (*H3* and *H4*) address the issues of the evaluation of the system intelligence of the intelligent building control systems.

H1: *The critical selection criteria (CSC) affecting the selection of each of the building control systems in the intelligent building differs, reflecting their distinctive and unique roles.*

H2: *Each proposed set of critical selection criteria (CSC) exerts a considerable degree of influence on determining respective building control systems.*

H3: *The intelligence attributes of 'autonomy' and 'human-machine interaction' are considered as two common components reflecting the degree of system intelligence of the building control systems, while 'controllability of complicated dynamics' and 'bio-inspired behaviour' are regarded as two specific intelligence attributes, depending on the operational characteristics of the building control systems.*

H4: *The operational benefits of the intelligent building exert a considerable degree of influence on the importance of intelligence indicators in the assessment of the degree of system intelligence of the building control systems.*

The development of hypotheses for this research is discussed in detail in Chapter 5.

1.4 METHODOLOGY OF THE THESIS

The methodology used to fulfil the aims and specific objective of this research is set out in five steps, which are illustrated in Figure 1.1 by means of a flow chart diagram. In general, a review of existing intelligent building literature (Step 1) was first conducted to choose and determine the selection criteria and intelligence indicators, and to set up the general conceptual models for the selection evaluation (Step 2a) and system intelligence analysis (Step 2b) of the seven key building control systems in the intelligent building. These conceptual models were respectively tested and refined by means of two consecutive questionnaire surveys (Step 3a and 3b). Then, the refined conceptual models were transformed into the practical models in order to demonstrate their practicability for selection evaluation (Step 4a) and intelligence performance appraisal (Step 4b). Finally, these practical models were validated by experts (Step 5a and 5b). Details of the methodology of this thesis are summarised as follows:

- **Review of Literature (Step 1)**: The existing intelligent building literature provides a diversified nature and scope of studies that enhances understanding and improves the knowledge of the intelligent building. A critical review of the intelligent building literature was conducted in order to identify the research deficiencies, address the research scope and formulate a set of hypotheses to be examined.

- **Establishment of the Conceptual Models (Step 2a and 2b)**: Two groups of seven general conceptual models were designed, drawing from the literature review. The first group of conceptual models (step 2a) specify the perceived critical selection criteria (CSC) of each of the seven key intelligent building control systems correspondingly. The latter group of conceptual models (step 2b) highlight the proposed attributes and indicators of system intelligence, and specify the interdependent relationships between intelligence attributes and the operational benefits that arise from each of the seven building control systems.

- **Examination and Refinement of the Conceptual Models (Step 3a and 3b)**: To test the general conceptual models, two successive surveys were undertaken for data collection. Surveys are conducted to examine and validate these conceptual models.

This is a common method in many empirical studies. To test the conceptual selection evaluation models (step 3a), a general survey was first undertaken to collect the views of the building professionals regarding their perception of CSC for each of the seven building control systems. Mean scores of each proposed CSC were calculated, and the *t*-test analysis was employed to determine their level of importance. As the intelligent building is a new form of building development which is yet to mature, it was not possible to obtain a large sample size of professionals and experts. A more subjective method, the Analytic Hierarchy Process (AHP), was employed to test the conceptual models. The second questionnaire survey based on the AHP method was used to collect useful opinions of experts, and to evaluate the comparability of the CSC. The mean weights of CSC were computed using the AHP, which helped to prioritise or rank the CSC and distinguish the more important CSC from the less important ones.

Another two surveys were developed to examine seven conceptual intelligence analytic models (step 3b) in Research Part Two. Firstly, a different general questionnaire was used to elicit and identify the ‘suitable’ intelligence indicators. Both mean scores and *t*-test analysis were used to determine the importance level of the intelligence indicators. In the second survey, an approach of combining the AHP and the Analytic Network Process (ANP) was purposely conducted to prioritise the intelligence indicators, and to investigate the influences of interrelationships between the intelligence attributes and the operational benefits of the intelligent building on their relative importance. The results of the two surveys were used to refine the conceptual intelligence analytic models.

- **Development of Applicable Models (Step 4a and 4b)**: The conceptual selection evaluation models and system intelligence analytic models were finalised subsequent to the tests and refinement after Step 3a and 3b. In order to evaluate the feasibility and applicability of the developed conceptual models, two process steps were developed to transform the developed conceptual models from experimental/ theoretical framework formulations to the practical models. These two steps include: (1) the development of rating scales and assessment methods of evaluating each building control system candidate against its relevant CSC as well as the intelligence indicators; and, (2) the establishment of a score aggregation formula to produce one overall score for each of the candidate building control systems. The practicality of the models in both research parts was demonstrated by applying the models to a pair of real building control systems.

- **Model Validation by Experts (Step 5a and 5b)**: Model validation was then conducted to check the robustness of the practical models, to examine whether they could simulate the decision of the experienced intelligent building experts, and to test the reliability of the aggregate scores produced by the models. The validation exercises first required the experts to nominate two alternatives for each of the key building control systems. The models' relative ranking of each pair of building control system alternatives was then compared with the experts' order of preference. Scores of system alternatives given by the model and judged by the experts were further examined in their similarities by correlation analysis.

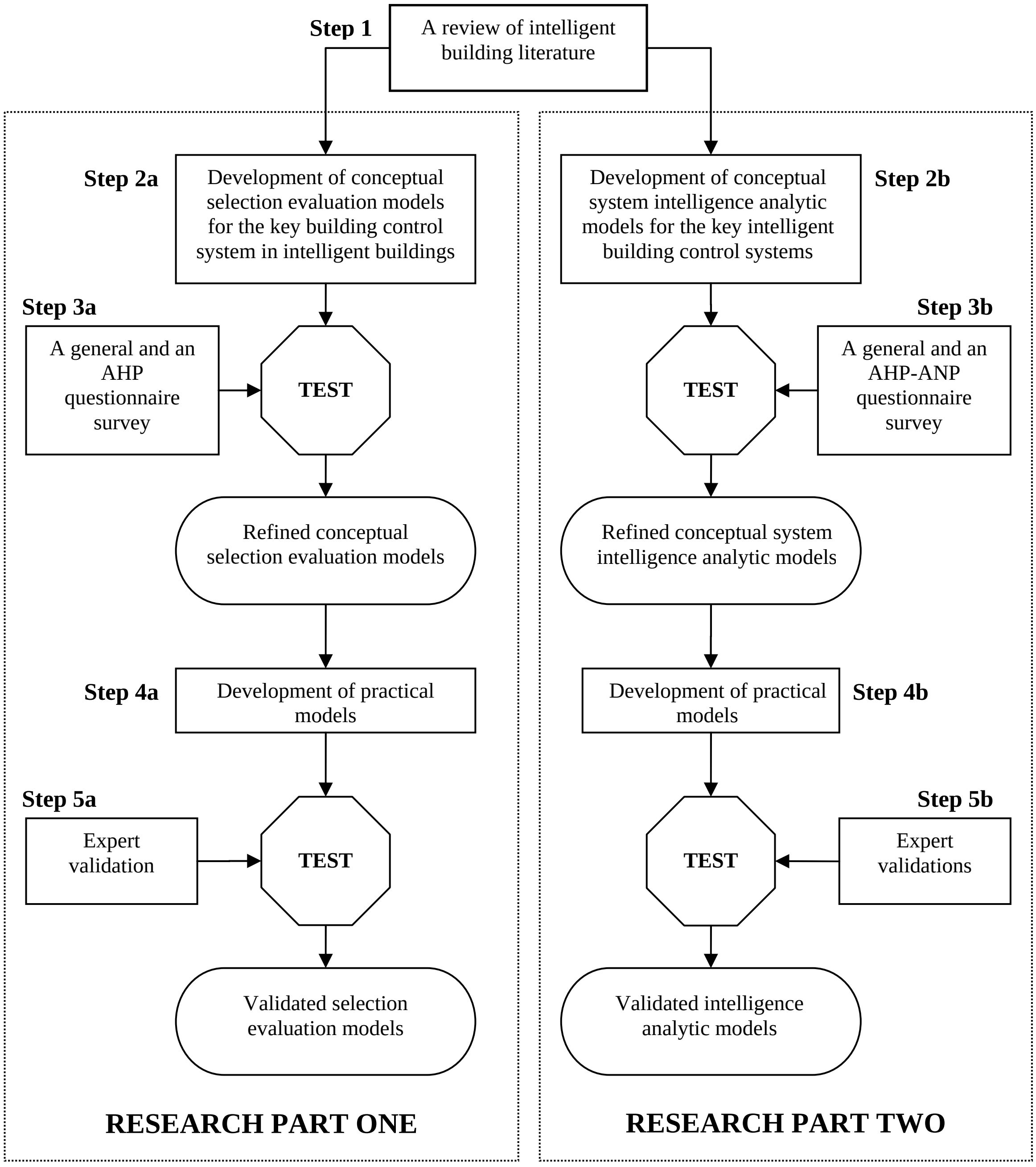


Figure 1.1: Flowchart of the Methodology of the Thesis

The rationale for the choice of methodology and the methods used in this research of this thesis will be presented in detail in Chapter 5.

1.5 CHAPTER ORGANISATION

This thesis is structured corresponding to the flow of methodology. The basis of the thesis is a compilation of six referred journal papers of the author (Wong *et al.*, 2005; Wong and Li, 2006 and 2007; Wong *et al.*, three under review), as listed in Appendix D (p.391). Contents of these papers are incorporated with further elaboration into the chapters as follows.

This introductory chapter presents the initial background to the research. It introduces the research problems and objectives that are addressed in this thesis. It also outlines the significance of the study, describes the methodology used and the organisation of the thesis.

Chapter 2 introduces the research context of the intelligent building. The research work begins with the discussion of the background and definitions of intelligent buildings. A literature review then sketches the discussion of the (seven) key control system components, and the (four) main potential benefits of the intelligent building. In the latter part of this chapter, the research deficiencies (i.e. selection evaluation and system intelligence analysis of the building control systems) in existing intelligent building literature that need to be addressed are highlighted. This constitutes the starting point for the literature review in the subsequent chapters. The chapter ends with a short discussion of the approach taken in the theoretical development of the research in this thesis.

The literature review is composed of two parts (Chapter 3 and 4) in this thesis. Chapter 3 provides a critical review of the development of selection evaluation models for building control systems in intelligent buildings (i.e., Research Part One) based upon research papers from referred journals and practical reports. This chapter sets out to discuss the problems of selecting and evaluating intelligent building options, including the existing practical problems and research limitations. This chapter presents and proposes general selection factors for the intelligent building control systems, intending to provide the basis for developing a theoretical framework summarising the selection criteria and factors of the optimum building control systems for the intelligent building. Chapter 4 reviews prior relevant literature of system intelligence analysis of building control systems (i.e. for Research Part Two). The first part of Chapter 4 reviews the concept of intelligence including both human intelligence and building intelligence. It also discusses the prevailing methodologies of measuring building and machine intelligence. The second part of Chapter 4 focuses on the development of seven conceptual models for measuring the degree of system intelligence of the seven different building control systems of the intelligent buildings. The proposed system intelligence analytic model is drawn on Bien's *et al.* (2002) concept of machine intelligence.

The rationale of the research design and methodology is presented in Chapter 5. The first part of this chapter covers the philosophical underpinning of the research. It provides the preface to the quantitative and qualitative paradigms, and the positivist orientation for the research in this thesis. Most importantly, the hypotheses are developed through the discussion of the conceptual models. The chapter then follows by discussing the key methods of analysis adopted, and how data obtained from the surveys is analysed. The two main tests (i.e., the AHP and ANP) that were employed are introduced and justified. Finally, the approach for model validation is discussed and presented.

Chapter 6 and 7 reports the major findings of the empirical studies. Chapter 6 first develops, examines and refines the conceptual models of the CSC for seven key intelligent building control systems which were established in Chapter 3. Two consecutive surveys (i.e., a general and an AHP survey) were undertaken to achieve this end. The hypotheses formulated for this part of research (*H1* and *H2*) are tested, and the research findings are analysed. A refined conceptual model is determined at the end of the chapter. Chapter 7 presents another two surveys (i.e., a general and an AHP-ANP based survey) to formulate and test the conceptual models of system intelligence analysis for the same seven building control systems. Another two hypotheses (*H3* and *H4*) that are formulated for this study are tested. Finally, seven refined conceptual system intelligence analytic models are generated.

Chapter 8 presents the process for the development of the practical models for the building control systems selection evaluation and system intelligence analysis as developed in Chapter 6 and 7. The applicability of the models is demonstrated. The models' robustness are validated by experts by the short validation questionnaires. The thesis concludes with Chapter 9 in which the major findings of the research are summarised and presented. Both research and practical implications are discussed. Finally, the limitations of the study together with recommendations for further research are addressed.

1.6 SUMMARY

This chapter outlined the purpose and significance of the research. The research problems and objectives of the thesis were described, and hypotheses were addressed.

The methodology and structure of the thesis were also presented, which offered a clear illustration of what will be achieved in this thesis.

CHAPTER 2

RESEARCH CONTEXT – THE INTELLIGENT BUILDING

“Many research projects arise from a study of current thinking in a field. The research project follows from identifying a gap in the literature. Most other research projects arise from awareness of a problem that is worth solving. In either case, a good start is an overview of current thinking in the field.”

(Bourner, 1996:8)

2.1 INTRODUCTION

This chapter presents the research context of the intelligent building. A background of the development and the definitions of the intelligent building are first discussed. The key building control systems of intelligent building are introduced and their latest developments are briefly presented. The potential benefits of the intelligent building are also reviewed. Then, the chapter identifies the gaps in the current intelligent building research that need to be addressed. This chapter ends with the discussion of the approach taken in the theoretical development of this research.

2.2 THE STIMULI OF INTELLIGENT BUILDING DEVELOPMENT

Few would dispute that the intelligent building has become a prevailing form of building development over the past decade or so. For many centuries, buildings have been designed, built, and occupied without the introduction of a perception of *intelligence*, and it can justifiably be questioned why the concept of intelligent building has been pertinent in recent years (Wigginton and Harris, 2002).

In general, the emergence of intelligent buildings can be explained by three notable changes in our environment. In the first stance, the major global environmental problems facing mankind over the last few decades are dominated by the imminent risk posed by the greenhouse effect and the consequential impact of climate change (Wigginton and Harris, 2002). Buildings have been criticised as a major burden on the environment and on efforts to lower energy consumption (Clements-Croome, 2001a; and Gann, 1990). They have an important role to play in the collective efforts required to avoid significant and possible disastrous environmental degradation. As reported by Wigginton and Harris (2002), a U.K based study found that buildings alone accounted for 46 percent of the total energy consumption and, in turn, are responsible for about half of the greenhouse effect due to carbon dioxide emissions. In Hong Kong, a recent government report on energy end-use also indicates that the residential and commercial buildings alone accounted for 85 percent of the total domestic electricity consumption (EMSD, 2006). Thus, there is an increasing recognition that buildings cannot be designed without consideration for energy conservation. As commented by Clements-Croome (2001a), energy demands have to be reduced not only because of the demand that is made on non-renewable fossil fuels, but also due to the large amounts of carbon dioxide emitted from the buildings, emissions which constitute almost half of the greenhouse effect.

Besides the environmental concerns, transformations in societal attitudes which reflect a higher standard of living and working have highlighted issues associated with the provision of a healthy living and working environment (Gouin and Cross, 1986; Neubauer, 1988; Gann, 1990; Loe, 1996; Smith, 2002; Himanen, 2004). Research in recent years has stressed the importance of a healthy and comfortable internal environment if people are to experience a good sense of well-being (Smith, 2002). As reported by Clements-Croome (2001a), a Japanese based study indicated that human productivity depends almost equally on three factors: the work process, the social ambience and the physical environment of a work organisation. Clements-Croome (2004) further highlighted that humans are not passive recipients of their environment, but adapt physiologically and behaviourally. People react individually and any response may be a transient one. Buildings have a vital role to play in helping to achieve this by providing environmental systems that support the productive, creative, intellectual and spiritual capacities of people. However, many traditional buildings are plagued with problems (see Table 2.1) associated with sick building syndrome (SBS) and their inability to provide comfortable and healthy conditions (Wigginton and Harris, 2002; Clements-Croome, 2001a; and Robathan, 1994). These problems need to be solved, and any solution must enhance the productivity, communication and overall satisfaction of occupiers and users.

Table 2.1: Examples of Major Problems in Traditional Buildings

Authors	Problems in Traditional Buildings
Wigginton and Harris (2002)	• Passive and static • Inanimate and inert nature • Slightly react to structural and thermal stresses • The internal environmental conditions vary with the changes of the external environment, modified by its mass and constructional configurations
Clements-Croome (2001b)	• Leads to building-related health symptoms • Affect work performance • Energy wastage
Robathan (1994)	• Independent operation of building systems

In addition, rapid evolution in the past two decades in building automation and microprocessor-based technologies have strongly driven the realisation of the ‘intelligent’ building (Gann, 1990; Loe, 1996; Kroner, 1997; Wigginton and Harris, 2002; and, Smith, 2002). The invention of the information super-highway or the Internet is one of the most important developments in the history of modern building. The onward improvements of information technology, along with the equally dramatic drop in the costs, have resulted in a lower and more affordable cost for the adoption of intelligent technologies in the building (Turk, 1988; Harrison *et al.*, 1998; and, Wan and Woo, 2004). Developers are struggling to meet the demands of the tenants for access to rapidly changing information technology services, demands that must be met in order to retain the tenants (Armstrong *et al.*, 2001). From the perspective of building environmental control, advances in information and building technologies provides better and more flexible environmental control by the end-users.

The world first building to incorporate intelligent technologies was City Place in Hartford, Connecticut in the U.S (Architects Journal, 1983). It was designed by Skidmore Owings and Merrill, and completed in 1984. This building contained a totally integrated services system linked by fibre optic cables. The network provided a link for both building system controls (i.e. air-conditioning, lifts, and safety system) and tenant word and data processing (Wigginton and Harris, 2002). A few years later, the Japanese adopted intelligent building technologies and developed a number of intelligent buildings (Harrison *et al.*, 1998). Examples of early intelligent buildings include the Toshiba Headquarters (in 1984) and NTT Twins (in 1986). Despite the efforts, the early intelligent building models from the U.S. and Japan were criticised for being entirely focused on building automation and information technology (Wigginton and Harris, 2002). Smith (2002) also maintained that many earlier intelligent buildings were complex in form and provided very little flexibility to the occupiers.

For the past two decades, the rapid economic growth in Asian cities such as Hong Kong, Shanghai, Singapore, and Taipei has led to a competition across the region to put up symbols of success and economic prosperity by building the tallest and most advanced building in the world (Naisbitt, 1996; and, Harrison *et al.*, 1998). Developers are racing to construct extremely tall buildings with the most advanced intelligent technologies, but few seem to be exploiting the true potential that the intelligent technology has to offer (Wigginton and Harris, 2002). Naisbitt (1996) criticise many of the existing intelligent buildings for failing to provide an eco-friendly work and a human-scale living environment. So and Chan (1999) also maintain that the industry still lacks a convergence outlook for intelligent buildings. Debate about the value of intelligent buildings remains. It is for this reason that it is necessary to develop a better understanding of the concept of ‘intelligent building’.

2.3 DEFINITIONS OF INTELLIGENT BUILDING

Prior to embarking on the exploration of the intelligent building, one must find out exactly what it means and of what it comprises. Since the concept of intelligent building is relatively new and yet to mature, a plethora of definitions exist. Wigginton and Harris (2002) identified over 30 separate definitions for the intelligent building. Earlier definitions of intelligent building were almost entirely centred on major technological systems such as building automation, communications and office automation (Harrison *et al.*, 1998; and Wigginton & Harris, 2002). For example, Cardin (1983: cited in Wigginton & Harris, 2002) defined the intelligent building as ‘one which has fully automated building service control systems’. The Intelligent Building Institution in Washington (1988: cited in Kroner, 1997 and Clements-Croome, 1997), on the other hand, referred to it as ‘one which integrates various systems to effectively manage resources in a coordinated mode to maximise technical performance, investment and operating cost savings, and flexibility’. Few early definitions explain the user interaction with the building (Bowell, 1990).

In fact, the purely technological definitions of the intelligent building in the early 1980s were criticised by many researchers. For example, DEGW *et al.* (1992) argued the early definitions described buildings which were unable to cope with changes in the organisations that occupy them or with changes in the information technology that they use. Such inflexibility would lead to the buildings becoming prematurely obsolete or requiring substantial refurbishment or demolition. Kell (1996) argued that technology should be seen as the enabler rather than as an end in itself, even though it is considered fundamental in intelligent building development,. Authors such as Robathan (1994), Loveday *et al.* (1997), Burmahl (1999), Preiser and Schramm (2002), and Wigginton & Harris (2002) also argued that a true intelligent building must be able to consider the needs and requirements of users. Clements-Croome (1997) pointed out that there has been a growing awareness of the relationship between the well-being of humans and the services systems and work process management of a building. The debate for an intelligent building definition which revolves around the issue of user comforts is particularly important since the building environment affects the well-being and comfort of humans in the workplace, and in turn influences productivity, morale and satisfaction. In recent years, debates over the definition of the intelligent building have extended to whether it should incorporate a learning ability and performance adjustment capability from its occupancy and the environment (Yang and Peng, 2001; and, Wigginton and Harris, 2002). The discussion implies that a real intelligent building should not only be able to react and change accordingly to individual, organisational and environmental requirements, but should also be capable of learning and adjusting performance from its occupancy and the environment.

In addition to the variations in the early and recent definitions, it appears that different intelligent building research institutes also have diverse interpretations of intelligent building. So *et al.* (2001) pointed out that intelligent building institutes in the U.S and U.K have inconsistent interpretations of what a building with intelligence is. The Intelligent Building Institute of the United States refers to it as “a building which provides a productive and cost-effective environment through optimization of its four basic elements including structures, systems, services and management and the interrelationships between them", while the European Intelligent Building Group in the U.K defines an intelligent building as "one that creates an environment which maximises the effectiveness of the building's occupants while at the same time enabling efficient management of resources with minimum life-time costs of hardware and facilities" (Wigginton and Harris, 2002). There is a discrepancy between these definitions, with the U.K definition more focused on users' requirements while the U.S definition is more concentrated on technologies.

Recapitulating the definitions and concepts of the intelligent building of CIB Working Group W098 (1995: cited in Clements-Croome, 2004) and other researchers, a more balanced definition of intelligent building was recently developed by Clements-Croome (2001a: 3). He suggests that an intelligent building is:

> "One that will provide for innovative and adaptable assemblies of technologies in appropriate physical, environmental and organizational settings, to enhance worker productivity, communication and overall human satisfaction."

In addition to the Clements-Croome's definition, Himanen (2004: 42) also provides a concept of intelligent building as:

> "One's performance can be implemented with environmental friendliness, flexibility and utilisation of space, movable space elements and equipment, life cycle costing, comfort, convenience, safety and security, working efficiency, an image of high technology, culture, construction process and structure, long term flexibility and marketability, information intensity, interaction, service

> orientation, ability of promoting health, adaptability, reliability, and productivity.”

The definitions of Clements-Croome (2004) and Himanen (2004) are so important that their definitions have reflected the significance of the integrated and intelligent systems in that they act as a balance between building contents, the organisation and services that determine if the value objectives of clients, facility managers and users are achieved. These objectives include creating a highly energy efficient and environmentally-friendly built environment with substantial safety, security, well-being and convenience, lower life-cycle cost, and long term flexibility and marketability. The achievement of these objectives would produce a building with the highest social, environmental and economic values.

2.4 SYSTEM COMPOSITION OF THE INTELLIGENT BUILDING

Prior to the invention of intelligent building technologies, buildings were traditionally designed so that power supplies, air-conditioning systems, lighting, security systems, communications and computers would all operate independently, allowing little or no flexibility (Loe, 1994; and Robathan, 1994). As argued by Wigginton and Harris (2002), humans must satisfy conflicting demands from the building and their organisation, as well as personal demands. The inability of passive inert buildings to provide comfortable conditions has led to a demand for efficient building systems to overcome these inadequacies.

In fact, intelligent buildings are distinct from conventional buildings as the former are fundamentally equipped with advanced and intelligent control technologies in order to provide the qualities that create a productive and efficient environment, such as functionality, security and safety; thermal, acoustical, air-quality and visual comfort; and building integrity (Bradshaw and Miller, 1993). In general, the intelligent building is characterised by a hierarchical presentation of the system's integration (Gann, 1990; DEGW *et al.*, 1992; Harrison *et al.*, 1998; Sharples *et al.*, 1999; So and Chan, 1999; Fu and Shih, 2000). The top level of building control usually refers to the integrated building management system (IBMS) or the building automation system (BAS), and underneath it a number of control systems manage building services (Carlini, 1988a and 1988b; and, Arkin and Paciuk, 1997). These services include the addressable fire detection and alarm system (AFA), heating, ventilation and air-conditioning control system (HVAC), digital addressable lighting control system (DALI), security monitoring and access control system (SEC) and smart and energy efficient lift system (LS) (So and Chan, 1999). The telecom and data system (ITS) acts as a communication network backbone to allow the building management and control systems to interrelate with one another in a natural way, allowing for the input and output between systems and the control of that system (Smith, 2002). An overview of the functions and latest development of each of these building management and services control systems in the intelligent building are presented and described in the following sections.

(1) Integrated Building Management System (IBMS)

The IBMS is considered as the core of intelligent building (Gann, 1990; and, Carlson and Di Giandomenico, 1991). The primary function of the IBMS is to provide automatic functional control and to maintain the building's normal daily operation. According to Luo *et al.* (2003), many current IBMSs also acquire the function of power quality monitoring and analysis, and distribution analysis of electricity, gas and water consumption, which is performed by the building automation system (BAS). The BAS was created in the 1980s and has been expanded or upgraded to what the industry call the IBMS. From a practical sense, the BAS can be categorised as automatic functional control of building services systems to maintain the building's normal daily operation with the emphasis on standalone, decentralised function units rather than centralised control and monitoring function, which was the approach in the 1980s. Whereas IBMS integrates all essential building services systems to provide an overall strategic management in all aspects with the capability to systematically analyse and report the building performance and connect with multiple sites/locations to give the corporation a portfolio view of the situation.

The IBMS has gained a great amount of attention in recent years, and a large amount of research in the technologies has been undertaken (Huang *et al.*, 2004). However, there exist two challenges in the current development of the IBMS (Wang *et al.*, 2007). First, incompatibilities between the products of different vendors limit integration opportunities. The second challenge is how to integrate the IBMS with the Internet and enterprise applications. Research is being conducted by engineering researchers to tackle these problems and it should be noted that these problems are not the research issue that this thesis intends to tackle.

(2) Telecom and Data System (ITS)

The primary function of the ITS is to generate, process, store and transmit information in the intelligent building (So and Chan 1999: 47). The key components of the modern ITS include PABX, total building integration cablings, broadband Internet access and CATV connections, and public address systems. The latest building communication system development involves the wireless network and intelligent control system, technologies that employ Bluetooth, LonWorks, C-Bus, RF, IR, Internet technology, Java, soft-computing for system diagnosis and monitoring as well as universal plug and play (Luk, 2006). The use of Web-enabled devices allows remote monitoring of the building by interaction of the central IBMS or BAS workstation with the remote dial-up system via modem (Finch, 2001:396). The data from sensors and controllers can be relayed from the IBMS or BAS workstation and the settings of actuators that control the services can be adjusted. Web-enabled devices, which provide a low cost mechanism for reporting building performance remotely without the need for on-site computers, help to reduce the security and maintenance costs associated with running an IBMS or a BAS. This is particularly useful in unmanned facilities.

(3) Addressable Fire Detection and Alarm System (AFA)

Fire detection is critical in modern buildings. Prompt fire control is critical as it can contribute significantly to the success of rescue operations and to limiting the degree of damage (Tränkler & Kanoun, 2001). The immediate reaction and the reliability of fire detection and alarm systems are very important to maintaining the safety of the occupants in the buildings. However, the problems associated with conventional fire detection system have been well-documented in literature which has criticised them for their slow response rate and false alarming (So and Chan, 1999).

According to So and Chan (1999), one of the latest intelligent fire detection system developments involves the use of microprocessor-based distributed process system technology. This adds intelligence to the fire alarm control unit to reduce the problems of false-alarming and to improve system reliability and flexibility. Stand-alone intelligent fire alarms use intelligent initiating circuit sensors. Intelligent indicating circuit devices are also used to provide software driven fire alarm notification. Each intelligent building circuit sensor and indicating circuit device contains a custom integrated circuit, enabling two-way communication to a stand-alone intelligent fire alarm system control unit.

(4) Heating, Ventilation and Air-conditioning (HVAC) Control System

A heating, ventilation and air-conditioning (HVAC) system is extensively considered as a critical service in the modern buildings, which provides a comfortable indoor environment for people to live and work (So and Chan, 1990). The HVAC system has a significant impact on the external environment as it consumes energy to maintain a comfortable and healthy internal environment (Clements-Croome, 2001a). Research on building energy usage found that HVAC systems alone generally account for between 25 to 30 percent of the total building energy usage (Orme, 1998). The study of So and Chan (1999:93) also illustrated that the HVAC systems consumes up to 50 percent of the total electricity consumption of a building. This implies that energy efficiency is a key issue in the design of the control of the HVAC system.

According to So and Chan (1999), conventional control of HVAC relies on measuring devices such as thermostats and humidistats to monitor the temperature and humidity of the supply and return air of an air-conditioned space. Some modern HVAC control systems are installed with a computer vision system, which can count the number of residents within an air-conditioned space and informs the control system of the distribution of the residents so that real time zone control becomes possible (So and Tse, 2001). Another advancement of the HVAC control system involves the use of an Internet-based IBMS or BAS which turns everything inside the whole building into one sensor (So and Tse, 2001). Internet-based HVAC control system allows every authorised user to keep close contact with the IBMS/BAS, wherever the user is.

(5) Digital Addressable Lighting Control System (DALI)

The quality of lighting is a critical aspect in the building as the illumination and contrast values have a direct impact on the well-being, motivation and productivity of persons in the building (So and Chan, 1999). In intelligent buildings, lighting level control is generally accomplished by two different methods, which are multi-level lighting, and modulated lighting, which calls for specifically designed control ballasts (Harrison *et al.*, 1998:22). The use of occupied-unoccupied lighting control can schedule the on/off time of luminaries for a building or zone to coincide with occupancy schedules. In addition, the hardware devices are developed in line with the control program to provide lighting control, including light sensors, motion detectors, photocells, touch switches, and dimmable ballasts. The devices are connected to the controller and provide discretionary control of frequently unoccupied areas.

(6) Security Monitoring and Access Control System (SEC)

Security systems are designed to anticipate, recognise and appraise a crime risk and to initiate actions to remove or reduce that risk (Chicago Police Department, cited in So and Chan, 1999). The presence detection of persons plays a key role in the comprehensive control and protection systems (Tränkler & Kanoun 2001). In intelligent buildings, simple security systems involve automatic functions such as access monitoring, card access control, guard tour monitoring and/or motion detectors, networked digital closed-circuit TV and person identification systems (So and Chan, 1999). Sensor systems are designed to inform the users about the state of windows, doors, entrances and exits of the building at any time for intrusion detection. For further information on the advanced security components in intelligent buildings, refer to Manolescue (2003).

(7) Smart and Energy Efficient Lift System (LS)

The main objective of the lift system is to transport passengers to the desired floors quickly, safely and with comfort (Bien *et al.*, 2002). In recent years, lift control systems have been designed to promote a higher handling capacity, improved riding comfort and a better man-machine interface (So and Chan, 1999). Advanced lift control technologies can fall into two streams: advanced drives and artificial intelligence based supervisory control. Lift group control systems respond to the necessity of providing efficient control of a group of automatic lifts servicing a common set of landing calls (CIBSE, 2000). The latest technology also allows the computer to estimate the number of passengers waiting at each lobby and travelling in each lift car through image processing and understanding (So and Chan, 1999).

2.5 THE BENEFITS OF IMPLEMENTING INTELLIGENT BUILDNG TECHNOLOGIES

From the above it is obvious that intelligent buildings often encompass a set of advanced and intelligent control systems. Recent research has indicated that the upward interest in intelligent buildings in recent years is not related to its technological advancement, but to the potential benefits that it delivers to developers and end-users (Cho and Fellows, 2000; and Wigginton and Harris, 2002). An inspection of intelligent building literature reveals that the benefits of intelligent buildings can be generally classified into the following four categories (See Figure 2.1):-

2.5.1 Enhanced Operational and Energy Efficiency

A fundamental objective of the intelligent building is to ensure that the installed building control systems have the capacity to handle expected user requirements (or can be readily modified to do so) and to cope with likely changes of user requirements in the future (Clements-Croome, 2001a). According to Armstrong *et al.* (2001), end-users expect good lighting, thermal comfort, and a clean and adequate supply of fresh and re-circulated air that is free of odours as well as contaminants. In this regard, the intelligent building should be able to respond promptly to meet the needs of end-users or occupiers in a timely and consistent manner by embedding knowledge, and should possess the ability to reason through its automation systems. Building control systems are designed to improve operational efficiency by providing tools that help operation and maintenance staff target their efforts more effectively.

As mentioned in this chapter earlier, there has been increasing recognition that buildings should be designed with consideration of their social impact on the environment. Clements-Croome (2001b) points out energy efficiency continues to be a top priority in intelligent building design as most of the energy demand is made on non-renewable fossil fuels. Any unnecessarily purchase and consumption of energy by the building implies a pure wastage. In fact, intelligent building technologies are likely to provide a contribution toward using energy more efficiently in buildings and controlling the building sector's contribution to atmospheric carbon concentrations (Armstrong *et al.*, 2001). Consequently, one essence of the intelligent building is to provide energy efficient and environmentally approved conditions for occupants in order to minimise waste production and energy consumption (The CIB Work Group, 1995).

2.5.2 Enhanced Cost Effectiveness

Over the last decades, end-users are continuously demanding high quality, more sophisticated and more reliable building services, including, for example, high-speed Internet access and improved internal security. However, the use of modern technology to enhance the effectiveness of a building is associated with additional capital costs when compared with those of less sophisticated buildings (Clements-Croome, 2001). With respect to this, Clements-Croome (2001a) argued that when one examines the true cost of an intelligent building, one should take the initial capital costs as well as all of the whole life costs into consideration. Whole life costs are incurred by a building during its life span, which include its operating, maintenance and disposal costs (Flanagan and Norman, 1983; Bradshaw and Miller, 1993; and, Woodward, 1997). Whole life costing helps to justify decisions that have beneficial health and safety, environmental and sustainability implications. Clements-Croome (2001a) further argued that although energy costs may only account for a small proportion of turnover, the energy costs are significant as a percentage of profits.

2.5.3 Increased System Robustness and Reliability

In addition to improved operational/energy efficiency and lower whole life cycle costs, literature also suggests that intelligent technology can further help to enhance reliability and reduce the level of maintenance required (Neubauer, 1988; and, So and Chan, 1999). The advances in information technologies provide new technologies by which high quality, flexible environmental control can be ensured, and thus enhance system robustness. However, it is noteworthy that building services wear out relatively quickly and need space and regular maintenance. As pointed out by Clements-Croome (2001a), the risk of current technology becoming obsolete is a potential risk of the intelligent building. When building services become unstable and unserviceable due to breakdowns, lack of control, misuse and ineffective maintenance, the building becomes obsolete and loses tenants very quickly as the tenants seek other buildings which meet their requirements, or offer more sophisticated services.

2.5.4 Improved User Comfort and Productivity

According to Harrison *et al.* (1998), user comfort is determined by a range of psychological as well as physiological factors. For example, poor air quality affects the health of building users and the method of ventilation has implications for air quality issues. For ventilation to be effective, good air must reach the breathing space of building occupants. In addition, thermal discomfort has detrimental effect on performance and noise levels can affect concentration, ease of communication between staff and privacy of communications. Inadequate illumination levels, poor colour rendering, inappropriate directional effects and lighting systems that result in glare problems can lead to deterioration of visual acuity. Clements-Croome (2001a) also argues that user comfort is associated with the well-being and productivity of human beings, whereas productivity relies on a general sense of high morale and satisfaction with the environment. All of these arguments suggest that the building and its services systems are closely related to the well-being of staff inside the building.

Intelligent buildings have an important role to play in providing environmental systems that support productive, creative, intellectual and spiritual capacities of people (Clements-Croome, 2001a). A number of empirical studies have supported the notion that an increase in individual control of a building results in an increase in user comfort. For example, a study conducted by the British Council for Offices (Clements-Croome, 2001a) concluded that advanced building intelligence can increase the productivity of occupants by 10 percent annually and improve efficiency to the satisfaction of owner-occupants. Another study conducted by the University of Reading (reported in Clements-Croome, 2001a) also suggested that human productivity is increased by 10% when the indoor environment is improved. A good indoor working environment helps to reduce additional spending on upgrading facilities and produces an optimum level of productivity.

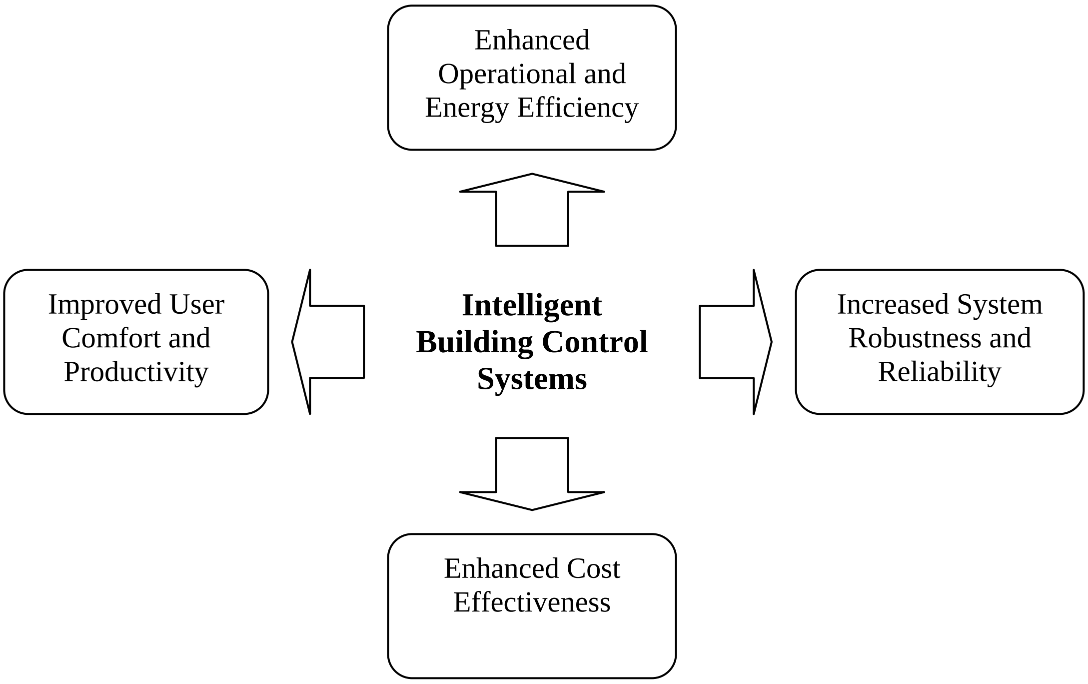


Figure 2.1: The Benefits of Implementing Intelligent Building Technologies

2.6 AN IMBALANCE IN INTELLIGENT BUILDING RESEARCH

For the past two decades, the idea of intelligent building has achieved considerable attention in the academic arena as well as within the industry. Investigation into intelligent buildings has become ubiquitous. Accordingly, substantial amounts of research and practical papers have been generated and published in mainstream construction and engineering journals. As the concept of intelligent building is comparatively new, a diversified nature and scope of studies has been documented so far. Although the existing literature facilitates the understanding and improves the knowledge of practitioners, the existing intelligent building studies still lack a systematic review and a clear further research direction. Because of the substantial amount of articles on intelligent buildings that have been published, a comprehensive review and critique of the research is deemed to be important and valuable. Such review further stipulates the type of research required to provide the knowledge base for improving our understanding of intelligent building issues.

Wong *et al.* (2005) conducted a review on the intelligent building literature. Their review provides a systematic investigation on what areas of study have been covered by industrial players and academics, and considers how researchers can proceed to learn more. Wong *et al.* (2005) surveyed journal articles and practical papers published in the last 20 years that relate to intelligent buildings. An extensive literature search reveals that research on intelligent buildings can be divided into following three main directions: *innovation in intelligent building technology; selection and justification of intelligent building options;* and, *developing performance evaluation models for the intelligent building.* Most importantly, the main purposes of this thesis will deal with some of the key research deficiencies that are identified and discussed below.

2.6.1 Innovation in Intelligent Building Technology

An extensive search of intelligent building literature reveals that a great deal of research efforts has been placed on the development of innovative building control systems and the integrated network technologies. Examples of outstanding works include those published by So and Chan (1999); Tränkler and Kanoun (2001); So and Tse (2001); Bernard and Kuntze (2001); Lüthi *et al.* (2001); Mügge (2001); Wigginton and Harris (2002); Hetherington (1999); Thuillard *et al.* (2001); Schofield, *et al.* (1997); Marchesi *et al.* (2001); Finch (1998 and 2001); Fu and Shih (2000); and, Wang and Xie (2002). A brief introduction of the key building control systems of the intelligent building have been presented in section 2.4.

In general, a more recent development of intelligent building technologies involves the use of automated diagnostic tools including neural networks and fuzzy logic, as well as other artificial intelligence based technologies to detect problems (Kroner, 1997, Ivanovich and Gustavson, 1999, and Wang and Wang, 1999). A number of joint research projects have also been set up to investigate advanced building technologies. For example, the IEA BSC research program Annex 25 (Hyvarinen and Karki, 1996) and Annex 34 (Dexter and Pakanen,. 2001), involving over 10 universities and research institutions from different countries, conducted extensive research on the methodology, strategy and application of fault detection and diagnosis in HVAC systems. Despite such research efforts, Bien *et al.* (2002) criticised the tremendous efforts that have been spent to make building systems more ‘intelligent’. Little serious research has been done to understand how to measure the intelligence of a building system or components. Park *et al*. (2001) also criticise prior studies in intelligent systems for not investigating a measure of the performance of the intelligent systems. The deficiency of system intelligence assessments of intelligent building control systems will be discussed in further detail in the subsequent section.

2.6.2 Models of Selecting and Evaluating Intelligent Building Options

Wong *et al.* (2004), in their intelligent building review paper, argue that though many studies of intelligent building selection and justification (Wong *et al.* 2001, Yang and Peng 2001, Keel 2003, and ABSIC Group 2001) appear relevant, there are two main deficiencies in the existing research that need urgent addressing: (1) selection evaluation, and (2) system intelligence analysis of the building control systems of the intelligent building.

According to Wong *et al.* (2004), many current studies have been concerned with the financial performance of intelligent building alternatives. Little attention is paid to the non-financial criteria in many existing evaluation approaches (Hastak, 1998). Researchers including Loe (1990); Yang and Peng (2001), and Suttell (2002) argue that the problems of over-reliance on the financial evaluation techniques by decision makers can be attributed to the lack of information and support for decision-making at the conception stage of intelligent building development. Hastak (1998) pointed out that complications arise when the alternative processes under consideration are new and insufficient data is available to effectively evaluate all pros and cons. The lack of sufficient historical data constrains a decision maker, forcing them to make decisions based on technology selection. As a result, they tend to give assessment based on their knowledge, past experience and subjective judgments. This current imbalance towards justification research needs to be redressed. One reason is that the evaluations based solely on financial viability would lead to selection myopia as the components with initial cost savings habitually chosen. Eventually, this would lead to biased decisions on the selection of the systems of an intelligent building.

A review of intelligent building literature reveals that that many existing intelligent building selection models are limited to the evaluation of the intelligent building as a whole (i.e., Building A or B) (Wong *et al.*, 2005). There is a dearth of research attempting to investigate the problems of selecting and evaluating the appropriate building control systems (for example, IBMS) for the intelligent building. In fact, the importance of the decision of which building systems selection to choose has been stressed by a number of researchers. For example, Wigginton and Harris (2002:3) point out that the mechanical and electrical services can account for 30-40% or more of the total building project cost. In another study, Wigginton and McCarthy (2002) also suggest that between 30% and 35% of the capital cost of a well-serviced and high-specification office building is attribute to building services. Alibaba and Özdeniz (2004) also importantly point out that the failure of a building to recognise the significance of performance and systems interface can lead to system incompatibility, malfunctioning and risk of obsolescence, and, in turn, additional liabilities to the building owners. Clements-Croome (2001a) also maintains that if building systems go wrong, it affects the business operations of occupants. The maintenance costs and the costs associated with a potential plunge in revenue arising from a loss of tenants have an adverse effect on the financial viability of the building. In this sense, there is considerable potential to improve the currently limited understanding of selection and justification of the intelligent building control systems.

2.6.3 Frameworks for Intelligent Building Performance Assessment

For the last few years, there has been an increasing emphasis within intelligent building research and practice on the demand to develop performance evaluation frameworks in order to meet the growing demands being placed on the industry by its clients, professionals and occupants (for example, Arkin and Paciuk, 1997). Wong *et al.* (2005) generally distinguish previous performance evaluation models of intelligent building (Arkin and Pacuik, 1995; Harrison *et al.*, 1998; Smith, 1999; Yang & Peng, 2000;

Preiser, 2001; Preiser and Schramm, 2002; and, So and Wong, 2002) into three approaches – tangible, intangible, and integrated approaches. However, a problem with prior studies is that they are fraught with problems of fairness, are partially subjective and lack a generally accepted tool for assessing the intelligent performance of the intelligent building (So and Wong, 2002).

In addition, Wong *et al.* (2005) also argue that the current focus of many performance appraisals is largely on categorical modelling of intelligent buildings, in which the research concentrates on classifying the intelligent building to a definite category according to their overall performance (Boyd and Jankovic, 1994; Smith, 2002; So and Wong, 2002; and Wong and Jan, 2003). Rarely has research focused upon the development of integrated systematic methodologies and techniques to measure the intelligent performance of intelligent building systems and components (Wong and Li, unpublished). Bien *et al.* (2002) also argue that there is a shortage of evaluations of machine intelligence in the current research. The need for a new system intelligence measurement is also stressed by Park *et al.* (2001), who argue that such a measure could assist system developers to estimate some products using the index to manifest their intelligent superiority and could help clients to compare several products from the viewpoint of intelligence. Since the intelligent performance of the intelligent building as a whole has already been examined, it is only necessary at this point to specifically identify and measure the system intelligence of the building control systems in the intelligent building.

As mentioned by Loosemore (1996), the problems in any relatively unexplored research field is the plethora of issues which are worthy of investigation. There is a risk of choosing too wide a range of issues to investigate, something which could compromise the quality and eventual value of the research. To avoid such a problem, this thesis focuses on two outstanding research focuses which were identified in the above literature review. In specific, this thesis first aims to develop selection evaluation models for the seven key building control systems which were identified in Section 2.4. Then, this thesis investigates the measures of the degree of system intelligence of the same seven intelligent building control systems and develops the system intelligence analytic models. The relevant literature related to theory and research of the above two research focuses will be critically reviewed in Chapter 3 and 4 respectively.

2.7 THEORETICAL DEVELOPMENT OF THE RESEARCH

In the previous sections, a review of intelligent building research was conducted and two research deficiencies were delineated and defined. Prior to an investigation of these research problems, the theoretical basis of this research is discussed and considered.

2.7.1 Fundamentals of Decision Making

Decision making takes place on a daily basis for human-beings and occurs mainly in an instinctive way. However, there are many responsibilities which are of a complex structure or of great impact on the well-being of human and/or matter and, therefore, implementing a decision requires careful preparation and analysis. Glaser (2002:7) points out that the first and most crucial constituent of decision making is the presence of a rational individual (‘decision-maker’). It is assumed that the decision maker is endowed with certain ideals, motives or desires and the freedom to choose. Decision problems take place when at least one decision maker encounters a situation which demands or invites a choice, based on the person's underlying objectives, between two or more mutually exclusive alternatives. To allow for a formal analysis of the real-life decision problem and for the application of quantitative methods of decision theory to the real-life decision problem, a transformation into a mathematically formal representation ('decision model') is required.

According to Resnik (1987), there are two main branches of decision theory: normative (or prescriptive) decision theory and descriptive decision theory. Descriptive decision theorists have sought to explain both decisions made in real-life situations and observed behaviour in individuals and groups on the basis of the hypothesis of rational choice. This allows them to make predictions about similar future decisions. Normative decision theorists, on the other hand, have sought to address the question of how people ought to make decisions in various types of circumstances if they wish to be regarded as 'rational'. Rapoport (1989) points out that normative decision theory is much more formalised than descriptive theory as it makes use of mathematical language, modes of discourse and concepts. The assertions of normative decision theory, which are generated by rigorous deduction from assumed idealised conditions, cannot be interpreted as predictions of actual human decisions or of their consequences. Thus, the normative decision theory tends to disclose the logical essence of an idealised decision problem instead of trying to predict decisions or their consequences. In contrast, descriptive decision theory aims to deal with the real life situations. The expected observations are defined in ways that make them recognisable. This research, as stated in the introductory chapter, is focused on investigating the important selection criteria and intelligence indicators that the decision makers consider as important for selecting the building control system and evaluating system intelligence. Thus, the focus of this research is on the descriptive decision making (*'what people actually do or have done'*) instead of normative or prescriptive decision making(*'what people should and can do'*).

2.7.2 Multi-Criteria Decision Making (MCDM)

In real world situations, the diversity of human character traits, needs and tastes, as well as the multiplicity of existing goods, services and technologies suggests that the decision problems world is not one-dimensional (Glaser, 2002). As argued by Glaser (2002: 7), reality poses a number of challenges to decision theory. The main categories of conflict include intra-personal conflict and the conflicting use of resources in combination with the conflicting employment of technologies in activity analysis (production theory) of productivity and environmental issues. The multi-criteria decision making (MCDM) approach is characterised by the methods that support the processes of planning and decision through collecting, storing and processing different kinds of information in order to deal with the above two objects of interest (Lahdelma *et al.* , 2000).

As Zhang *et al.* (2004) point out, decision making theorists have applied the MCDM to the preference decision making (i.e., evaluation, prioritisation, and selection) on available alternatives in terms of multiple, and usually conflicting, criteria. Two main theoretical streams can be distinguished in MCDM (Zimmermann, 1996; Glaser, 2003; and Triantaphyllou, 2000), with multi-attribute decision making (MADM) and multi-attribute utility theory (MAUT) on one side, and with the multiple objective decision making (MODM), which is also known as vector optimisation theory and multi-objective optimisation, on the other side. Glaser (2003:22) argues that both MADM and MAUT are characterised by a finite number of discrete alternatives (i.e., explicit list), implicit objectives (i.e., attributes for each alternatives) and explicit preferences for resolving the conflict (i.e., value function and/or utility function). In contrast, MODM is characterised by an infinite number of alternatives which are implicitly given by means of constraints, explicit objectives in the form of functions and by implicitly expressed preferences for overcoming the conflicts. This takes place through the choice of compromise models and their according parameters. The terms of MADM and MCDM are very often used to represent the same class of models (Triantaphyllou, 2000).

There are a number of notions of the alternatives and attributes to the MCDM/MADM. Triantaphyllou (2000) highlights the assumptions of the notions as follows:

(1) The alternative represents the different choices of action available to the decision maker. The set of alternatives is assumed to be finite.

(2) Each problem of MCDM/MADM is associated with multiple attributes (also referred as *goals* or *decision criteria*) and these attributes represent the various dimensions from which the alternatives can be viewed. When there are a large number of criteria available, the criteria may be arranged in a hierarchical manner. Each criterion may be associated with several sub-criteria.

(3) Different criteria represent different dimensions of the alternatives and, thus, they may conflict with each other.

(4) Different criteria may be associated with different units of measurement;

(5) Criteria are to be assigned weights of importance. Usually the weights are normalised to add up to one;

(6) The problem of MCDM/MADM can be easily expressed in a matrix format. A decision matrix (for example, matrix A) is an matrix in which elements a_{ij} indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j (for $i = 1, 2, 3, \ldots, m$, and $j = 1, 2, 3, \ldots, n$). It is also assumed that the decision maker has determined the weights of relative performance of the decision criteria (denoted as w_j, for $j = 1, 2, 3, \ldots, n$).

In this research, selecting as well as evaluating the intelligent performance of the building control system alternatives for the intelligent building project is considered as a problem of MCDM/MADM. The decision makers might encounter a number of alternatives in making their decision. A number of criteria might be considered by the decision makers and these factors might also conflict with each other. Consequently, the approach taken in the theoretical development of this research is to view the selection evaluation decision and system intelligence evaluation as the making of the multi-criteria decisions.

2.8 CHAPTER SUMMARY

This chapter reviewed the research context of the intelligent building. It first provided a discussion on the background and definitions of the intelligent building. Then, seven key building control systems in the intelligent building were identified and the benefits of the intelligent building were discussed. A succinct review of preceding research efforts in the intelligent building field was also presented, aimed at identifying the research deficiencies to be investigated in this study. Two outstanding research deficiencies were identified. The first research problem relates to the development of selection evaluation models for the seven identified building control systems, while the second research problem concerns the development of models for measuring the degree of intelligence of the same seven building control systems. Finally, the theoretical basis for this research was presented. A brief discussion of the decision theory indicated that multi-criteria decision making (MCDM) is more appropriate for modelling the selection evaluation and intelligence performance evaluation of the building control systems.

CHAPTER 3

FACTORS AND CRITERIA TO CONSIDER IN SELECTING OPTIMUM BUILDING CONTROL SYSTEMS FOR INTELLIGENT BUILDINGS

"…a review of the literature is important because without it you will not acquire an understanding of your topic, of what has already been done on it, how it has been researched, and what the key issues are….you will be expected to show that you understand previous research on your topics. This amounts to showing that you have understood the main theories in the subject area and how they have been applied and developed, as well as the main criticisms that have been made of work on the topic."

(Hart, 1998: 1)

3.1 INTRODUCTION

This chapter critically reviews relevant literature related to the research of the constructs (i.e., factors and criteria) in the proposed selection evaluation models for the building control systems of intelligent buildings. This literature review sets out to discuss the problem of selecting and evaluating intelligent building options, including the existing research efforts and practical problems. Then, it discusses general building control system selection factors. Finally, seven general conceptual models, along with posited critical selection criteria (CSC) for seven intelligent building control systems, are formulated.

3.2 DIFFICULTIES IN EVALUATING AND SELECTING INTELLIGENT BUILDING CONTROL SYSTEMS

To understand the challenges that design teams face in making a decision on the optimal intelligent control systems for the intelligent building projects, it is necessary to understand what makes the evaluation of building control systems for intelligent building projects distinctive. According to Wong and Li (unpublished), there is considerable evidence to suggest that higher complexities are involved in the design and evaluation of components of intelligent buildings. In the first stance, most of the intelligent buildings incorporate state-of-the-art technologies to enhance workplace automation, energy management, safety, security and telecommunication systems (Clements-Croome, 2001a). Intelligent technologies are capital-intensive and entail a higher initial capital investment (Loe, 1996; Wong *et al.*, 2001). It is important for intelligent buildings to demonstrate an economic benefit to the end-users/developers to balance the additional investment costs. Secondly, as argued by Clements-Croome (2001a), the risk of obsolescence of current technology distinguishes the appraisal of intelligent buildings. If technologies embedded in an intelligent building become obsolete, tenants would be lost very quickly. Finally, lack of experience and knowledge of intelligent building design and development can make decisions risky to both developers and design teams (Yang and Peng, 2001). In the roundtable discussion of intelligent building development, Ivanovich and Gustavson (1999) reported that the engineers in U.S lacked knowledge of how to work high-end, software-driven intelligent building technologies into their designs. Developers also lacked understanding of the value of intelligent building technologies which can add to their properties. These two challenges worry practitioners over the long term development of the intelligent building.

In intelligent building designs, the evaluation and selection of building system configuration has been considered an important procedure. This decision has a significant impact on the overall performance of the intelligent building (Nasser *et al.*, 2003). Ling *et al.* (2003) argue that a satisfactory building can never be produced if the design is not right. Wrong selection of building elements can cause serious problems associated with efficiency and building functionality which will not be easy to correct (Aygün, 2000; and, Alibaba and Özdeniz, 2004). This is so important that de Wilde *et al.* (2002) also argue that intelligent building systems need to deliver a living and working environment as expected by occupants and users, otherwise there is a mismatch between what users expect from an intelligent building and what it actually can deliver (DEGW *et al.*, 1992). In fact, one of the main reasons for this mismatch is that the intelligent building has often been defined in terms of its technologies rather than in terms of the goals of the organisations that occupy it (DEGW *et al.*, 1992). The subservience of the occupier to the technologies usually leads to a situation where the technology is inappropriate for the occupiers needs and, eventually, adversely affects productivity and costs.

For the past decade, the rapid development in microprocessor-based technologies and a growing awareness of building constraints has made available a host of advanced and ‘intelligent’ building devices with diverse applications. While a plethora of ‘intelligent building’ products have been accessible, it has become increasingly evident that design teams are not familiar with new building components. They are also confronted with a problem of choosing the apposite components or products, ones that suit the needs and accomplish the unique configuration of a particular project, while simultaneously resolving any conflicts between the performance criteria (Wong and Li, 2006).

Developers also lack a comprehensive list of criteria to select the innovative building systems and are short of logical and systematic methods to evaluate optimal or suitable building control systems. Consequently, these problems may prevent the developers and design teams from effectively evaluating and selecting optimal building control systems for the intelligent building projects.

3.3 A REVIEW OF MODELS OF INTELLIGENT BUILDING EVALUATION AND SELECTION

As concisely described in the preceding chapter, a quantity of evaluation and selection models have been developed in intelligent building literature in the past two decades, but there have been criticisms that the majority of existing evaluation and selection models are focused on the assessment of the financial viability of the building options (Wong *et al.*, 2005). For example, Wong *et al.* (2001) propose a model to assess the financial viability of intelligent buildings based on a Faustmann approach of assessment. The model applies the net present value (NPV) method to assess the two competing building alternatives: conventional or intelligent building. The measures for the selection are based on eight ‘Quality Environmental Modules’ in the *Intelligent Building Index* (AIIB, 2001) which are environmental/energy conservation, space utilisation and flexibility, life cycle costing, human comfort, work efficiency, safety, culture, and technological image module.

Keel (2003), who worked with the Continental Automated Building Association (CABA), developed a framework for selecting the optimum building alternative of different levels of integration. The model measures the life cycle cost (LCC) of three different building approaches, including non-integration, partial integration, and full integration. The model takes various components of the life cycle cost into account, including first costs, operating and maintenance costs, utility costs, and costs of upgrading. The most distinctive finding of the Keel's model is that the full integration approach has the lowest net present value (NPV). However, the model of Keel (2003) is under initial development and his proposed model is limited to the financial factors in intelligent building options selection.

ABSIC Group (2001) developed a selection framework for advanced and innovative building systems based on the cost-benefit analysis approach. This model identifies the cost-benefits of advanced building technologies with ten areas of life-cycle justifications (i.e., first costs, energy, operation and maintenance, individual productivity, organisational productivity, health, attraction/retention, organisational and technological renewal, tax/insurance, and salvage). In general, ABSIC's model was very practical and suggestive but it is difficult to interpret the nature of the methodologies based on the fact that it is incorporated within a multi-media decision support tool. Despite these research efforts, Smith (2002) and Chen *et al.* (2006) argue that many existing evaluation and selection models are perceived to be either incomprehensive or difficult to manipulate. In their review of intelligent building assessment models, So and Wong (2002) also criticise some evaluation models for being fraught with problems of fairness and being partially subjectivity, because some important elements did not receive sufficient emphasis and less important elements are ignored.

In addition to the underlying problems in the existing evaluation and selection models, little attention is paid to the selection and evaluation of building control systems for the intelligent building projects in the current research (Wong *et al.*, 2005; and, Smith, 2002). The literature lacks a discussion of the model which is to be used to ascertain the suitability of the intelligent components to be employed for an intelligent building. As early as the 1980s, Ioannou and Carr (1987) had stressed the need for this research because many potential users (i.e. developers/end-users) of innovative technologies in the U.S building industry had no formal system for evaluating innovative building technologies. After two decades, this research deficiency has not yet been rectified in the literature to date. Wong and Li (2006), in their review of intelligent building evaluation approaches, highlight the shortage of serious studies that have analysed the decision on the selection of intelligent building control systems, and also point out the lack of development of a conceptual framework of general factors and criteria for the systems evaluation and selection. Thus, it is for these reasons that the evaluation and selection of intelligent building control systems form part of the research focus of this thesis.

With respect to the selection factors and criteria of intelligent building alternatives, previous research has generally developed a number of measures. For example, the Asian Institute of Intelligent Buildings developed an ‘Intelligent Building Index’ (IBI) (AIIB, 2001 and 2004) to evaluate the performance of intelligent buildings. Their latest version of the index provides ten categories of performance measures for the intelligent building, including green index, space index, comfort index, working efficiency index, culture index, high-tech image index, safety and security index, construction process and structure index, cost effectiveness index and health and sanitation index. Although the index summarises the key performance variables of each building systems into different categories, the works of AIIB are not purposely designed for particular building control systems selection, and some items (i.e. culture, and construction process and structure index) seem to be less appropriate for use in the building systems selection. Most recently, the UK-based Building Research Establishment (BRE) developed an intelligent building performance assessment matrix system named *MATOOL* (Bassi, 2005). The model introduces five factors for the building performance measurement which include building environment, responsiveness, functionality, economic issues and suitability. However, the model is currently still under development.

A few building component selection models, besides the worlds of AIIB and BRE, have also been documented in the construction literature. For example, Lutz *et al.* (1990) proposed a model for the evaluation of new building technologies, but the assessment is limited to the evaluation of the workability of the technologies. De Wilde *et al*. (2002) also developed a model of energy saving building components selection and suggest six general factors of building components selection. Specifically, these factors include comfort, functionality, safety, architectural value, financing and environmental impact. Figure 3.1 illustrates de Wilde's *et al*. model.

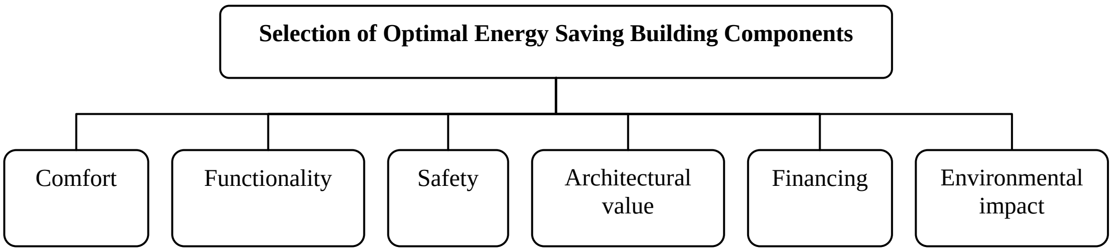


Figure 3.1: Model of the Selection of the Energy Saving Building Components

(Reference from de Wilde et al., 2000)

3.4 PROPOSED FACTORS FOR SELECTING INTELLIGENT BUILDING CONTROL SYSTEMS

Prior to the discussion of the potential factors for the evaluation and selection of intelligent building control systems, it is necessary to differentiate between the meanings of factors and criteria in order to avoid confusion. Lim and Mohamed (1999) discriminate the term '*factors*' from '*criteria*' by their meanings in the Concise English Dictionary. The Dictionary defines a *factor* as "any circumstance, fact, or influence which contribute to a result", whereas a *criterion* is described as "a principle or standard, by which anything is or can be judged". Lim and Mohammed (1999) point out that factors are significant, but they do not determine the success or failure of the result. Instead, the success or failure to comply with the criteria would lead to a success or failure in result. Thus, the general selection factors in this study are further divided into specific selection criteria. The pictorial representation of criteria and factors is illustrated in Figure 3.2.

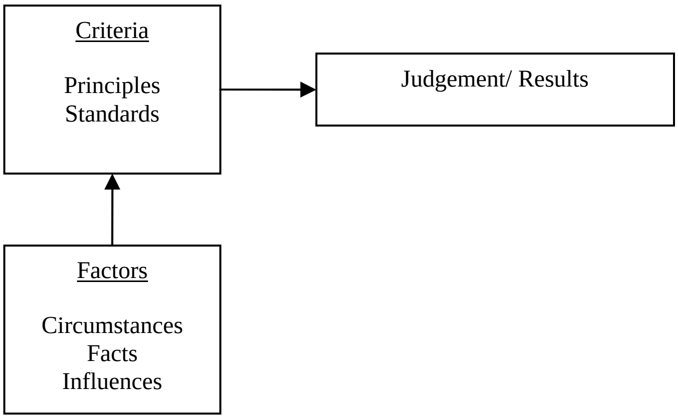


Figure 3.2: Pictorial Representation of Criteria and Factors

(Source from Lim and Mohamed, 1999: 244)

A review of literature in the areas of intelligent building and engineering indicates that it is a fragmented one which lacks a general agreement on the factors and set of crucial criteria for selecting the building control systems for the intelligent buildings. A bibliographic review suggested the variables that might influence the type of intelligent building systems selected could be generally classified into six factor groups including *cost effectiveness, work efficiency, environmental, user comfort, technological* and *safety-related factors*.

3.4.1 Cost Effectiveness Factor

Cost effectiveness is regarded as a key factor in selecting the components for the intelligent building (Clements-Croome, 2002). Loe (1996) highlights the expectation of intelligent building users that a cost benefit will flow from their investment. Keel (2003) also argues that the life cycle cost is the *'sine qua non'* of intelligent building development for the developers and end-users. Armstrong *et al*. (2001) finds that the main concern of building developers is to search for ways to reduce costs of operating and maintaining of the building and to increase its value. Despite the importance of these, some researchers (Flax, 1991; Loe, 1996; and Clements-Croome, 2002) argue that since the greatest savings in the adoption of an intelligent building are seen in a reduction in energy consumption and operational costs, and given the higher initial capital investment compared to a traditional building, the cost benefits of an intelligent building would not be immediately appreciable.. Raftery (1991:49) also points out the importance of the *life cycle cost* in the consideration of the cost in a building or property. He maintains that any planning and monitoring of the assets of a building should cover the entire life cycle from the early development stage to the final disposal stage. In general, life cycle cost is referred to as the total cost of owning, operating, and maintaining a planned project over its useful life (Bradshaw and Miller, 1993; and, Woodward, 1997). The operating costs comprise of the costs for maintenance, energy, taxes, insurance, interest on borrowed money, and any other recurring costs over the useful life (Bradshaw and Miller, 1993), whereas the maintenance costs, as stated in British Standard BS3811 (British Standards Institution, 1993), refer to the combined costs of 'all technical and associated administrative actions intended to retain an item in, or store it to, a state in which it can perform its required function'.

For selecting the appropriate building control systems for the intelligent buildings, some authors argue that the financial decisions should consider the whole life cycle cost instead of the initial cost alone (Wong *et al*, 2001; and So *et al.*, 2001). This is supported by an empirical study of DEGW *et al.* (1992) which suggests that the scale of cost savings in the intelligent building ranges from 10 to 40 percent of the operating and maintenance costs of a traditional building. Suttell (2002) also points out that the initial set up cost covers only 25 percent of the total cost over the lifetime of a building, while the operating and maintenance costs cover approximately 75 percent.

3.4.2 Work Efficiency Factor

In addition to the cost factor, the capabilities of a system in managing the complexity and enhancing the functionality of the building are widely considered as an indispensable factor in the decision on the intelligent building components selection. For example, Smith (2002) argues that the overriding function of the intelligent building systems is to support the capabilities inherent in it. Developers need to deliver the building's desired capabilities with the adaptability and functionality desired by the end-users. Cho and Fellows (2000) emphasise the importance of work efficiency in the intelligent building because the fundamental purpose of adopting the intelligent building systems is to offer improved operational effectiveness and efficiency, as well as reduced maintenance. Loe (1996) also maintains that the essence of the automation systems in the intelligent building is to enhance service reliability, improve building management, tailor requirements, increase the lifespan of equipment, and ease data collection.

In literature, researchers have discussed different measures for assessing the work efficiency of the intelligent building systems. Some studies have paid more attention to the work efficiency criteria of building control systems in general, while some others have focused on the specific criteria of each individual building control system. For example, Piper (2002) describes a number of important general criteria in evaluating the functionality of advanced building systems. These criteria include reliability, efficiency, system grade or level, service life, possibility of system further upgrade, compatibility with different network protocols. In particular, in the investigation of functionality of the IBMS, Wang *et al.* (2007) and Dwyer (2003) argue that it is important for an IBMS to demonstrate its ability to integrate products from different vendors. An efficient IBMS is also expected to be able to achieve total integration by requiring all building systems to communicate with the control server using a common protocol supported by the LAN as well as the interoperability of the various building systems (Tay *et al.*, 2002; Wang and Xie, 2002). Dwyer (2003) further maintains that an efficient IBMS should possess the function of remote building monitoring. The systems can be interrogated, monitored, assessed and controlled from anywhere in the world with an internet connection.

With respect to other building control systems, Song and Hong (2007) highlight three important criteria in the selection of the fire detection and alarm system (AFA): response time, survivability, and flexibility. Response time refers to the delivery speed of fire alarm signals and any other fire related information, while the survivability indicates that the status of signal delivery system must be monitored in real-time. The flexibility of AFA suggests that the system should be flexible in design, installation, operation and management. This can be procured from interoperability among devices supplied by different manufacturers. This makes the system more easily integrated, modified and upgraded. Apart from these criteria, researchers (Chow and Chow, 2005; Armstrong *et al.*, 2001; Luo *et al.*, 2002; AIIB, 2001; Shanghai Construction and Management Committee, 2001; and, Tränkler and Kanoun, 2001) also emphasise the importance of the AFA in its compliance with regulations as well as its abilities of remote control.

For selecting an appropriate HVAC control system, Xiao *et al.* (2005), AIIB (2001) and Wang and Wang (1999) emphasise the presence of automatic fault detection and diagnosis of the HVAC control system, while some authors such as Curtis (2001) place high emphasis on the system reliability and stability. In the selection of a lift control system (LS), authors including AIIB (2001), So and Yu (2001), and Siikonen (1997) argue that the system functionality is reflected from the lift interval time, waiting and journey time of passengers, and handling capacity. AIIB (2001) maintains that additional criteria, including frequency of lift servicing and repair, efficiency of the drive and control system, and automatic and remote monitoring, are also dominant in determining the efficiency of the intelligent lift control system. Apart from the above intelligent building systems, AIIB (2001) and researchers (for example, Bushby, 1997; Smith, 2002; Armstrong *et al.*, 2002; Chebrolu *et al.*, 2005; and Hetherington, 1999) also propose a quantity of criteria for measuring the functionality of the telecom and data system (ITS), security monitoring and access control system (SEC), and digital addressable lighting control system (DALI). The proposed work efficiency factors and criteria relating to each of the building control systems are tabulated in Table 3.1.

3.4.3 User Comfort Factor

According to Clements-Croome (2001a), the basic intention of a building is for it to be planned, designed, built and managed to offer an environment which occupants can carry out their work, feel well and to some extent feel refreshed by the environment. A truly intelligent building must address occupant well-being and health, and it needs to take the quality of the working and living environment into account when bringing in new technology for the purpose of improving the performance of business organisations (Clements-Croome, 2001a). Thus, maintaining a stable and comfortable internal environment for the end-users becomes a crucial objective in the design and selection of building control systems as the intelligent building needs to provide the people working and living in it a good sense of well-being.

While it is important to ensure a permanently healthy environment for the end-users and allow an optimal performance in their activities, de Wilde *et al.* (2002) indicate that the conditions in the indoor environment must be adjusted as to ensure and maintain five main comfort conditions. These are thermal comfort, air quality, visual comfort, acoustical comfort and vibration control. For example, thermal comfort is regarded as a critical consideration in maintaining the well-being of persons in a building (Bernard and Kuntze, 2001; and Tränkler and Kanoun, 2001). The main physical and physiological parameters that determine the state of thermal comfort include air temperature, mean radiant temperature, air humidity and air motion. In addition, Bischof *et al.* (1993, citied in Tränkler and Kanoun, 2001) observe that indoor air quality (IQA) is critical for the well-being of occupiers because inadequate ventilation in buildings can lead to serious problems including sick building syndrome, building-related illnesses and mildew (AIIB, 2001; Chow and Chow, 2005; Pan *et al.*, 2003; and, Alcalá *et al.,* 2004). In addition, a comfortable and healthy visual environment is critical to support the activities of the occupants. As argued by Reffat and Harkness (2001), a well-designed visual environment is essential for perceiving space, form and colour. Oral *et al.* (2004) highlight the fact that in order to provide visual comfort conditions in buildings, certain values and limits for the illumination levels and luminance must be set and the influence of colours must be taken into account.

3.4.4 Environmental Factor

In recent years, increasing anthropogenic carbon emissions have been recognised as a cause of global climate change. A number of studies have identified buildings as being responsible for about half of all energy consumption, and, in turn, as responsible for about half of the greenhouse effect due to carbon dioxide emissions (Wigginton and Harris, 2002). This has aroused a growing awareness of the need for energy-efficiency in the design of the modern buildings. For example, Armstrong *et al.* (2001) argue that the intelligent building technologies should contribute to greater energy efficiency in buildings, and should control the contribution of the building sector to atmospheric carbon concentrations. Clements-Croome (2001b) also maintains that attention needs to be given to minimising unnecessary consumption of energy, water usage and waste production in the selection of the building components for the intelligent building.

Of all the building services concerned, HVAC and lighting systems are regarded as the most energy-intensive. So *et al.* (1997) point out that it is important for building control systems to conserve energy while providing satisfactory performance. For example, an efficient HVAC control should not only provide an efficient control scheme to maintain human comfort under any load conditions, but should also reduce energy usage by keeping the process variables (i.e., temperature and pressure) to their set points (Canbay *et al.*, 2004). The significance of energy consumption control in the selection of a HVAC control system is also supported by other researchers including Fong *et al.* (2006), Alcalá *et al.* (2004), Liu *et al.* (2002); Mügge (2001), and Rousseau and Mathews (1993). On the other hand, Smith (2002) argues that in designing intelligent lighting control, it is important to ensure that the system can reduce energy consumption without compromising energy effectiveness. Li *et al.* (2006) also emphasise that energy can be saved through the utilisation of daylight, because it allows a lower electric lighting demand and reduced peak electrical demands. The utilisation of daylight can also lead to lower cooling energy consumption and potentially allows for a smaller HVAC plant.

3.4.5 Technological Factor

For the past decade, it has been observed that there have been an increasing number of developers considered adding “intelligence” to their building. According to Wan and Woo (2004), a main stimulus for the development of intelligent buildings is that the building developers are more receptive to new technologies. They not only desire to create product differentiation and to project their high-tech building image by incorporating innovative and intelligent building components, but they also struggle to meet demands of end-users for access to rapidly changing information technology services (Armstrong *et al.*, 2001). To retain the tenants (i.e., the end-users), it is necessary to keep up with changes in information technology and provide for upgrades as technology evolves.

As argued by Neubauer (1988), the phenomenon of demanding a high-tech building can be explained by the *Hierarchy of Human Needs*, which was developed by Maslow in 1954. Maslow's human needs theory begins with physiological needs at its base and then ascends through safety, social and esteem needs levels to self-actualisation needs at its top (Figure 3.3). To apply this theory to the concept of intelligent building, people initially use buildings to meet their basic physiological needs in terms of heating, air conditioning, ventilation, lighting and water. The next stage involves the requirements of satisfying their safety needs from the standpoint of security and fire protection. Building intelligence then appears in the form of information systems designed to better meet physiological and safety needs by automatically monitoring and managing energy consumption, security, fire protection and the ever-rising needs of building end-users (Neubauer, 1988). However, the sole emphasis of advanced technology in intelligent building has been criticised by many researchers. For example, both Hartkopf *et al.* (1997) and Preiser and Schramm (2002) point out that the focus of the intelligent building is not only on its technological advancement but also on the building users and their needs.

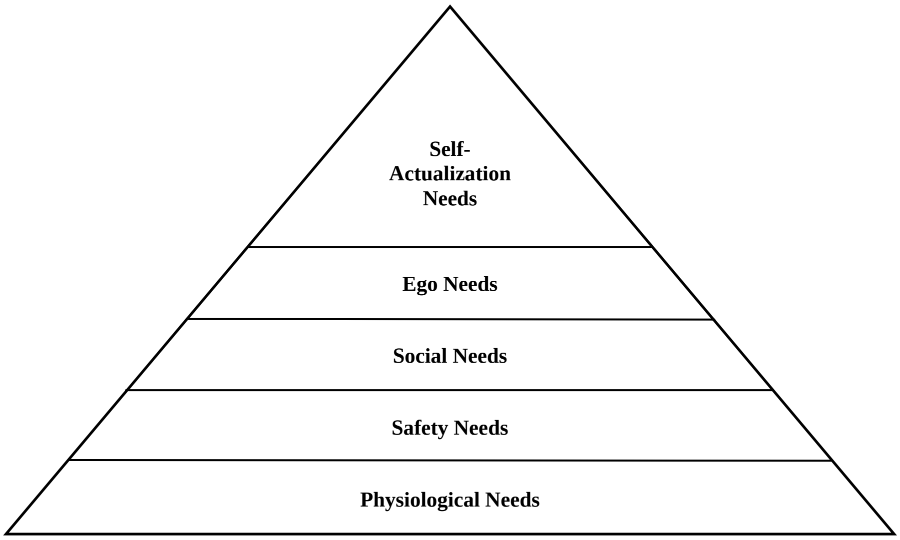


Figure 3.3: A Hierarchy of Human Needs

(Source: Neubauer, 1988: 4)

3.4.6 Safety Related Factor

The final proposed factor for intelligent building components selection relates to the safety issue. For the protection of human beings, safety is considered as an important goal that cannot be tampered with in the design of the building systems of the intelligent building (Becker, 2002). Of all the building services concerned, the safety issues of lift control systems (LS) and fire detection systems (AFA) are a major concern in the intelligent building (So and Chan, 1999). For example, AIIB (2004) argues that it is important for a lift control system in the intelligent building to detect and identify trapped passengers inside a lift car.

3.5 CONCEPTUAL FRAMEWORK FOR THE SELECTION OF INTELLIGENT BUILDING CONTROL SYSTEMS

A review of the literature on intelligent buildings indicates that the research in the selection of building control systems is segmented. Past research lacks general agreement on the selection variables and is also short of a developed model of general critical criteria for the evaluation and selection of the building control systems. Researchers have proposed different criteria for evaluating and selecting the different building control systems in intelligent buildings (for example: AIIB, 2001; Myer, 1997; Piper, 2002; Dwyer, 2003; Finch, 1998 and 2001; Bushby, 1997; Smith, 2002; Curtis, 2001; Clements-Croome, 2001a; Armstrong *et al.*, 2002; Chow and Chow, 2005; Luo *et al.*, 2002; Shanghai Construction and Management Committee, 2001; Tränkler and Kanoun, 2001; Wang and Jin, 2000; Pan *et al.*, 2003; Alcalá *et al.*, 2004; Reffat and Harkness, 2001; Earp *et al.*, 2004; Chebrolu *et al.*, 2005; Hetherington, 1999; Siikonen, 1997; Fong *et al.*, 2006; Canbay *et al.*, 2004; Liu *et al.*, 2002; Mügge, 2001; Schofield *et al.*, 1997; Yost and Rothenfluh, 1996; Atif and Galasiu, 2003; and, So and Yu, 2001). The proposed selection criteria were identified from the literature and were grouped under their relevant singular factor. Table 3.1 summarises the factors and their associated criteria for each of the seven key intelligent building systems.

Using the concepts developed from the review above, a conceptual framework summarising the proposed critical selection factors and criteria of the optimal building systems for the intelligent building is illustrated in Figure 3.4. Under each of the selection factors, there are common criteria and specific criteria for individual intelligent building systems. Common criteria are selection criteria that are found in every building control system, while specific criteria are found in only some of the building control systems. This suggests that the selection decision is complicated by a multitude of decision factors, criteria and options available. As a result, the nature of the problem fits nicely with multi-criteria decision making (MCDM) (Wong and Li, 2006) as mentioned in Chapter 2. Using a multiple criteria decision approach, each intelligent building control system can be evaluated and rated in order to ascertain its performance potential.

3.6 CHAPTER SUMMARY

This chapter provided a critical review of the literature related to the existing research limitations and practical problems in the selection and evaluation of the intelligent building control systems. It suggested that the current research is fragmented, lacking general agreement on the selection crucial factors and criteria. A detailed discussion of the general selection factors was presented in this chapter, which was intended to provide the basis for developing a general conceptual model for the evaluation and selection of the seven key building control systems of the intelligent building.

Table 3.1: List of Predominant Intelligent Building Control Systems Selection Criteria Proposed in Literature

Intelligent Building Control Systems/ **Selection Factors and Criteria**	**Authors**																												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Integrated Building Management System (IBMS)																													
Cost Effectiveness																													
Initial costs		✓	✓							✓																			
Operating and maintenance costs		✓	✓					✓		✓																			
Work Efficiency																													
Grade/level of system	✓																												
Integration/interface with service control systems		✓	✓	✓	✓																								
Compliance with standard		✓	✓	✓	✓	✓																							
Compatible with different network protocols							✓	✓																					
System reliability and stability			✓						✓																				
Efficiency and accuracy			✓						✓																				
Further upgrade of system			✓																										
Frequency of maintenance			✓																										
Remote monitoring and control				✓	✓																								
Service life										✓																			
Telecom and Data System (ITS)																													
Cost Effectiveness																													
Initial costs		✓								✓	✓																		
Operating and maintenance costs		✓								✓																			
Work Efficiency																													
Transmission rate	✓										✓																		
System reliability and stability	✓										✓																		
Electromagnetic compatibility	✓																												
Provision of fibre digital data interface (FDDI)	✓																												
Further upgrade of system							✓																						
Service life										✓																			
Technological Related																													
Existence of advanced IT system	✓						✓	✓																					
Addressable Fire Detection and Alarm System (AFA)																													
Cost Effectiveness																													
Initial costs		✓								✓																			
Operating and maintenance costs		✓								✓																			

Table 3.1: List of Predominant Intelligent Building Control Systems Selection Criteria Proposed in Literature (cont.)

Intelligent Building Control Systems/ Selection Factors and Criteria	Authors																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Addressable Fire Detection and Alarm System (AFA)																													
Safety Related																													
Compliance with the code of minimum fire service installations or equipment	✓											✓																	
Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	✓											✓																	
Work Efficiency																													
Ability of automatic detection of flame/smoke/gas	✓												✓	✓	✓														
Remote control	✓				✓		✓																						
System response time and survivability	✓																												
Comprehensive scheme of preventive maintenance	✓																												
Service life										✓																			
Further upgrade of system												✓																	
System interface with other building systems		✓																											
Integration with IBMS		✓												✓															
Technological Related																													
Artificial intelligent (AI) based supervisory control	✓												✓																
System modernisation	✓																												
HVAC Control System																													
Cost Effectiveness																													
Initial costs		✓								✓																			
Operating and maintenance costs		✓								✓																			
Work Efficiency																													
System reliability and stability	✓																												
Detection of refrigerant leakage	✓																												
Detection of condensate drain water leakage	✓																												
Service life										✓																			
Further upgrade of system		✓																											
System interface with other building systems		✓																											
Integration with IBMS		✓												✓															
Environmental related																													
Energy recycling	✓																												
Total energy consumption	✓	✓														✓	✓	✓							✓				

Table 3.1: List of Predominant Intelligent Building Control Systems Selection Criteria Proposed in Literature (cont.)

Intelligent Building Control Systems/ Selection Factors and Criteria	Authors																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
HVAC Control System																													
User Comfort																													
Control of predict mean vote (PMV)	✓										✓							✓											
Control of indoor air quality (IQA)	✓									✓		✓					✓	✓	✓										
Optimum overall thermal transfer value (OTTV)	✓																												
Provision of adequate fresh air changes	✓																		✓										
Minimisation of noise level from ventilation and A/C	✓																		✓										
Control of odour	✓																	✓	✓										
Technological Related																													
Artificial intelligent (AI) based supervisory control	✓	✓												✓				✓											
System modernisation							✓																						
Digital Addressable Lighting Control System (DALI)																													
Cost Effectiveness																													
Initial costs		✓								✓																			
Operating and maintenance costs		✓								✓																			
Work Efficiency																													
Permanent artificial lighting average power density		✓					✓																						
Uniformity of lux level		✓																											
Automatic control and adjustment of lux level		✓																											
Frequency of system maintenance		✓																										✓	
Service life										✓																			
Further upgrade of system		✓																											
System interface with other building systems		✓																											
Integration with IBMS		✓																											
User Comfort																													
Adequate daylighting	✓																		✓	✓									
Ventilation for excessive heat from lighting	✓																												
Minimisation of noise from luminaries	✓																												
Ease of control	✓																												
Acceptable average colour temperature	✓																		✓										
Suitable colour rendering	✓																		✓										
Suitable glare level	✓																		✓										

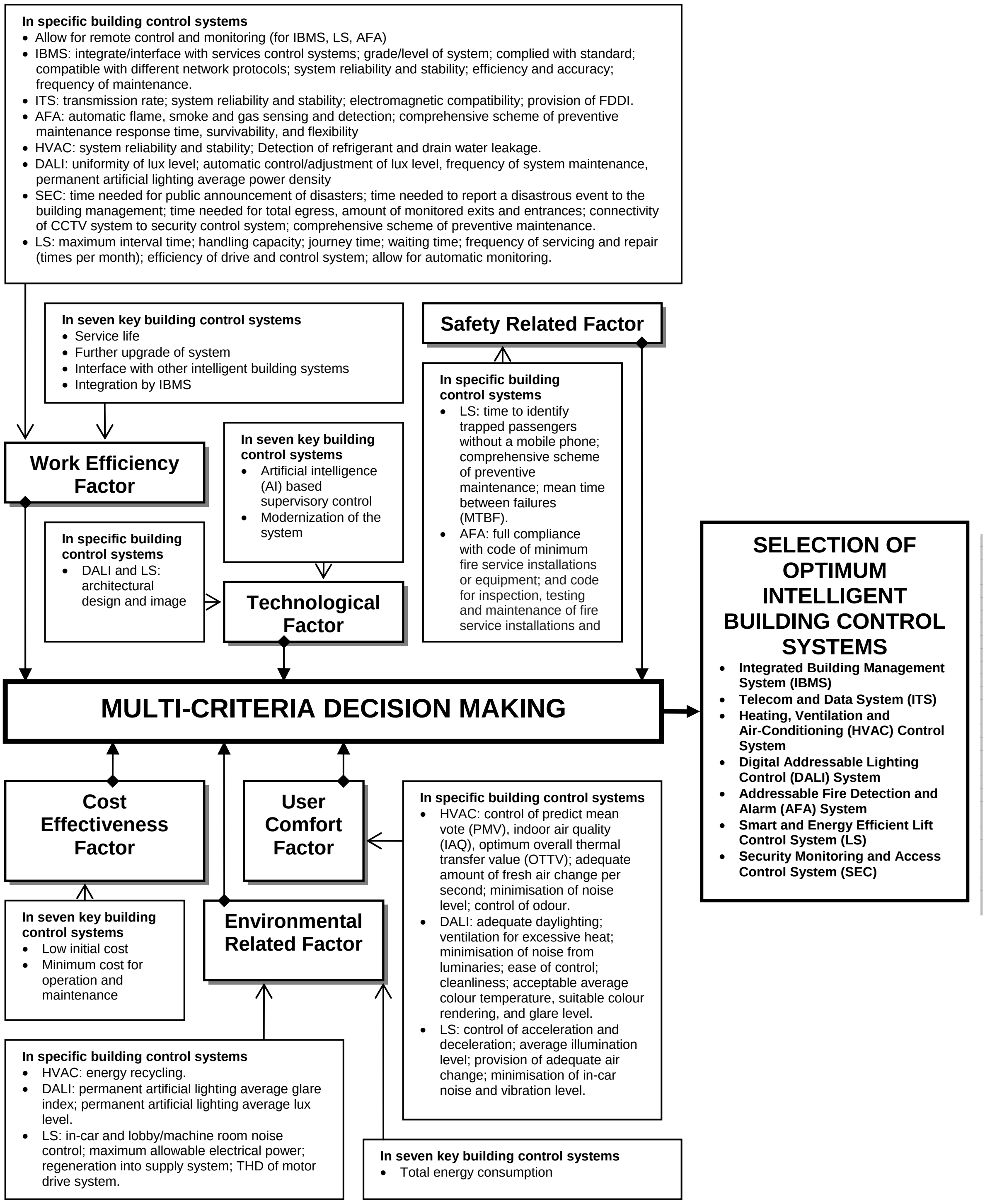
Table 3.1: List of Predominant Intelligent Building Control Systems Selection Criteria Proposed in Literature (cont.)

Intelligent Building Control Systems/ Selection Factors and Criteria	**Authors**																												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Security Monitoring and Access System (SEC)																													
Environmental Related																													
Permanent artificial lighting average glare index	✓																												
Permanent artificial lighting average lux level	✓																												
Total energy consumption	✓																		✓										
Technological Related																													
Artificial intelligent (AI) based supervisory control	✓																												
System modernization	✓																												
Cost Effectiveness																													
Initial costs		✓								✓																			
Operating and maintenance costs		✓								✓																			
Work Efficiency																													
Time needed for public announcement of disasters	✓																				✓								
Time needed to report disastrous event to building management	✓																				✓								
Time for total egress	✓																				✓								
Connectivity of CCTV system to security control system	✓													✓							✓	✓							
Amount of monitored exits and entrances	✓																												
Comprehensive scheme of preventive maintenance	✓																				✓								
Service life	✓																												
Further upgrade of system		✓																											
System interface with other building systems		✓		✓																		✓							
Integration with IBMS		✓																											
Technological Related																													
Artificial intelligent (AI) based supervisory control	✓																												
System modernization	✓						✓																						
Smart and Emery Efficient Lift System (LS)																													
Cost Effectiveness																													
Initial costs		✓								✓																			
Operating and maintenance costs		✓								✓																			
Work Efficiency																													
Maximum interval time	✓																						✓	✓			✓		
Handling capacity																								✓					✓
Journey time	✓																						✓	✓			✓		✓

Table 3.1: List of Predominant Intelligent Building Control Systems Selection Criteria Proposed in Literature (cont.)

Intelligent Building Control Systems/ Selection Factors and Criteria	Authors																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Smart and Emery Efficient Lift System (LS)																													
Work Efficiency																													
Waiting time	✓																						✓	✓			✓		✓
Frequency of servicing and repair	✓																												
Efficiency of drive and control system	✓																												
Automatic and remote monitoring	✓																												
Service life										✓																			
Further upgrade of system		✓																											
System interface with other building systems		✓									✓																		
Integration with IBMS		✓																											
User Comfort																													
Control of acceleration and deceleration	✓																												
Average illumination	✓																												
User Comfort																													
Provision of adequate air change	✓																												
Minimisation of in-car noise level	✓																												
Minimisation of in-car vibration level	✓																												
Environmental Related																													
Total energy consumption	✓																					✓							
In-car and lobby noise control	✓																												
Machine room noise control	✓																												
Maximum allowable electrical power	✓																												
Total harmonics distortion (THD) of motor drive systems	✓																												
Regeneration into supply system	✓																												
Technological Related																													
Artificial intelligent (AI) based supervisory control	✓																									✓			
System modernization	✓																												
Architectural design/ image	✓																												
Safety Related																													
Time to identify trapped passengers without a mobile phone	✓																												
Mean time between failures per month	✓																												
Safety regulations compliance	✓																												

Notes: 1= AIIB (2001); 2= Myer (1997); 3= Piper (2002); 4= Dwyer (2003); 5= Finch (1998); 6= Bushby (1997); 7= Best and de Valence (2002); 8= Finch (2001); 9= Curtis (2001); 10= Clements-Croome (2001a); 11= Armstrong *et al.* (2002); 12= Chow and Chow (2005); 13= Luo *et al.* (2002); 14= Shanghai Construction and Management Committee (2001); 15= Tränkler and Kanoun (2001); 16= Wang (2000); 17= Pan *et al.* (2003); 18= Alcalá *et al.* (2004); 19= Reffat and Harkness (2001); 20= Earp *et al.* (2004); 21= Chebrolu *et al.* (2005); 22= Hetherington (1999); 23= Siikonen (1997); 24= Chu *et al.* (2003); 25= Fong *et al.* (2006), Canbay *et al.* (2004), Liu *et al.* (2002) and Mügge (2001); 26= Schofield *et al.* (1997); 27= Yost and Rothenfluh (1996); 28= Atif and Galasiu (2003); 29= So and Yu (2001)



In specific building control systems
- Allow for remote control and monitoring (for IBMS, LS, AFA)
- IBMS: integrate/interface with services control systems; grade/level of system; complied with standard; compatible with different network protocols; system reliability and stability; efficiency and accuracy; frequency of maintenance.
- ITS: transmission rate; system reliability and stability; electromagnetic compatibility; provision of FDDI.
- AFA: automatic flame, smoke and gas sensing and detection; comprehensive scheme of preventive maintenance response time, survivability, and flexibility
- HVAC: system reliability and stability; Detection of refrigerant and drain water leakage.
- DALI: uniformity of lux level; automatic control/adjustment of lux level, frequency of system maintenance, permanent artificial lighting average power density
- SEC: time needed for public announcement of disasters; time needed to report a disastrous event to the building management; time needed for total egress, amount of monitored exits and entrances; connectivity of CCTV system to security control system; comprehensive scheme of preventive maintenance.
- LS: maximum interval time; handling capacity; journey time; waiting time; frequency of servicing and repair (times per month); efficiency of drive and control system; allow for automatic monitoring.

In seven key building control systems
- Service life
- Further upgrade of system
- Interface with other intelligent building systems
- Integration by IBMS

Safety Related Factor

In specific building control systems
- LS: time to identify trapped passengers without a mobile phone; comprehensive scheme of preventive maintenance; mean time between failures (MTBF).
- AFA: full compliance with code of minimum fire service installations or equipment; and code for inspection, testing and maintenance of fire service installations and

Work Efficiency Factor

In seven key building control systems
- Artificial intelligence (AI) based supervisory control
- Modernization of the system

In specific building control systems
- DALI and LS: architectural design and image

Technological Factor

MULTI-CRITERIA DECISION MAKING

SELECTION OF OPTIMUM INTELLIGENT BUILDING CONTROL SYSTEMS
- **Integrated Building Management System (IBMS)**
- **Telecom and Data System (ITS)**
- **Heating, Ventilation and Air-Conditioning (HVAC) Control System**
- **Digital Addressable Lighting Control (DALI) System**
- **Addressable Fire Detection and Alarm (AFA) System**
- **Smart and Energy Efficient Lift Control System (LS)**
- **Security Monitoring and Access Control System (SEC)**

Cost Effectiveness Factor

User Comfort Factor

In specific building control systems
- HVAC: control of predict mean vote (PMV), indoor air quality (IAQ), optimum overall thermal transfer value (OTTV); adequate amount of fresh air change per second; minimisation of noise level; control of odour.
- DALI: adequate daylighting; ventilation for excessive heat; minimisation of noise from luminaries; ease of control; cleanliness; acceptable average colour temperature, suitable colour rendering, and glare level.
- LS: control of acceleration and deceleration; average illumination level; provision of adequate air change; minimisation of in-car noise and vibration level.

In seven key building control systems
- Low initial cost
- Minimum cost for operation and maintenance

Environmental Related Factor

In specific building control systems
- HVAC: energy recycling.
- DALI: permanent artificial lighting average glare index; permanent artificial lighting average lux level.
- LS: in-car and lobby/machine room noise control; maximum allowable electrical power; regeneration into supply system; THD of motor drive system.

In seven key building control systems
- Total energy consumption

Figure 3.4: A Conceptual Framework Summarising the Selection Factors and Criteria of Optimal Building Control Systems for the Intelligent Buildings

CHAPTER 4

MEASURING THE DEGREE OF SYSTEM INTELLIGENCE IN BUILDING CONTROL SYSTEMS

"The ability to carry out a competent literature review is an important skill for the researcher. It helps to place your work in the context of what has already been done, allowing comparisons to be made and providing a framework for further research. While this is particularly important, indeed will be expected, if you are carrying out your research in an academic context, it is probably a helpful exercise in any circumstances. Spending some time reading the literature relevant to your research topic may prevent you from repeating previous errors or re-doing work which has already been done, as well as giving you insights into aspects of your topic, which might be worthy of detailed exploration."

(Blaxter et al., 1996: 16)

4.1 INTRODUCTION

This chapter reviews the literature on the system intelligence of building control systems. It first presents and discusses the concept of intelligence and follows with a review of the prevailing methodologies of building and machine intelligence measurement. The chapter ends with an introduction of the conceptual framework for measuring the degree of system intelligence in building control systems, which is drawn on Bien's *et al.* (2002) concept of machine intelligence.

4.2 THE CONCEPT OF INTELLIGENCE

How intelligence can be measured is evidently dependent on how building intelligence is defined, and thus the evaluation of building intelligence should be commenced with a review of the concept of intelligence. The establishment of a more formal definition of what constitutes intelligence would also benefit the discipline of intelligent building control and its practitioners (Meystel and Messina, 2000). The discussion of the concept of intelligence is generally divided into ‘human intelligence’ and ‘building intelligence’ in the subsequent sections.

4.2.1 Human Intelligence

The meaning of intelligence, particularly in terms of human intelligence, has been considered a controversial subject (Albus, 2000). Over the last one hundred years, a number of studies have been developed about what ‘human intelligence’ means. The word ‘intelligence’ is originally derived from a Latin word ‘*intelligentia*’, which comes from ‘*intelligere*’, meaning to discern or select (Wigginton and Harris, 2002). In the Oxford English Dictionary, intelligence is defined as the ‘power of learning, understanding and reasoning; or a mental ability’ (Cowie, 1993). Since early last century, academics and scholars have defined intelligence in so many different ways that it is impossible to arrive at a consensus. For example, in his book “General Intelligence”, Spearman (1904, citied in Bien *et al*., 2002), proposes the case that human intelligence is basically characterised by a single general intelligent factor, *mental energy*. Thurstone (1924, citied in Bien *et al.*, 2002) has, in addition, identified seven additional specific factors of human intelligence, which include verbal comprehension, word fluency, number skills, spatial relations, associative memory, perceptual speed and general reasoning. As argued by Bien *et al.* (2002), these early interpretations, however, abbreviate the concept of intelligence.

In the last fifty years, a number of definitions of human intelligence have been developed. Cattell (1968) sorts human intelligence into two groups, crystallised intelligence (breadth and depth of knowledge) and fluid intelligence (ability to reason quickly without specific reference and to distinguish patterns of relationships). Heim (1970) also suggests five factors of the real human intelligence. These factors include an ability to learn, an ability to adjust and adapt to cope with new situations, an ability to inhibit instinctive responses, and an ability to anticipate the future. Most recently, a theory of multiple intelligences was proposed by Gardner (1997). In his book 'Extraordinary Minds', Gardner suggests that there are seven abilities and skills that constitute intelligence, namely linguistical, logical-mathematical, spatial, musical, bodily kinesthetic, understanding of people and oneself, and understanding the link between the human and natural worlds. Recently, Albus (2000) categorised three hierarchical levels of intelligence. The lowest level of intelligence requires the ability to sense the environment, to make decisions and to control action. The middle levels of intelligence may include the ability to recognise objects and events, to represent knowledge in a world model and to reason about and plan for the future. At the highest levels, intelligence provides the capacity to predict the future, to perceive and understand what is going on in the world, to choose wisely and to act successfully under a large variety of circumstances so as to survive, prosper and replicate in a complex, competitive and often hostile environment.

In addition to the above debates, intelligence is also perceived differently in control and psychological theories. Control theory suggests that intelligence is ‘a phenomenon which emerges as a result of the integration of knowledge and feedback into a sensory-interactive, goal-directed control system that can make plans and generate effective purposeful actions to achieve goals’. In contrast, in the psychological or biological schools of thought, intelligence is referred to a ‘behavioural strategy that gives each individual a means for maximising the likelihood of success in achieving its goals in an uncertain and often hostile environment’ (Albus, 2000: 2). Contradicting the definitions from control theory, psychological or biological perceptions of intelligence highlight the integration of perception, reason, emotion and behaviour in a sensing, perceiving, knowing, feeling, caring, planning and acting system that can formulate and achieve goals.

4.2.2 Building Intelligence

With increasing application of advanced microprocessor and information technologies to building environments over the past two decades, the debate of the perspective of intelligence has extended to buildings. Early in this debate, Piaget (1980) argued that intelligence was a complex hierarchy of information processing skills, underlying an adaptive equilibrium between individuals and their environment. Piaget’s definition highlighted the significance of interaction between those people working or living in a building and its micro-climate, the building fabric and the external environment (Clements-Croome, 2004). Boyd and Jankovic (1994) point out that a building with real intelligence should be able to “respond automatically to external changes; learning from the past in order to provide a more optimum solution for the future”. On the other hand, Smith (2002: 36) argues for two perspectives of intelligence in the modern building. One view is related to how the building responds to change, while the other view is closely related to adaptability. As such, a real intelligent building is considered as one which is ‘able to respond and adapt in all these ways’.

Despite these efforts, Wigginton and Harris (2002) review the concepts of building intelligence and argue that many of the existing definitions have focused on the ability of the building components to enter into the realm of artificial intelligence (AI). In fact, AI relates to the capacity of an object to perform similar functions to those that characterise human behaviour by emulating the thought process of living beings. It is a manner to imitate the human capacity to process information by learning, inferring and making and acting on decisions. However, AI is also criticised for not approaching the true complexity of intelligent and cognitive thought (Wigginton and Harris, 2002: 17). McCarthy (2002) also points out that AI is only considered as “the science and engineering of making intelligent machines, especially intelligent computer programs”. It relates to the similar task of using computers to understand human intelligence, but it is unable to confine itself to methods to those that are biologically observable.

Wigginton and Harris (2002) maintain that in the consideration of real ‘building intelligence’, biological behaviours (or ‘natural intelligence’) must be incorporated into all of the reactive and cognitive actions. The concept of natural intelligence (NI) relates to ‘aspirations of appropriating or devising faculties found in living beings, and the biological capacity’ (Wigginton and Harris, 2002: 18). According to Benzon and Hays (1988), the principles of NI can be grouped into five classes: feeling**,** coherence, action, finitisation and analysis. Wigginton and Harris (2002) suggest that an example of the closest biological comparisons for the intelligent building is the installed sensors of a building which are able to detect fire and intruders in the same way that the human senses detect danger. From the review above it comes to an argument that a building with real intelligence should behave in such a way as to be more closely related to the realms of both artificial intelligence (AI) and natural intelligence (NI) with the ability to respond and react to external stimuli in a predictable manner (Wigginton and Harris, 2002).

4.3 EXISTING BUILDING INTELLIGENCE ASSESSMENT METHODOLOGIES

For the past decade, building intelligence has been increasingly perceived by developers as a unique and important measure to reflect the specific performance and properties of intelligent buildings. According to Smith (2002), developers have increasingly acknowledged the direct relationship between a building's intelligence and its value, as the attributes of the intelligent building can make it attractive to prospective buyers. The attributes also provide an environment which will promote maximum profitability for their own business.

A review of intelligent building literature in Chapter 2 briefly indicates that many methods and techniques have been documented to benchmark the intelligent performance of the intelligent building. Less clear in the past research, however, is a detailed understanding towards the measurement of the degrees of system intelligence in the building systems. In contrast, a well defined theory of machine intelligence does exist outside the intelligent building literature. Many of them have been developed in the field of advanced engineering. An overview of existing studies of building intelligence assessment in both intelligent building and engineering literature is presented in the following section.

4.3.1 Building Intelligence Evaluation

The models of building intelligence evolve from early intelligent building performance evaluation studies and refine them. Examples of pioneer building intelligence rating methods include the Orbit 2.1 (Davis *et al.*, 1985), Post Occupancy Evaluation (Preiser *et al*, 1988), Building-In-Use assessment methods (Dillon and Vischer, 1987), BREEAM (Baldwin *et al.*, 1990), and Environmental Impact Analysis (Rau and Wooten, 1980). Each of the aforementioned authors or research bodies has used a different approach to examine the performance of the intelligent building. However, these models delved more specifically into the environmental impacts and the evaluation of physical parameters. Boyd and Jankovic (1994) argue that these approaches insufficiently reflect the degree of intelligence of the building.

Boyd and Jankovic (1994) combine the essential features of performance rating methodologies from past intelligent building research and propose a building intelligence measure named *Building IQ* to evaluate a combination of individual user needs, organisation/owner needs and local and global environmental needs. Boyd and Jankovic argue that such a rating system allows both positive and negative derivations from the generic profile of similar buildings, and the results reflect both under-provision and over-provision of building technologies. Despite this, Harrison *et al.* (1998: 133) argue that the model by Boyd and Jankovic contains problems in the collection of qualitative data and the determination of relevant building intelligence factors.

A few years later, Arkin and Paciuk (1995) proposed a quantitative score approach, *Magnitude of Systems Integration,* to quantify building intelligence in terms of the building systems installed and the level of integration that exists between them. The scoring method of Arkin and Paciuk is based on a rating scale for systems integration with the lowest rating reserved for buildings with no systems integration and the highest rating reserved for the comprehensive integration of building systems across the entire building information spectrum. The most distinctive contribution of the score model is that it provides a readily understandable comparison of buildings for the purpose of assessing the level of intelligence of a building (Smith, 2002). However, the limitation of Arkin's and Paciuk's work is that it is limited to the tangible aspect of the intelligent building (Smith, 2002: 55).

Considering the significance of both tangible and intangible aspects of the intelligent building in the assessment of building intelligence, Smith (1999) developed two building intelligence measures: '*Reframing*' and '*Building Intelligent Assessment Index (BIAI)*'. The former approach focuses on the measurement of the enabling ability of intelligent buildings to meet organisational objectives through the examination of the organisational structure, politics, human resources and culture. The latter approach aims to assess the level of building intelligence through seven key building characteristics: site specification, operational cost, intelligent architecture, identity, intelligent technology, system responsiveness, and access and security. However, both measures are considered incomplete as the ‘reframing’ approach is limited to an analysis of the intangible aspects of organisations and their relationship with the building they occupy, while the ‘*Building Intelligent Assessment Index (BIAI)*’ is restricted to the evaluation of the structures and systems associated with intelligent building (Smith, 2002).

Besides the works of these academics, a number of professional institutes have published their intelligent performance assessment tools and standards for the intelligent building. For example, as discussed in a previous chapter, the AIIB (2001 and 2004) in Hong Kong developed a few editions of ‘Intelligent Building Index (IBI)’ in an attempt to categorise the intelligent performance of the entire intelligent building. The latest version of IBI covers ten ‘Quality Environment Modules (QEM)’, which include green, space, comfort, working efficiency, culture, high-tech image, safety and security, construction process and structure, cost effectiveness, and health and sanitation. Each index possesses a score which is a real number (within the range of 1 to 100) calculated by a conversion formula. A building is ranked from Class A to E to indicate the overall intelligent performance. However, Chen *et al.* (2005) recently criticised the work of AIIB for its lack of reliability in its calculation method for four reasons: non-determinism of criteria, non-sequitur calculation method, non-uniqueness of calculation results, and non-organisational judgment of assessment procedures.

Overseas, the Intelligent Building Society of Korea (IBSK) (2002) established an ‘Assessment Standard for Certifying Intelligent Building (ASCIB)’. The ratings of intelligent buildings consist of six specialised fields which include architectural environment & services, mechanical systems, electrical systems, information and communication, system integration, and facility management. However, in line with the problems in Boyd’s and Jankovic’s model (1994) stated earlier, a problem with IBSK’s work is that it includes the employment of occupation density as one indicator to assess architectural environment and services of intelligent buildings (Chen *et al.*, 2005). Such measurement implies that a building with a larger occupation area will get a higher ‘intelligent’ score. Most recently, a new building intelligence assessment tool, the Intelligent Building Ranking Method, has begun development by the project Task Force 1 of the Continental Automated Building Association (CABA, 2004). This method focuses on the evaluation of the level of integrated systems within an intelligent building. The model, however, is still under initial development.

Given the above literature review, it can be seen that the majority of the past research in building intelligence have been limited to assessing the overall intelligent performance of buildings and classifying them into particular forms of simplified and generic indexes of intelligence (Wong *et al.*, 2005). However, little is done on the assessment of the system intelligence of building control systems. Furthermore, a plethora of intelligent components and products have been introduced and made available in the building markets over the last twenty years. The adjective “intelligent” has been extensively applied to portray the smart properties of the building system products. Manufacturers of intelligent technologies often claim their systems are more intelligent than others of their kind, but these assertions tend to be vague and unjustified (Bien *et al.*, 2002). Considering the existing problems in the research as well as in practice, a new index that represents the degree of system intelligence and indicates the desirable goal in designing intelligent building control systems must be developed (Schreiner, 2000; and Park *et al.*, 2001). Therefore, the important issues are to investigate and determine how to measure the system intelligence, and to determine the key intelligence indicators for assessing the degrees of system intelligence of the building control systems in intelligent buildings.

4.3.2 Machine Intelligence Measurement

While there is a dearth of research investigating the degree of intelligence of building control systems in intelligent building and construction literature, some closely related studies in machine intelligence measurement have been documented in engineering literature over the past decade (Szu, 2000; Park *et al.*, 2001; Bien *et al.*, 1998 and 2002). For example, in the 1990s Saridis and his colleagues (Saridis, 1991; Valavanis and Saridis, 1992; and, Lima and Saridis, 1993 and 1996) developed a series of analytical models to describe and control various functions of intelligent machines according to the 'principle' of increasing precision with decreasing intelligence. Zadeh (1994), in his discussion paper, identifies the key factor to making machine intelligence as the use of soft computing techniques to mimic the ability of the human mind in effectively employing modes of reasoning, which are approximate rather than exact. Despite these efforts, Antsaklis (2000) and Bien *et al.* (2002) criticise early studies in machine intelligence for being focused on developing a way to make a system or a machine more intelligent. Little attention is paid to the measurement and assessment of the degree of intelligence in existing systems or machines.

In recent years, a breakthrough has been recorded in machine system research. In an investigation of the intelligent characteristics of a controller, Zames (reported by Antsaklis, 2000) developed a machine intelligence quotient (MIQ) to measure the task performances that an intelligent controller can achieve compared to those achieved by a classical controller. While Zames' work was an important initial step in establishing the benchmark for machine intelligence measurement, Antsaklis (2000) argued that the challenge in the quotient development is related to the 'characterization of performance in unknown environments, learning, controller and task complexity, and associated tradeoffs'. On the other hand, Szu (2000) proposed a machine IQ measure by a logarithmic-like non-linear but monotonic scale with up to 50 percent of the measurement based on the supervised learning capability. The work of Szu is interesting and innovative, but it is considered rather subjective in nature (Bien *et al.*, 2002). Bien *et al.* (2002) argue that intelligence is an entity related to complex and unstructured phenomena which is not a straightforward activity that can easily be measured. Based on the ontological and phenomenological points of view on intelligent machines, Bien *et al.* (1998 and 2002) recently developed a revised Machine Intelligence Quotient (MIQ) for the measurement of the machine IQ. Details of the model of machine intelligence proposed by Bien *et al.* are discussed in the following section.

4.4. THE MACHINE INTELLIGENCE QUOTIENT

Contradicting the works of Zames (stated in Antsaklis, 2000) and Szu (2000), Bien's machine intelligence model is developed from the ontological and phenomenological points of view on intelligent machines and systems. The most distinctive contribution of the framework is that it systematically organises the properties of machine intelligence and provides a quantitative measurement of intelligence. The model generally includes four key attributes of machine intelligence which were identified from a vast review of intelligent control system literature. These four key intelligence attributes are:

- Autonomy;

- Controllability of complicated dynamics;
- Man-machine interaction; and,
- Bio-inspired behaviour.

Each of the four key attributes is discussed as specified below:

4.4.1 Autonomy

Autonomy refers to the abilities of performing self-operative functions (Bien *et al.*, 2002). According to Liu *et al.* (2005), autonomy is generally considered as the condition or quality of being (1) autonomous and independent; and, (2) self-governing or having the right of self-government, self-determining and self-directing. This implies that an intelligent system should be designed in a manner that allows minimum human intervention as much as possible during the execution of a task. Liu *et al.* (2005) elaborate these interpretations and argue that all these conditions or qualities relate to freedom from control by others with respect to primitive behaviour. Strube (1996, cited in van der Vyver *et al.*, 2004) examines the concepts of machine autonomy in the field of artificial intelligence and identified five essential aspects of autonomy:

- The ability to make independent decisions based upon observations, to plan, to draw conclusions and to make judgments concerning consequences;
- The warranty of autonomy through guidelines and policies;
- The independent completion of tasks by combining the planning and controlling steps;
- The ability to learn and eliminate mistakes; and,
- The ability to cooperate, in particular with other machines.

Bien *et al.* (2002) argue that there are four key autonomous features or indicators of intelligent systems. These are (1) self-calibration, (2) self-diagnostics, (3) fault-tolerance and (4) self-tuning. Self-calibration is an autonomous feature as it includes measuring methods and systems which are made tolerant towards realisation errors and deviations of system components by using internal reference quantities and special algorithms (Liu and Frühauf, 1999, and Liu *et al.*, 1999). In the self-calibration algorithm, the reference quantities are measured by the original measuring system, and the calibration factors are determined by using the measuring values.

Liu and Frühauf (1999) define self-diagnostics as the self-correction or self-compensation of short-term stable systematic errors using long-term stable reference quantities and special algorithms. System fault-tolerance, on the other hand, was referred as the ability of a system to avoid failure (i.e. to keep behaving according to specifications) after faults in the system's design/implementation had caused errors (i.e. the appearance of incorrect, contaminated or incoherent states) (Cortellessa *et al.*, 2005). Self-tuning control, in contrast, is based on the principle of separating the estimation of the unknown process parameters from the design of the controller (Swidenbank *et al.*, 1999 and Isermann and Lachmann, 1985). A basic self-tuning adaptive control consists of two loops. The outer loop incorporates the process and a feedback regulator while the inner loop comprises a recursive parameter estimator and a design calculation. Burnham *et al.* (1995) also point out that there are two coupled sub-algorithms included in the basic self-tuning control, one for on-line estimation of the parameters of an assumed model structure, and the other for the implementation of an appropriate control law.

4.4.2 Man-machine Interaction

A second key attribute of intelligent systems and machines is the level of man-machine interaction. This is related to the abilities of an intelligent system to interface with operator and working staff, which make the human users feel more comfortable and the system more user-friendly (Bien *et al.*, 2002).

As pointed out by Cacciabue (1996: 351), there are three reasons driving the adoption of man-machine interaction with system behaviour. First, the technological development and design of mechanical and electronic devices has reached such a stage of accuracy that major mistakes of the machine/system are avoided or counteracted by its protection devices. Second, many human operators in the control loop are removed from direct interaction with the on-going phenomena. They use accurate remote control systems and interact with decision support systems which help in the identification and diagnosis of malfunctions. This forms a new control strategy when the machine/system is managed by collaboration between humans and an 'intelligent' support system. Finally, the complexity of the system under control and the dynamic characteristics of the system/machine lead to 'decision-making tasks which have to be performed in complex working environments and which are very demanding in terms of cognitive and reasoning abilities'.

According to Bálint (1995), a machine or system that is said to allow man-machine interaction needs to fulfil five important requirements. It needs to facilitate satisfactory monitoring of machines by humans, to support human intervention in machine operations, to help human decision-making by providing system state diagnosis and intervention possibilities, to establish error-free or error-tolerating operation of the full system, and to produce efficient and reliable system performance.

Bien *et al.* (2002) also suggest that the intelligent machine and system should possess a number of important man-machine features (or indicators): ergonomic design, emergence of artificial emotion, and human-like understanding or communication. Ergonomic design is considered a main feature of human-friendly interaction between man and machine. Beevis and Slade (2003) point out that the emphasis of ergonomic design was primarily aimed at improving the performance of given man-machine combinations instead of producing improvements in efficiency, which is measured in terms of value added per man hour. The design of ergonomics needs to comply with four objectives: to achieve satisfactory performance by the operator, control and maintenance personnel, to reduce skill requirements and training time, to increase the reliability of personnel-equipment combinations, and to foster design standardisation within and among systems (Beevis and Slade, 2003: 413). Emotion also plays an important role in the human decision-making process (Martínez-Miranda and Aldea, 2005). As argued by Cañamero (2005), in order to make users more prone to accept and engage in interactions with the machine/system, it is crucial for the machine and system to possess the ability to display emotional expressions and to recognise and respond appropriately to the emotional states of the users. This can make them appear more ‘life-like’ and ‘believable’ (Bates, 1994). Furthermore, the intelligent machine and system should be able to interact and make decisions in dynamic, unpredictable and potentially ‘dangerous’ environments. These environments are functionally equivalent to emotions present in biological systems facing the same types of problems (Martínez-Miranda and Aldea, 2005). If those emotions are included in systems that aim to simulate human behaviour in certain circumstances, the system will be user-friendly and act more similarly to human behaviour. Despite this, Martínez-Miranda and Aldea (2005) make an important warning that if human emotions such as anxiety, fear and stress are incorporated into the intelligent systems which deal with complex and critical tasks, the results could be disastrous.

4.4.3 Controllability of Complicated Dynamics

The third key attribute of intelligent machines or systems is their level of control over complicated dynamic systems.

Dynamic systems are systems within which changes occur constantly (Ottosson and Björk, 2004). Bien *et al.* (2002) argue that a system is considered ‘intelligent’ when it possesses the ability to perform interactive operative functions and is able to make a very complicated dynamic system well-controlled. The essence of the controllability feature is its ability to force the system into a particular state by using an appropriate control signal. If a state is not controllable, then no signal will ever be able to force the system to reach a level of controllability (Wikipedia encyclopedia, 2006).

In general, the key features or indicators of controllability for complicated dynamic systems are considered to be non-conventional model-based, adaptation, non-linearity, and motion planning under uncertainty (Bien *et al.*, 2002). Farrell *et al.* (1993) argue that the adaptation ability is different from the learning ability of intelligent systems. The adaptive control has an objective to maintain some desired closed-loop behaviour in the face of disturbances and dynamics that appear to be time-varying, but such control is inefficient for problems involving significant nonlinear dynamics. Thus, non-linearity and uncertainty are regarded as key problems in the development of the dynamic system as they raise various issues associated with estimation, planning or execution control (Fabiani *et al.*, 2002; and Bos and Justel, 2005). Both Tsypkin (1973) and Farrell *et al.* (1993) suggest that the necessity of applying learning arises in situations where ‘a system must operate in conditions of uncertainty, and in a situation when the available *a priori* information is so limited that it is impossible or impractical to design in advance a system that has fixed properties and also performs sufficiently well’.

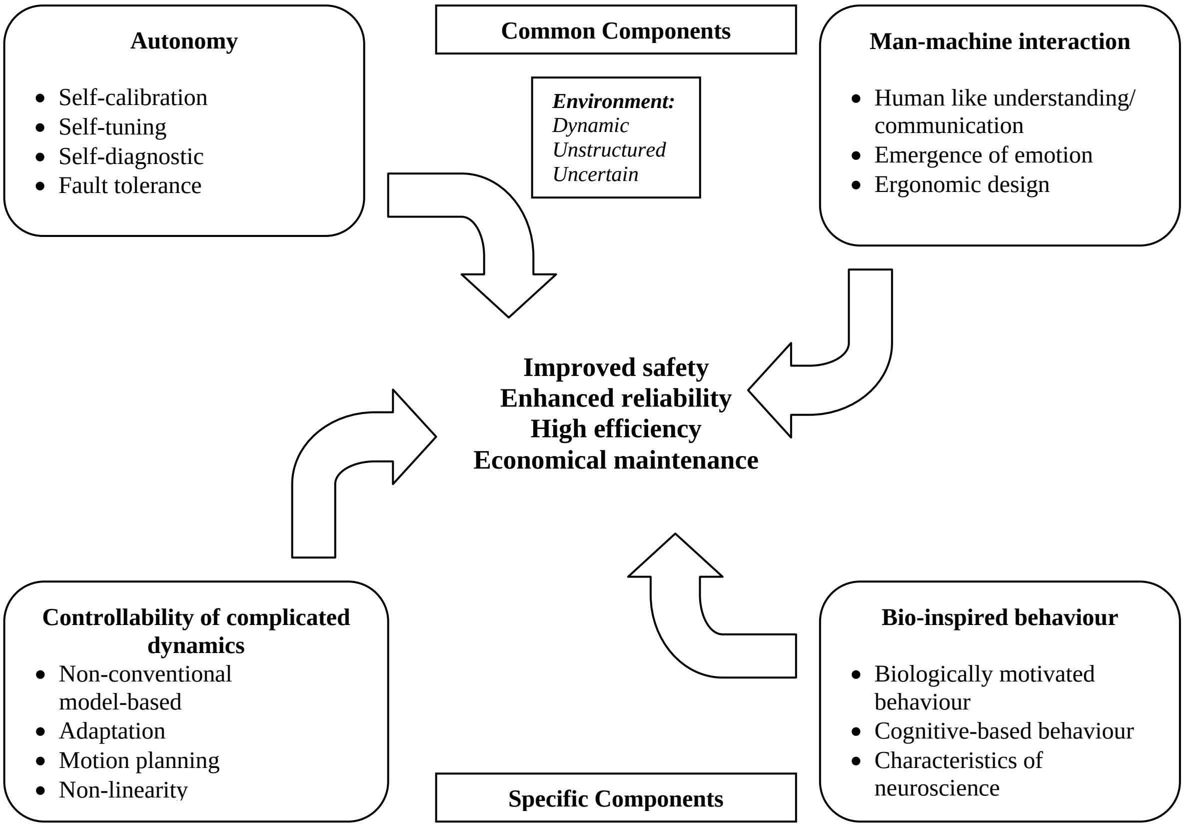
4.4.4 Bio-inspired Behaviour

The last attribute of intelligent systems is the existence of bio-inspired behaviour in the system. According to Bien *et al.* (2002), this relates to the system’s capability of performing bio-inspired behavioural traits, and the system’s ability to interact with the building environment and the services provided. In the design of autonomous intelligent systems or machines, biological organisms have been regarded as a source of inspiration (Steels, 1995; and Floreano and Mondada, 1998). McFarland and Boesser (1993) point out that biological organisms like animals and humans ‘display robust adaptation and stable behaviour in changing environments with minimal external supervision and control’. Floreano and Mondada (1998) also point out that the biological organisms can inspire the development of autonomous systems or machines with respect to a set of fundamental principles, which includes ‘the nature of the adaptation mechanisms, such as philogenetic evolution and ontogenetic learning, the preference for behavioural stability and robustness over precision, self-organization and self-selection of goals and values, and adaptation while interacting with an environment’.

In fact, biological organisms are complex systems exhibiting ‘a range of desirable characteristics that…[have] proved difficult to realize using traditional engineering approaches’ (Teuscher *et al.*, 2003). Within the past few decades, there have been many attempts to design intelligent systems with the features similar to those of biological autonomous agents. Teuscher *et al.* (2003) argue that the biological inspiration in the intelligent system should provide a number of promising characteristics such as fault-tolerance, self-replication or cloning, reproduction, evolution, adaptation and learning, growth, etc. Bien *et al.* (2002) also point out that an intelligent system should exhibit a number of bio-inspired traits: biologically motivated behaviour, cognitive-based behaviour, and characteristics of neuroscience. As defined by the Society of Neuroscience in US (2007), neuroscience is the study of the nervous system which advances the understanding of human thought, emotion, and behaviour. Bien *et al.* (2002) point out that the inclusion of the neuroscience in the investigation of system or machine intelligence provides better understanding of human and animal motor control mechanisms and related sensory systems.

4.4.5 Model of Machine Intelligence

From the above, it can be seen that the theory of machine intelligence by Bien *et al.* (2002) assumes that an intelligent machine or system should be autonomous, be capable of man-machine interaction, exhibit bio-inspired behaved, and possess the ability to control complicated dynamics. Under each of these intelligence attributes, there is a list of indicators. According to Roy (1999: 1-31), an indicator is regarded as ‘an instrument which synthesizes, in qualitative or quantitative terms, certain information which should lay the foundation for a judgment of an action relative to certain of its characteristics or effects (consequences) which might arise from its implementation’. The model further posits that, regardless of the classes of intelligent machines/systems, autonomy and man-machine interaction are considered as two common components, while the controllability for complicated dynamics and bio-inspired behaviour are regarded as a specific components of intelligent systems according to the operational characteristics of the groups. The intelligent system operates under dynamic, unstructured and uncertain environments. Bien *et al.* (2002) further point out that each intelligent system has a unique set of intelligence attributes and measures. Any intelligent system with the four identified intelligence attributes can generally lead to improved safety, enhanced reliability, higher efficiency, and more economical maintenance. The model of machine intelligence is illustrated and presented in Figure 4.1.



Source from Bien et al. (2002: 8)

Figure 4.1: Taxonomy of Key Intelligence Attributes in a General Intelligent Machine or System

4.5 CONCEPTUAL FRAMEWORK FOR MEASURING SYSTEM INTELLIGENCE OF INTELLIGENT BUILDING CONTROL SYSTEMS

In this thesis, the model of machine intelligence by Bien *et al.* is extended to investigate and evaluate the degree of system intelligence of the seven key intelligent building control systems (as identified in Section 2.4). However, the proposed model in this research differs somewhat from that suggested by Bien *et al.* in that the interrelationships between the intelligence attributes of the building control systems and the operational benefits of the intelligent building are taken into consideration. This is based on the argument that the adoption of intelligent technologies in buildings should not be limited to advances in technology, as the abilities of the installed intelligent control systems to enhance the goals or benefits of the clients and end-users are equally significant (Clements-Croome, 2001b; and, Smith, 2002). The model of Bien *et al.* is extended to consider the relationship between the degree of intelligence possessed by the intelligent building control systems and the extent of the expected benefits/goals achieved (Wong and Li, unpublished). In specific, investigating their relationships is based on the assumption that the intelligence attribute(s) of the building control systems (for example, an HVAC control system) will be most important when in achieving the decision maker’s goal of improved operational benefits. In contrast, each intelligence attribute (i.e. autonomous features of an HVAC control system) might have a varied degree of importance in generating four identified operational benefits. The four key operational benefits of intelligent building were discussed in Chapter 2, which are improved operational effectiveness and energy efficiency, enhanced cost effectiveness, increased user comfort and productivity, and improved safety and reliability.

Figure 4.2 provides a general conceptual system intelligence framework for a typical intelligent building control system. In fact, as argued by Bien *et al.* (2002), each intelligent system also possesses a unique set of intelligence attributes and measures (or *indictors*), and this thus implies that each building control system possibly has unique measures of intelligence. The development and tests of the ‘suitable’ indicators of each intelligence attribute will be discussed in details in Chapter 7.

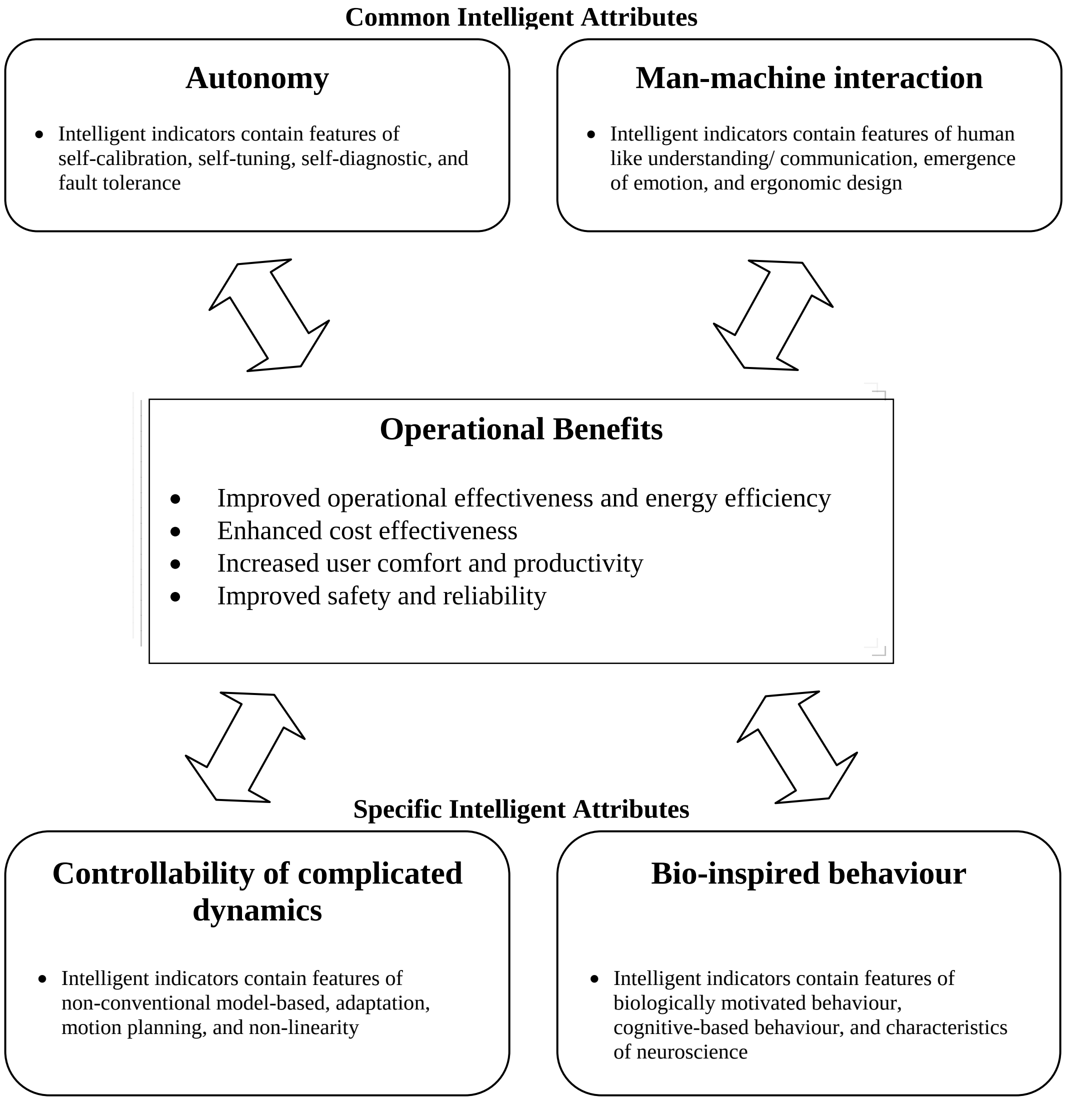


Figure 4.2: Conceptual Framework of System Intelligence of a General Building Control System in the Intelligent Building

4.6 CHAPTER SUMMARY

This chapter discussed the concept of intelligence in various perspectives. A detailed review of previous approaches towards building intelligence assessment and machine intelligence evaluation was presented. Most importantly, the chapter introduced the conceptual framework of the system intelligence of intelligent building systems, which was drawn from the machine intelligence model developed by Bien *et al.* (2002).

CHAPTER 5

METHODOLOGY AND METHOD

“The question ‘quantitative or qualitative?’ is commonly asked, especially by the beginning researchers. Often, they are putting the ‘methods cart’ before the ‘content horse’. The best advice in those cases is to step back from questions of method [and tools], and give further consideration to the purposes and research questions, bearing in mind that the way questions are asked influences what needs to be done to answer them”

(Punch, 1998:245)

5.1 INTRODUCTION

This chapter describes the research methodology and methods that were adopted in this thesis. The first part of this chapter provides a discussion of the methodology and hypotheses of this research. This involves a bibliographic review and discussion of the philosophical aspects of research methodology. The main paradigm adopted is positivistic, with predominantly quantitative data. The methodology adopted is multiple cross-sectional surveys. The second part of the chapter focuses on the discussion of the methods adopted for analysis. The main tests that are employed in this thesis are introduced and justified. The validity and reliability of this research are also addressed.

5.2 RESEARCH METHODOLOGY

Before describing the methodological issues of this research, it is essential to clarify the concepts of *methodology* and *method*. According to Runeson and Skitmore (1999: 39), there are two meanings for the word '*methodology'*. The first meaning concerns the principles and procedures of orderly thought or processes applied to a particular scientific discipline, while the second meaning relates to the branch of logic that deals with the nature of such principles and processes. Hussey and Hussey (1997: 54) referred to *methodology* as the overall approach to the research process, from the theoretical underpinning to the data collection and analysis. It provides the starting point for choosing an appropriate make up of theories, ideas, concepts and definitions of the topic. In this sense, all research and every investigation has a distinct *methodology* which will vary from study to study (Edum-Fotwe *et al.*, 1996). The word *'method'*, on the other hand, refers to the specific means or techniques that are used or available by which data can be collected and/or analysed (Runeson and Skitmore, 1999:39; Hussey and Hussey, 1997: 54).

According to Leedy (1997), research methodology is determined by two factors: *the nature of the data*, and *the problem for research*. Data and methodology are inextricably interdependent. Ng (2003) argues that if the data collected is verbal, the methodology is qualitative, and if it is numerical, the methodology is quantitative. In addition, the type of research problem also influences the choice of research methodology. Research that involves the collection and analysis of empirical evidence can be achieved by broad methodological categories including descriptive or normative surveys, interviews, case studies, and exploratory, experimental, quasi-experimental and statistical-analytical research. Leedy (1997: 108) maintains that in some occasions, a compatibility procedure has to be adopted to reconcile the qualitative and quantitative methodologies by eclectically using elements from each of the major methodologies, as both can contribute to the solution of the major problem.

Referring back to this study, the research problems and objectives are twofold as stated in the introductory chapter. The first research problem, which is identified in Research Part One, involves the development of general conceptual selection evaluation models for the seven key building control and management systems for the intelligent building projects, including the identification of *what* the selection factors and their critical selection criteria (CSC) are, and *how much* strength these CSC have. The second research problem, which is tackled in Research Part Two, deals with the establishment of the conceptual frameworks for measuring the degree of system intelligence of the same seven building control systems. In particular, the focus is on *what* the important ('suitable') intelligence attributes and indicators are, and *how much* strength these intelligent indicators have. The fundamental enquiry is therefore which research methodologies and methods should be adopted for the two different research objectives and associated activities. These issues will be discussed in the subsequent sections of this chapter.

5.2.1 The Quantitative and Qualitative Paradigms

In social science or human research, the design of a research study should always commence with the selection of a topic and a research paradigm (Creswell, 1994:1). According to Oakley (1999: 155), paradigms are ways of 'breaking down the complexity of the real world that tell their adherents what to do'. They help researchers to understand phenomena that advance assumptions about the social world, to improve understanding of how science should be conducted, and they tell them what legitimates problems, solutions, and criteria of "proof" (Creswell, 1994; Gioia and Pitre, 1990; Firestone, 1978; Kuhn, 1970). Phillips (1987) argues that paradigms encompass both theories and methods, although they are often contested and they evolve and differ according to their discipline fields. A review of any standard research textbook (Blaxter *et al.*, 1996; Hussey and Hussey, 1997; Leedy, 1997; Creswell, 1994) suggests that methodologies can be split into two main research paradigms for collecting and analysing data: the *quantitative (or positivistic)*, and the *qualitative (or phenomenological) paradigms*.

The quantitative approach has been referred to as the traditional, the positivist, the experimental, or the empiricist approach (Leedy, 1997: 104). From the epistemological position, the quantitative positivist is concerned with the testing of theories, and this is best achieved through the scientific method. The positivist epistemology is based on the belief that the investigation of human behaviour should be conducted in the similar way as research is conducted in the natural sciences (Toulmin, 1972). Burns (1997:3) explains that quantitative or positivist research approaches are employed in the scientific empirical tradition in attempts to establish universally applicable laws and models. On the other hand, the qualitative approach has been regarded as the interpretative, the naturalistic, the constructivist, or the post-positivist approach (Leedy, 1997). The qualitative naturalist epistemology is concerned with the generation of theories. Loosemore *et al.* (1996) argue that the naturalist aims to investigate the social world as naturally as possible, undisturbed by the researcher. According to this view, research should be carried out with sensitivity to the nature of the setting, and the primary aim should be to describe how those involved experience and perceive the actions of themselves and others (Loosemore *et al.*, 1996).

5.2.2 Philosophical Aspects of the Research Methodology

Understanding the philosophical foundation of the research is important as it improves understanding of the research designs and allows a choice of the most appropriate one to deal with a specific question (Creswell, 1994; and Easterby-Smith *et al.* 1999). Creswell (1994:5) identified five important components of research philosophy, which are *ontological, epistemological, axiological, rhetorical,* and *methodological* aspects. The philosophical basis of the two main research paradigms, i.e. positivistic and phenomenological paradigms, are summarised as follows (Creswell, 1994: 4-7; and Hussey and Hussey, 1997:48-50):

Ontology relates to the study of the nature of being. The ontological positions guide the way research questions are formulated and research is conducted. According to Hussey and Hussey (1997:49), quantitative researchers consider the world as ‘objective and external to the researcher’. Something can be measured objectively by using a questionnaire or an instrument. For the qualitative researcher, the only reality is the one constructed by the individuals involved in the research situation (Creswell, 1994:4). Qualitative researchers need to report these realities truly and to reply on the voices and interpretations of informants. The research in this thesis investigates and identifies the CSC and intelligence indicators of the building control systems in the intelligent building setting. This research concerns the reality of processes in that setting, and therefore the quantitative approach is adopted.

Epistemology is a theory or science of the method or grounds of knowledge. It is concerned with the study of knowledge and what is accepted as being valid knowledge (Hussey and Hussey, 1997). Positivists believe that only phenomena which are observable and measurable can be validly regarded as knowledge (Hussey and Hussey, 1997). They consider that ‘the social world exists externally and that its properties should be measured through objective methods rather than inferred subjectively through sensation, reflection or intuition’ (Easterby-Smith *et al.,* 1999:22). Positivists further believe that the researcher should maintain an independent and objective stance of the subject of research. In surveys and experiments, researchers attempt to control for bias, select a systematic sample, and be ‘objective’ in assessing a situation (Creswell, 1994). In contrast, phenomenologists view the subject matter of the social sciences as fundamentally different from the subject matter of the natural sciences. Phenomenologists consider the world and the ‘reality’ as not objective and exterior. They also attempt to minimise the distance between the researcher and that which is being researched. Qualitative researchers interact with those they study, whether this interaction assumes the form of living with or observing informants over a prolonged period of time, or actual collaboration (Creswell, 1994). In this thesis, the author assumes that both of the CSC and intelligence indicators are measurable. The author also maintains an independent and objective position. Thus, this research is considered as positivist in terms of epistemology.

Axiology refers to the role of the values in a study (Creswell, 1994). Positivists believe that science and the process of research is value-free, detached from what they are researching, and regard the phenomena which are the focus of their research as objects. They are also interested in the interrelationships of the objects they are studying. In contrast, phenomenologists consider that qualitative researchers have values even if they have not been made explicit. These values help to determine what are recognised as facts and the interpretations which are drawn from them. In this research, the author is detached. The ‘facts’ are reported impersonally, and the argument is developed closely from the evidence gathered in the studies.

The above first three philosophical assumptions are interrelated. As argued by Hussey and Hussey (1997), if one assumption is accepted within the positivistic or quantitative paradigm, logically the other two complement it.

In addition, the language of research (‘rhetorical assumption’) is also distinct from the two research paradigms. In qualitative studies, the language is personal, informal, and based on definitions that evolve during a study (Creswell, 1994). In contrast, when a quantitative researcher writes a study, the language should be impersonal and formal. Concepts and variables are well defined from accepted definitions. This orientation marks a quantitative study and directs the research reporting in this research.

From the discussions above, this research has been evidently located in the quantitative paradigm. According to Creswell (1994:7), the relationship between the researcher and that researched, the role of values, and the rhetoric of the study has emerged a methodology. In the quantitative methodology, concepts, variables and hypotheses are chosen before the study begins and remain fixed throughout the study. The intent of the quantitative study is to develop generalisations that contribute to the theory and that enable one to better predict, explain and understand some phenomenon. These generalisations are enhanced if the information and instruments used are valid and reliable. Apart from the above paradigm assumptions consideration, the nature of data collected also dictates the methodology used (Leedy, 1997: 103). Quantitative research is concerned with ensuring that any concepts used can be operationalised, and described in such a way that they can be quantified (Hussey and Hussey, 1997:50). The methodology adopted in this thesis is quantitative because all factual information and knowledge collected, in both parts of this research, is numerical. All collected data is coded and refined in such a way as to allow categorisation and quantification. The main assumptions and features of the quantitative (positivistic) and qualitative (phenomenological) paradigms are summarised and illustrated in Table 5.1.

Table 5.1: Assumptions of the Quantitative and Qualitative Paradigms

Assumptions	Question	Quantitative (Positivistic)	Qualitative (Phenomenological)
Ontological	What is the nature of reality?	• Reality is objective and singular, apart from the researcher	• Reality is subjective and multiple as seen by participants in a study
Epistemological	What is the relationship of the researcher to that researched?	• Researcher is independent from that being researched	• Researcher interacts with that being researched.
Axiological	What is the role of values?	• Value-free and unbiased	• Value-laden and biased
Rhetorical	What is the language of research?	• Formal • Based on set definitions • Impersonal voice • Use of accepted quantitative words	• Informal • Evolving decisions • Personal voice • Accepted qualitative words
Methodological	What is the process of research?	• Deductive process • Cause and effect • Static design-categories isolated before study • Context-free • Generalisations leading to prediction, explanation, and understanding • Accurate and reliable through validity and reliability	• Inductive process • Mutual simultaneous shaping of factors • Emerging design-categories identified during research process • Context-bound • Patterns, theories developed for understanding • Accurate and reliable through verification

Source: Adapted from Creswell (1994:5)

5.3 HYPOTHESES

In Chapter 3 and 4, the theoretical frameworks for the selection evaluation and system intelligence analysis were respectively established to perform the research objectives as stated in Chapter 1. On the basis of these frameworks there are four hypotheses that form the foundation of the research as a theoretical and empirical investigation of the key intelligent building control systems.

The first two hypotheses (*H1* and *H2*) are designed to determine the influences of CSC on the selection of the appropriate intelligent building control systems for the Research Part One. As reviewed in Chapter 3, the selection of building control systems for the intelligent building project is considered as a multi-criteria decision making (MCDM) problem. Literature lacks a general agreement on the selection factors and on a set of associated crucial criteria. Previous studies suggest life cycle cost (LCC) as the key factor to be considered by developers in the selection of intelligent building technologies because it allows them to search for ways to reduce the cost of operating and maintaining the building, and thus increases the building's value (Keel, 2003; and Armstrong *et al.*, 2001). Research also maintains that energy-efficiency and occupants' well-being are two major considerations in the design of the intelligent buildings (Wigginton and Harris, 2002). It is argued that user-comfort is significant when bringing in new technology for the purpose of improving performance of business organisations and minimising environmental deterioration. Furthermore, the capabilities of a system in managing the complexity and enhancing the functionality of the building are considered as requisite aspects of an intelligent building (Smith, 2002). Moreover, building developers aim to generate a high-tech building image by adding in intelligent building components to fulfil the requirement of end-users for access to rapidly changing information technology services (Armstrong *et al.*, 2001).

On the other hand, each intelligent control system is unique and special (Smith, 2002; and Bien *et al.*, 2002). Different criteria would possibly contribute considerably and differently to the final selection decision of the intelligent building control systems. The identification of the CSC and their associated factor group enables an effective selection and evaluation of building control systems, and helps to reduce biased selection decisions and guessing. Accordingly, the first two hypotheses take the following position:

H1: *The critical selection criteria (CSC) affecting the selection of each of the building control systems in the intelligent building differs, reflecting their distinctive and unique roles*

H2: Each proposed set of critical selection criteria (CSC) exerts a considerable degree of influence on determining respective building control systems.

The third and fourth hypotheses address the issues of the evaluation of the degree of intelligence in the intelligent building control systems (in Research Part Two). Recent years have seen a large amount of building components and products made available in the market that abuse the adjective “intelligent” in order to emphasis the intelligence attributes of the building system products. Such assertions tend to be vague and unjustified. The model of Bien *et al.* (2002) assumes four main attributes of machine intelligence. These are autonomy, controllability of complicated dynamics, man-machine interaction and bio-inspired behaviour. This model posits that, regardless of the classes of intelligent machines, 'autonomy' and 'human-machine interaction' are considered as two common components reflecting the degree of system intelligence of the building control systems, while 'the controllability of complicated dynamics' and 'bio-inspired behaviour' are regarded as two specific intelligence attributes, depending on the operational characteristics of the building control systems. Thus the third hypothesis ***(H3)*** predicts that: ***The intelligence attributes of 'autonomy' and 'human-machine interaction' are considered as two common components reflecting the degree of system intelligence of the building control systems, while 'controllability of complicated dynamics' and 'bio-inspired behaviour' are regarded as two specific intelligence attributes, depending on the operational characteristics of the building control systems.*** Such a machine intelligence model is extended to testing in the context of building control systems in intelligent building.

The fourth hypothesis addresses the degree of interdependent relationships between the intelligence attributes of intelligent building control systems and their operational benefits. The interdependencies are based on the fact that the choice of intelligence attributes is important in the maximisation of the operational benefits from the installation of the building control systems. In contrast, each intelligence attribute might have varied degrees of importance in fulfilling the operational benefits expected by developers and users. Consequently, the interdependencies would probably lead to potential impacts on the relative importance of each intelligence indicator. Thus, the last hypothesis predicts that:

H4: The operational benefits of the intelligent building exert a considerable degree of influence on the importance of intelligence indicators in the assessment of the degree of system intelligence of the building control systems.

5.4 JUSTIFICATION OF THE METHODS AND TESTS USED

After the research paradigm and hypotheses have been formulated, it is important to choose the most suitable research method(s) for the empirical studies. In this thesis, feedback is obtained from experienced building practitioners and experts regarding the importance of CSC and intelligence indicators. The data collected are used for the development of the selection evaluation as well as intelligence analytic models for the building control systems.

Surveys are considered as the most feasible and adequate research strategy for both research parts (i.e. Research Part One and Two) in this thesis as it is beneficial to deal with the questions of '*what*' the CSC/intelligence indicators are, and '*how much*' strength these criteria and indicators have (Yin 1994: 6). To develop and test the conceptual models, a series of two consecutive surveys are respectively employed in both Research Part One and Two. In Research Part One, two surveys that utilise a simple rating method and Analytic Hierarchy Process (AHP) are undertaken consecutively to develop, examine and refine the conceptual selection evaluation models. The simple rating method uses a self-completion postal questionnaire, sent to a large group of building experts and professionals who have knowledge and experience of intelligent buildings, to collect data and identify a group of critical selection criteria (CSC) for each building control system. Then, through the self-completed questionnaire sent to the group of experts, the AHP method was adopted to test the comparability of the CSC in every building control system. Their mean weights were computed with the aim to prioritise or rank the CSC and distinguish the most important CSC from the least important ones.

To elicit and examine the ‘suitable’ intelligence indicators, another two surveys, including the simple rating method and a combination of AHP and Analytic Network Process (ANP) approaches, are used in Research Part Two. A self-completion postal questionnaire using the simple rating method is employed first to test the criticality of the proposed intelligence indicators and to elicit groups of ‘suitable’ intelligence indicators for different building control systems. An AHP-ANP questionnaire was then employed to evaluate the comparability of each ‘suitable’ intelligence indicator, with the investigation of the interrelationships with operational benefits and intelligence attributes, in order to refine the system intelligence analytic models.

According to Sackett and Larson (1990), the adoption of multiple surveys that represent different samples is consistent with the triangulation theory. Different research methods can be incorporated in the surveys to achieve their different research objectives separately (Cheng, 2001: 88). This helps improve the degree of confidence (i.e., reliability and validity) in the accuracy of the research. In addition, the use of multiple surveys allows each successive questionnaire survey to draw on the experience and the respondent’s comments collected from the preceding survey. The adoption of multiple surveys in achieving the research objective appears in a number of construction studies (e.g. Cheng and Li, 2002, and Weston and Gibson, 1993).

The rationale for the adoption of the AHP and ANP as methods of analysis and the use of their procedures are explained in the following sections.

5.4.1 Research Part One: Why the Analytic Hierarchy Process (AHP)?

Although many other multi-criteria decision making models such as ELECTRE III or the ‘Superiority and Inferiority Ranking’ (SIR) approaches are available, they are not employed in this research for a number of reasons. ELECTRE III is an outranking method by Roy in 1978 which use cardinal scales with dominance concept based on graph theory to determine the best alternative when there is one and does not assume anything about rank preservation (Tam et al., 2003). However, as pointed out by Gilliams et al. (2005), there are a few problems in the application of the ELECTRE III. First, ELECTRE is not concerned with the way criteria or alternatives being examined are selected. The main concern of these methods is how to rank those alternatives that are selected with respect to criteria. ELECTRE III is also limited by its ambiguity of the solution as it does not provide a complete ranking. It commonly identifies plural strategies as the best solution. In addition, ELECTRE III has a larger variation of 66% in the results of a pair-wise comparison between the sets of preferences. Compared to other MCDM models, ELECTRE III method has a larger deviation than AHP and PROMETHEE II. The SIR approach, on the other hand, is a ranking approach which is based on the theory of fizzy bags that was proposed by Rebai in 1993, 1994 (Xu, 2001). It can process both cardinal and ordinal data and provides six different preference structures and incorporates outranking rationale to deal with the “poor” true-criteria preference structure (Brans and Mareschal 1990). It generates superiority, inferiority and non-inferiority scores via generalized criteria introduced in the Promethee methods

However, one limitation of the SIR is that the weightings to each criterion are required and are worked out through AHP (Tam et al., 2004).

As pointed out by Saaty (1996) and Triantaphyllou (2000), the Analytic Hierarchy Process (AHP) is a method of multi-criteria decision making (MCDM) and is considered as a descriptive approach to decision-making. The problem of MCDM deals with decisions involving the choice of a best or appropriate alternative from several potential ‘candidates’, subject to several criteria or attributes (Cho, 2003). To deal with a MCDM problem, a variety of factors and criteria are first proposed, and the identification of the important factors and criteria require the prioritisation or weighting of some factors. Those factors or criteria with high ranking are said to be critical.

In this research, the AHP is considered as an ideal systematic approach for several reasons. First, the AHP considers both qualitative and quantitative aspects of research and combines them into a single empirical inquiry (Cheng, 2001: 54). The AHP is able to adopt a qualitative way in building the decision hierarchy and also uses a quantitative approach in data collection and analysis to test the attributes of the models by using a self-completed questionnaire. The AHP has the capability to combine various types of criteria in a multi-level decision structure to obtain a single score for each alternative to rank the alternatives among the available multi-attribute approaches (Yurdakul, 2004: 365). Second, the selection of the AHP as a method of analysis in this study is also determined by the size of the sample population. In fact, a large sample size is expected to be less appropriate as the intelligent building is a new form of building development which is yet to mature. There is no record or publication reporting the number of practitioners participating in this type of development in Hong Kong. The AHP is an analytical method which permits a small survey group (Cheng and Li, 2002). It is thus helpful in collecting and analysing data from a small group of experts who have real experience in designing and developing the intelligent buildings. This explains why the AHP is appropriate for use as a method of test. Furthermore, the AHP provides a function of soliciting an expert’s judgements and provides a consistency check which makes it a reliable way to determine the priorities of a set of factors, which may then be incorporated into other evaluation systems (Cheng, 2001:54; and Chua *et al.*, 1999:43). By using the AHP approach, different levels of contribution of the selection factors and criteria towards the intelligent building control systems can be determined and identified.

5.4.2 Research Part Two: Why the Analytic Network Process (ANP)?

In Research Part Two, a combination of AHP and ANP analysis is proposed. ANP is an advanced version of the AHP which models a network structure that relaxes the hierarchical and unidirectional assumption in the AHP. The ANP can provide a more generalised model of multi-criteria decision-making that takes interdependent relationships into consideration (Cheng *et al.*, 2005). Similar to the AHP, the ANP possesses the same qualitative (decision model development) and quantitative (decision model analysis) procedures to structure and analyse a decision problem. It can further consider quantitative steps to solve a network decision problem, and thus it is appropriate when the interdependencies between two components are investigated. Despite this, the methodological procedure of the ANP is relatively more complicated than its ancestor, and it is still a new method that is not well-known to the operations research community and practitioners (Meade and Sarkis, 1999). So far the use of the

ANP in solving decision-making problems in construction and intelligent building research with illustrative examples has been very limited (for example: Chen *et al.*, 2005; Cheng *et al.*, 2005; and Cheng and Li, 2007). Further application of the ANP approach in construction research is needed (Cheng *et al.*, 2005). As discussed in Chapter 4, the model of Bien *et al.* was further elaborated and extended to consider the interdependencies between the intelligence attributes of intelligent building control systems and the building's operational benefits. It is for these reasons that the ANP is proposed for use as a method of analysis for the second part of research in this thesis.

5.4.3 Reliability and Validity

The determination of how to measure the variable of interest is an important consideration of every research process. In either qualitative or quantitative research, any measure or observation taken by an instrument needs to provide an accurate assessment of the variable (i.e. be reliable) and enable the researcher to draw inferences to a sample or population (i.e. be valid) (Creswell, 2002:180). Errors in measurement in any measure can distort the scores so that the observations do not accurately reflect reality (Hair *et al.*, 1995:8). Measurement errors can further reduce the observed strength of a relationship between variables (Graziano and Raulin, 2000: 81). As argued by Rubin and Babbie (2005:182), the generic steps taken to minimise measurement error are closely related to triangulation, which involves making sure, before implementing the study, that the measurement procedures have acceptable levels of reliability and validity. Hence, reliability and validity, are considered as two main criteria for testing the value of measures.

In the abstract sense, reliability is the ability of the research study to be replicated and, when replicated, generate similar results. Good measures should provide the same results each time they are used and regardless of who does the measuring. According to Martella *et al.* (1999: 64), the primary concern of quantitative researchers is the completeness and accuracy of their findings. They further argue that concepts of reliability and validity constitute not only the framework to guide the design and implementation of measurement procedures, but also the framework to judge the trustworthiness of the findings. However, the criterion of reliability may not be given so much status under a qualitative/phenomenological paradigm. Hussey and Hussey (1997: 57) suggest that 'it is not important whether qualitative measures are reliable in the positivistic sense, but whether similar observations and interpretations can be made on different occasions and/or by different observers.'

In addition to being reliable, the measures must also be valid. In conventional usage, validity refers to the extent to which a measurement procedure actually measures what it is intended to measure rather than measuring something else (Leary, 2004). It is also the degree to which variability in participants' scores on a particular measure reflects variability in the characteristic one wants to measure. The typical types of validity are measurement validity, internal validity and external validity (Bryman, 2001). However, researcher errors, including faulty research procedures, poor samples and inaccurate or misleading measurement, can undermine the level of research validity (Hussey and Hussey, 1997). Hussey and Hussey (1997:58) further maintain that the validity is higher in the phenomenological paradigm than in the positivistic paradigm. The precision of measurement and the ability to be able to repeat experiment reliability are important in the establishment of validity, though in the positivist paradigm there is often a danger that validity will be very low. In contrast, researchers in the phenomenological paradigm aim to gain full access to the knowledge and meaning of those involved in the phenomenon, capturing the essence of the phenomena and extracting data which is rich in its explanation and analysis.

Pertaining to this thesis, the employment of the simple rating method, the AHP and ANP in this study do not aim at testing any causal relationship among a group of variables, and thus validity and reliability issues do not need addressing (Cheng, 2001). Instead, as stated by Cheng (2001: 51), various approaches can be adopted to demonstrate the rigor of the research involving the AHP or ANP methods. First, it must be ensured that validity is a matter of arrangement during the research design and data collection. There needs to be a clear understanding of what is to be measured in order to assure that the measurement is ‘correct’ (Hair *et al.*, 1995). Walker (1997) suggests that a pilot questionnaire helps to test the accuracy of data sought for the purposes of testing the validity and practicality of the of research question. In this study, methods including the simple rating method, the AHP method and the ANP method are employed. Second, distortion can be addressed in univariate statistical analysis (i.e., mean in interval variables) under the simple rating methods. Dispersion measures, including the calculation of the standard deviation (SD), help to reveal any distorting effect of the statistics. Third, both the AHP and ANP methods possess the consistency test which makes sure that only reliable responses are employed. Finally, the conceptual models developed from the two research parts (in Chapter 6 and 7 respectively) are validated by experts (in Chapter 8). Correlation tests are employed to measure the models’ reliability and validity. The model is said to be reliable if it shows a high correlation in the correlation analysis. Details of the procedures of the expert validation will be discussed in following section 5.6 and in Chapter 8.

5.5 METHODS OF ANALYSIS

5.5.1 Analytic Hierarchy Process (AHP)

The AHP is a decision making theory, developed by Thomas L. Saaty (1980), is aimed at handling a large number of decision factors and providing a systematic procedure for ranking many decision variables (Tang *et al.*, 2004). It was developed in early 1970s in response to military contingency planning, scarce resources allocation, and the need for political participation in disarmament agreements (Saaty, 1980). The AHP is a structural approach which assists in eliciting preference opinions from decision makers, allowing both qualitative and quantitative approaches to solve complex decision problems. It then 'combines' them into a single empirical inquiry (Cheng and Li, 2002). The fundamental rule of the AHP is that the use of factual data and the knowledge and experience of experts is to be equally important in the decision making process (McIntyre *et al.*, 1999).

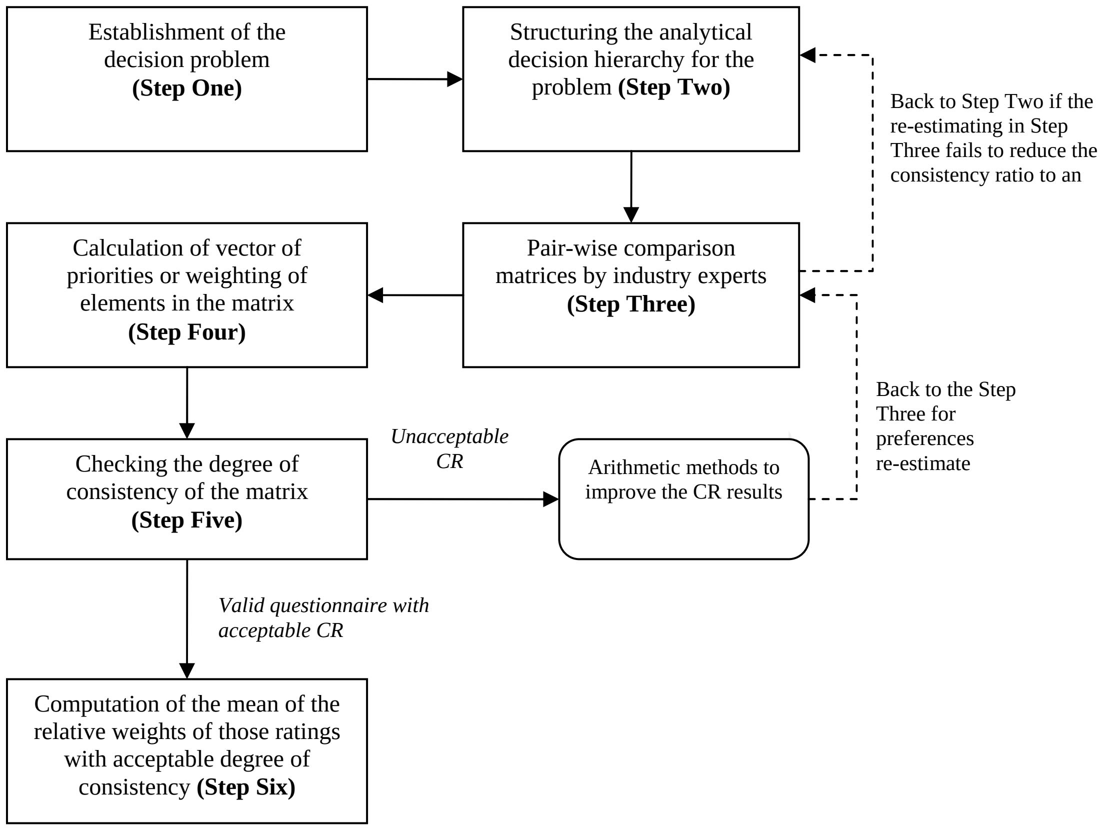
The AHP has its widest applications in multi-criteria decision making, in planning and resource allocation and in conflict resolution (Vargas, 1990; and Zahedi, 1986a). The AHP method has been increasingly applied in construction research for various goals. For example, Cheung *et al.* (2001) employed the AHP method to identify the critical procurement selection criteria and procurement strategies in Hong Kong. The works of Fong and Choi (2000) also apply the AHP in a similar manner for final contractor selection. Chua *et al.* (1999) and Cheng (2001), on the other hand, use the AHP method to weigh the relative importance of the factors in different types of construction projects, allowing them to identify the critical success factors (CSF).

In the AHP, the process of decision making originates with the identification of the overall objective and goal to be achieved. A complex decision problem is expressed as a hierarchy. A hierarchy is a particular type of system which is based on the assumption that the entities can be grouped into disjoint sets with the entities of one group influencing the entities of only one other group and being influenced by the entities of only one other group (Saaty, 1980:11). It consists of the overall objective or goal of the decision at the top of the hierarchy, and, from there, the main criteria, sub-criteria and decision alternatives or scenarios to be selected are on each descending level of the hierarchy (Crowe *et al.*, 1998). The main criteria represent the first level that contributes to the successful fulfilment of the goal, while the sub-criteria associated with each criterion would be identified when the succeeding levels consist of elements with increasing degree of details. The AHP can quantitatively prioritise (or ‘pair-wise’ compare) a set of attributes and distinguish, in general, the more important factors from the less important factors. The pair-wise comparison judgments were made with respect to the attributes of one level of hierarchy given the attributes of the next higher level of hierarchy (from the main criteria to the sub-criteria). The AHP is also able to solicit consistent subjective expert judgments via the consistency test.

Over the last two decades, there have been numerous algorithm procedures designed for the AHP. The set of principles for the method developed by Saaty (1980) and Vargas (1994) are the most acceptable. Mclntyre *et al.* (1999:89) simplify the mathematical theory and outline a seven-step algorithmic procedure. This study adopts the AHP procedures developed by Mclntyre *et al.* (1999) and Cheng (2001) as the foundation, and summarises them into six steps (Figure 5.1) for prioritising the crucial selection criteria of the intelligent building systems in Research Part One. The AHP algorithmic procedures are described step-by-step as follows:

AHP Step One: *Establishment of the Decision Problem*

Prior to the adoption of method, it is important to ensure that the AHP is an appropriate method for the existing decision problem. According to Shen *et al.* (1998), the AHP is best suited to multi-criteria problems in which accurate quantification of the impact of the alternatives on the decision-making problem is not possible. The AHP method is concerned with deriving a priority structure associated with a hierarchy whose elements represent issues relevant to a specific decision problem (Arbel and Vargas, 1993). The essence of the process is a decomposition of a complex problem into a hierarchy with a goal at the top of the hierarchy, then the main-criteria, and sub-criteria at levels and sub-levels of the hierarchy, and finally decision alternatives at the bottom of the hierarchy. In many AHP studies, the structure for synthesising a decision hierarchy is developed for alternative selection purposes. However, it should be stressed that this survey employs the AHP for prioritising the critical selection factors and criteria of the intelligent building control systems. The use of the AHP for factor prioritisation has been attempted by Cheng and Li (2002). They employed the AHP for prioritising the criteria and factors influencing the performance of the construction projects.



Note: Reference from Cheng (2001: 57)

Figure 5.1: The AHP Method for Prioritising the Critical Selection Criteria (CSC) for Intelligent Building Control Systems

AHP Step Two: Structuring the Analytical Decision Hierarchy for the Problem

The second step of the AHP is to structure the decision problem into a hierarchical model. This involves the decomposition of the decision problem into elements according to their common characteristics. In this study, the hierarchies depict the attributes for selecting intelligent building control systems. The top level is the selection **goal** (i.e. prioritisation of the CSC for appropriate building control systems selection), and following this are the **selection factors** (the second level) and, finally, **selection criteria** (the third level), which expands from the objectives.

The analytical decision hierarchy of the AHP provides a chain of hierarchies to represent the system of the problem. According to Cheng (2001: 58), the formation of the system is based upon two assumptions, without which a problem cannot be dealt with using the AHP:

- Each element of a level should be related to the elements at the next level, and the AHP approach accepts the interaction between elements of two adjacent levels; and,
- It is expected that there is no hypothesised relationship between the elements of different groups at the same level in the AHP method.

In this study, no inter-relationships between the elements of different groups at the same level are assumed.

AHP Step Three: Construction of Pair-wise Comparison Matrices

After setting up the decision hierarchy, the next step involves the construction of a set of pair-wise comparison matrices for each of the lower levels of the hierarchy. The theory of the AHP assumes that an element in the higher level governs the elements in the lower levels. The pair-wise comparisons are done in terms of which elements are more important than other elements. The opinion of the expert is elicited for comparing the elements in the hierarchy.

The selection of the right experts for the decision problem is critical for the AHP matrices comparison exercise. Data concerning the relative importance of selection criteria in this study are obtained from questionnaire survey to those experts and professionals who are actively involved in intelligent building design and development. According to Cheng (2001), the AHP approach is a subjective methodology for which a large sample size is not necessary. Previous research by Cheng and Li (2002) invited nine construction experts to undertake a survey to test comparability of critical success factors for construction partnering. Lam and Zhao (1998) also invited eight experts for a quality-of-teaching survey. The AHP is greatly useful for exploratory studies or for research focusing on a small area where a large sample is not mandatory. The criteria for the selection of the experts for this study will be discussed in detail in section 6.4.1.

The major component of the AHP method is concerned with deriving a priority structure related to a hierarchy whose elements represent issues relevant to a specific decision problem. A distinction is made between local and global priorities in deriving these priorities. In general, a local priority (LP) refers to the importance, or priority, of an element in a certain level with respect to an element in a level immediately above it, while the global priority (GP) represents the importance of an element with respect to the focus of the decision problem (Arbel, 1989). The derivation of LPs is conducted through the use of a comparison scale and a pair-wise comparison matrix. A comparison matrix for deriving the priority vector, for example, $w^T = [w_1, w_2, \ldots, w_n]$, is associated with n elements in a specific level with respect to a single element in the immediate level above it. The matrix, denoted as A, is represented as Equation 5.1:

$$A = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \ldots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \ldots & w_2/w_n \\ \vdots & \vdots & & \vdots \\ w_n/w_1 & w_n/w_2 & \ldots & w_n/w_n \end{pmatrix} = \begin{pmatrix} 1 & a_{12} & \ldots & a_{1n} \\ 1/a_{12} & 1 & \ldots & a_{2n} \\ \vdots & \vdots & & \vdots \\ 1/a_{1n} & 1/a_{2n} & \ldots & 1 \end{pmatrix} \qquad \text{(Eq. 5.1)}$$

In this above matrix, every element (for example, a_{ij}) is a solution to a pair-wise comparison question inquiring as to the relative importance of element i relative to element j. For example, if a comparison is conducted for the i-th element with the j-th element, a comparison is being made also of the j-th element with the i-th element. This causes the comparison matrix to form a reciprocal matrix satisfying $a_{ij} = 1/a_{ji}$. The relative importance of each element was rated by the nine-point scale of measurement proposed by Saaty (1980), as shown in Table 5.2, which indicates that the level of relative importance from equal, moderate, strong, very strong, to extreme levels by 1, 3, 5, 7, and 9 respectively. The intermediate values between two adjacent arguments are represented by 2, 4, 6, and 8. After all elements have been compared with the priority scale in pairs, a paired comparison or judgment matrix is formed.

Table 5.2: The AHP Pair-wise Comparison Scale

Intensity of weight	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objectives
3	Weak/moderate importance of one over another	Experience and judgement slightly favoured one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent scale values	Used to represent compromise between the priorities listed above
Reciprocals of above non-zero numbers		If activity ***i*** has one of the above non-zero numbers assigned to it when compared to activity ***j***, then ***j*** has the reciprocal value when compared with ***i***.

Source: Adapted from Saaty (1980:54)

As an illustration of a comparison matrix, a sample of the priority rating of a level with three elements is shown as Table 5.4. This matrix is composed of three rows and three columns, a 3-by-3 matrix. In this table, it shows that element A is moderately more important than element B, and so shows the importance of A over B as 3, and the reciprocal (i.e. 1/3) is entered in row B column A. Compared to element C, element B is very strongly to absolutely less important (scale ‘1/6’). A “1” is assigned when the same element is compared in row and column. However, it is noteworthy that zero cannot be included in the scale of comparisons in the AHP (and ANP) approach.

Table 5.3: A Sample Pair-wise Comparison Matrix

Level	A	B	C
A	1	3	1/2
B	1/3	1	1/6
C	2	6	1

AHP Step Four: Calculation of a Vector of Priorities or Weighting of Elements in the Matrix

After the matrix has been developed, the next step is to calculate a vector of priorities or weighting of elements in the matrix. Saaty (1990) pointed out that there is an infinite number of ways to derive the vector of priorities from the matrix (a_{ij}), but an emphasis on consistency would lead to the eigenvalue formation $Aw = nw$, where w is the priority vector and n is the number of elements being compared, or an eigenvalue of matrix A by definition (Tang *et al.*, 2004). In terms of matrix algebra, Crowe *et al.* (1998) explain that the development of a vector of priorities or weighting of elements in the matrix involves the calculation of the ‘principal vector’ (eigen-vector) of the matrix (i.e., the relative weight of elements A, B and C for the illustrated example in Table 5.3), and then normalising it to sum to 1.0 or 100 per cent (i.e., sum of w_A, w_B, and w_C). This is calculated by first dividing the elements of each column by the sum of that column (normalising the column), then adding the elements in each resulting row to obtain the eigenvector (‘row sum’). This sum is then divided by the number of elements in the row in order to get the ‘priority weight’ (Cheng, 2001).

AHP Step Five: Checking the Degree of Consistency of the Matrix

Once the priority vectors have been determined, it is necessary to check on the consistency of judgements in the pair-wise comparison (Saaty, 1980). Ozdemir (2005) argues that consistency is a critical ingredient that derives from the decision maker’s decomposition of complexity into a hierarchic or network structure, which allows a better understanding of the connection between its parts and the establishment of priorities for them within that structure. Saaty (1980) also argues that inconsistency happens due to the lack of transitivity of preferences. As decision makers are often inconsistent in their judgments, the AHP technique incorporates managerial inconsistencies into the model and provides the decision maker with a measure of these inconsistencies. A consistency test can be employed to compute the consistency ratio to ascertain the matrices, and such a measure refers to the consistency index of judgement matrices.

Using the pair-wise comparison matrix exercise in Table 5.4 as an illustration, if element A is three times more important than element B, and element B is two times more important than element C, then, for a perfect consistency, element A should be six times more important than element C. If element C is rated more important than element A, there is a high degree of inconsistency. In the AHP exercise, a consistency test is normally required after the completion of the calculation of the relative weights of the matrices. Inconsistent ratings from the individual respondents in the AHP questionnaire can affect the overall consistency of the test, and therefore the degree of consistency needs to be tested prior to the combination of all responses from the survey respondents (Cheng, 2001). Those with unacceptable consistency would be excluded from the final calculation of the mean value of the relative weights for the test. In this test, the consistency test was used to calculate the individual consistency value for all respondent questionnaires and only those with acceptable consistency are included for the final examination. Saaty (1994) and Cheng & Li (2002) have set the acceptable CR value for different matrix's sizes as: 0.05 or below for a 3-by-3 matrix, 0.08 or below for a 4-by-4 matrix, and 0.1 or below for matrices larger than 5-by-5. Crowe *et al.* (1998:211) describe a step-by-step algorithm method for calculating the consistency ratio in the AHP, which is adapted from Canada and Sullivan (1989). The consistency ratio is determined by the following steps:

- Multiplying the pair-wise comparison matrix (A) by the principle vector or priority weights (B) to obtain a new vector (C). The equation for multiplying the matrix A (a_{ij}), vector B (b_j) to obtain vector C (c_i) can be expressed as:

$$c_i = \sum_{j=1}^{n} a_{ij} b_j \text{ , (i = 1, 2,…, n)} \qquad \text{(Eq. 5.2)}$$

- Compute a new eigenvector (D) by dividing the vector (C) by its corresponding element in vector (B).
- Compute the maximum eigenvalue (λ_{max}) by averaging the numbers in vector (D).

- Work out the consistency index (CI) for a matrix of size *n* based on the formula:

  $CI= (\lambda_{max} - n)/(n-1)$ (Eq. 5.3)

- Compute the consistency ratio (CR) using the formula: CR = CI / RI, where RI is the random index for the matrix size, *n*. RI has been approximated based on a large number of simulation runs. Table 5.4 represents a random index table for matrix sizes of 1 to 15 (Crowe *et al.*, 1998)

Crowe *et al* (1998) further maintain that if the inconsistency ratio is greater than 10 per cent, the quality of judgements in making pair-wise comparison should be improved. This empirically indicates excessive intransitivities of preferences. Normally the CR can be reduced by re-estimating preferences (i.e., return to *AHP Step Three*). If this fails, then the problem should be more accurately structured (i.e. grouping similar elements under a more meaningful attributes scheme) and the process should return to *AHP Step Two* to re-structure the hierarchical model of the decision problem to a better attribute representation. In this study, the AHP software package *Expert Choice* (Saaty and Vargas, 1994) was employed to facilitate the computation of the consistency ratios and the relative weights of factors/criteria.

AHP Step Six: Computation of the Mean of the Relative Weights of those Ratings with an Acceptable Degree of Consistency

As stated in many AHP textbooks and papers (for examples: Saaty, 1980; Zahedi, 1986b; Saaty and Vargas, 1994; and, Cho, 2003), the procedure after consistency checking involves the aggregation of weights across various levels to obtain the final weights of alternatives. This is done by calculating the weighted priority vector by multiplying the weighted vectors at the sub-criteria level by the corresponding weight vectors at the criteria level (Mclntyre *et al.*, 1999). The aggregate vectors are computed by adding the weighted priority vectors with respect to each of the criteria. An aggregate matrix is then formed from the aggregate vectors. A final priority vector is calculated from the aggregate matrix that actually defines the preferences of the possible alternatives with respect to all of the criteria and sub-criteria. However, the step of final priority vectors was not computed in this study. Instead, the final step in this study involves the calculation of the mean relative weights (i.e. local priority and global priority) estimated by experts on each level of the hierarchy according to the factor prioritisation approach of AHP proposed by Cheng (2001).

Table 5.4: Consistency Ratio Random Number Index based on Matrix Size

Size of matrix (n)	**Random index (RI)**
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.54
13	1.56
14	1.57
15	1.59

Source: Adapted from Crowe et al. (1998: 221)

5.5.2 Analytic Network Process (ANP)

In the real world, many decision problems cannot be structured hierarchically because they involve the interaction on and dependence of higher-level elements on a lower-level element (Saaty, 1996). The AHP model does not permit dependencies between attributes at one hierarchy level, nor does it permit interdependencies between attributes in higher and subordinate levels (Lee and Kim, 2001, and Cheng *et al*., 2005). Thus, Saaty (1996) develops the Analytic Network Process (ANP) which enables users to consider dependencies and interdependencies between all attributes, both within one particular level and also across levels. In fact, the ANP was not developed with the intention of replacing the AHP approach. Instead, Saaty (1996) suggests the use of the AHP to solve the problem of independence on alternatives or criteria, and the employment of the ANP method to solve the problem of dependence among alternatives or criteria.

The most important function of the ANP is considered as its ability to determine the relationships in a network structure or the degree of interdependence of its attributes (Lee and Kim, 2000). According to Meade and Sarkis (1998) and Cheng and Li (2004), interdependence can occur in several ways: (1) uncorrelated elements are connected (i.e. in a looped arc within the same level of analysis), (2) uncorrelated levels are connected, and (3) the dependence of two levels is two-way (i.e. two way arrows or arcs among levels). The ANP method is capable of handling interdependence among elements by obtaining the composite weights through the development of a *super-matrix*. The super-matrix adjusts the relative importance weights in individual matrices to form a new ‘overall’ matrix with the eigenvectors of the adjusted relative importance weights (Meade and Sarkis, 1998). In this thesis, the ANP method is employed to develop the weightings of the system intelligence measures for the building control systems. As shown in Figure 5.2, five steps of the ANP method were proposed for prioritising the intelligence measures for assessing the system intelligence of various building control systems. The algorithm procedures of the ANP primarily follow the AHP approach, except for the intrusion of interdependent relationships and the formation of super-matrix. The proposed ANP algorithm procedure was established based on the concept developed by Saaty (1996) and extended by Meade and Sarkis (1998) and Cheng *et al.* (2005). The algorithmic procedures are presented step-by step hereinafter.

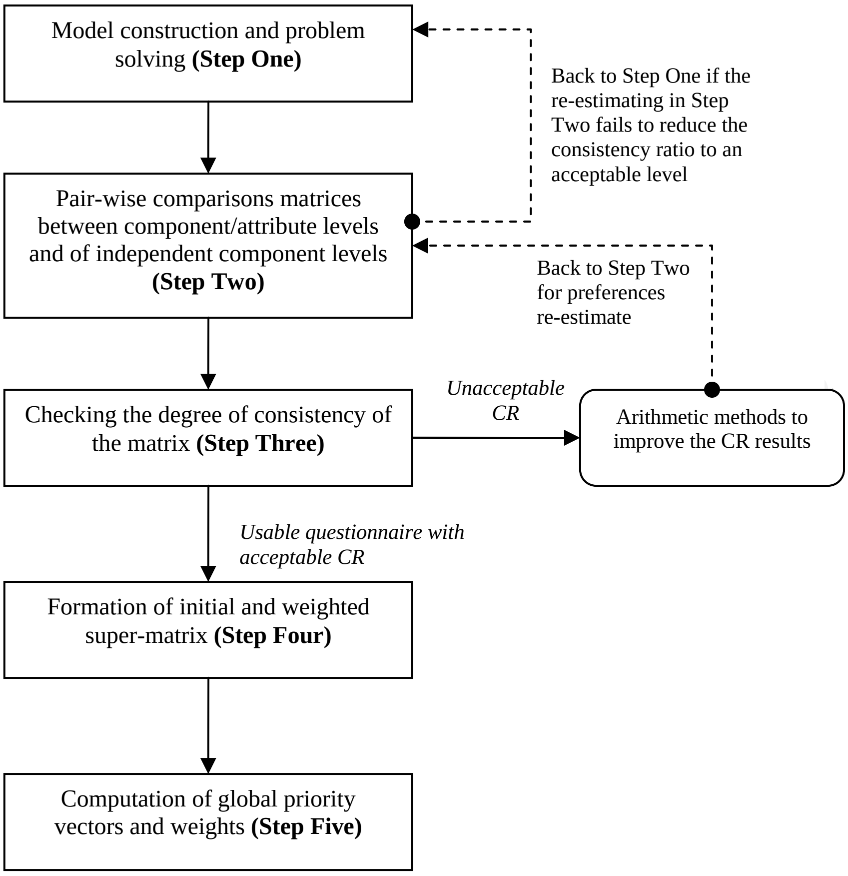


Figure 5.2: The ANP Approach for Prioritising Intelligence Indicators for Intelligent Building Control Systems

ANP Step One: Model Construction and Problem Structuring

Like the AHP, the ANP problem formulation commences with the modelling of the problem that depicts the dependence and influences of the factors involved to the goal or higher-level performance objective (Tesfamariam and Lindberg, 2005). In designing an ANP model, the topmost elements in the hierarchy of criteria are decomposed into sub-criteria, in a similar way as in the AHP (Meade and Sarkis, 1998). Figure 5.3 provides a snapshot of the proposed framework for the model developed for evaluating the system intelligence of the intelligent building systems in this research. The ultimate objective of the hierarchy is to measure the overall degree of system intelligence of seven key building control systems in the intelligent building. The model illustrates an interactive and interdependent relationship between the intelligence attributes and the building's operational benefits. A similar type of interdependent relationship with external components is also examined and included in the studies of Cheng *et al.* (2005) and Meade and Sarkis (1998), which prioritise the criteria affecting shopping mall location selection and the attributes of the principles of logistics respectively.

ANP Step Two: *Pair-wise Comparisons Matrices between Component/Attribute Levels and of Independent Component Levels*

The next steps require a series of pair-wise comparisons where the user compares two elements at a time with respect to an upper level control criterion. Pair-wise comparisons of the elements in each level of the ANP model are conducted with respect to their relative importance towards their control criterion based on the principle of the AHP (Neaupane and Piantanakulcjai, 2006; and, Meade and Sarkis, 1998) as stated in '*AHP Step 3: Construction of Pair-wise Comparison Matrices'* in Section 5.5.1. The relative importance weight (denoted as a_{ij}) of interdependence in the ANP is equally determined by the same nine-point priority scale of pair-wise judgment (Saaty, 1980) as tabulated in Table 5.2.

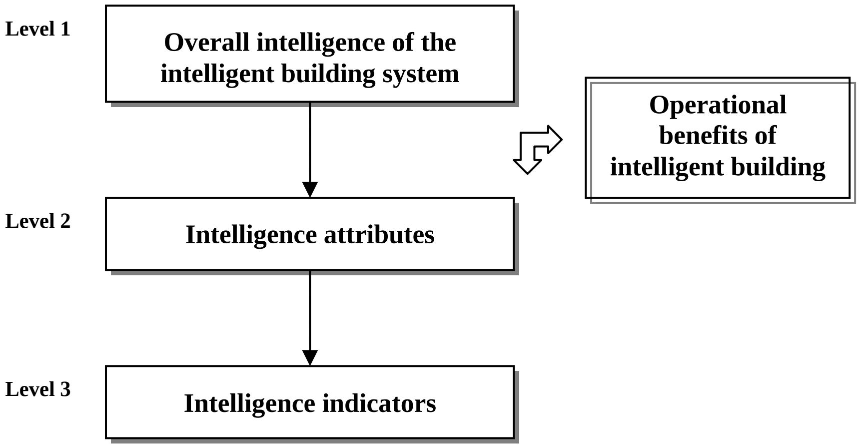


Figure 5.3: Graphical Representation of the Relationship for the Proposed ANP Framework for Measuring the System Intelligence of the Building Control Systems

In this research, the interdependent relationships between the level of intelligence attributes and their associated variables are not taken into consideration in order to maintain some parsimony for ease of exposition. Instead, the pair-wise comparison of the elements at the intelligence indicators level (i.e. level 3) is conducted with respect to their relative influence (eigenvector determination) towards their control criteria (i.e. intelligence attributes in level 2).

ANP Step Three: Checking the Degree of Consistency of the Matrix

The problem in the transitivity or consistency of the pair-wise comparisons is also a key concern in the ANP. The possible inconsistency revealed in the criteria weights needs to be eliminated through the computation of the consistency of each matrix. In general, if the consistency index is less than 0.10, satisfaction of judgements may be derived (Saaty, 1980). Details of the acceptable consistency index for the ANP approach have been discussed in the *'AHP Step 5: Checking the Degree of Consistency of the Matrix'* of the AHP algorithm procedures in section 5.5.1.

ANP Step Four: Formation of Initial and Weighted Super-matrix

The super-matrix promotes a resolution of the effects of the interdependence that exists between the elements of the ANP model (Meade and Sarkis, 1998). This can be achieved by entering the local priority vectors (LPV) in the super-matrix, which in turn obtains the 'global' priority vectors (GPV). There are three mathematical steps in the calculation of the 'super-matrix' (Neaupane and Piantanakulchai, 2006; Wolfslehner *et al.*, 2005; Saaty, 1996). These steps include *initial super-matrix*, *weighted super-matrix,* and *limit super-matrix*.

The initial super-matrix is first calculated from all local priorities derived from pair-wise comparisons among those elements that influence each other. The elements within each cluster are compared with regard to their influencing element outside the cluster, and the eigenvector of the influence of all clusters on each other cluster. The initial super-matrix consists of several eigenvectors, each of which sums to one, and the initial super-matrix must be transformed to a matrix in which each of its column sums to unity. To minimise the column sum to unity, each of the elements in the block of the super-matrix is factored by its priority weight to the control criterion. The eigenvector derived from the cluster level comparison with respect to the control criterion is applied as the cluster weight. This results in a matrix of its columns, each of which must sum to unity. If any block in the super-matrix contains a column with all zero elements, that block must be normalised by the cluster's weights to make sure that the columns sum to unity. Such a matrix is called a stochastic matrix or a weighted matrix.

ANP Step Five: Calculation of Global Priority Vectors and Weights

After the weighted matrix, a limit super-matrix is formed. This is done by raising the entire weighted super-matrix to a limiting power to get the global priority vectors as $\lim_{k\to\infty} W^k$. If the super-matrix has the effect of cyclicity, there may be two or more N limiting super-matrices. In this situation, the Cesaro sum is calculated to get the average priority weights by the equation:

$$\lim_{k\to\infty}\left(\frac{1}{N}\right)\sum W_i^k \qquad \text{(Eq. 5.4)}$$

In this study, for the average limiting super-matrix, the final and relative weight of each important intelligent measure was computed with the aid of the ANP software package *Super Decisions* (Saaty, 2003). The development of the limit super-matrix is illustrated with the results of the ANP survey in Chapter 7.

5.6 MODEL VALIDATION BY EXPERTS

In this thesis, after the general selection evaluation models and system intelligence analytic models are examined and refined, the developed models are then converted to the practical models that need to be validated. According to Leeflang *et al.* (2000), model validation is an important procedure in the process of model development. This process implies assessing the quality or the success of the model. The model should be tested before it can be put to use. In fact, there are three possible decisive factors for a validated model (Leeflang *et al.*, 2000: 51):

- The degree to which the results are in accordance with theoretical expectations or well-known empirical facts;
- The degree to which the results satisfy statistical criteria or tests; and,
- The degree to which the result is relevant to the original purpose.

Larichev *et al.* (1995) also argue that a model is considered to have made the right decision when it can identify the option that is consistent with the preference of the respondents. However, identifying the right decision option is highly complicated as many multiple attribute decision tasks do not have a right answer or because an objectively best decision does not exist (Larichev *et al.*, 1995).

Models must be validated to various degrees of rigour. According to Ling (1998), a more rigorous method involves the comparison of the outcome of an independent measurement with the answer given by the model in order to determine the model's ability to arrive at a similar conclusion. For example, in testing the contractor evaluation model, Liston (1994) worked with a number of project clients to evaluate 11 contractors. The same 11 contractors were also evaluated by clients' in-house evaluation methods.

This aimed to compare the results from these two evaluation models to see if the model categorised the contractors in a similar manner as in the owner's in-house evaluation methods. However, the evaluation method of comparing the proposed model and the in-house methods is less appropriate for this research in this thesis as there may be a lack of any prevailing in-house methods or models developed for selecting and evaluating the system intelligence of intelligent building systems. Neter *et al*. (1989: 466) points out that in some cases, theory, simulation results, or previous empirical results may be helpful in determining whether the selected model is reasonable, but there might be a problem if there is little empirical data that can be used to validate the model, especially when the research problem is relatively new.

Rather than a rigorous model validation approach, Ling (1998) proposes a less rigorous method that involves inviting experts to provide judgement and feedback. The selection of the right people for judgement is an important step prior to model validation. According to Ayyub (2001:98), an expert should be a very skilful person who has had much training and has knowledge in some special field. The formal judgement of an expert involves a subjective assessment, evaluation, impression or estimation of the quality or quantity of something of interest that seems true, valid, or probable to the expert's own mind (Ayyub, 2001). Modarres (1993) also argues that the experts invited for the model validation should have extensive knowledge and experience in the subject field, not limited to one-time events. In this thesis, selected experts for the models' validation were required to be familiar with the design and the operational and engineering aspects of intelligent building control systems. It is more appropriate to select those experts with basic engineering or technological knowledge. It might also be necessary to include experts from management with engineering knowledge, and/or a broader knowledge of the intelligent building equipment and components, and/or experience in selection evaluation and system intelligence evaluation of building control systems.

In general, the use of expert judgments in decision making is a two-step process: *elicitation* and *analysis* (Ayyub, 2001). The method of *elicitation* may take the form of individual interviews, interactive group sessions, or the Delphi approach (Leeflang *et al.* 2000). In social science research, the common elicitation method is by the questionnaires. The analysis portion involves combining expert opinions to produce aggregate estimates. For example, Russell and Skibniewski (1988) conducted a non-rigorous survey soliciting general comments from 25 decision makers regarding the contractor prequalification model. The method for combining expert opinions can be classified into consensus and mathematical methods. The mathematical methods can be based on assigning equal or different weights to the experts (Ayyub, 2001). Statistical methods can be applied to estimate the reliability of the scores and test measurement errors. The collected assessments from the experts for an issue should be assessed for internal consistency, and analysed and aggregated to obtain composite judgements for the issues. This reliability consideration requires aggregation procedures of expert opinions to include measures of dispersion and correlation, etc. (Ayyub, 2001:98).

A review of construction literature revealed that one method of model validation involves a comparison of the output of the model with the solutions given by the experts (Nkado, 1992). Ling *et al.* (2003) tested their selection model for design consultants for design-and-build projects in Singapore by consulting a number of experts. Experts were presented with the statistically important attributes and asked whether these attributes represented all the factors that should be involved in evaluating consultants. The model's relative ranking of different consultants was compared with the experts' order of preference. Following this, the similarity between the scores given by the model and the experts was evaluated. In this thesis, the model validation design was based on the approach of Ling *et al.* (2003). The details of expert validation methods are presented hereafter.

5.6.1 Comparison between Experts' Preferences and the Models' Rankings of Alternative Intelligent Building Control Systems

Before the model validation, the construction of a practical model is necessary. According to Ling *et al.* (2003), after obtaining the weights of variables the examination of the practicability of the developed conceptual model requires the development of ratings of each candidate options on each of the variables and the formulation of an aggregation formula to sum up the weighted ratings. In this research, these two process steps are adopted to move the developed conceptual models to the practical models. In order to evaluate the candidate building control systems against each CSC and intelligence indicator in the models developed, the assessment methods and standard summated rating scales must first be set up for each of these CSC and intelligence indicators. Having established the assessment methods and rating scores for each CSC and intelligence indicator, the scores of CSC and intelligence indicators are then respectively aggregated in order to produce one overall score for each candidate building control system. To derive the weighted rating or scores, the important weights of each CSC and intelligence indicator are multiplied by the ratings that the candidate building control system obtains for the corresponding CSC and intelligence indicator. Details and procedures of practical models development will be explained in Chapter 8.

To validate the practical models, the model's aggregate score must first be compared with the global scores given by the experts (Ling *et al.*, 2003). In this research, each expert was asked to recall their past experience and was required to supply two examples of real intelligent building control systems they had encountered. They were told to evaluate the nominated intelligent building system alternatives based on their expert judgement and on their global impression of them. Each proposed building system alternative was first ranked according the experts' preferences for them. The experts were then requested to use the practical selection evaluation models and system intelligence analytic models to evaluate each of the nominated building system alternatives. The results will compare the aggregate scores in both models and test whether they are consistent with the preferences of the experts for both parts.

5.6.2 Correlation Analysis between Experts' and Models' Rankings of CSC and Intelligence Indicators

The consistency between the model's aggregate scores and the experts' global scores are further tested and analysed by the statistical methods. Statistical tests are proposed to compare the degree to which the scores of the experts and the models are related to one another in a strong, linear fashion (Leary, 2004). Correlation analysis is used to describe the strength and direction of the linear relationship between two variables or sets of data (Pallent, 2001: 115). To test the correlation between two variables, a number of correlational methods are available. The method used depends on the scale of measurement of two variables (Barnes and Lewin, 2005). The Pearson correlation coefficient (*r*) is the most appropriate approach for the interval or ratio measures, while the Spearmen rank order correlation coefficient (*rho*) is more suitable when one or both variables are ordinal or ‘ranked’ (Furlong *et al*., 2000). The Kendall’s *tau* is only used (Field, 2000) when the data set is small, with many observations equally ranked. In this thesis, the measures in both parts of research include intervals and ranking. Thus, both Spearman’s *rho* and Pearson’s *r* are employed to ascertain the strength and direction of the relationship between the scores of models and experts. If there is a high correlation between the two sets of scores, this means that the model is able to reflect the expert’s preference.

5.7 CHAPTER SUMMARY

This chapter presented the methodology and methods adopted in this thesis. The chapter first described the research paradigm and four hypotheses of this research, followed by a discussion of the research methods and strategies. Multiple surveys were employed in both parts of research to develop, test and modify the general conceptual models. Justification for the use of analysis methods was also discussed. Methods of the AHP, the ANP and the process of experts’ validation were presented in this chapter.

CHAPTER 6

DATA ANALYSIS AND RESULTS – RESEARCH PART ONE

“Researchers typically collect data under the assumption that a computer will be used to analyse it. At least two important steps lie between the collection of data and its computer-base analysis using advanced statistic methods. One must first properly ‘prepare’ the data for entry into a computer file or database, and once the data are correctly entered, one should examine the data distributions of each variable. There are many perils and pitfalls that can derail even an experienced researcher at these critical and necessary steps. To put it bluntly, if you err early, all later analyses, no matter how sophisticated, could be meaningless.”

(Newton and Rudestam, 1999:1)

6.1 INTRODUCTION

The objective of this chapter is to develop, examine and refine the conceptual models of the critical selection criteria (CSC) for the seven key intelligent building control systems which were proposed in Chapter 3. Two consecutive surveys were undertaken to achieve these ends. The first survey used a general questionnaire to collect data regarding perceptions of building professionals toward the CSC of each intelligent building control system, data that was used to test the conceptual frameworks which can be used to guide the selection of building control systems. The hypotheses *H1* and *H2* are tested in the first questionnaire survey. In order to evaluate the comparability of the CSC, their mean weights were computed using the AHP method in the second survey, which helped to prioritise the CSC and to distinguish the more important factors from the less important ones. The AHP survey also aims to re-affirm hypothesis *H2*. The flow of two successive surveys in this Research Part One is illustrated in Figure 6.1.

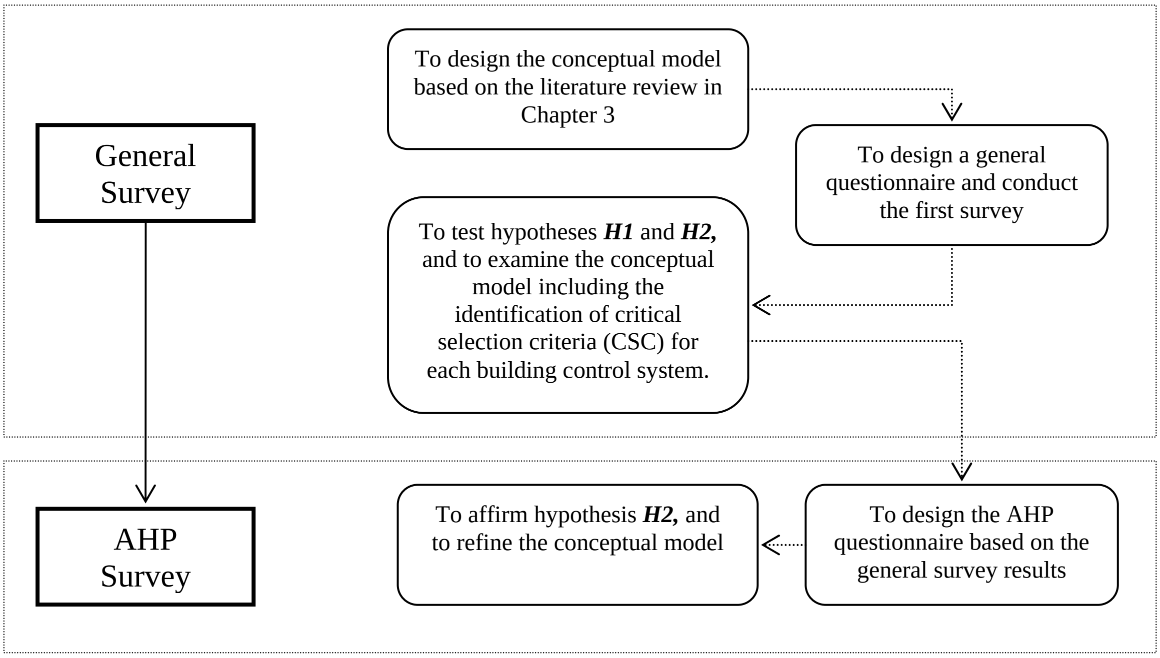


Figure 6.1: Two Consecutive Surveys for Testing and Refining the Conceptual Model of the CSC

6.2 A GENERAL SURVEY: DESIGNING AND TESTING OF CONCEPTUAL SELECTION EVALUATION MODELS

6.2.1 Defining the Target Population and Sampling Method

To achieve the stated aims of the surveys, it is important first to define and select the target population for the survey questionnaires (Figure 6.2). Only practitioners who had experience in intelligent building design and development were invited to take part in the research. To seek the right respondents for inclusion, the first step was to compile a list of companies and contact persons in each company. The company profiles and job histories of professional bodies (including the Association of Consulting Engineers of

Hong Kong, the Hong Kong Institute of Architects, and the Hong Kong Institute of Surveyors) were first reviewed, through the bodies' websites, in order to elicit those consultancies that have participated in intelligent building projects. Large property developers, building contractors and intelligent building research institutes were also invited to participate in the surveys. Contact with the companies commenced in August 2004. Phone calls were made in order to identify and confirm the key person in the company before the invitation letters were sent out.

A survey invitation letter was prepared and addressed to the executives or directors of all targeted companies via postage or, in a few cases, e-mail. The invitation letter attempted to confirm which companies had real practical experience in intelligent building design and development, and to obtain approval and pre-agreement for participation in the surveys. Only those companies with relevant experience are included in this study. Finally, a total of 78 invitation letters were sent in early September 2004 to ask for the acceptance and assistance of the targeted companies. By the end of October 2004, 36 reply letters or e-mails were received. Of all these responses, 13 companies were not willing to participate in this survey: 4 because either their companies had not participated in intelligent building design or development or because of a lack of time, while nine did not state any reason. The number of companies that agreed to participate in the survey was thus narrowed to 23.

In order to maximise the survey sample size, the author adopted the 'snowball' sampling approach by asking the directors or executives of the targeted companies in the invitation letter for the referrals to additional intelligent building experts or practitioners that they knew (Creswell, 2002). The purpose is to ‘snow-ball’ from a few potential respondents to many respondents. Attached to most of the reply letters were the contact details of additional intelligent building experts and practitioners. Finally, the contact details of a total of 136 respondents in the intelligent building professionals were obtained by mid-November 2004.

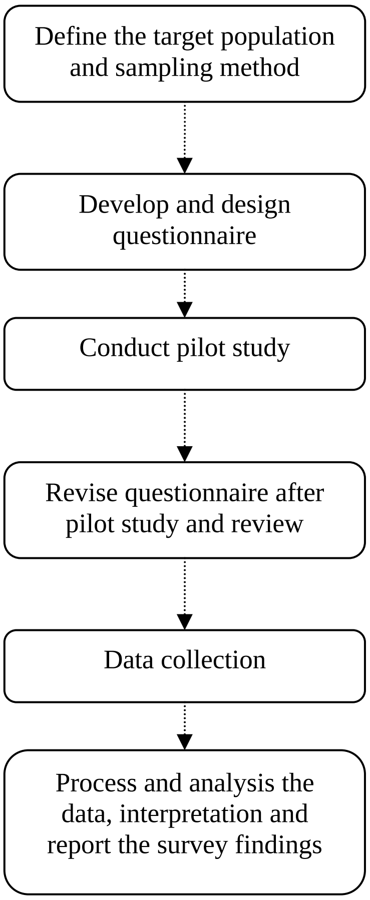


Figure 6.2: Survey Design for the General Survey of Research Part One

6.2.2 Pilot Study, Questionnaire Review and Responses

To collect general views from respondents regarding the perceived CSC, a structured survey questionnaire (the first questionnaire (A1) as shown in Appendix A, p.310) was designed, consisting of two parts. Part One was intended to ask the respondents to choose and verify the CSC when they selected the appropriate intelligent building control systems. Part Two of the questionnaire sought respondents' details in order to obtain their profile. This survey required the respondents to rate the influence of pre-determined attributes based on their judgement and experience. They were also invited to add new attributes if necessary. A covering letter was included as part of the questionnaire. The objective of this letter was to explain the purpose of the study and to assure the complete confidentiality of the information provided by the respondents.

A pilot study was conducted on the initial questionnaire to check on the posited selection factors and criteria of the seven intelligent building control systems in order to ascertain their criticality, and to collect more opinions to elicit omitted factors before sending the survey out again. Two rounds of pre-testing were performed. The first round was conducted on interviews with five directors and managing executives of design consultancies and property developers during late November and December 2004 to test the suitability and comprehensibility of the questionnaire. They were asked to comment and review on the clarity and relevance of the questionnaire. Based on their feedback, some selection criteria were rephrased for clarity. The second round of pre-testing was carried out with two academic researchers in the area of intelligent building. They were invited to provide further comments on the questionnaire design. After minor final refinements, the questionnaire was deemed ready for data collection.

In early January 2005, the questionnaires were sent to a total of 136 local building practitioners and experts including academics, developers, design consultants and building contractors. With their varied background and knowledge in the field, their views provided an accurate reflection of the selection factors/criteria and their relative importance. Altogether, a total of 79 replies are received in late February 2005. However, eight replies were excluded due to either incomplete questionnaire responses or wrong use of the rating scale, resulting in 71 valid usable replies for the analysis, representing a response rate of 52%.

6.2.3 Statistical Tests

The respondent perceptions were measured on the interval basis using a 5-point Likert-type scale (where 1 represented ‘not important at all’, and 5 represented ‘extremely important’). They were asked to rank the selection criteria in descending order. A Likert-type scale is appropriate for the data collection in this survey as it is an ordinal scale which can be employed to generate hierarchies of preferences and allows comparison across groups of respondents as per the sampling frame (Fellows and Liu, 2003:148). It also allows the determination of various groups of respondents’ views of an issue by asking respondents from each group to respond to a common set of statements/measures against the Likert scale. In the questionnaire, respondents were also invited to add new attributes or criteria if necessary. All survey data collected were examined and analysed using a standard version of the Statistical Package for the Social Science (SPSS®).

Descriptive statistics is employed in this general survey to elicit the CSC from the building practitioners and professionals. All proposed selection criteria are first calculated, ranked and compared according to their mean score ratings with the purpose of testing the hypothesis *H1*. The mean score rating was calculated using the following formula (Ekanayake and Ofori, 2004; and, Holt, 1997):

$$Mean = \frac{1(n_1) + 2(n_2) + 3(n_3) + 4(n_4) + 5(n_5)}{(n_1 + n_2 + n_3 + n_4 + n_5)} \qquad \text{(Eq. 6.1)}$$

where n_1, n_2, n_3, n_4, n_5 represent the total number of responses for selection criteria as 1 to 5 respectively.

The *t*-test analysis was employed to determine the importance level of each of the selection criteria. The test was to assess the statistical significance between two sample means for a single dependent variable (Hair *et al*., 1995: 261). The rule of *t*-test set out where the null hypothesis ($\mu_1 < \mu_0$) against the alternative hypothesis ($\mu_1 > \mu_0$) were tested, where μ_1 represents the population mean, and μ_0 represents the critical rating above which an attribute is considered as most important. The value of μ_0 was fixed at ‘4’ as it represents the ‘importance’ and ‘extreme importance’ of an attribute according to the scale in this questionnaire. The decision rule was to reject null hypothesis when the calculation of the observed *t*-values (t_O) (Eq. 6.2) was greater than the critical *t*-value (t_C) (Eq.6.3) as shown in equation (Eq.) 6.4 (Ekanayake and Ofori, 2004; and, Holt, 1997). This implies that, for research rigor, only those criteria with mean ratings above or equal to ‘4’ (‘important’) were included for consideration.

$$t_O = \frac{\overline{\chi} - \mu_0}{\hat{s}_D \big/ \sqrt{n}}, \qquad \text{(Eq. 6.2)}$$

$t_C = t_{(n-1,\alpha)}$, (Eq. 6.3)

$t_O > t_C$, (Eq. 6.4)

where $\overline{\chi}$ is the sample mean, $\hat{s}_D/\sqrt{n}$ is the estimated standard error of the mean of different scores (i.e. $\hat{s}_D$ is the sampled standard deviation of difference scores in the population, n is the sample size, which was 71 in this study), $n-1$ represents degree of freedom, and α represents the level of statistical significance. The level of statistical significance (α) is the degree of risk that researchers are willing to take in rejecting a null hypothesis when it is true (i.e. Type 1 error) in reporting results of statistical tests (Salkind, 2004: 144). The level of significance set at 0.05 represents a 5% chance of making a Type 1 error on any one test of the null hypothesis (Salkind, 2004).

In this study, the CSC were tested using equation 6.4. If the observed *t*-value was larger than the critical *t*-value ($t_O > t_C$), $t_{(70,\ 0.05)} = 1.6669$ at 95% confidence interval, then the null hypothesis (H_0) that the attributes that were ‘neutral’, ‘unimportant’ and ‘not important at all’ were rejected and only the alternative hypothesis (H_1) was accepted. If the observed *t*-value of the mean ratings weighted by the respondents was less than the critical *t*-values ($t_O < t_C$), only the null hypothesis that was ‘neutral’, ‘unimportant’, and ‘not important at all’ was accepted.

To further investigate whether there were statistically significant differences in the importance of the selection criteria between six different groups of building practitioners, the non-parametric Kruskal-Wallis one-way ANOVA test was undertaken. The matched parametric testing method was not employed since the parametric assumptions were not fulfilled, and the variables were measured by an ordinal scale of measurement in this study (Abdel-Kader and Dugdale, 2001; Love *et al*., 2004). The results of the Kruskal-Wallis test are interpreted by the Chi-square and degree of freedom (df). The statistical significance of the test is reported by the *p*-value. This is the probability of obtaining a test statistic value that is more extreme than the value of the actual sample when the null hypothesis in a test is true, or, in other words, the *p*-value is the observed significant levels in the test (Mendenhall *et al*., 1989: 374). A small value of the p-value represents a heavier weight of sample evidence for rejecting a null hypothesis (Mendenhall *et al*., 1989). Decisions of rejecting a null hypothesis are made, as is the common practice of statistical analysis, when the p-value of a test statistic exceeds 0.05. In this study, it indicates that if the p-value is <0.05, there is a significant difference between the groups.

6.2.4 Survey Findings and Discussions

Some demographic information relating to the respondents was collected. Seventy-one industry practitioners participated in this survey. Demographic information demonstrates that almost 75% of the practitioners in this survey worked in consultancies including mechanical and electrical (M&E) engineering, architectural design and quantity surveying. The remainder had backgrounds in construction (15%), property development (6%), and intelligent building research (4%). About 61 percent of the respondents had been working in building and construction industry for 10 years or more. All respondents reported knowledge of intelligent buildings, and 30% of them had direct involvement in at least one intelligent building project

Table 6.1 summarises the descriptive and inferential statistics for the selection criteria that respondents valued as ‘important’ (i.e. those with a value ≥ 4.00). As shown in the table, a total of 59 critical selection criteria for seven key building control systems were elicited. The first column of Table 6.1 illustrates the intelligent building control systems and their CSC. The second and third columns show the mean scores (including the standard deviation) and the ranks of these CSC, while the sixth to eleventh columns represent the mean rank of each CSC from six groups of industry practitioners. Pursuant to Table 6.1, some key findings and patterns are identified as follows:

1. The survey results indicated that at least eight selection criteria were considered important in four of the intelligent building control systems, including the HVAC Control System, Security Monitoring and Access Control System (SEC), Smart and Energy Efficient Lift System (LS), and Digital Addressable Lighting Control System (DALI). This implied these four building control systems could not be justified by just a few CSC due to their complexity. For instance, the t-test results suggested 14 CSC for the selection of the LS. The three dominant criteria were: ‘mean time between failures’, ‘service life’ and ‘waiting time’. Also, nine CSC were drawn out by the respondents for the DALI system.

2. Further analysis of the survey results indicated most of the CSC belonged to the factors of ‘Work Efficiency’ and ‘Cost Effectiveness’. Work efficiency has been a top priority in intelligent building design in literature (Clements-Croome, 2001a, and Smith, 2002). This suggests that the fundamental requirement in the selection of

appropriate building control systems is assuring that components function according to their specifications and with acceptable durability, service life and sustainability.

3. Amongst all the selection criteria, both ‘service life’ and ‘operating and maintenance costs’ were repeatedly considered the most important CSC in a number of building control systems. Although ‘initial cost’ was considered as one of the decisive factors for the adoption of intelligent building technologies in literature (for example: Sobchak, 2003), the survey findings indicated that the ‘initial cost’ declined from being the most important CSC. It was only considered as moderately critical in the HVAC (rank 9th) and SEC (rank 7th) systems. This may suggest that in general the majority of the building practitioners and professionals in the survey tend to be more concerned with the costs of running, maintaining and refurbishing than the initial capital costs in selecting the intelligent building control systems.

4. Four CSC which determine the choice of the IBMS were elicited. These criteria were ‘reliability and stability’; ‘operation and maintenance costs’; ‘integration and interface with service control systems’; and, ‘efficiency and accuracy’. The *t*-test of the means of the CSC further suggested that ‘operation and maintenance cost’ was more significant than ‘initial cost’, which suggests that the respondents were concerned more with the running and maintenance costs than the initial expense of the IBMS. On the other hand, ‘reliability and stability’ is also considered as a prime criterion to be considered for the selection of a Telecom and Data System (ITS) for the commercial intelligent building. Other CSC of the ITS include ‘further upgrade

of system’, ‘operation and maintenance costs’; ‘service life’; and, ‘transmission rate of data’.

5. Ranks of CSC in the AFA system reveal that, apart from the needs to comply with fire codes (i.e., ‘compliance with the code of minimum fire service installations or equipment’ and ‘compliance with the code for inspection, testing and maintenance of fire service installations and equipment’), time performance (‘system response time and survivability’) was also considered as the leading selection criterion. Likewise, ‘time needed for public announcement of the disasters’ was equally elicited by the respondents as the top CSC in determining the appropriate the SEC system.

6. User comfort was considered as one of the main concerns in the selection of an HVAC control system. Four CSC under the factor of *User Comfort* include ‘control of predict mean vote’; ‘control of indoor air quality’; ‘minimisation of plant noise’; and, ‘adequate fresh air changes’. This was consistent with the literature view that although work efficiency and cost effectiveness of HVAC systems is important, the need to provide the occupants with a comfortable and productive working environment which satisfies their physiological needs is also significant (Alcalá *et al*., 2005).

7. Further analysis regarding the potential variations across various building practitioner groups for the significance of each CSC by the Kruskal-Wallis one-way ANOVA test indicated that the variations in mean scores were not significant except for four criteria with *significant* different degrees of importance. A *p*-value in the last column

of Table 6.1 of less than 0.05 represents a significant difference between the groups. The results suggested that four CSC were indicated with significantly different degrees of importance: '*further upgrade*' under the AFA system ($\chi^2 = 11.20$, $p<0.04$) and SEC system ($\chi^2 = 13.80$, $p<0.01$); '*operation and maintenance cost*' under the HVAC control system ($\chi^2 = 12.39$, $p<0.03$) and DALI system ($\chi^2 = 12.43$, $p<0.02$). The survey results suggested that, for HVAC control and DALI systems, '*operating and maintenance costs*' was perceived as slightly more significant to other building professionals than to developers.

8. In summary, the findings of the general survey implied that there are different sets of CSC affecting the decision on the selection of different key building control systems. Each building control system has a different and unique set of CSC. In consequence, the first hypothesis (H1), which predicts that '*The critical selection criteria (CSC) affecting the selection of each of the building control systems in the intelligent building differs, reflecting their distinctive and unique roles*', is generally supported. Ranks of the CSC also reflect that each CSC exerts a different degree of influence on the selection of each of the intelligent building control systems. Some CSC are more important than the others. The second hypothesis (H2), which predicts that '*Each proposed set of critical selection criteria (CSC) exerts a considerable degree of influence on determining respective building control systems.*' is therefore generally supported. In order to re-affirm *H2*, the ranking of CSC would be further examined and verified by a group of intelligent building experts in the AHP survey. The results and analyses from this first survey also form the basis for establishing the decision hierarchy for the second AHP survey.

Table 6.1: Results of Mean Scores, Ranking, and Kruskal-Wallis Test regarding the Critical Selection Criteria (CSC) for the Key Building Control Systems

Building Control Systems and Their Crucial Selection Criteria (CSC)	**Mean (S.D.)**	**Rank***	***t*-value****	**Selection Factor group**	**Mean Rank of Different Professional Groups**						**Kruskal -Wallis Statistics** $^{\Delta}$	***p*-value**
					G.1	**G.2**	**G.3**	**G.4**	**G.5**	**G.6**		
Integrated Building Management System (IBMS)												
System reliability and stability	4.32 (.807)	1	3.384	*Work Efficiency*	37.63	35.20	53.00	36.82	32.50	38.50	3.40	0.63
Operation and maintenance costs	4.30 (.705)	2	3.535	*Cost Effectiveness*	35.75	34.70	35.67	34.77	38.62	33.13	0.64	0.98
Integrated and interface with service control systems	4.23 (.721)	3	2.633	*Work Efficiency*	36.04	37.65	57.50	28.23	36.93	28.00	6.56	0.25
Efficiency and accuracy	4.20 (.715)	4	2.488	*Work Efficiency*	44.67	36.05	48.33	32.32	31.24	35.63	5.61	0.34
Telecom and Data System (ITS)												
System reliability and stability	4.35 (.739)	1	4.016	*Work Efficiency*	28.58	36.75	43.67	35.50	38.21	38.50	2.78	0.73
Further upgrade of system	4.28 (.740)	2	3.206	*Work Efficiency*	42.42	35.38	55.50	31.36	36.33	16.25	9.51	0.09
Operation and maintenance costs	4.24 (.726)	3	2.778	*Cost Effectiveness*	38.75	33.00	57.50	38.09	33.38	34.63	5.21	0.39
Service life	4.23 (.680)	4	2.791	*Work Efficiency*	38.83	27.75	38.17	36.32	44.36	22.38	10.43	0.06
Transmission rate of data	4.20 (.689)	5	2.411	*Work Efficiency*	37.08	33.40	41.33	38.45	38.24	23.25	2.97	0.70
Addressable Fire Detection and Alarm System (AFA)												
Compliance with the code of minimum fire service installations or equipment	4.25 (.751)	1	2.846	*Safety Related*	32.33	32.00	46.50	43.77	35.29	41.50	4.46	0.48
Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	4.24 (.783)	2	2.576	*Safety Related*	28.25	34.85	46.50	42.86	33.95	49.00	6.53	0.25
Operation and maintenance costs	4.24 (.783)	2	2.576	*Cost Effectiveness*	38.25	31.45	39.67	36.68	39.38	29.63	2.51	0.77
System response time and survivability	4.23 (.778)	3	2.709	*Work Efficiency*	34.33	35.60	30.67	38.91	35.24	43.00	1.18	0.94
Further upgrade of system	4.23 (.701)	4	2.440	*Work Efficiency*	40.54	40.90	46.83	22.86	31.55	49.25	11.20	0.04***
Automatic detection of fire, gas and smoke	4.21 (.695)	5	2.561	*Work Efficiency*	32.88	34.13	58.50	32.59	37.79	37.88	5.36	0.37
Service life	4.17 (.793)	6	1.797	*Work Efficiency*	40.00	30.75	38.67	35.00	36.05	50.75	4.50	0.48

Note: (1) * represents ranking within each building control system; ** represents the t-value that is >cut of t-value (1.6669); *** represents the p-value that is less than 0.05; $^{\Delta}$ shows the df for Kruskal-Wallis test = 5.
(2) **S.D.** = Standard Deviation; **G.1**= architect; **G.2**= M&E engineer; **G.3=** research & development; **G.4**= construction; **G.5**= quantity surveyor; and, **G.6**= developer

Table 6.1: Results of Mean Scores, Ranking, and Kruskal-Wallis Test regarding the Critical Selection Criteria (CSC) for the Key Building Control Systems (cont.)

Building Control Systems and Their Crucial Selection Criteria (CSC)	**Mean (S.D.)**	**Rank***	***t*-value****	**Selection Factor group**	**Mean Rank of Different Professional Groups**						**Kruskal -Wallis Statistics $^{\Delta}$**	***p*-value**
					G.1	**G.2**	**G.3**	**G.4**	**G.5**	**G.6**		
Heating, Ventilation and Air-Conditioning Control System (HVAC)												
Service life	4.24 (.706)	1	2.856	*Work Efficiency*	43.21	36.70	37.50	29.05	36.26	27.50	4.07	0.53
Control of predict mean vote (PMV)	4.24 (.706)	1	2.856	*User Comfort*	39.63	33.70	47.50	41.14	34.43	22.13	4.93	0.42
Operation and maintenance costs	4.23 (.778)	2	2.440	*Cost Effectiveness*	42.96	27.30	56.50	42.32	36.64	22.50	12.39	0.03***
Control of indoor air quality (IQA)	4.21 (.735)	3	2.422	*User Comfort*	43.63	31.83	40.67	37.09	35.81	28.50	3.68	0.59
Total energy consumption	4.21 (.773)	4	2.303	*Environmental*	41.42	37.28	56.50	35.64	31.36	23.38	7.41	0.19
Integrated by IBMS	4.21 (.791)	5	2.250	*Work Efficiency*	41.21	35.50	46.83	31.23	35.52	30.38	2.88	0.71
System reliability and stability	4.21 (.827)	6	2.154	*Work Efficiency*	42.46	37.95	46.33	34.55	30.86	30.13	4.37	0.49
Minimisation of plant noise	4.20 (.749)	7	2.219	*User Comfort*	45.79	32.85	48.33	41.86	30.69	24.88	9.25	0.09
Interface with other building control systems	4.20 (.786)	8	2.114	*Work Efficiency*	43.92	34.88	31.33	26.55	37.86	37.63	5.15	0.39
Initial costs	4.18 (.683)	9	2.260	*Cost Effectiveness*	42.54	32.30	29.50	44.32	33.60	29.50	5.57	0.35
Adequate fresh air changes	4.17 (.756)	10	1.885	*User Comfort*	40.83	35.10	32.00	40.73	34.38	24.50	3.17	0.67
Digital Addressable Lighting Control System (DALI)												
Operation and maintenance costs	4.32 (.692)	1	3.943	*Cost Effectiveness*	40.96	28.93	55.50	29.41	42.76	24.50	12.43	0.02***
Interface with other building control systems	4.25 (.788)	2	2.712	*Work Efficiency*	40.25	32.08	45.83	30.95	37.60	41.00	3.42	0.63
Integrated by IBMS	4.24 (.765)	3	2.638	*Work Efficiency*	38.42	33.33	37.00	29.82	39.17	41.75	2.67	0.75
Permanent artificial lighting average power density	4.20 (.710)	4	2.342	*Work Efficiency*	35.67	37.42	31.33	30.27	38.10	38.13	1.60	0.90
Further upgrade of system	4.18 (.743)	5	2.077	*Work Efficiency*	46.67	31.78	39.00	28.68	37.21	36.63	6.45	0.26
Service life	4.18 (.762)	6	2.025	*Work Efficiency*	36.33	32.85	38.83	31.27	41.81	31.13	3.44	0.63
Ease of control	4.17 (.697)	7	2.044	*User Comfort*	33.96	38.58	39.83	31.09	39.00	24.13	3.49	0.62
Total energy consumption	4.17 (.717)	8	1.987	*Environmental*	40.17	37.00	14.67	29.00	40.24	31.50	7.15	0.20
Automatic control and adjustment of lux level	4.17 (.774)	9	1.839	*Work Efficiency*	46.54	31.03	32.00	33.59	36.38	36.88	5.23	0.38

Note: (1) * represents ranking within each building control system; ** represents the t-value that is >cut of t-value (1.6669); *** represents the p-value that is less than 0.05; $^{\Delta}$ shows the df for Kruskal-Wallis test = 5.
(2) **S.D.** = Standard Deviation; **G.1**= architect; **G.2**= M&E engineer; **G.3=** research & development; **G.4**= construction; **G.5**= quantity surveyor; and, **G.6**= developer

Table 6.1: Results of Mean Scores, Ranking, and Kruskal-Wallis Test regarding the Critical Selection Criteria (CSC) for the Key Building Control Systems (cont.)

Building Control Systems and Their Crucial Selection Criteria (CSC)	**Mean (S.D.)**	**Rank***	***t*-value****	**Selection Factor group**	**Mean Rank of Different Professional Groups**						**Kruskal -Wallis Statistics** $^{\Delta}$	***p*-value**
					G.1	**G.2**	**G.3**	**G.4**	**G.5**	**G.6**		
Security Monitoring and Access System (SEC)												
Time needed for public announcement of disasters	4.42 (.601)	1	5.919	*Work Efficiency*	43.33	33.48	43.33	33.18	35.90	29.38	3.55	0.61
Operation and maintenance costs	4.41 (.709)	2	4.857	*Cost Effectiveness*	40.63	32.15	52.50	31.27	38.43	29.25	5.59	0.34
Time needed to report a disastrous event to the building mgt.	4.27 (.755)	3	2.986	*Work Efficiency*	44.21	31.30	39.33	37.05	38.43	16.75	7.98	0.15
Interface with other building control systems	4.25 (.751)	4	2.846	*Work Efficiency*	44.00	34.50	36.50	40.14	32.90	24.00	4.93	0.42
Integrated by IBMS	4.24 (.765)	5	2.638	*Work Efficiency*	44.83	26.63	37.00	41.23	39.17	24.63	10.16	0.07
Service life	4.20 (.768)	6	2.165	*Work Efficiency*	47.83	31.95	38.17	4.68	33.24	18.00	10.48	0.06
Further upgrade of system	4.20 (.768)	6	2.165	*Work Efficiency*	45.42	30.90	47.83	46.95	31.48	18.00	13.80	0.01***
Initial costs	4.18 (.743)	7	2.077	*Cost Effectiveness*	37.13	34.35	38.67	35.59	38.19	28.50	1.19	0.94
Time for total egress	4.18 (.798)	8	1.932	*Work Efficiency*	49.75	34.15	40.67	33.14	32.64	26.00	8.42	0.13
Smart and Energy Efficient Lift System (LS)												
Mean time between failures	4.42 (.750)	1	4.750	*Safety Related*	42.25	33.75	41.00	33.27	37.43	24.75	3.81	0.57
Service life	4.34 (.736)	2	3.872	*Work Efficiency*	46.50	33.60	44.00	33.27	34.29	27.00	5.91	0.31
Waiting time	4.34 (.736)	2	3.872	*Work Efficiency*	46.50	31.50	34.00	36.00	37.14	22.50	7.03	0.21
Maximum interval time	4.30 (.782)	3	3.188	*Work Efficiency*	43.00	32.92	44.50	35.18	35.64	28.13	3.48	0.62
Total energy consumption	4.28 (.721)	4	3.293	*Environmental*	40.17	35.00	36.00	40.55	32.67	33.50	1,98	0.85
Acceleration and deceleration control	4.27 (.736)	5	3.064	*User Comfort*	40.38	32.83	29.67	35.41	39.10	28.88	2.64	0.75
Journey time	4.25 (.751)	6	2.846	*Work Efficiency*	42.25	31.60	36.67	38.36	37.52	24.25	4.16	0.52
Integrated by IBMS	4.24 (.783)	7	2.576	*Work Efficiency*	42.21	34.25	30.33	36.68	34.45	36.63	1.84	0.87
Interface with other building control systems	4.24 (.801)	8	2.518	*Work Efficiency*	44.42	31.40	30.17	36.50	36.05	36.50	3.77	0.58
Operation and maintenance costs	4.24 (.801)	8	2.518	*Cost Effectiveness*	40.46	32.70	55.50	33.91	35.26	34.13	4.56	0.47
Minimisation of in-car noise	4.23 (.680)	9	2.791	*User Comfort*	43.92	30.40	28.00	32.23	40.00	35.63	5.84	0.32
Adequate fresh air changes	4.23 (.778)	10	2.440	*User Comfort*	43.33	31.20	30.67	33.82	39.43	30.00	4.42	0.48
Minimisation of in-car vibration	4.23 (.778)	10	2.440	*User Comfort*	45.17	30.65	27.50	31.18	39.83	34.75	6.47	0.26
Automatic and remote control	4.17 (.774)	11	1.839	*Work Efficiency*	44.25	35.92	22.83	36.09	34.05	31.50	4.03	0.54

Note: (1) * represents ranking within each building control system; ** represents the t-value that is >cut of t-value (1.6669); *** represents the p-value that is less than 0.05; $^{\Delta}$ shows the df for Kruskal-Wallis test = 5.
(2) **S.D.** = Standard Deviation; **G.1**= architect; **G.2**= M&E engineer; **G.3=** research & development; **G.4**= construction; **G.5**= quantity surveyor; and, **G.6**= developer

6.3 THE AHP SURVEY: REFINING THE CONCEPTUAL MODELS

The elicitation of CSC in the general survey revealed that different sets of CSC affect the decision on the selection of building control systems. To provide a more meticulous prioritisation of these tested CSC and to reaffirm whether the CSC exerted different degrees of influence on the decision of the building control systems, ranks of the CSC would be undertaken in the second survey by capturing the opinions of the experienced intelligent building experts using the AHP method. This would reflect the reality in the intelligent building context. Prioritising these selection criteria and their factor groups provides a better understanding of their importance in influencing the selection decision. In fact, apart from its use in prioritising and selecting decision alternatives, the AHP is also well known for its usefulness in prioritising a set of factors and identifying the key factors (Cheng, 2001). It allows intangible factors to be considered by soliciting consistent subjective expert judgment (Chua *et al*., 1999). In construction research, the use of AHP for the identification of critical factors has been attempted by Chua *et al*. (1999) and Cheng and Li (2002). Their studies employed the AHP approach to prioritise a set of critical success factors (CSFs) for the success of various project objectives and partnering projects.

6.3.1 Sample, Questionnaire Design and Data Collection

To help evaluate the comparability of the CSC, a questionnaire (the second questionnaire (A2) as shown in Appendix A, p.319) was designed to facilitate systematic data collection. The questionnaire format was synthesised with reference to an AHP matrix proposed by Saaty (1996). Since the assignment of weights requires logical and analytical thinking, only the relevant intelligent building experts or professionals who were capable of providing penetrating insights were highly valuable to this empirical inquiry. To search for appropriate respondents, a question in the earlier general survey questionnaire asked the respondents if they were experienced or specialised in the intelligent building design and development. An invitation note for the AHP survey was sent by e-mail to those participants who reported that they were experienced in intelligent building projects.

Of all the experienced building practitioners contacted, 10 professionals expressed interest and were willing to participate in providing their opinion to the second stage AHP questionnaire survey. The relatively small size of sample population in the AHP survey is mainly attributed to two reasons. First, intelligent building is such an innovative form of building design and development that the concept has only been gained popularity in local building industry over the last ten years. The numbers of building professionals experienced in intelligent building design and development is limited. Thus, this restricted the pool size of the available respondents. Second, some of the practitioners contacted were reluctant to participate in the AHP survey merely because of the need to complete pair-wise comparisons of a total of 59 CSC for seven key building systems of the intelligent building. In fact, the AHP is a subjective method that does not require a large sample, and it is useful for research focusing on a specific issue where a large sample is not mandatory (Cheng and Li, 2002). Cheng and Li (2002) maintain that AHP method may be impractical for a survey with a large sample size as “cold-called” respondents may have a great tendency to provide arbitrary answers, resulting in a very high degree of inconsistency. A review of literature also found that AHP surveys with small sample sizes have been undertaken and reported. For example, Cheng and Li (2002), in their empirical study, invited nine construction experts to undertake a survey to test comparability of critical success factors (CSFs) for the partnering project. Lam and Zhao (1998) also invited eight experts in an AHP survey to evaluate the effectiveness of seven identified teaching techniques in achieving each of ten educational objectives. All these studies indicate that AHP method is appropriate for research focusing on a specific area, where there are difficulties in achieving a large sample size or high response rate.

Due to the small sample size involved, it is important to ensure that only valid and good quality data are acquired. Chua *et al*. (1999) provide a number of suggestions in the design of AHP questionnaire surveys which help to achieve these ends. Their suggestions include:

- A brief presentation with regard to the objective and methodology of the AHP should be made to every respondent individually. An illustrative example should be provided in the questionnaire.
- The respondents should be reminded of the importance of observing consistency in their answers in the questionnaire.
- The questions relating to different aspects should be presented in different sections. This helps respondents to focus on one aspect at a time.

Prior to the design of the pair-wise comparison matrices for the survey, the decision hierarchies need to be established. The chain of decision hierarchy is established based on the results of the general survey stated in preceding section (Table 6.1). Concisely, using the IBMS as an illustrated example, Figure 6.3 illustrates the decision hierarchy of the CSC for the IBMS. The top level was the goal, that is the prioritisation of the CSC for the IBMS, and following this was two critical selection factors: ‘Work Efficiency’ and ‘Cost Effectiveness’. The third level includes those CSC which were organised under the critical selection factors, including ‘system reliability and stability’, ‘integrated and interface with service control systems’, ‘efficiency and accuracy’, and ‘operation and maintenance costs’. The hierarchies of CSC for the remaining six building control systems were also formed based on the results of the first survey in Table 6.1. Their decision hierarchies are depicted in Figures 6.3 to 6.9 respectively.

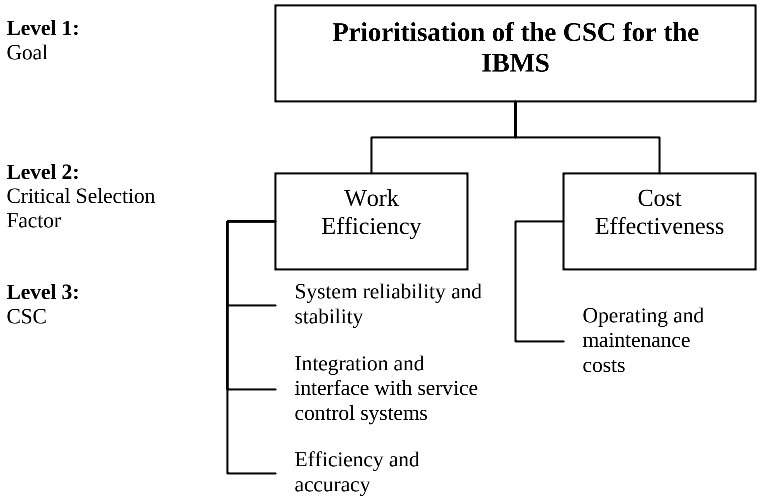


Figure 6.3: Hierarchy of the Critical Selection Criteria (CSC) for the Integrated Building Management System (IBMS)

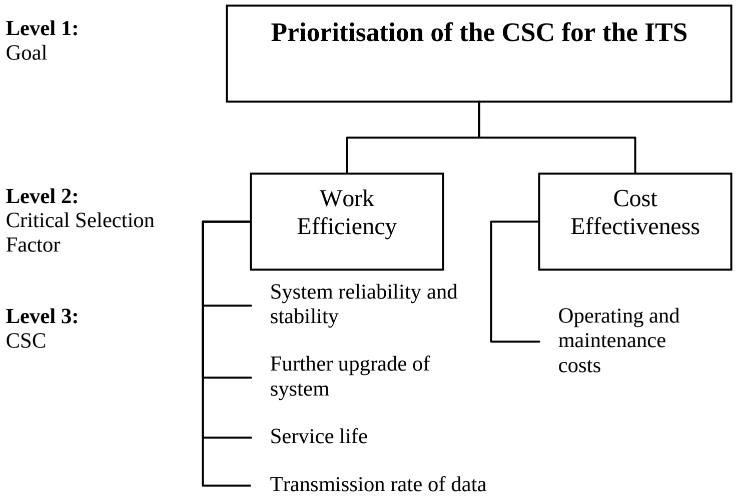


Figure 6.4: Hierarchy of the CSC for the Telecom and Data System (ITS)

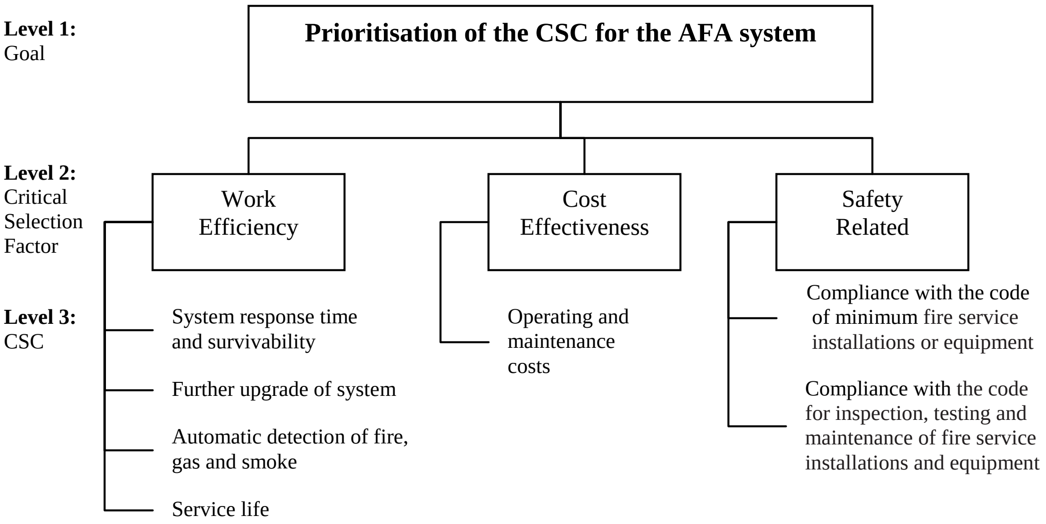


Figure 6.5: Hierarchy of the CSC for the Addressable Fire Detection and Alarm System (AFA)

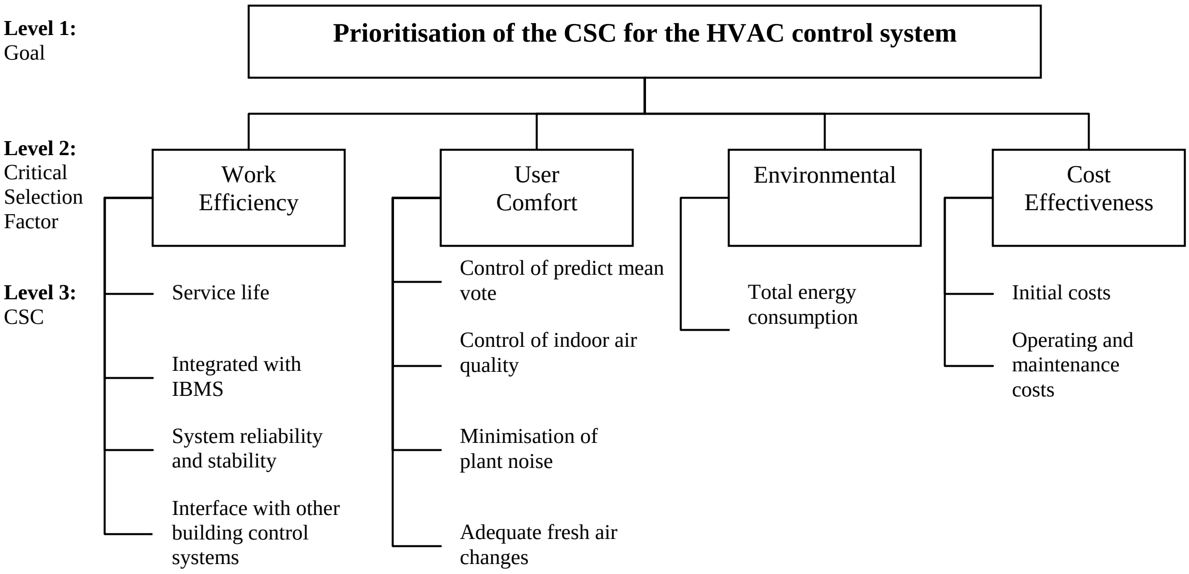


Figure 6.6: Hierarchy of the CSC for the HVAC Control System

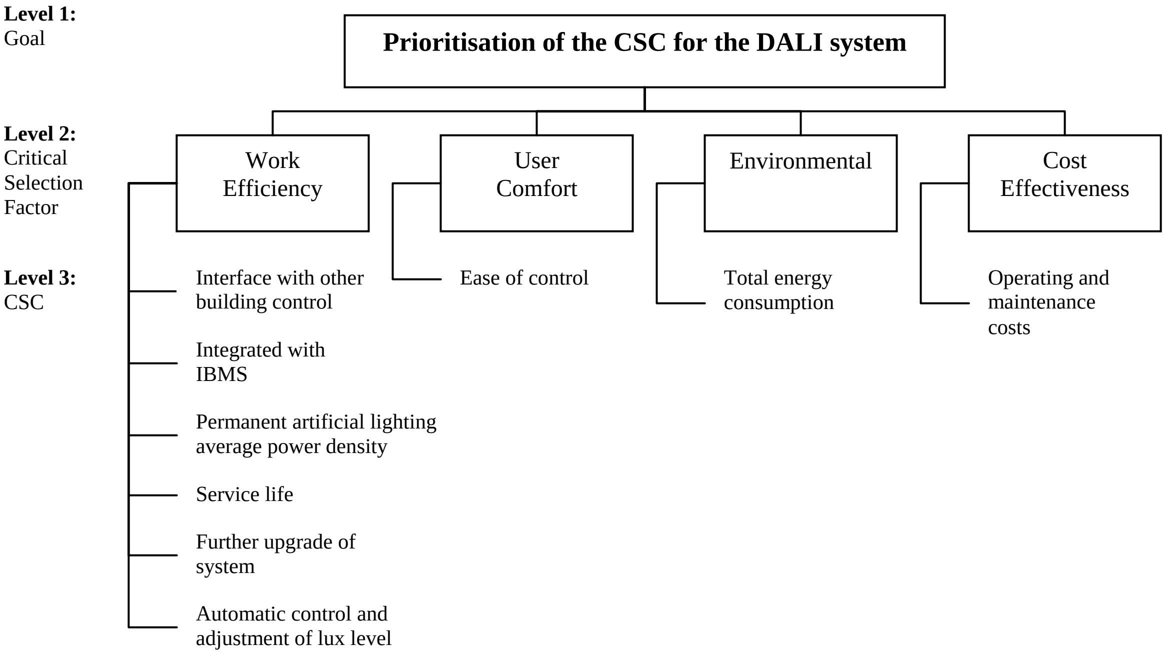


Figure 6.7: Hierarchy of the CSC for the Digital Addressable Lighting Control System (DALI)

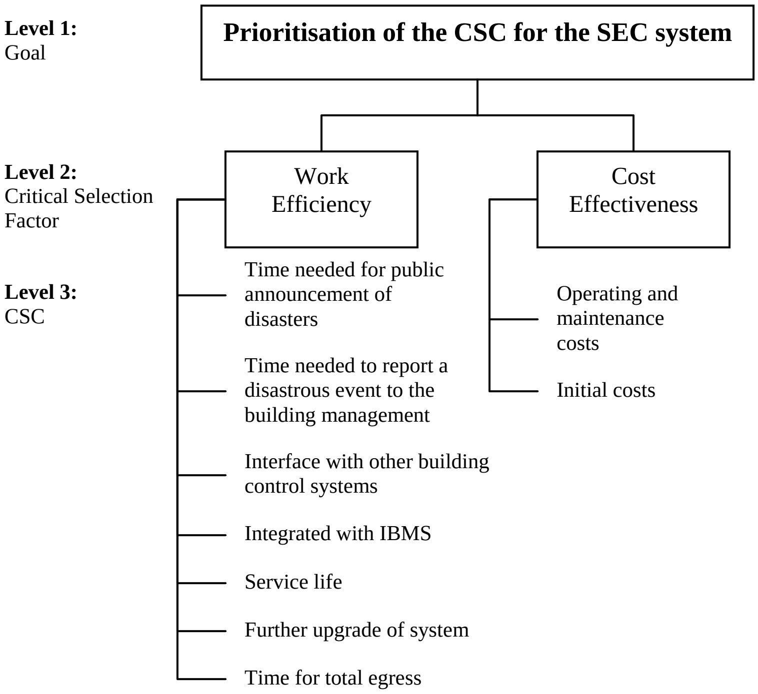


Figure 6.8: Hierarchy of the CSC for the Security Monitoring and Access Control System (SEC)

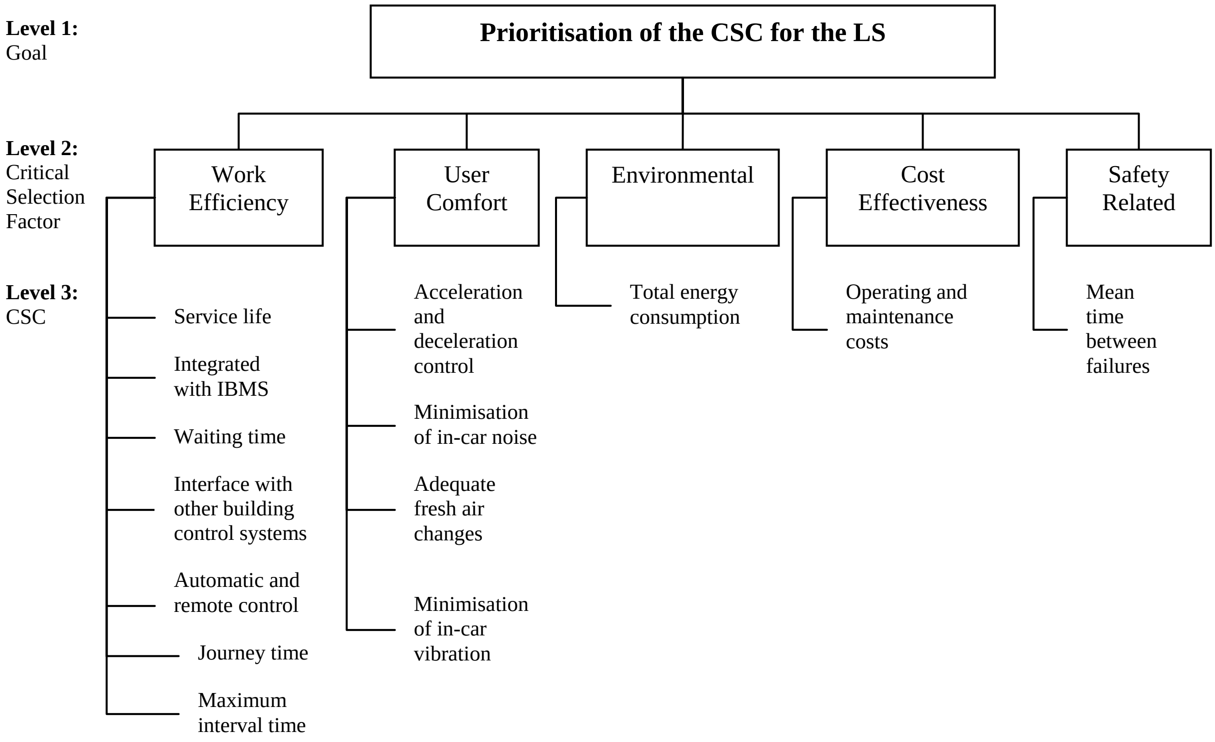


Figure 6.9: Hierarchy of the CSC for the Smart and Energy Efficient Lift System (LS)

The consistency check of the AHP approach is an important procedure which makes it a reliable way to determine the priorities of factors or criteria to a set. Cheng (2001) summarises four procedures of measuring and checking the inconsistency in the pair-wise comparison developed in the questionnaire survey. The procedure by Cheng is summarised as follows:

- If over half of the weighting sections failed the consistency test, the questionnaire is said to be unusable and is disqualified.
- In the usable questionnaires, those sections with a consistency ratio (CR) larger than the acceptable value are excluded from analysis. The acceptable CR values for different sizes of matrix were discussed in section 5.5.1.
- The arithmetic methods of Saaty (1980:65) are adopted for judgemental revision and consistency improvement if there are very few or no usable questionnaires.
- If the judgmental revision in the above step fails to improve the consistency, the preferences are required to be re-estimated (i.e., move back to *AHP Step Three* of AHP, prioritising procedures as depicted in Figure 5.2) in order to improve the CR. If this fails, then the problem should be more accurately structured (i.e. grouping similar elements under a more meaningful attributes scheme) and the process should return to *AHP Step Two* of Figure 5.2 to re-structure the hierarchical model of the decision problem to a better attribute representation.

Of the ten expert respondents in this survey, nine of the survey responses appeared to have acceptable consistency after the consistency test (as shown in Table 6.2) and would thus enter into analysis. These nine respondents (i.e., EXA1 to EXA9) were equally highly-experienced in the building industry, though in different aspects such as building services engineering and design, property development and architecture. Eight of them have participated in not less than three intelligent building projects, and all replied with an average of 10 years of experience in construction field.

Table 6.2: Consistency Ratio (CR) Values for the Judgment Matrices

Expert **Matrix set**	**EXA1**	**EXA2**	**EXA3**	**EXA4**	**EXA5**	**EXA6**	**EXA7**	**EXA8**	**EXA9**
IBMS1 (2 by 2)	0	0	0	0	0	0	0	0	0
IBMS2 (3 by 3)	0.010	0.010	0.028	0	0	0	0	0	0
ITS1 (2 by 2)	0	0	0	0	0	0	0	0	0
ITS2 (4 by 4)	0	0	0	0	0	0.023	0	0	0
AFA1 (3 by 3)	0	0	0	0	0	0	0	0	0
AFA2 (2 by 2)	0	0	0	0	0	0	0	0	0
AFA3 (4 by 4)	0	0.031	0.024	0	0	0	0	0.022	0.020
HVAC1 (4 by 4)	0.023	0.019	0.058	0	0	0	0	0.070	0
HVAC2 (4 by 4)	0.000	0	0.010	0	0	0	0	0	0.020
HVAC3 (4 by 4)	0.017	0.012	0.023	0	0	0	0	0.023	0
HVAC4 (2 by 2)	0	0	0	0	0	0	0	0	0
DALI1 (4 by 4)	0.070	0.058	0.017	0	0	0	0	0.023	0
DALI2 (6 by 6)	0.034	0.049	0.039	0	0	0	0	0.080	0.060
SEC1 (2 by 2)	0	0	0	0	0	0	0	0	0
SEC2 (7 by 7)	0.021	0.068	0.053	0	0.020	0.010	0	0.066	0.020
SEC3 (2 by 2)	0	0	0	0	0	0	0	0	0
LS1 (5 by 5)	0	0.074	0.012	0	0	0	0	0.016	0.040
LS2 (7 by 7)	0.084	0.054	0.020	0	0	0	0.084	0.034	0.010
LS3 (4 by 4)	0.070	0	0	0	0	0	0.023	0.023	0

Note: (1) Nine respondents with acceptable consistency are assigned with ref. EXA1 to EXA9; (2) Acceptable CR values (Saaty; 1994, and Cheng & Li; 2002): 0.05 or below for a 3-by-3 matrix, 0.08 or below for a 4-by-4 matrix; 0.1 or below for matrices larger than 5-by-5; (3) No value is larger than the acceptable CR value in this study.

6.3.2 Data Analysis and Results

To analyse the survey findings, the judgment matrices were pair-wise compared and analysed via the use of *Expert Choice*. The local priority weights (LPW) of all selection factors and their associated criteria (CSC) were first calculated. Then, these were combined with all successive hierarchical levels in each matrix to obtain a global priority vector (GPV). The higher the mean weight of GPV of the CSC, the greater the relative importance is. This helps to distinguish the more important elements from the less important ones.

The distributive summary in Table 6.3 suggests that each group of CSC have different prioritisation according to the mean weight of the respondents in the final selection of the building control systems. The mean global priority weight (GPW) differs for the CSC (from the lowest 0.021 to the highest of 0.424). Comparing the results of two surveys in this study revealed that the rankings of CSC in the AHP survey were slightly different from those of the first survey, but that they have a common basis in that the criteria are all important and comparable. This AHP survey further confirms the significance of all CSC by the experts who have a high level of experience in intelligent building projects. According to Table 6.3, some key findings of AHP survey are summarised below:

- *‘Work Efficiency’* was continuously perceived as the most important selection factor in the IBMS (0.655), ITS (0.576), and SEC (0.664) systems, while *‘User Comfort’* was considered as slightly more important in HVAC (0.337) and DALI (0.312) systems. On the other hand, the *‘Safety Related’* factor was more important to AFA (0.545) and LS (0.302) systems.
- Consistent with the results of the preceding general survey, ‘*system reliability and stability*’ (0.351) and ‘*operating & maintenance costs*’ (0.345) were further judged as the top CSC for the IBMS in this AHP survey. This is consistent with the views

of So and Chan (1999) in which the system reliability was reported as a key criteria of choosing the right IBMS. '*Operating and maintenance costs*' was also considered by the experts as the top CSC in the ITS (0.424) and SEC (0.196) systems.

- The survey findings further revealed that no single CSC was dominant in all building control systems. For instance, a number of CSC under *'Work Efficiency'* were judged as equally important in the LS, SEC, and DALI systems.
- The GWP and the rankings of the CSC in Table 6.3 reflect that expert respondents consider that each CSC have a varied degree of relative importance. The findings further re-affirm the second hypothesis *(H2)*.

6.4 DISCUSSION OF TESTS RESULTS

Contrasting the results of the two surveys indicates that the findings in the second AHP survey are slightly different from those of the first survey. In fact, two surveys involve different samples to be considered. The first survey used a larger size of sample (n = 71) including building practitioners and professionals with a knowledge of intelligent building, while the AHP survey involved nine experts who are highly experienced in intelligent building design and development. Despite the slight different in the ranking of CSC in these two surveys, they have confirmed similar level of significance of all CSC. The first survey identified the CSC for different building control systems. The results indicated that there are disparate sets of CSC which reflect the distinctive requirements and functions of each building control system in the intelligent building. In the AHP survey, the results further reaffirmed that each group of CSC exert substantial levels of influence on the respective building control systems.

Table 6.3: Relative Importance and Rankings of the CSC

Building Control Systems	Criteria Selection Group	LP	Critical Selection Criteria (CSC)	LP	GP	Ranking
Integrated Building Management System (IBMS)	*WE*	0.655	System reliability and stability	0.536	0.351	1
		0.655	Integration and interface with services control systems	0.205	0.134	4
		0.655	Efficiency and accuracy	0.258	0.169	3
	CE	0.345	Operating and maintenance costs	1.000	0.345	2
Telecom and Data System (ITS)	*WE*	0.576	System reliability and stability	0.362	0.209	2
		0.576	Further upgrade of system	0.220	0.127	3
		0.576	Service life	0.214	0.123	4
		0.576	Transmission rate of data	0.203	0.117	5
	CE	0.424	Operating and maintenance costs	1.000	0.424	1
Addressable Fire Detection and Alarm System (AFA)	*SR*	0.545	Compliance with the code of minimum fire service installations or equipment	0.559	0.305	1
		0.545	Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	0.441	0.240	2
	WE	0.217	System response time and survivability	0.254	0.055	5
		0.217	Further upgrade of system	0.170	0.037	7
		0.217	Automatic detection of fire, gas and smoke	0.324	0.070	4
		0.217	Service life	0.252	0.055	6
	CE	0.238	Operating and maintenance costs	1.000	0.238	3
Heating, Ventilation & Air-Conditioning (HVAC) Control System	*WE*	0.278	Service life	0.194	0.054	9
		0.278	System reliability and stability	0.442	0.123	2
		0.278	Integrated with IBMS	0.205	0.057	8
		0.278	Interface with other bldg. systems	0.158	0.044	10
	UC	0.337	Control of predict mean vote	0.226	0.076	6
		0.337	Control of indoor air quality	0.294	0.099	4
		0.337	Minimisation of plant noise	0.254	0.086	5
		0.337	Adequate fresh air changes	0.226	0.076	6
	EN	0.198	Total energy consumption	1.000	0.198	1
	CE	0.187	Initial costs	0.399	0.075	7
		0.187	Operating and maintenance costs	0.601	0.112	3

Note: LP= Local Priority; GP= Global Priority; WE= work efficiency, CE= cost effectiveness, EN= environmental, UC= user comfort; SR= safety related

Table 6.3: Relative Importance and Rankings of the CSC (cont.)

Building Control Systems	Criteria Selection Group	LP	Critical Selection Criteria (CSC)	LP	GP	Ranking
Digital Addressable Lighting Control System (DALI)	*WE*	0.23	Interface with other bldg. systems	0.131	0.030	9
		0.23	Integrated with IBMS	0.146	0.034	8
		0.23	Permanent artificial lighting average power density	0.180	0.041	6
		0.23	Further upgrade of system	0.158	0.036	7
		0.23	Service life	0.203	0.047	4
		0.23	Automatic control and adjustment of lux level	0.182	0.042	5
	UC	0.312	Ease of control	1.000	0.312	1
	EN	0.191	Total energy consumption	1.000	0.191	3
	CE	0.267	Operating and maintenance costs	1.000	0.267	2
Security Monitoring and Access Control System (SEC)	*WE*	0.664	Time needed for public announcement of disasters	0.139	0.092	6
		0.664	Time needed to report a disastrous event to the building management	0.170	0.113	3
		0.664	Interface with other bldg. systems	0.137	0.091	7
		0.664	Integrated with IBMS	0.146	0.097	5
		0.664	Service life	0.129	0.086	9
		0.664	Further upgrade of system	0.130	0.086	8
		0.664	Time for total egress	0.149	0.099	4
	CE	0.336	Initial costs	0.416	0.140	2
		0.336	Operating and maintenance costs	0.584	0.196	1
Smart & Energy Efficient Lift System (LS)	*WE*	0.228	Service life	0.099	0.023	12
		0.228	Waiting time	0.234	0.053	4
		0.228	Maximum interval time	0.200	0.046	8
		0.228	Journey time	0.175	0.040	10
		0.228	Integrated with IBMS	0.090	0.021	13
		0.228	Interface with other bldg. systems	0.081	0.018	14
		0.228	Automatic and remote control	0.122	0.028	11
	UC	0.196	Minimisation of in-car noise	0.248	0.049	7
		0.196	Acceleration and deceleration control	0.232	0.045	9
		0.196	Adequate in-car fresh air changes	0.264	0.052	5
		0.196	Minimisation of in-car vibration	0.257	0.050	6
	SR	0.302	Mean time between failures	1.000	0.302	1
	EN	0.149	Total energy consumption	1.000	0.149	2
	CE	0.125	Operating and maintenance costs	1.000	0.125	3

Note: LP= Local Priority; GP= Global Priority; WE= work efficiency, CE= cost effectiveness, EN= environmental, UC= user comfort; SR= safety related

Comparing and investigating the importance of CSC in two surveys indicates that 'operating and maintenance costs' was seen as an important criterion in almost all of the building control systems. In the first survey, 'operating and maintenance costs' was ranked as one of the top three CSC in all seven intelligent building control systems in this study, except for the LS. Its importance is further supported by the results of the AHP survey, which showed that experts considered 'operating and maintenance costs' as the top CSC in ITS, AFA and SEC systems. It was also ranked either second or third CSC for the remaining four building control systems. This finding is as expected, as the cost savings that can be produced in long run have been regarded as a top concern in the intelligent building (Sobchak, 2003). Curtis (2001) maintains that the importance of 'operating and maintenance costs', particularly in SEC system, is probably due to the fact that the incremental cost of upgrading a sensor of the security building system is associated with the life-cycle-cost, which includes a consideration for energy, reliability and maintenance costs over the system's expected service life.

In addition, the importance of operation and maintenance costs over the initial cost (Wong *et al*, 2001; and So *et al.*, 2001). For examples, Suttell (2002) points out that the initial set up cost covers only 25 percent of the total cost over the lifetime of a building, while the operating and maintenance costs cover approximately 75 percent. Fuller and Boyles (2000), in their report of life-cycle costing for energy conservations in buildings, also clearly expressed in their report that choosing building systems on the basis of first cost alone can increase the long-run owning and operating costs of a building. The greater part of the buildings' life-cycle cost is usually attributable to ongoing operating, maintenance, repair, and energy costs. It should be noted that 'initial costs' was still ranked as the second CSC in SEC system. This is because the sensor installation and setup cost is a significant part of the total installed cost for the security monitoring and access system due to the large number of sensors and detectors involved. ‘Initial costs’ was also considered as an CSC in the HVAC control system, and this finding is also supported by a number of studies: For examples: Buys and Mathews (2005) argued that the initial capital outlay is one of the largest expenses of any HVAC system, which has a 20–50% contribution to the life-cycle cost. Walawalkar et al. (2002) also pointed out that, for modern office buildings, a typical lighting system the initial cost (installation cost) is hardly 10 % of the lifecycle cost of the system, where as for a typical HVAC system the initial cost could be 20-30% of the life-cycle cost.

Further analysis of the survey results indicates that the rankings of the CSC for the IBMS in the AHP survey are almost identical to their rankings in the first survey. This implies that both practitioners and experts in the two surveys have consistent views over the priorities of CSC. The top CSC was ‘system reliability and stability’ which is probably due to the common view that the IBMS acts as ‘the heart of intelligent building’ (So and Chan, 1999:41), allowing independent building systems to be seemingly integrated into a single comprehensive building system (Piper, 2002). Instability and unreliability of the IBMS would possibly lead to disastrous results in the operation of the intelligent building. The importance of another two ‘Work Efficiency’ criteria in the IBMS – ‘efficiency and accuracy’ and ‘integration and interface with services building systems’ – further indicate a strong concern for work performance in IBMS selection.

Literature has suggested that a good and sophisticated communications system is fundamental to the success of the intelligent building (Smith, 2002). In this research, three CSC were identified in the first surveys for the ITS. These criteria include ‘operating and maintenance costs’, ‘reliability and stability’ and ‘further upgrade of system’. Communication and information technologies evolve from time to time, and this might explain why the costs of maintenance and the possibility of further system upgrade are two of the prime selection criteria. System stability and the reliability of communication networks in delivering the data is critical to the intelligent building as it provides a platform for system integration among energy management, HVAC, spatial comfort, lighting and security, and also supports the transfer of building diagnostic information (Smith, 2002). Thus, this may explain why the experts place higher emphasis on these CSC.

While the survey results suggested that those criteria under *‘Work Efficiency’* and *‘Cost Effectiveness’* are critical to the selection of the majority of building control systems, the study also suggested the *‘Safety Related’* factor as another important consideration. In AFA systems, ‘compliance with the code of minimum fire service installations or equipment’ and ‘compliance with the code for inspection, testing and maintenance of fire service installations and equipment’ were equally judged as two top CSC in both the general and AHP surveys, followed by the ‘operating and maintenance costs’ and a number of work efficiency criteria (i.e., ‘automatic detection of fire, gas and smoke’, ‘system response time and survivability’, ‘service life’, and, ‘further upgrade of system’). There is no doubt that all AFA systems must fundamentally comply with all statutory requirements to secure human lives against abrupt fire, and this might suggest why they are the top CSC for AFA systems.

Apart from the above, contrasting to the results of the general survey, ‘total energy consumption’ was judged more important than ‘service life’ and ‘control of predict mean vote’ as the top CSC for HVAC control system selection in the AHP survey. Experts emphasise efficient energy management in the HVAC control system in order to reduce the energy wastage of the intelligent building. The higher importance of the ‘total energy consumption’ is probably due to the fact that the energy consumption in electricity has the highest percentage in the HVAC system among all building services and electric appliances (Fong *et al*., 2006). This confirms the view of Rousseau and Mathews (1993: 439) that the ‘energy efficiency of HVAC systems is more important and is a major issue’. On the other hand, the importance of ‘operating and maintenance costs’ was reflected by the similar ranking in the general survey (ranked 2nd) and in the AHP survey (rank 3rd). Energy cost is associated with the operation and maintenance of HVAC systems, and thus, it was perceived as a CSC with a high ranking by the building practitioners and experts in both surveys. Further examination of the surveys indicated that the importance of *‘system reliability and stability’* improved from being the sixth most important criterion in the first survey to the second in the AHP survey. Faults in HVAC systems in intelligent buildings are harmful to service quality and relate to the energy use efficiency (Wang and Wang, 1999). System instability would result in comfort complaints, indoor air quality issues, control problems, and exorbitant utility cost (Alcalá *et al*., 2006; and Curtis, 2001). For these reasons, it was not surprising that the experts judged the *‘system reliability and stability’* as a high ranking CSC in the selection of a HVAC control system.

Prior research in intelligent lift systems generally accepted a good lift system must be able to ‘provide the passengers with highest handling capacity, and shortest waiting time and travelling time of passengers with the most economic solution’ (So and Yu, 2001). In line with this argument, the first survey of this research showed that ‘waiting time’ and ‘journey time’ were part of the CSC for the intelligent lift system, but they were not judged as the top CSC in the AHP survey. Perhaps, a short waiting and journey time would possibly be judged by the experts as more basic and indispensable requirement for the intelligent lift system. Thus, these factors were not perceived as the top CSC as in the first general survey. Instead, ‘mean time between failures’ is considered by the experts as a more important CSC. This suggests that reliability of the lift group in a building is a major factor in affecting the success or failure of a building as a place to work, live or receive a service. A lift system with high reliability should avoid frequent abnormal stoppage or any accidents (AIIB, 2001). In addition, two other CSC, ‘total energy consumption’ and ‘operating and maintenance costs’ improved from being the fourth and eighth most important CSC respectively in the general survey to the second and third positions in the AHP survey. This suggests that an energy-efficient lift system with low running costs is more important.

Findings of this study further indicated that user comfort is an important consideration in the decision of the DALI system selection. The importance of ‘ease of control’ indicates that a certain degree of individual control that enables a personal choice of lighting conditions is deemed desirable by the experts. Such control should be set up in a way that unnoticeably affects the lighting conditions in and viewing conditions from adjoining areas. Furthermore, the higher ranking of the ‘total energy consumption’ in the AHP survey implies that a good lighting system must be designed and managed to achieve good control of energy consumption. Many writers also consider this criterion to be of importance for DALI system because the efficient use of energy can reduce energy costs and provide a better indoor working environment for the staff (Li *et al*., 2006). A poor lighting control system not only means an increase in the electric lighting demand, higher running costs, and higher peak electrical demands, but also indicates larger cooling energy consumption and the need for a larger HVAC plant in order to provide a comfortable indoor environment. In addition, as the consideration about energy consumption is usually financial, it is not surprising that 'operating and maintaining costs' is perceived by the experts as the top CSC for the DALI system in the AHP survey.

Perhaps one of the most surprising findings of the two surveys in this study is that the technological factor is considered less critical in the selection of the intelligent building control systems. It was expected that the technological factor would receive a certain level of importance. This expectation was based on two points. First, developers are more open to new technologies (Wan and Woo, 2004). They desire to create product differentiation and to project their high-tech building image by incorporating innovative and intelligent building components. Second, developers need to retain the tenants or end-users by keeping up with changes in information technology and providing for upgrades as technology evolves (Armstrong *et al.*, 2001). However, the findings of the first survey revealed that the technological factor was not an important consideration. Perhaps this is because the use of stable and reliable building systems is preferable to the building practitioners and experts. As argued by Clements-Croome (2001a), most updated 'untested' technology has a higher risk of becoming obsolete. DEGW *et al*. (1992) also argue that a true intelligent building does not need to be a building with purely advanced technologies. Instead, it should be the one that can ensure efficiency, enhance user comfort and cost effectiveness. The research generally confirms the view of DEGW *et al*. (1992), and this may possibly explain why technological issues have a low score in this study.

Figure 6.10 summarises the critical selection criteria (CSC) for seven building control systems in the intelligent building. This model provides a summary of the CSC of each of the seven intelligent building control systems, and is developed to replace the original conceptual models developed in Chapter 3. The practicality and validity of the refined conceptual models will be investigated in Chapter 8.

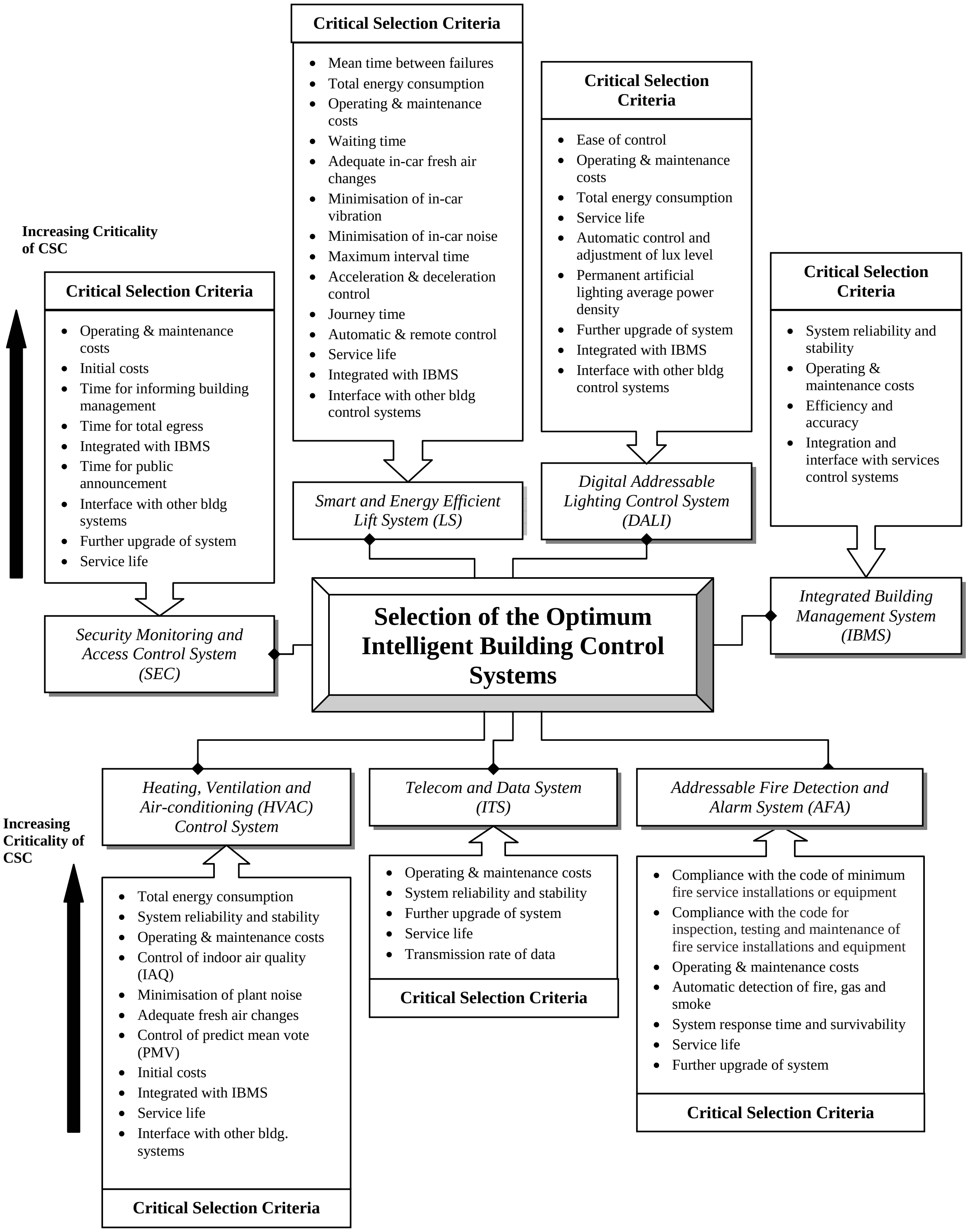


Figure 6.10: A Refined Conceptual Model Summarising the Critical Selection Criteria (CSC) of the Key Building Control Systems of the Intelligent Buildings

6.5 CHAPTER SUMMARY

This chapter was designed to develop, test and modify the proposed conceptual models of the CSC for seven key intelligent building control systems. Two hypotheses (*H1* and *H2*) were tested via two surveys. The results of first survey indicated that there are different sets of CSC influencing the selection of the building control systems *(HI is supported)*, while the AHP survey results found that each CSC exerts a substantial level of influence on the respective intelligent building control systems (*H2 is supported*). Finally, a modified conceptual selection evaluation model of the building control systems was developed.

CHAPTER 7

DATA ANALYSIS AND RESULTS – RESEARCH PART TWO

"In general, you will find that this pattern works in writing each section (presenting the results). First, state a generalization that summarises the results. Then refer to any table or figure that you have developed. Finally, provide the specific evidence."

(Glatthorn and Joyner, 2005: 201)

7.1 INTRODUCTION

In the preceding chapter, the conceptual models of the CSC for seven key building control systems were formulated and refined in line with the findings from the general and AHP surveys in Chapter 6. This chapter focuses on the second research problem which aims to develop and test the conceptual models of system intelligence of the same seven intelligent building control systems. The chapter is structured to first identify a set of key intelligence indicators for each building control system, and to present a systemic analytical approach for system intelligence evaluation. To achieve these ends, two different consecutive surveys, including a general survey and an AHP-ANP survey, are undertaken. Two hypotheses (*H3* and *H4*) that were formulated for this study are tested. Finally, seven modified conceptual models of system intelligence for the seven intelligent building systems are developed.

7.2 EXPLANATION OF METHODOLOGY

To pursue objectives specified earlier, and to test the two hypotheses formulated for this part of study, two successive surveys were undertaken. As illustrated in Figure 7.1, the system intelligent models are formulated and tested step by step according to the following procedures:

- A general survey (the third questionnaire (A3) as shown in Appendix A, p.327) is designed first to collect general views from industry practitioners to determine the relevance and suitability of the indicators to measure the degree of system intelligence of the listed building control systems. The first survey was also set up to facilitate the formulation of a team of experts with rich knowledge and experience in intelligent building design and development. They were invited to participate and complete the AHP-ANP survey. Hypothesis *H3* is tested in the first survey.
- An AHP-ANP survey (the fourth questionnaire (A4) as shown in Appendix A, p.336) is adopted to compute the mean weights of all relevant and suitable intelligence indicators identified in the general survey, and to prioritise and distinguish the more important indicators from the less important ones. The interdependent relationships between the intelligence attributes and the operational benefits of the intelligent building are also taken into consideration. The algorithm procedures of the ANP approach proposed in Chapter 5 are adopted. Hypothesis *H4* is tested in this survey.

Contrary to the method of testing adopted in Research Part One, the multiple dimensions of system intelligence in the key intelligent building systems in Research Part Two are to be evaluated through an analytic hierarchy-network process (i.e., a combination of AHP and ANP approaches). The ANP is employed as it allows a more comprehensive analytic framework through the inclusion of additional relationships between the intelligence attributes of the building control systems and the building's operational benefits.

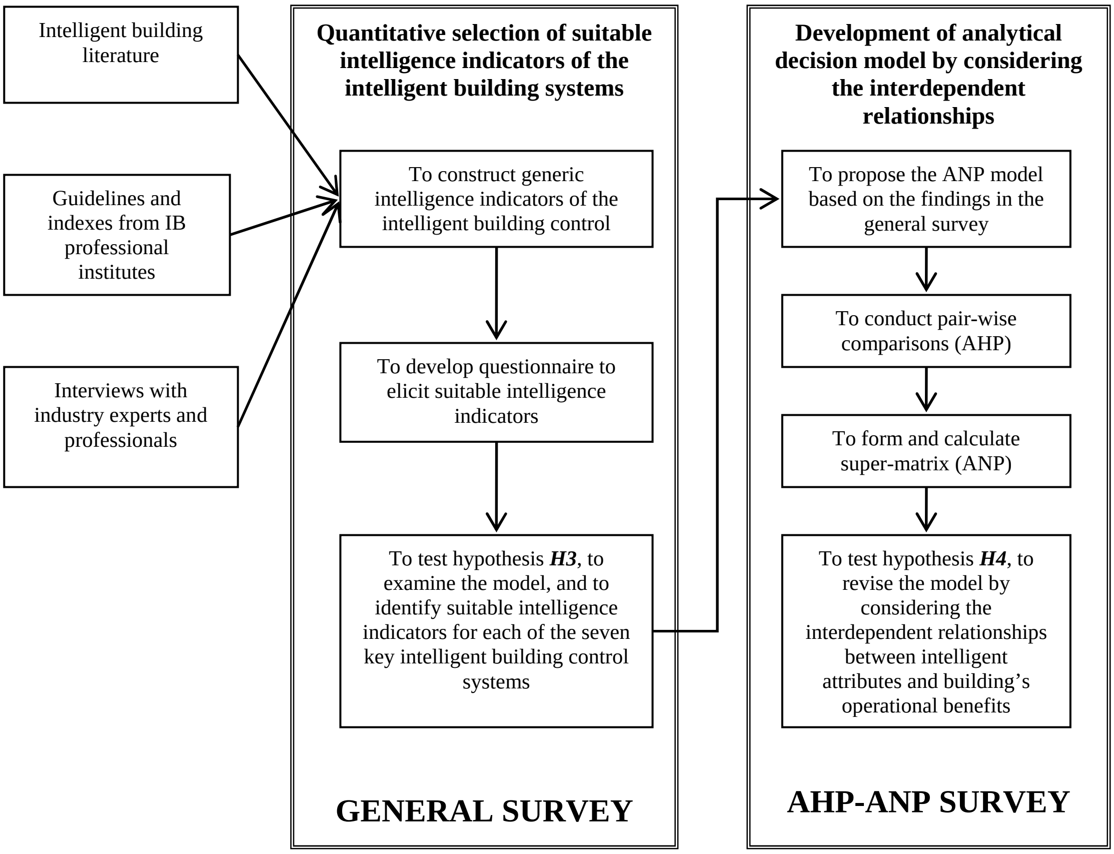


Figure 7.1: Research Methodologies of Research Part Two

7.3 THE GENERAL SURVEY: IDENTIFYING ‘SUITABLE’ INTELLIGENCE INDICATORS

7.3.1 Questionnaire Design and Data Control

Development of Posited Intelligence Indicators

The first general survey is designed to elicit the ‘suitable’ intelligence indicators for the seven key intelligent building systems. The list of proposed intelligence indicators was derived from an extensive review of intelligent building literature and trade publications, and expanded on with the advice of industry experts and practitioners. A number of available building services guides and intelligent building indices provide valuable information and useful insight into the generic intelligent performances and measures of the intelligent building systems and components. The posited intelligence indicators were developed and organised into four main intelligence attributes suggested by Bien *et al*. (2002) (i.e., *autonomy, controllability of complicated dynamics, man-machine interaction and bio-inspired behaviour*). In addition, two experts, including an M&E engineering consultant and a property developer who both participated in the AHP survey of Research Part One, were consulted in order to review, justify, and further expand the list of proposed intelligence indicators.

Pilot Survey and Data Collection Design

A pilot study was first undertaken to test the suitability and comprehensibility of the questionnaire. Five experts (comprising of two M&E engineers, an architect, a property developer, and an academic) were selected to pilot the questionnaire. The experts were asked to assess whether the proposed indicators sufficiently represented the intelligent characteristics or attributes of the intelligent building control systems being examined;

whether the descriptions were acceptable or whether they should be changed to make them more understandable to the respondents; and whether additional indicators that were not included should be added. Comments were received and minor amendments were made to the original instrument. At the end of consultations, a total of 102 intelligence indicators were generated for the seven intelligent building systems. These were grouped under four intelligence attributes (Table 7.1). The list in Table 7.1 is not an exhaustive list of indicators but it is expected that, based on literature and expert opinion, they are appropriate generic intelligence indicators. Individual respondents were able to add intelligence indicators if they were deemed to be essential.

In this survey, three approaches were used to acquire an appropriate sample size. First, an invitation message was sent by e-mail to the intelligent building practitioners who had participated in Research Part One of this thesis, to ask for their further assistance. The snowball sampling method was further applied in this second part of research in order to boost the survey sample size. Respondents were invited to distribute the questionnaires to those colleagues or professionals they knew that had rich experience in intelligent building design and development. In addition, an invitation letter was also posted to those design (i.e. architecture and engineering) consultancies and property developers who had not participated in previous research. A total of 58 additional industry practitioners and experts contacts were received by the end of November 2005. Finally, a total of 157 questionnaires were sent out and distributed, and 48 questionnaire surveys were returned by the end of February 2006. Four completed questionnaires were removed due to erroneous use of the rating scale or because the respondents were inappropriate for the research, leaving only 44 usable replies for the analysis, giving a net usable response rate of 28%.

Questionnaire Design and Analytical Tools

The first general questionnaire in the Research Part Two (as shown in Appendix A3, p.327) consists of two sections (Part 1 and 2). The objectives and scope of the survey were first introduced, and the terminology of each intelligent building system and intelligence attribute was defined in order to clarify their meanings. Part 1 was used to collect demographic data regarding the respondent’s previous experience and general knowledge in building control systems in order to select those experts who were suitable for the subsequent ANP survey. Part 2 of the questionnaire asked the respondents to elicit the ‘suitable’ intelligence indicators for assessing the degree of system intelligence of each building control system.

In the questionnaire, participants were invited to elicit their opinions on the suitability of each of the proposed intelligence indicators on a five-point Likert-scale format (1= Not suitable; 2= Less suitable; 3= Suitable; 4= More suitable; and, 5= Most suitable). Likert scales facilitate the quantification of responses so that statistical analysis could be taken and differences between participants could be observed and generalised (Abdel-Kader and Dugdale, 2001). In this survey, the critical rating was fixed at scale ‘3’ since ratings above ‘3’ represent ‘suitable’, ‘more suitable’ and ‘most suitable’ according to the scale. This survey employed similar statistical techniques used in the general survey in Research Part One (Chapter 6), including the mean score ratings and *t*-test analysis, to elicit and analyse the ‘suitable’ intelligence indicators. The basic rules of the *t*-test, including equations 6.1 to 6.4 developed in previous chapter, still applied here, i.e. the indicators with value > 3.00 are considered to be critical (or suitable).

Table 7.1: Proposed Intelligence Indicators of the Key Building Control Systems

Building Control System	**Intelligence Attributes and Their Proposed Associated Indicators**			
	Autonomy	***Controllability for Complicated Dynamics***	***Man-machine Interaction***	***Bio-inspired Behaviour***
Integrated Building Management System (IBMS)	• Adaptive limiting control algorithm including max/min threshold limiter, fault-tolerance adaptation (AL) • Self-diagnostic of operation deviations (SD) • Year-round time schedule operation (YT)	• Ability to link multiple standalone building control systems from a variety of manufacturers (interoperability) (ALMS) • Remote control via internet (RCI) • Ability to connect multiple locations (ACML) • Alarms and events statistics (AES) • Control and monitor HVAC equipments on sequence control, time scheduling, thermal comfort, ventilation, fault recovery operations (MHVAC) • Control and monitor security system interlock operation with "other services" (MSE) • Control and monitor lighting time schedule / zoning operation (ML) • Control and monitor fire detection interlock operation with "other services" (MFD) • Control and monitor lift operation (MLO)	• Web based interface to any location and wireless terminal for functional access including PALM, pocket PC, mobile phone (WBI) • Reports generation and output of statistical and trend profiling of controls and operations (RG) • Ability to provide operational and analytical functions for totalised building performance review (APOAF) • Single operation system/ platform for multiple location supervision (SOS) • Graphical representation and real-time interactive operation action icons (GR) • Run continually with minimal human supervision (RC)	• Analyse operation function parameters to select the best and effective operation logic to run the building services systems over time (AOF) • Automatically adapt to daily occupied space changes to control building services systems (AADO) • Provide adaptive control algorithms based on seasonal changes to control building services systems (PAC)
Telecom and Data System (ITS)	• Adaptive limiting control algorithm including max/min threshold limiter, fault-tolerance adaptation (AL) • Self-diagnosis to detect the timeworn parts (SD)	• Integrate multiple network or service providers (IMS) • Transmission capacity control and diversion (TCCD) • All digital system (ADS)	• Fixed hub/terminal port installed for flexibility connections and expansions (FHTP) • System life and turn-round complexity (SLTC) • End-user terminal provisions (ETP)	• Interactive voice system (IVS) • Transmission/processing analysis (TA)

Table 7.1: Proposed Intelligence Indicators of the Key Building Control Systems (cont.)

Building Control System	Intelligence Attributes and Their Proposed Associated Indicators			
	Autonomy	*Controllability for Complicated Dynamics*	*Man-machine Interaction*	*Bio-inspired Behaviour*
Addressable Fire Detection and Alarm System (AFA)	• Alarm deployment algorithm within the building and notification to Fire Department (ADA) • Adaptive limiting control algorithm including max/min threshold limiter, fault-tolerance adaptation (AL) • Self-diagnostic analysis for false alarm reduction (SDF) • Self test of sensors, detectors and control points (STS) • Self-diagnosis to detect the timeworn parts (SD)	• Integration and control of sensors, detectors, fire-fighting equipment (ICSD) • Interface with Energy Management System (EMS), Building Automation System (BAS), or Integrated Building Management System (IBMS) (INTF) • Interact with security systems (INTSS) • Interact with HVAC systems (INTHVAC) • Interact with lift systems (INTLS) • Interact with lighting and emergency generator systems (INTLG)	• Run continually with minimal human supervision (RC) • Provide management staff with database and analytical tools for operation and service evaluation (DAT) • Pre-scheduled of special events and incidents (PSSE) • Provide access for tenants and occupants concurrent information of the services provision (PATO)	• Analysis of alarm and false alarm events patterns (AAFA)
Heating Ventilation Air-conditioning (HVAC)Control System	• Adaptive limiting control algorithm including max/min threshold limiter, fault-tolerance adaptation (AL) • Sensing the internal temperature and humidity, and auto-adjustment of systems (ITS) • Sensing of external temperature and humidity, and auto-adjustment of systems (ETS) • Automated fault detection (AFD) • Self-diagnosis to detect timeworn parts (SD)	• Operation control mechanism to achieve efficient power consumption (OCM) • Interface with EMS, BAS, or IBMS (INTF) • Interact with lighting and sun-blinds systems (INTLB)	• Provide management staff with database and analytical tools for operation and service evaluation (DAT) • Pre-programmed responses and zoning control (PPR) • Graphical representation and real-time interactive operation action icons (GR)	• Adaptive to occupancy work pattern (AOWP) • Utilise natural ventilation control to reduce air-conditioning power consumption (UNVC)

Table 7.1: Proposed Intelligence Indicators of the Key Building Control Systems (cont.)

Building Control System	**Intelligence Attributes and Their Proposed Associated Indicators**			
	Autonomy	***Controllability for Complicated Dynamics***	***Man-machine Interaction***	***Bio-inspired Behaviour***
Digital Addressable Lighting Control System (DALI)	• Adaptive limiting control algorithm including max/min threshold limiter (AL), fault-tolerance adaptation • Monitoring capabilities that lamp performance and hours run can be logged (MCLP) • Self-diagnosis to detect the timeworn parts (SD)	• Adaptive to occupancy work schedule (AOWS) • Presence detection including dimmable occupancy sensor, access triggered control (PD) • Control of individual luminaries, groups of luminaries or lighting zone (CIL) • Interface with EMS, BAS, or IBMS (INTF)	• Provide management staff with database and analytical tools for operation and service evaluation (DAT) • Provide access for tenants and occupants concurrent information of the services provision (PATO) • Pre-programmed response and control (PPSC) • User interface via internet/intranet or remote control (UI)	• Provide multiple level and control mode for occupants to program custom-made settings (PMLC) • Sensing the light intensity and angle of projection and solar radiation to maximise natural light/reduce lighting power (SLI) • Automatic lighting or shading controls (AUTLS)
Security Monitoring and Access Control System (SEC)	• Adaptive limiting control algorithm including. max/min threshold limiter, fault-tolerance adaptation (AL) • Sabotage proof to resist physical damage and modification (SP) • Self-diagnosis to detect the timeworn parts (SD)	• Dynamic programming including routing, time schedule, monitoring sequence, control reaction, etc. (DP) • Configurable to accurately implement the security policies for the premises (CAISP) • Interface with other system, e.g. communication network, phone system, etc (INTSY) • Interface with EMS, BAS, or IBMS (INTF) • Multiple detection or verification mechanism (MDVM)	• Run continually with minimal human supervision (RC) • Provide management staff with database and analytical tools for operation and service evaluation (DAT) • Provide access for tenants and occupants concurrent information of the services provision (PATO) • Pre-scheduled set up of special events and normal routines (PSSU)	• Human behaviour analysis and diagnostic (HBAD) • Adaptive to demands in high traffic or occupancy situations (ADHT)

Table 7.1: Proposed Intelligence Indicators of the Key Building Control Systems (cont.)

Building Control System	**Intelligence Attributes and Their Proposed Associated Indicators**			
	Autonomy	***Controllability for Complicated Dynamics***	***Man-machine Interaction***	***Bio-inspired Behaviour***
Smart and Energy Efficient Lift System (LS)	• Adaptive limiting control algorithm including max/min threshold limiter, fault-tolerance adaptation (AL) • Auto-controlled navigation at emergency with remote override (AE) • On-line data logging facilitating routine maintenance (ONDL) • Self-diagnosis to detect the timeworn parts (SD)	• Accommodate changes of passenger traffic pattern (up peak/ down peak) (ACPTP) • Remote monitoring (RM) • On-line investigation and analysis of lift activity (ONIA) • Interface with EMS, BAS, or IBMS (INTF)	• Human engineering design to facilitate convenience of passengers including voice announcement, fit for disables, lighting, floor display up/down, etc (HED) • Provide management staff with database and analytical tools for operation and service evaluation (i.e. levelling) (DAT) • Provide access for tenants & occupants concurrent info. of services provision (PATO) • Pre-scheduled of special events and normal routines (PSSE)	• User designation, verification and specific control (static sectoring or dynamic sectoring) (UDVS) • Integration with building usage schedule for travel programming (IBUS)

7.3.2 Data Analysis and Results

Background of Respondents

The sample characteristics of this survey are summarised in Table 7.2. Forty-four industry practitioners, including design consultants, property developers, and facility managers, participated in the survey. About 61 percent of the respondents were from a design background (i.e. M&E engineers, and architects), and the remainder were property developers (21%) and facility managers (18%). Most respondents (84%) had more than six years of work experience in the building and construction sector, and 5% of respondents had more than 30-years work experience. About 35% of respondents reported that they were currently, recently and directly involved in intelligent building development, especially relating to the design and decision on the building control systems and components. The types of intelligent building projects that the respondents had participated in included commercial/residential (30%) and commercial/office (37%). Other developments included commercial/hotel-resort (14%), commercial/recreational (6%), and residential (13%) developments.

Findings and Discussions

Table 7.3 presents the mean scores and *t*-test results. This table reported and compared the mean scores, standard deviation, and ranking of each of the proposed intelligence indicators amongst three different groups of industry practitioners. Based on the survey results, 64 'suitable' intelligence indicators (marked with '*' in Table 7.3) were extracted from a total of 102 proposed indicators for seven building control systems. Pursuant to this table, some patterns were identified:

Table 7.2: Demographic Details of the General Survey Respondents

Demographic information	No.	%
Nature of work		
Design consultants (M&E engineers)	27	61%
Developers	9	21%
Facility managers	8	18%
TOTAL	**44**	**100%**
Year of experience		
0-5 years	7	16%
6-10 years	16	36%
11-15 years	7	16%
16-20 years	7	16%
21-25 years	1	2%
26-30 years	4	9%
Over 30 years	2	5%
TOTAL	**44**	**100%**
Experience in intelligent building development		
Commercial/ residential	25	30%
Commercial/ office	30	37%
Commercial/ hotel-resort	11	14%
Commercial/ recreational	5	6%
Industrial/ warehouse	0	0%
Industrial/ manufacturing	0	0%
Residential/ single block villa	3	4%
Residential/ complex	7	9%
TOTAL	**81**	**100%**

- **Integrated Building Management System (IBMS):** A total of 16 indicators were judged as 'suitable' for evaluating the degree of intelligence of the IBMS. The top three ranked intelligence indicators were the '*ability to link multiple standalone building control systems from a variety of manufacturers*'; the '*graphical representation and real-time interactive operation action icons*'; and the '*ability to connect multiple locations*'. The highest ranking of '*ability to link multiple standalone building control system from a variety of manufacturers*' reflects an awareness among industry practitioners of the importance of total integration of the sub-systems by the IBMS. The high ranking is probably caused by the frustrations encountered by industry practitioners regarding the incompatibilities and limited opportunities for the integration of building automation and control systems among product of different manufacturers (Wang *et al*., 2004). Respondents recognised that the ability of IBMS to accommodate all devices and to conform them to the protocol standard being used is significant. Devices from different manufacturers should employ the same communications network, communicating with their peers and not interfering with other equipment.

The existence of a graphical representation and real-time interactive operation action icon were judged as the second suitable intelligence indicator of the IBMS by the industry practitioners. Graphical displays of plant operation allow diagrams of plants with live point values displayed, and provides on-screen displays of temperatures, flows etc. It also allows the display of the operating states of items in the plant, and set points may be adjusted directly and plant items switched on and off (CIBSE, 2000b). This finding suggested that an 'intelligent' IBMS should be able to display a real-time trend graph of the present situation or a review of historical data.

Interestingly, among the three-categories of industry practitioners, the developer group particularly ranked the '*self-diagnostic of operation deviations*' as the most 'suitable' intelligence indicator of the IBMS. This indicates that there is a high level of awareness amongst developers of the importance of detecting and diagnosing faults of the IBMS.

Table 7.3: Perceptions of ‘Suitable’ Intelligence Indicators by Industry Practitioners

Building control system	**Level 1 Intelligence attributes**	**Level 2 Intelligence indicators**	**Mean (SD, ranking)**				***t*-value**
			All (*N*=44)	Design consultants (*N*=27)	Developers (*N*=9)	Facility managers (*N*=8)	
Integrated Building Management System (IBMS)	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**3.32 (.740, 12)**	3.33 (.832, 11)	3.11 (.601, 5)	3.50 (.535, 3)	2.852*
	AUT	Self-diagnostic of operation deviations	**3.45 (.761, 7)**	3.56 (.751, 8)	3.56 (.527, 1)	3.00 (.926, 7)	3.961*
	AUT	Year-round time schedule operation	**3.25 (.751, 14)**	3.41 (.844, 10)	3.00 (.000, 6)	3.00 (.756, 7)	2.208*
	CCD	Ability to link multiple standalone building control systems from a variety of manufacturers (interoperability)	**3.93 (.900, 1)**	4.15 (.770, 1)	3.56 (.882, 1)	3.63 (1.188, 2)	6.871*
	CCD	Remote control via internet	**3.30 (.978, 13)**	3.56 (1.050, 8)	2.56 (.726, 8)	3.25 (.463,5)	2.003*
	CCD	Ability to connect multiple locations	**3.61 (.618, 3)**	3.81 (.557, 2)	3.22 (.667, 4)	3.38 (.518, 4)	6.585*
	CCD	Alarms and events statistics	**3.59 (.816, 4)**	3.74 (.813, 3)	3.44 (.726, 2)	3.25 (.886, 5)	4.803*
	CCD	Control and monitor HVAC equipments on sequence control, time scheduling, thermal comfort, ventilation, fault recovery operations	**3.57 (.759, 5)**	3.81 (.736, 2)	3.33 (.500, 3)	3.00 (.756, 7)	4.963*
	CCD	Control and monitor lighting time schedule/ zoning operation	**3.39 (.722, 10)**	3.63 (.742, 6)	3.11 (.333, 5)	2.88 (.641, 8)	3.548*
	CCD	Control and monitor security system interlock operation with ‘other systems’	**3.20 (.930, -)**	3.59 (.747, -)	2.44 (.882, -)	2.75 (.886, -)	1.460
	CCD	Control and monitor fire detection system interlock operation with ‘other systems’	**3.23 (1.031, -)**	3.63 (.926, -)	2.67 (1.000, -)	2.50 (.756, -)	1.462
	CCD	Control and monitor lift operation.	**3.14 (.878, -)**	3.37 (.839, -)	2.89 (.782, -)	2.63 (.916, -)	1.030
	MMI	Web base interface to any location and wireless terminal for functional access (i.e., PALM, pocket PC, mobile phone)	**3.02 (.976, -)**	3.26 (.903, -)	2.78 (.972, -)	2.50 (1.069, -)	0.154
	MMI	Reports generation, output of statistical and trend profiling of controls and operations	**3.39 (.868, 10)**	3.59 (.931, 7)	3.00 (.707, 6)	3.13 (.641, 6)	2.951*
	MMI	Ability to provide operational and analytical functions for totalized building performance review	**3.43 (.728, 8)**	3.48 (.802, 9)	3.56 (.527, 1)	3.13 (.641, 6)	3.934*
	MMI	Single operation system/ platform for multiple location supervision	**3.32 (.740, 12)**	3.41 (.797, 10)	3.22 (.441, 4)	3.13 (.835, 6)	2.852*
	MMI	Graphical representation & real-time interactive operation action icons	**3.66 (.939, 2)**	3.67 (1.038, 5)	3.44 (.726, 2)	3.88 (.835, 1)	4.658*
	MMI	Run continually with minimal human supervision	**3.41 (.897, 9)**	3.63 (.926, 6)	3.22 (.833, 4)	2.88 (.641, 8)	3.024*
	BIB	Analyse operation function parameters to select the best and effective operation logic to run the building services systems over time	**3.34 (.745, 11)**	3.48 (.753, 9)	2.89 (.333, 7)	3.38 (.916, 4)	3.034*
	BIB	Automatically adapt to daily occupied space changes to control building services systems	**3.16 (.914, -)**	3.41 (.888, -)	2.78 (.833, -)	2.75 (.886, -)	1.155
	BIB	Provide adaptive control algorithms based on seasonal changes to control building services systems	**3.52 (.902, 6)**	3.70 (.912, 4)	3.00 (.707, 6)	3.50 (.926, 3)	3.845*

Table 7.3: Perceptions of ‘Suitable’ Intelligence Indicators by Industry Practitioners (cont.)

Building control system	**Level 1 Intelligence attributes**	**Level 2 Intelligence indicators**	**Mean (SD, ranking)**				***t*-value**
			All (*N*=44)	Design consultants (*N*=27)	Developers (*N*=9)	Facility managers (*N*=8)	
Telecom & Data System (ITS)	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**3.05 (.569, -)**	3.11 (.641, -)	3.00 (.500, -)	2.88 (.354, -)	0.530
	AUT	Self-diagnosis to detect the timeworn parts	**3.09 (.640, -)**	3.19 (.622, -)	2.89 (.333, -)	3.00 (.926, -)	0.942
	CCD	Integrate multiple network or service providers	**3.77 (.774, 1)**	3.81 (.879, 1)	3.56 (.527, 1)	3.88 (.641, 1)	6.627*
	CCD	Transmission capacity control & diversion	**3.55 (.791, 3)**	3.59 (.931, 3)	3.44 (.527, 2)	3.50 (.535, 2)	4.574*
	CCD	All digital system	**3.14 (.734, -)**	3.26 (.764, -)	2.78 (.667, -)	3.13 (.641, -)	1.232
	MMI	Fixed hub/terminal port installed for flexibility connections and expansions	**3.57 (.661, 2)**	3.67 (.734, 2)	3.33 (.500, 3)	3.50 (.535, 2)	5.701*
	MMI	System life & turn-round complexity	**3.23 (.642, 4)**	3.41 (.694, 4)	2.78 (.441, 4)	3.13 (.354, 3)	2.348*
	MMI	End-user terminal provisions	**3.16 (.861, -)**	3.37 (.839, -)	2.78 (.833, -)	2.88 (.835, -)	1.225
	BIB	Interactive voice system	**2.91 (.802, -)**	2.93 (.781, -)	2.89 (.782, -)	2.88 (.991, -)	-0.752
	BIB	Transmission/processing analysis	**3.09 (.709, -)**	3.19 (.681, -)	2.89 (.782, -)	3.00 (.756, -)	0.850
Addressable Fire Detection and Alarm System (AFA)	AUT	Alarm deployment algorithm within the building and notification to Fire Department	**3.73 (.949, 1)**	3.96 (.759, 1)	3.56 (1.130, 1)	3.13 (1.126, 5)	5.083*
	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**2.91 (.640, -)**	2.96 (.759, -)	2.89 (.333, -)	2.75 (.463, -)	-0.942
	AUT	Self-diagnostic analysis for false alarm reduction	**3.68 (.601, 2)**	3.74 (.656, 4)	3.56 (.527, 1)	3.63 (.518, 1)	7.522*
	AUT	Self test of sensors, detectors and control points	**3.45 (.791, 8)**	3.78 (.506, 3)	2.44 (.726, 7)	3.50 (.756, 2)	3.811*
	AUT	Self-diagnosis to detect the timeworn parts	**2.98 (.590, -)**	3.07 (.616, -)	2.78 (.441, -)	2.88 (.641, -)	-0.255
	CCD	Integration and control of sensors, detectors, fire-fighting equipment	**3.48 (.952, 7)**	3.56 (.934, 6)	3.33 (1.00, 2)	3.38 (1.061, 3)	3.325*
	CCD	Interface with EMS, BAS, or IBMS	**3.20 (.701, 9)**	3.30 (.724, 7)	3.11 (.782, 4)	3.00 (.535, 6)	1.934*
	CCD	Interact with security systems	**3.66 (.861, 3)**	3.81 (.834, 2)	3.22 (.833, 3)	3.63 (.916, 1)	5.077*
	CCD	Interact with HVAC systems	**3.61 (.813, 4)**	3.78 (.801, 3)	3.11 (.782, 4)	3.63 (.744, 1)	5.006*
	CCD	Interact with lift systems	**3.45 (.848, 8)**	3.67 (.877, 5)	2.89 (.333, 5)	3.38 (.916, 3)	3.556*
	CCD	Interact with lighting/ emergency generator systems	**3.50 (.976, 6)**	3.67 (.961, 5)	3.22 (.833, 3)	3.25 (1.165, 4)	3.397*
	MMI	Run continually with minimal human supervision	**3.57 (.974, 5)**	3.81 (.834, 2)	2.78 (.972, 6)	3.63 (1.061, 1)	3.869*
	MMI	Provide management staff with database and analytical tools for operation and service evaluation	**3.25 (.991, -)**	3.41 (.888, -)	2.56 (1.130, -)	3.50 (.926, -)	1.673
	MMI	Provide access for tenants and occupants concurrent information of the services provision	**2.70 (.765, -)**	2.96 (.706, -)	2.11 (.782, -)	2.50 (.535, -)	-2.562
	MMI	Pre-scheduled of special events and incidents	**3.07 (.661, -)**	3.22 (.641, -)	2.78 (.667, -)	2.88 (.641, -)	0.684
	BIB	Analysis of alarm and false alarm events patterns	**2.86 (.765, -)**	3.04 (.854, -)	2.67 (.500, -)	2.50 (.535, -)	-1.182

Table 7.3: Perceptions of ‘Suitable’ Intelligence Indicators by Industry Practitioners (cont.)

Building control system	**Level 1 Intelligence attributes**	**Level 2 Intelligence indicators**	**Mean (SD, ranking)**				***t*-value**
			All (*N*=44)	Design consultants (*N*=27)	Developers (*N*=9)	Facility managers (*N*=8)	
HVAC Control System	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**3.32 (.561, 8)**	3.48 (.580, 5)	2.89 (.333, 6)	3.25 (.463, 4)	3.760*
	AUT	Sensing the internal temperature and humidity, and auto-adjustment of systems	**3.57 (.818, 3)**	3.70 (.775, 1)	3.11 (.782, 4)	3.63 (.916, 1)	4.606*
	AUT	Sensing of external temperature and humidity, and auto-adjustment of systems	**3.25 (.943, 10)**	3.56 (.892, 3)	2.78 (.667, 7)	2.75 (1.035, 6)	1.758*
	AUT	Automated fault detection	**3.50 (.849, 5)**	3.52 (.802, 4)	3.44 (.527, 3)	3.50 (1.309, 2)	3.906*
	AUT	Self-diagnosis to detect the timeworn parts	**3.23 (.677, 11)**	3.33 (.679, 7)	2.89 (.333, 6)	3.25 (.886, 4)	2.226*
	CCD	Operation control mechanism to achieve efficient power consumption	**3.52 (.952, 4)**	3.56 (.801, 3)	3.56 (.882, 2)	3.38 (1.506, 3)	3.642*
	CCD	Interface with EMS, BAS, or IBMS	**3.61 (.689, 2)**	3.70 (.669, 1)	3.44 (.527, 3)	3.50 (.926, 2)	5.905*
	CCD	Interact with lighting and sun-blinds systems	**2.80 (.904, -)**	3.07 (.829, -)	2.11 (.601, -)	2.63 (1.061, -)	-1.500
	MMI	Provide management staff with database & analytical tools for operation & service evaluation	**3.27 (.845, 9)**	3.44 (.801, 6)	2.89 (.601, 6)	3.13 (1.126, 5)	2.140*
	MMI	Pre-programmed responses and zoning control	**3.64 (.685, 1)**	3.63 (.688, 2)	3.67 (.707, 1)	3.63 (.744, 1)	6.161*
	MMI	Graphical representation and real-time interactive operation action icons	**3.34 (.834, 7)**	3.48 (.849, 5)	3.00 (.707, 5)	3.25 (.886, 4)	2.712*
	BIB	Adaptive to occupancy work pattern	**2.89 (.841, -)**	3.11 (.892, -)	2.33 (.500, -)	2.75 (.707, -)	-0.896
	BIB	Utilise natural ventilation control to reduce air-conditioning power consumption	**3.43 (.759, 6)**	3.56 (.751, 3)	2.89 (.333, 6)	3.63 (.916, 1)	3.772*
Digital Addressable Lighting Control System (DALI)	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**3.14 (.668, -)**	3.19 (.622, -)	3.11 (.601, -)	3.00 (.926, -)	1.354
	AUT	Monitoring capabilities that lamp performance and hours run can be logged	**3.18 (.815, -)**	3.22 (.801, -)	3.22 (.667, -)	3.00 (1.069, -)	1.480
	AUT	Self-diagnosis to detect the timeworn parts	**3.00 (.682, -)**	2.96 (.808, -)	3.00 (.500, -)	3.13 (.354, -)	0.000
	CCD	Adaptive to occupancy work schedule	**3.18 (1.018, -)**	3.44 (.892, -)	2.33 (.866, -)	3.25 (1.165, -)	1.185
	CCD	Presence detection including dimmable occupancy sensor, access triggered control	**3.23 (.803, 6)**	3.37 (.742, 4)	2.78 (.441, 4)	3.25 (1.165, 5)	1.877*
	CCD	Control of individual luminaries, groups of luminaries or lighting zone	**3.80 (.734, 1)**	3.81 (.736, 1)	3.78 (.667, 1)	3.75 (.886, 2)	7.190*
	CCD	Interface with EMS, BAS, or IBMS	**3.64 (.718, 2)**	3.81 (.681, 1)	3.33 (.866, 2)	3.38 (.518, 4)	5.877*

Table 7.3: Perceptions of 'Suitable' Intelligence Indicators by Industry Practitioners (cont.)

Building control system	**Level 1 Intelligence attributes**	**Level 2 Intelligence indicators**	**Mean (SD, ranking)**				***t*-value**
			All (*N*=44)	Design consultants (*N*=27)	Developers (*N*=9)	Facility managers (*N*=8)	
Digital Addressable Lighting Control System (DALI)	MMI	Provide management staff with database & analytical tools for operation & service evaluation	**3.27 (.845, 4)**	3.19 (.736, 6)	3.33 (.866, 2)	3.50 (1.195, 3)	2.140*
	MMI	Provide access for tenants and occupants concurrent information of the services provision	**2.77 (.774, -)**	2.74 (.813, -)	2.78 (.667, -)	2.88 (.835, -)	-1.949
	MMI	Pre-programmed response and control	**3.25 (.839, 5)**	3.26 (.764, 5)	3.33 (.866, 2)	3.13 (1.126, 6)	1.977*
	MMI	User interface via internet/intranet or remote control	**2.91 (.802, -)**	2.93 (.675, -)	2.67 (1.118, -)	3.13 (.835, -)	-0.752
	BIB	Provide multiple level and control mode for occupants to program custom-made settings	**3.18 (.896, -)**	3.33 (.877, -)	2.67 (.707, -)	3.25 (1.035, -)	1.346
	BIB	Sensing the light intensity and angle of projection and solar radiation to maximise natural light and reduce lighting power (i.e. photoelectric switching and dimming control)	**3.64 (.967, 2)**	3.67 (.877, 2)	3.22 (.833, 3)	4.00 (1.309, 1)	4.367*
	BIB	Automatic lighting or shading controls	**3.39 (.841, 3)**	3.44 (.801, 3)	3.22 (.441, 3)	3.38 (1.302, 4)	3.046*
Security Monitoring & Access Control System (SEC)	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**3.02 (.731, -)**	3.15 (.770, -)	2.78 (.441, -)	2.88 (.835, -)	0.206
	AUT	Sabotage proof to resist physical damage and modification	**3.41 (.693, 4)**	3.48 (.700, 3)	3.11 (.782, 4)	3.50 (.535, 2)	3.917*
	AUT	Self-diagnosis to detect the timeworn parts	**2.91 (.563, -)**	2.93 (.616, -)	2.78 (.441, -)	3.00 (.535, -)	-1.071
	CCD	Dynamic programming (routing, time schedule, monitoring sequence, control reaction, etc)	**3.32 (.909, 6)**	3.37 (.884, 5)	3.22 (.833, 3)	3.25 (1.165, 3)	2.321*
	CCD	Configurable to accurately implement the security policies for the premises	**3.61 (.722, 1)**	3.74 (.764, 1)	3.33 (.500, 2)	3.50 (.756, 2)	5.636*
	CCD	Interface with other system, e.g. communication network, phone system, etc	**3.59 (.622, 2)**	3.74 (.594, 1)	3.44 (.527, 1)	3.25 (.707, 3)	6.302*
	CCD	Interface with EMS, BAS, or IBMS	**3.25 (.751, 7)**	3.33 (.832, 6)	3.00 (.707, 5)	3.25 (.463, 3)	2.208*
	CCD	Multiple detection or verification mechanism	**3.11 (.895, -)**	3.44 (.751, -)	2.22 (.667, -)	3.00 (.926, -)	0.842
	MMI	Run continually with minimal human supervision	**3.57 (.950, 3)**	3.70 (.912, 2)	3.11 (.782, 4)	3.63 (1.188, 1)	3.968*
	MMI	Provide management staff with database and analytical tools for operation and service evaluation	**3.34 (.834, 5)**	3.41 (.844, 4)	2.89 (.782, 6)	3.63 (.744, 1)	2.712*
	MMI	Provide access for tenants and occupants concurrent information of the services provision	**2.98 (.792, -)**	3.22 (.641, -)	2.22 (.833, -)	3.00 (.756, -)	-0.190
	MMI	Pre-scheduled set up of special events and normal routines	**3.20 (.734, 8)**	3.30 (.775, 7)	3.11 (.601, 4)	3.00 (.756, 4)	1.849*
	BIB	Human behaviour analysis and diagnostic	**2.68 (.800, -)**	2.85 (.770, -)	2.44 (.726, -)	2.38 (.916, -)	-2.637
	BIB	Adaptive to demands in high traffic or occupancy situations	**2.91 (.772, -)**	3.04 (.706, -)	2.56 (.726, -)	2.88 (.991, -)	-0.781

Table 7.3: Perceptions of ‘Suitable’ Intelligence Indicators by Industry Practitioners (cont.)

Building control system	**Level 1 Intelligence attributes**	**Level 2 Intelligence indicators**	**Mean (SD, ranking)**				***t*-value**
			All (*N*=44)	Design consultants (*N*=27)	Developers (*N*=9)	Facility managers (*N*=8)	
Smart and Energy Efficient Lift System (LS)	AUT	Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	**3.18 (.843, -)**	3.26 (.944, -)	3.00 (.707, -)	3.13 (.641, -)	1.431
	AUT	Auto-controlled navigation at emergency (with remote override)	**3.61 (.841, 1)**	3.59 (.844, 1)	3.44 (.726, 2)	3.88 (.991, 1)	4.838*
	AUT	On-line data logging facilitating routine maintenance	**3.16 (.608, 7)**	3.19 (.681, 6)	3.22 (.441, 4)	3.00 (.535, 5)	1.736*
	AUT	Self-diagnosis to detect the timeworn parts	**2.93 (.759, -)**	3.00 (.832, -)	2.78 (.667, -)	2.88 (.641, -)	-0.596
	CCD	Accommodate changes of passenger traffic pattern (up peak/down peak)	**3.43 (.974, 3)**	3.48 (.975, 2)	3.44 (.882, 2)	3.25 (1.165, 3)	2.941*
	CCD	Remote monitoring	**3.16 (.939, -)**	3.37 (.839, -)	2.56 (1.014, -)	3.13 (.991, -)	1.124
	CCD	On-line investigation and analysis of lift activity	**3.30 (.765, 5)**	3.33 (.734, 4)	3.11 (.601, 5)	3.38 (1.061, 2)	2.562*
	CCD	Interface with EMS, BAS, or IBMS	**3.41 (.972, 4)**	3.41 (.971, 3)	3.67 (.707, 1)	3.13 (1.246, 4)	2.791*
	MMI	Human engineering design to facilitate convenience of passengers (i.e. voice announcement, fit for disables, lighting, floor display up/down etc)	**3.48 (.849, 2)**	3.59 (.797, 1)	3.33 (.866, 3)	3.25 (1.035, 3)	3.730*
	MMI	Provide management staff with database and analytical tools for operation and service evaluation	**3.20 (.795, 6)**	3.22 (.698, 5)	3.11 (.782, 5)	3.25 (1.165, 3)	1.707*
	MMI	Provide access for tenants and occupants concurrent information of the services provision	**2.91 (.741, -)**	2.96 (.706, -)	2.78 (.667, -)	2.88 (.991, -)	-0.813
	MMI	Pre-scheduled of special events and normal routines	**3.20 (.734, 6)**	3.22 (.698, 5)	3.11 (.601, 5)	3.25 (1.035, 3)	1.849*
	BIB	User designation, verification and specific control (static sectoring or dynamic sectoring)	**3.02 (.762, -)**	3.07 (.730, -)	2.78 (.441, -)	3.13 (1.126, -)	0.198
	BIB	Integration with building usage schedule for travel programming	**3.18 (.815, -)**	3.22 (.698, -)	2.89 (.782, -)	3.38 (1.188, -)	1.480

Note: AUT = autonomy; CCD = controllability for complicated dynamics; MMI = man-machine interaction; and, BIB = bio-inspired behaviour
* represents the *t*-values which is higher than cut of t-value (1.6820) indicating the significance of the indicators

- **Telecom and Data System (ITS):** The ITS lays the high-speed framework for exchanging voice, data and video within the building and to the external world. Four intelligence indicators were identified as 'suitable', including *'integrate multiple network or service providers'*, '*fixed hub/terminal port installed'*, *'transmission capacity control and diversion'*, and *'system life and turn-round complexity'*. This ranking implies that during data transmission, 'smart' communication network systems should not only be able to integrate networks or services from different providers, but they should also be able to deal with message prioritisation/diversion and the avoidance of message collision when several devices attempt to transmit at the same time (CIBSE, 2000b). In addition, network intelligence should possess fixed terminal ports for any flexible connections and expansions. In this survey, it is interesting that three groups of industry practitioners had similar rankings over the four indicators.

- **Addressable Fire Detection and Alarm System (AFA):** In the contemporary building, the key function of the AFA system is to provide effective fire control, detection and fighting. In this survey, ten intelligence indicators were elicited by the industry practitioners as 'suitable' for assessing the degree of intelligence of the AFA. The top two indicators include '*alarm deployment algorithm within the building and notification to Fire Department'*, and *'self-diagnostic analysis for false alarm reduction'*. Facility managers further considered three indicators as more 'suitable'. They are '*interface with security systems', 'run continually with minimal human supervision'*, and *'interface with HVAC systems'*. During a fire incident, it is important for the AFA system to effectively and efficiently notify the IBMS (or BAS) of a fire, which in turn instructs the security system to unlock access. Emergency doors and other security entrance controllers should be disabled to allow easy evacuation of the building occupants (CIBSE, 2000b). The control strategy for each subsystem of the HVAC plant should set up the control action to be taken in the event of receiving a fire alarm signal. Much of the plant should be shut down in response to a fire alarm. The air handling unit (AHU) plant will be shut down, though either continuing the supply and extract fans with inlet and exhaust dampers closed, or with the extract fan continuing to run with the exhaust damper open (CIBSE, 2000b). However, the overall rankings of these three indicators, which were rated highly by facility managers, were 3rd or lower. This outcome indicated that these three intelligent performances might have been regarded as relatively less 'suitable'.

- **HVAC Control System:** To judge the intelligent performance of the HVAC control system, design consultants placed higher emphasis on the system ability of '*sensing the internal temperature and humidity, and auto-adjustment*'. The PID (Proportional-Integral-Derivative) controls are incorporated in the HVAC control system to control the supply air temperature, supply static pressure, and return air flow rate. Optimum control strategies are used to reset the set points of the local PID control loop of the supply static pressure (for VAV/AHU system). Sensors concerned in this are the temperature sensors of the fresh air, return air, supply air, humidity sensors of the return air and fresh air, and the static pressure sensor of the supply air. These sensors are essential in monitoring and automatic control of the air handling process (Xiao *et al.*, 2005).

Developers and facility managers, on the other hand, judged '*pre-programmed responses and zoning control'* as a more suitable intelligence indicator. This implies the importance of the existence of pre-programmed control modules in the software of HVAC control systems to facilitate their daily control and monitoring. As specified by CIBSE (2000b), there are a number of logic control functions which may be used to improve control operation. The controller is designed to set its internal parameters to match the characteristics of the actual combination of the building and heating system. This configures to meet the requirements of the actual control strategy to be implemented. The averaging module, is an example of pre-programmed control models, is used to produce a mean value of a number of inputs. The system may be set up to control mean zone temperature, averaged over several temperature sensors.

- **Digital Addressable Lighting Control (DALI) System:** A total of seven intelligence indicators were identified by the respondents as 'suitable' for intelligent performance assessment of the DALI system. The survey findings indicate '*control of individual luminaries, groups of luminaries, and, lighting zones'* as the most suitable intelligence indicator, while both *'interface with EMS, BAS, or IBMS'* and '*sensing the light intensity, angle of projection, and the solar radiation'* as the second most 'suitable' intelligence indicators. In lighting control, the luminaire incorporates a presence detector and a downward-looking photocell which measures the level of illumination (CIBSE, 2000b). The built-in controller ensures that illumination is only provided when the space is occupied and provides a constant level of illumination in varying ambient light levels. The luminaries can communicate with each other over a bus system. A group of luminaries is switched on if a presence is detected by any one of them. The luminaries can be programmed to provide general background illumination to avoid isolating a person in a pool of light. The luminaires may be individually controlled by permitted users over the telephone system or from a PC. The suitability of ‘*sensing the light intensity, angle of projection, and the solar radiation’* as one of the key intelligence indicators reflects that an ‘intelligent’ lighting control should be able to provide photoelectric switching and dimming control (i.e. photocells) to monitor the light level in a space and regulate the lighting accordingly. A ceiling-mounted photocell looking downwards responds to the combined daylight and artificial illumination and the control system is set to provide a constant level of illumination.

- **Security Monitoring and Access Control (SEC) System:** A total of eight ‘suitable’ intelligence indicators were identified. The two most ‘suitable’ indicators were ‘*configurable to accurately implement security policies for the premises’* and *‘interface with other systems’,* This implies that an intelligent SEC system should fundamentally be able to adapt to the building or company’s security needs, but also be able to integrate with the HVAC system and lighting occupation zones (Smith, 2002). Of all the indicators, facility managers particularly ranked ‘*run continually with minimal human supervision’,* and *‘provide management staff with database and analytical tools for operation and service evaluation’* as the two most ‘suitable’ intelligence indicators. Their importance is possibly due to the fact that these intelligent features help save the amount of time and manpower required for daily security duties.

- **Smart and Energy Efficient Lift System (LS):** Eight intelligence indicators were elicited by the respondents as most 'suitable'. The top three were '*auto-controlled navigation at emergency', 'human engineering design'*, and, '*accommodate changes of passenger traffic pattern'*. The *'auto-controlled navigation at emergency'* relates to the automatic control and monitoring of lift navigation/operation during special or emergency events (AIIB, 2001). Lifts can be remotely monitored from a control centre operated by the maintenance companies so that the performance and real-time status of lift can be analysed and recorded, but this intelligent performance only ranked sixth in this survey. The survey findings further implied that an 'intelligent' lift system should incorporate the human engineering design in order to facilitate the convenience of passengers (CIBSE, 2000a). Examples of the human engineering design in lifts include voice announcements, suitability for the disabled and in-car information display. The survey findings also suggested that intelligent lift systems should be able to accommodate changes in passenger traffic patterns (CIBSE, 2000a). For example, artificial intelligence techniques would be employed to identify the number of passengers. The supervisory control algorithm (i.e. dynamic and static sectoring control algorithm) would be developed to detect passenger traffic patterns and peak traffic.

The survey results further suggest that the interpretation of 'intelligence' is different from one intelligent building system to another which implies that each intelligent building system performs in a non-unique way and contains unique measures of system intelligence. The findings further reveal that 'autonomy' was not judged as an important intelligence attribute to reflect the degree of system intelligence in the ITS and DALI systems. This is slightly different to the predictions of *H3* that *'The intelligence attributes of 'autonomy' and 'human-machine interaction' are considered as two common components reflecting the degree of system intelligence of the building control systems, while 'controllability of complicated dynamics' and 'bio-inspired behaviour' are regarded as two specific intelligence attributes, depending on the operational characteristics of the building control systems'*. To conclude, only five building control systems supported *H3*.

7.4 THE AHP-ANP SURVEY: INVESTIGATING INTERDEPENDENT RELATIONSHIPS

Once the suitable intelligence indicators are identified, the results form the basis for establishing the decision hierarchy for the final survey. For a penetrating insight of the measurement of the degree of system intelligence in building control systems, a more meticulous investigation and prioritisation of the 'suitable' intelligence indicators was needed by the intelligent building experts. The influence of the interdependent relationship between intelligence attributes of building control systems and the operational benefits of intelligent buildings was also taken into consideration. A combination of the AHP and ANP methods was utilised to execute the prioritisation of indicators. The AHP was selected to perform the prioritisation of the elements (i.e. intelligence indicators), while the ANP is employed to take the interdependent relationships abovementioned into consideration, resulting in the formation of network-like structural framework.

Due to the experience required for this new and specific research area (i.e., appraisal of the system intelligence), it was difficult to acquire a massive amount of participants. It is the intention of this research to collect data from the experts who had rich experience in designing and evaluating advanced building systems for intelligent building projects. As discussed in previous chapters, both the AHP and ANP are subjective approaches where a large survey sample is not required.

7.4.1 Data Collection and Analytical Model Construction

Decision Model Development and Problem Structuring

The application of the AHP-ANP approaches first requires the construction of a hierarchical decision network for the decision problem which is to be evaluated. For maintaining simplicity in the presentation, the integrated building management system (IBMS) is taken as an illustrative example, and its system intelligence analytic model will be established and tested step by step in the following sections. For the rest of the six intelligent building control systems, the same approach and procedures was also applied, and these findings will be summarised and tabulated in Appendix B (B1-B6, p.371-384) for the sake of brevity. Their survey findings and results are still discussed and analysed in later sections of this chapter.

The conceptual analytical framework for the system intelligence of the IBMS is illustrated in Figure 7.2. At the top of the control hierarchy is the ultimate objective to achieve. In this case, the ultimate objective is to determine the overall degree of system intelligence of the IBMS. The top level is broken down into intelligence attributes (Level 2) and their corresponding intelligence indicators (Level 3). In order to investigate the interdependent relationships between intelligence attributes and operational benefits, another separate but related component, relating to the building's operational benefits, is depicted above the intelligence attributes in the decision models. Four operational benefits act as external variables and form network relationships with the four intelligence attributes in the analytical decision model. The list of operational benefits is not exhaustive, but they are considered as prominent benefits or goals promoted by the intelligent technologies in the available intelligent building literature. The remainder of the decision network hierarchy is more conventional in that the elements have a hierarchical relationship (i.e., the relationship between the intelligence attributes and their corresponding indicators). The proposed analytical models for other six key intelligent building control systems were illustrated in Figure 7.2 to Figure 7.8.

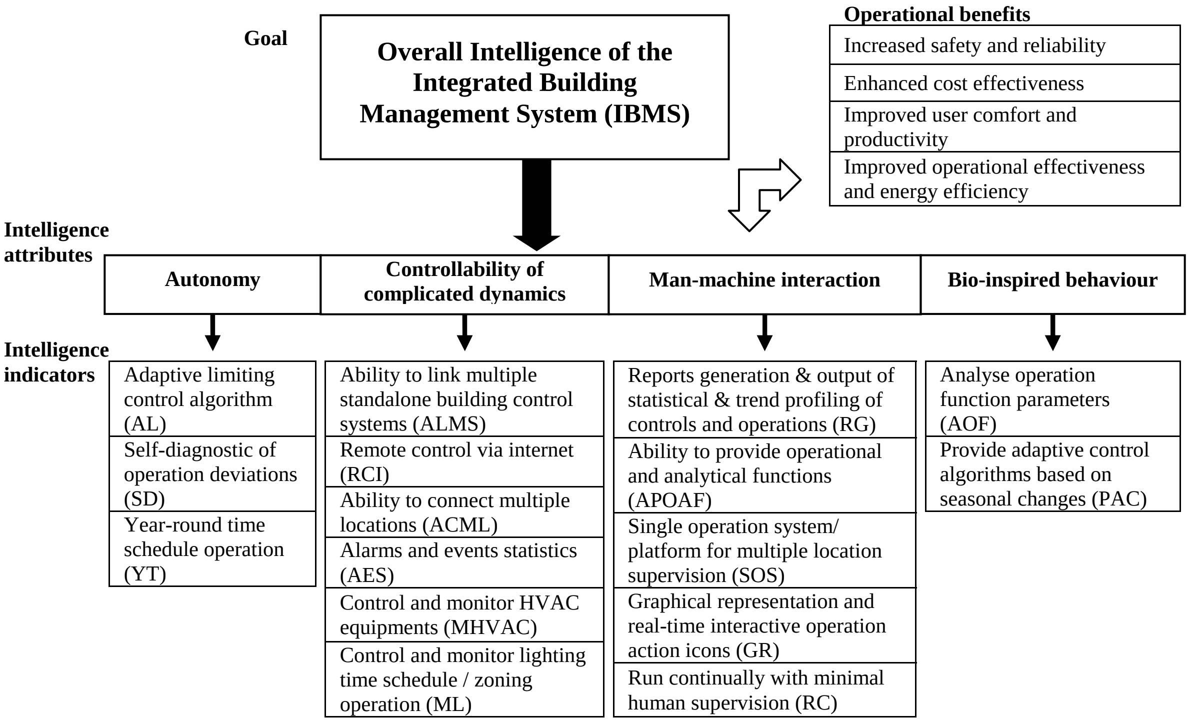


Figure 7.2: ANP Decision Model for the System Intelligence Measurement of the Integrated Building Management System (IBMS)

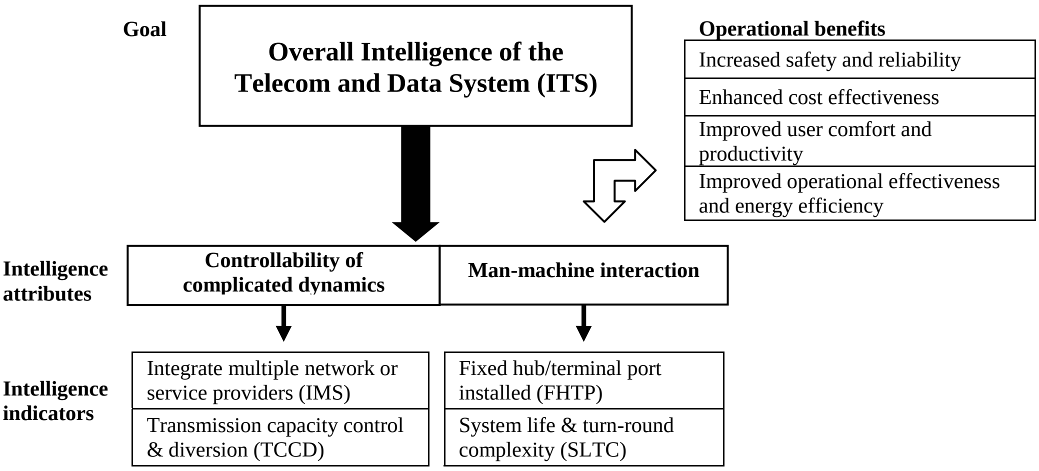


Figure 7.3: ANP Decision Model for the System Intelligence Measurement of the Telecom and Data System (ITS)

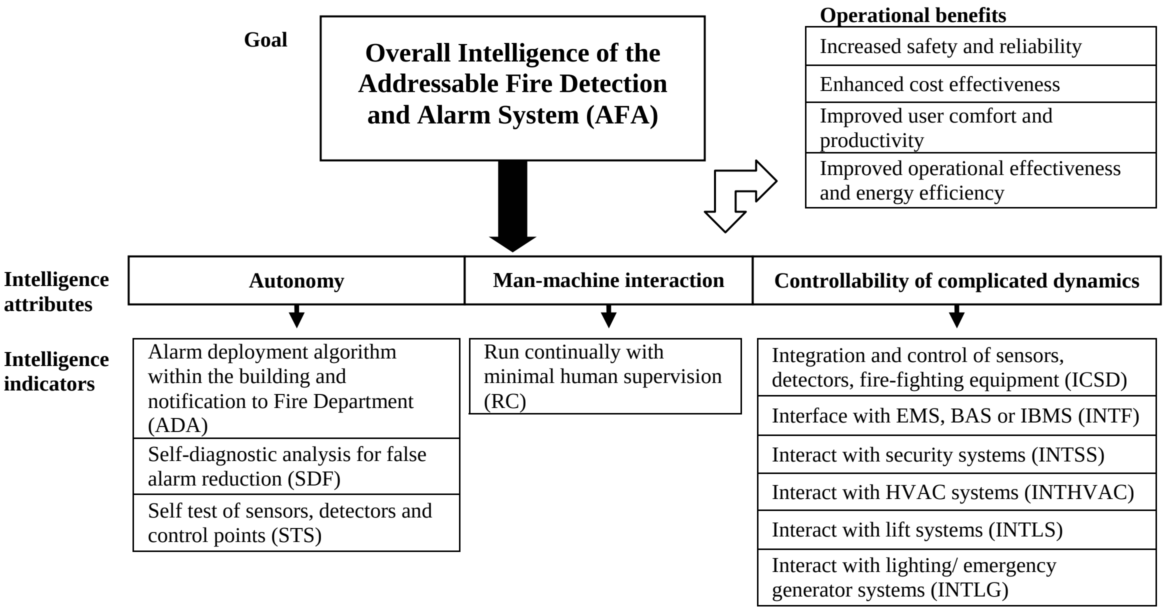


Figure 7.4: ANP Decision Model for the System Intelligence Measurement of the Addressable Fire Detection and Alarm System (AFA)

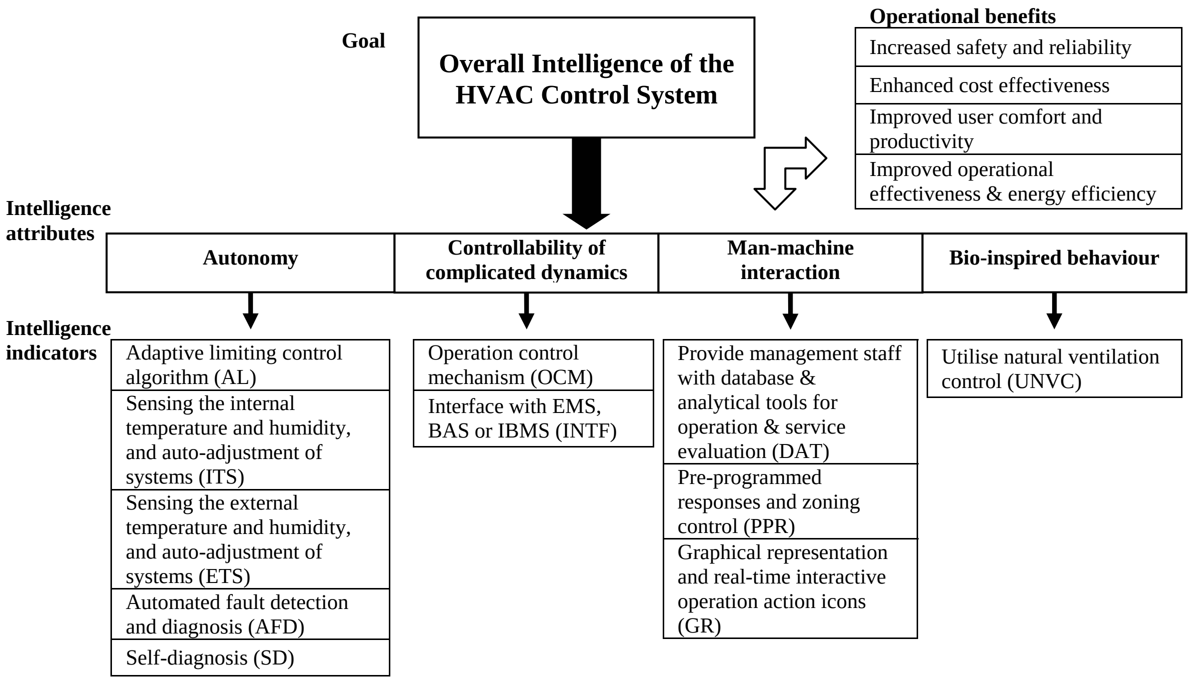


Figure 7.5: ANP Decision Model for the System Intelligence Measurement of the HVAC Control System

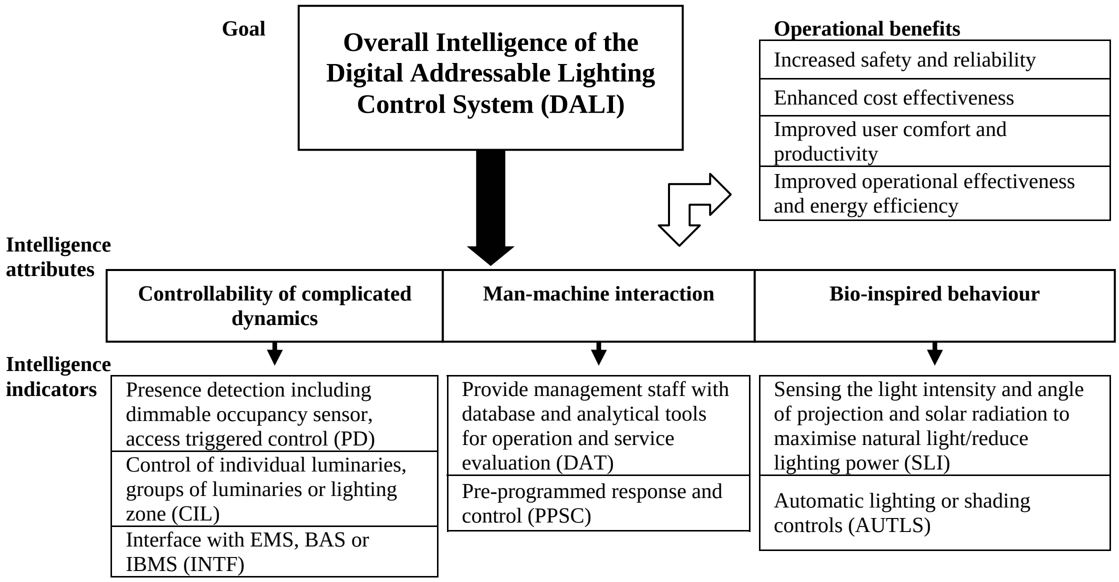


Figure 7.6: ANP Decision Model for the System Intelligence Measurement of the Digital Addressable Lighting Control System (DALI)

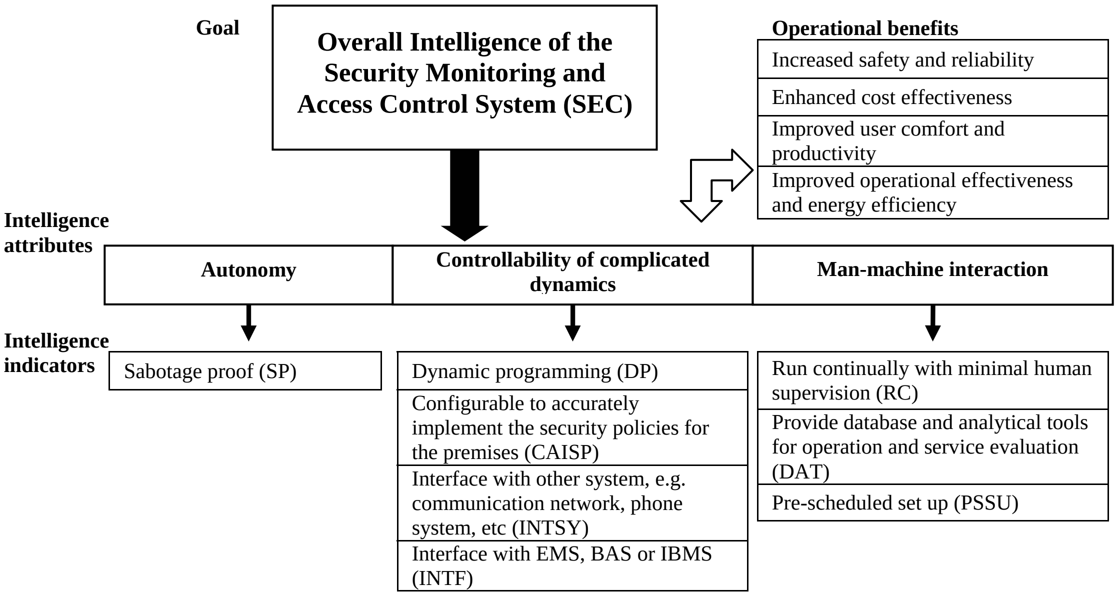


Figure 7.7: ANP Decision Model for the System Intelligence Measurement of the Security Monitoring and Access Control System (SEC)

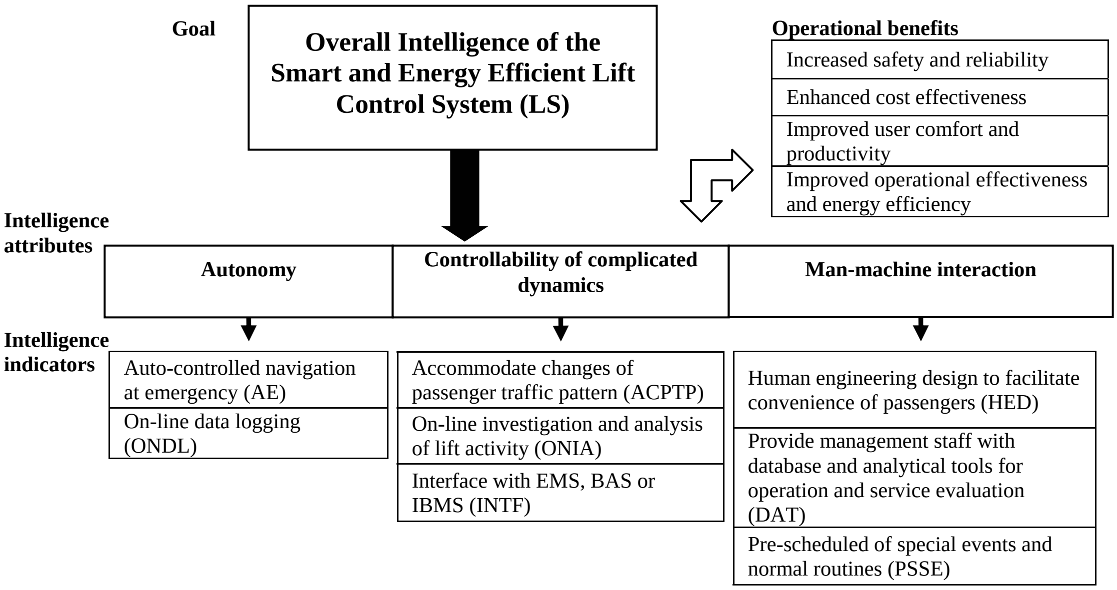


Figure 7.8: ANP Decision Model for the System Intelligence Measurement of the Smart and Energy Efficient Lift Control System (LS)

Sampling Method and Questionnaire Design

Once the analytical model is developed, the matrices should be designed for pair-wise comparison. In order to collect the views on the relative importance of elements, the AHP-ANP questionnaire was designed in accordance with the intelligence attributes and their associated indicators of the decision model to allow the respondents to assign weights to the elements. As stated earlier, the information solicited required in-depth knowledge and rich experience of intelligent building design and development, thus a purposive method was employed to select the expert respondents (Chan *et al*., 2001; Bryman, 1996; Edmunds, 1999; and Morgan, 1998).

In this survey, two criteria were developed for the selection of the eligible participants: (1) experts had to be involved in intelligent building development currently, recently and directly, especially relating to the design evaluation and decision making process on the building control systems and components; and (2) experts had to have a comprehensive knowledge of intelligent building technologies. Only those experts who satisfied these sampling criteria were invited to participate by providing their opinions in completing the questionnaire. Questions relating to the above two criteria were asked in the first general questionnaire survey of this research in order to elicit the real experts. As a result, 15 experts satisfied these criteria and were invited to the final AHP-ANP survey by either an invitation email or telephone call. Finally, nine experts expressed their willingness to participate in this second stage (i.e., AHP-ANP) survey by accepting our survey invitation. A list of the experts and their positions in the corresponding companies is summarised in Table 7.4. The names of these nine experts and their companies were undisclosed in order to respect their anonymity.

It is also noteworthy that the sample size for this survey is considered acceptable. First, it is not mandatory for the ANP to include a large sample size (Cheng *et al*, 2005). Considering the time and effort that was required for the experts to complete an 18-page questionnaire composed of cumbersome pair-wise comparisons for the seven intelligent building control systems, a total of nine respondents (EXB1 to EXB9) in the current survey is considered quite reasonable.

Table 7.4: List of Experts for the AHP-ANP Survey

Expert reference	Designation	Organization type	Years of experience	Number of IB project(s) participated
EXB1	Manager	M&E engineering consultancy	16	6
EXB2	Manager	M&E engineering consultancy	25	6
EXB3	Senior M&E Engineer	Building contractor	10	5
EXB4	Project Engineer	M&E engineering consultancy	6	3
EXB5	Senior Project Engineer	M&E engineering consultancy	15	4
EXB6	Manager	Government architectural services	10	3
EXB7	Director	Engineering department of property developer	30	6
EXB8	M&E Engineer	Building contractor	4	2
EXB9	Director	M&E engineering consultancy	17	5

The AHP-ANP questionnaire (the fourth questionnaire as shown in Appendix A4, p.336) in this survey was designed in a format similar to the AHP questionnaire in preceding chapter, which was based on the recommendations of Chua *et al.* (1999) and Chen *et al.*

(2005). In order to ensure that good quality data was collected, the objectives of the survey were briefly presented, and an example of pair-wise comparison was illustrated. The questions relating to different aspects are also clearly presented in different sections.

Pair-wise Comparisons Matrices of Interdependent Component Levels and Variables of Intelligence Attributes

Like the AHP, the ANP is established on the ratio scale measurement. Pair-wise comparisons of elements are undertaken to determine their relative importance or priority. The estimation of the relative importance of the two compared elements follows the *Step Two* of ANP approach (section 5.5.2) in Chapter 5. The relative importance weight of interdependence was also determined by using a nine-point priority scale of pair-wise judgement which was developed by Saaty (1996).

Using the IBMS as an illustrative example, the comparison matrix (i.e., the relative importance) of the four intelligence attributes with respect to the decision problem (i.e., measuring the overall degree of system intelligence of the IBMS) was first determined. The four intelligence attributes (level 2) were rated pair-by-pair with respect to the decision problem (level 1) in Figure 7.9 (Matrix 1). Then, the relative importance of the intelligence attributes (e.g. autonomy vs. man-machine interaction) with respect to a specific operational benefit of the intelligent building was investigated. A pair-wise comparison matrix was required for each of the operational benefits for calculation of impacts of each of the intelligence attributes, and the results are illustrated in Figure 7.10 (Matrix 2 to 5). Then, four pair-wise comparison matrices were next required to calculate the relative impacts of each operational benefit (i.e., enhanced cost effectiveness vs. improved operational effectiveness and energy efficiency) on a specific intelligence attribute as depicted in Figure 7.11 (Matrix 6 to 9). As a result, a total of eight pair-wise comparison matrices were required to describe the two-way relationship.

Matrix 1: Intelligence attributes with respect to the decision problem (the overall intelligence of IBMS)

GOALS	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**Mean Weight**
AUT	0.4236	0.2850	0.5617	0.2436	0.2359	0.0578	0.3509	0.2312	0.0965	0.2762
BIB	0.0429	0.0424	0.0993	0.4146	0.0995	0.1249	0.1091	0.1484	0.4094	0.1656
CCD	0.4236	0.3942	0.1986	0.2436	0.1221	0.5812	0.3509	0.4258	0.2047	0.3272
MMI	0.1098	0.2784	0.1404	0.0982	0.5426	0.2361	0.1891	0.1945	0.2895	0.2310

Note: B1-B9 = expert no. 1 -9; AUT = autonomy; BIB = bio-inspired behaviour; CCD = controllability of complicated dynamics; and MMI = man-machine interaction.

Figure 7.9: Summary of Comparison Matrix Results (‘Eigenvectors’) of Intelligence Attributes with respect to the Decision Problem from Experts

Once the pair-wise comparisons were completed, the local priority was calculated. The relative importance of each intelligence indicator with respect to each of their corresponding intelligence attributes was investigated, and the results were tabulated in the matrices 10 to 13 in Figure 7.12. The local priority vector is an array of weight priorities containing a single column, whose components (denoted as w_i) are derived from a judgement comparison matrix. The local priority vector is computed by following the procedure discussed in *Step Two* of the ANP method in Chapter 5.

Matrix 2: Intelligence attributes with respect to the operational benefits of enhanced cost effectiveness

ECE	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
AUT	0.6426	0.5815	0.3213	0.2436	0.2359	0.0578	0.2857	0.3300	0.4182	0.3463
BIB	0.0483	0.2507	0.3034	0.4146	0.0995	0.1249	0.1429	0.1404	0.1205	0.1828
CCD	0.1545	0.0616	0.3034	0.2436	0.1221	0.5812	0.2857	0.3300	0.2707	0.2614
MMI	0.1545	0.1062	0.0718	0.0982	0.5426	0.2361	0.2857	0.1996	0.1906	0.2095

Matrix 3: Intelligence attributes with respect to the operational benefits of improved operational effectiveness and energy efficiency

OEE	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
AUT	0.3153	0.6473	0.6344	0.2778	0.2609	0.1059	0.3509	0.3353	0.3682	0.3662
BIB	0.0350	0.0471	0.1160	0.3659	0.1190	0.1636	0.1091	0.0966	0.1153	0.1297
CCD	0.2683	0.1445	0.1465	0.2326	0.1689	0.4476	0.3509	0.3808	0.3216	0.2735
MMI	0.3814	0.1611	0.1031	0.1238	0.4512	0.2829	0.1891	0.1873	0.1949	0.2305

Matrix 4: Intelligence attributes with respect to the operational benefits of improved user comfort and productivity

UC	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
AUT	0.2643	0.3199	0.5845	0.2015	0.2071	0.0886	0.1622	0.1385	0.2000	0.2407
BIB	0.0507	0.0526	0.1309	0.4254	0.2071	0.4336	0.5243	0.4646	0.4000	0.2988
CCD	0.6131	0.5498	0.1670	0.2483	0.2929	0.2389	0.1513	0.1573	0.2000	0.2910
MMI	0.0719	0.0777	0.1176	0.1248	0.2929	0.2389	0.1622	0.2396	0.2000	0.1695

Matrix 5: Intelligence attributes with respect to the operational benefits of increased system safety and reliability

S&R	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
AUT	0.4471	0.5141	0.5338	0.2219	0.2857	0.2722	0.3564	0.3261	0.3374	0.3661
BIB	0.0383	0.0413	0.1144	0.4564	0.1429	0.1109	0.0982	0.1480	0.1261	0.1418
CCD	0.1317	0.1317	0.2199	0.2143	0.2857	0.3619	0.2946	0.3629	0.2631	0.2518
MMI	0.3829	0.3129	0.1319	0.1074	0.2857	0.2550	0.2508	0.1630	0.2734	0.2403

Note: B1-B9 = expert no. 1 -9; ECE = enhanced cost effectiveness; OEE = improved operational effectiveness and energy efficiency; UC = improved user comfort and productivity; S&R=increased safety and reliability; AUT = autonomy; BIB = bio-inspired behaviour; CCD = controllability of complicated dynamics; and MMI = man-machine interaction.

Figure 7.10: Summary of Comparison Matrix Results (‘Eigenvectors’) of the Intelligence Attributes of the IBMS with respect to their Operational Benefits from Experts

Matrix 6: Operational benefits with respect to the intelligence attributes of autonomy

AUT	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
ECE	0.0613	0.0663	0.2601	0.3060	0.1250	0.1630	0.1936	0.1142	0.1692	0.1621
OEE	0.2610	0.2657	0.2947	0.4328	0.3496	0.3261	0.3257	0.3959	0.2879	0.3266
UC	0.3710	0.3584	0.3655	0.1530	0.0924	0.1480	0.1243	0.1225	0.2046	0.2155
S&R	0.3067	0.3096	0.0797	0.1082	0.4330	0.3629	0.3564	0.3674	0.3383	0.2958

Matrix 7: Operational benefits with respect to the intelligence attributes of bio-inspired behaviour

BIB	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
ECE	0.1003	0.1205	0.3253	0.3187	0.1512	0.1028	0.1287	0.1404	0.1976	0.1762
OEE	0.4146	0.3155	0.3484	0.3898	0.2668	0.1722	0.1658	0.2322	0.1682	0.2748
UC	0.4146	0.4954	0.2510	0.2152	0.3880	0.5417	0.5070	0.3952	0.3952	0.4004
S&R	0.0706	0.0685	0.0753	0.0763	0.1940	0.1833	0.1985	0.2322	0.2390	0.1486

Matrix 8: Operational benefits with respect to the intelligence attributes of controllability of complicated dynamics attribute

CCD	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
ECE	0.1783	0.0951	0.3755	0.1933	0.1788	0.0855	0.1428	0.1186	0.1783	0.1718
OEE	0.1296	0.1419	0.2644	0.4734	0.3198	0.4547	0.3849	0.5216	0.3890	0.3421
UC	0.3031	0.3271	0.2944	0.2367	0.1382	0.1393	0.0874	0.1278	0.1296	0.1982
S&R	0.3889	0.4359	0.0657	0.0966	0.3632	0.3205	0.3849	0.2320	0.3031	0.2879

Matrix 9: Operational benefits with respect to the intelligence attributes of man-machine interaction attribute

MMI	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
ECE	0.3973	0.2941	0.2273	0.2345	0.1634	0.1575	0.1372	0.1381	0.1357	0.2095
OEE	0.4238	0.5062	0.3508	0.3500	0.2781	0.4189	0.2656	0.2761	0.2873	0.3508
UC	0.1073	0.1302	0.3508	0.2923	0.3952	0.1284	0.4228	0.3905	0.3400	0.2842
S&R	0.0715	0.0696	0.0711	0.1231	0.1633	0.2952	0.1744	0.1953	0.2370	0.1556

Note: B1-B9 = expert no. 1 -9; ECE= enhanced cost effectiveness; OEE= improved operational effectiveness & energy efficiency; UC= improved user comfort & productivity; S&R=increased safety & reliability; AUT= autonomy; BIB= bio-inspired behaviour; CCD= controllability of complicated dynamics; MMI= man-machine interaction.

Figure 7.11: Summary of Comparison Matrix Results (‘Eigenvectors’) of the Operational Benefits with respect to the Intelligence Attributes of the IBMS from Experts

Matrix 10: Intelligence indicators with respect to the intelligence attributes of autonomy

AUT	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
AL	0.0738	0.1852	0.6833	0.5499	0.1830	0.1562	0.5000	0.3333	0.4286	0.3437
SD	0.1218	0.6587	0.1998	0.2098	0.7418	0.1852	0.2500	0.3333	0.4286	0.3477
YT	0.8044	0.1562	0.1169	0.2403	0.0752	0.6587	0.2500	0.3333	0.1429	0.3086

Note: AL= adaptive limiting control algorithm; SD= self-diagnostic of operation deviations; YL= year-round time schedule operation

Matrix 11: Intelligence indicators with respect to the intelligence attributes of bio-inspired behaviour attribute

BIB	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
AOF	0.5000	0.5000	0.1429	0.2500	0.2000	0.8000	0.8000	0.5000	0.5000	0.4659
PAC	0.5000	0.5000	0.8571	0.7500	0.8000	0.2000	0.2000	0.5000	0.5000	0.5341

Note: AOF= provide adaptive control algorithms based on seasonal changes; PAC= automatically adapt to daily occupied space changes

Matrix 12: Intelligence indicators with respect to the intelligence attributes of controllability of complicated dynamics attribute

CCD	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
ALMS	0.0314	0.1736	0.4677	0.0543	0.1332	0.0370	0.0688	0.1736	0.2491	0.1543
RCI	0.0314	0.1736	0.1036	0.0468	0.0447	0.1040	0.0593	0.1736	0.1021	0.0932
ACML	0.0314	0.1736	0.0956	0.0694	0.2290	0.0478	0.0834	0.1736	0.1836	0.1208
AES	0.3492	0.1597	0.0999	0.2716	0.1400	0.3766	0.2575	0.1597	0.1517	0.2184
ML	0.2074	0.1597	0.1322	0.2465	0.0868	0.2173	0.3253	0.1597	0.1567	0.1880
MHVAC	0.3492	0.1597	0.1011	0.3114	0.3664	0.2173	0.2058	0.1597	0.1567	0.2253

Note: ALMS= ability to link multiple standalone building control systems from a variety of manufacturers; RCI= remote control via internet; ACML= ability to connect multiple locations; AEC= alarms and events statistics; ML= control and monitor lighting time schedule / zoning operation; MHVAC= control and monitor HVAC equipments

Matrix 13: Intelligence indicators with respect to the intelligence attributes of man-machine interaction attribute

MMI	B1	B2	B3	B4	B5	B6	B7	B8	B9	Mean Weight
RG	0.2135	0.2000	0.0396	0.1044	0.0505	0.0590	0.1187	0.1667	0.0809	0.1148
APOAF	0.0861	0.2000	0.1453	0.1361	0.1546	0.1139	0.1463	0.1667	0.2952	0.1605
SOS	0.0266	0.2000	0.2004	0.1704	0.2548	0.1034	0.2135	0.1667	0.2952	0.1812
GR	0.2799	0.2000	0.2648	0.0592	0.3468	0.2873	0.0838	0.3333	0.0334	0.2098
RC	0.3939	0.2000	0.3499	0.5299	0.1932	0.4364	0.4377	0.1667	0.2952	0.3337

Note: R = reports generation and output of statistical and trend profiling of controls and operations; APOAF= ability to provide operational and analytical functions; SOS= single operation system/ platform for multiple location supervision; GR= graphical representation and real-time interactive operation action icons; RC= run continually with minimal human supervision

Figure.7.12: Summary of Comparison Matrix Results ('Eigenvectors') of the Intelligence Indicators with respect to Respective Intelligence Attributes from Experts

The process of averaging over normalised columns can be done by dividing each element in a column by the sum of the column elements and then summing the elements in each row of the resultant matrix and dividing by the *n* elements in the row. After applying this approach for all expert respondents, simple averaging of the weights was completed for final evaluation since it was assumed that the importance (i.e., knowledge, expertise, and perceptions) of all experts were equal. In the case of any unequal allocations of importance, a weighted average is used (Sarkis and Sundarraj, 2002: 342).

The consistency of the judgements is significant in the ANP measurement as it aims to eliminate the possible inconsistency revealed in the criteria weights through the computation of a consistency level of each matrix (Cheng and Li, 2002). The consistency ratio of the ANP pair-wise comparison follows the rules set by Saaty (1994) and Cheng & Li (2002) as mentioned in *AHP Step Five* in Section 5.5.1. In this survey, all completed pair-wise comparisons by the respondents appeared to have acceptable consistency.

After the calculation, the weighted priorities for each of the operational benefits were combined to form matrix A with four columns and four rows as shown in Figure 7.13. The local priority weights (LPW) for the relative importance of the benefits on the intelligence attributes were then investigated. As a result, the weighted priorities for each of intelligence attributes were combined to form a four column, four row matrix B as shown in Fig.7.14.

In maintaining some parsimony for ease of exposition, the interdependence of components on the same level (i.e. interdependent relationships among intelligence indicators) was not considered in this research. The pair-wise comparison of the elements at the indicators/variables level (level 3) is conducted with respect to their relative influence (eigenvector determination) towards their control criteria (i.e. intelligence attributes in level 2). The eigenvectors of separate pair-wise comparison matrices developed between level two and three (Matrix 10 to 13) are summarised in Figure 7.12.

Matrix A	**ECE**	**OEE**	**UC**	**S&R**
AUT	0.3463	0.3662	0.2407	0.3661
BIB	0.1828	0.1297	0.2988	0.1418
CCD	0.2614	0.2735	0.2910	0.2518
MMI	0.2095	0.2305	0.1695	0.2403

Note: ECE = enhanced cost effectiveness; OEE = improved operational effectiveness and energy efficiency; UC = improved user comfort and productivity; S&R=increased safety and reliability; AUT = autonomy; BIB = bio-inspired behaviour; CCD = controllability of complicated dynamics; and MMI = man-machine interaction.

Figure 7.13: The Combined Matrix (Matrix A) Formed from Eigenvectors ('Relative Importance Weights') for the Implications of Operational Benefits on Intelligence Attributes of the IBMS

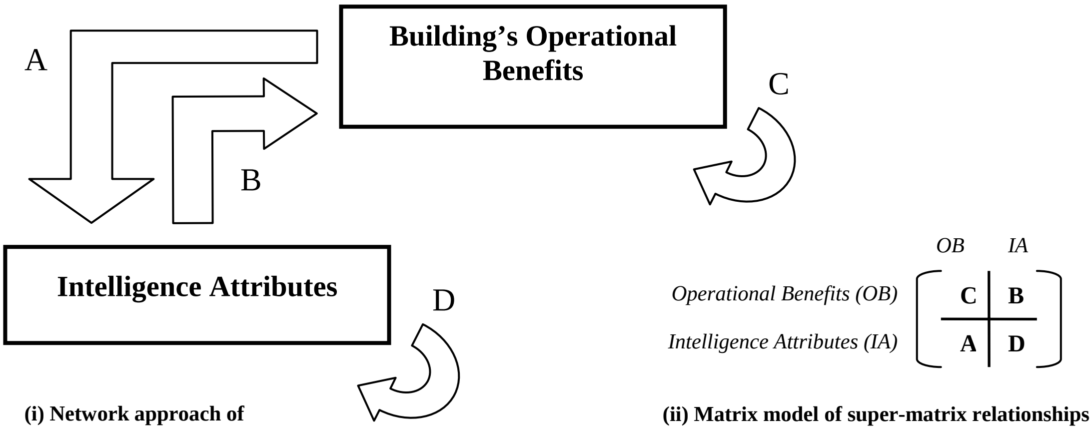
Matrix B	AUT	BIB	CCD	MMI
ECE	0.1621	0.1762	0.1718	0.2095
OEE	0.3266	0.2748	0.3421	0.3508
UC	0.2155	0.4004	0.1982	0.2842
S&R	0.2958	0.1486	0.2879	0.1556

Note: ECE = enhanced cost effectiveness; OEE = improved operational effectiveness and energy efficiency; UC = improved user comfort and productivity; S&R=increased safety and reliability; AUT = autonomy; BIB = bio-inspired behaviour; CCD = controllability of complicated dynamics; and MMI = man-machine interaction.

Figure 7.14: The Combined Matrix (Matrix B) Formed from Eigenvectors ('Relative Importance Weights') for the Implications of Intelligence Attributes of the IBMS on Promoting the Buildings' Operational Benefits

Super-matrix Formation and Analysis

The super-matrix promotes a resolution of the effects of the interdependence that exists between the elements of the ANP model. This can be achieved by entering the local priority vectors (LPV) in the super-matrix, which in turn obtains the 'global' priority vectors (GPV). This process has been described in detail in *ANP Step Four* and *Five* in Section 5.5.2. In Figure 7.15, the matrices A and B represent interdependence between the intelligence attributes and the external components of a building's operational benefits, while relationships C and D represent the interdependence of a level of components on itself. Cheng *et al.* (2005) and Meade and Sarkis (1998) suggested that if the impacts of the components in the same level are deemed to be insignificant, then all the values in sub-matrices (i.e., sub-matrices C and D in this illustrative example) should be assigned a zero value. Otherwise, the normalisation step will be required to make the column stochastic if the sub-matrices were non-zero matrices.



(i) Network approach of super-matrix relationships of an intelligent building control system

(ii) Matrix model of super-matrix relationships

(Reference: Meade and Sarkis, 1998: 210)

Figure 7.15: Super-matrix Relationship

In this study, if the same level impacts are assumed not to be significant, then matrices A and B are required to combine to form the super-matrix ('E') shown in Fig. 7.16. The super-matrix summaries the eigenvectors associated with the four intelligence attributes with respect to the decision problems. It also includes the eigenvectors from the interdependent influences between the four intelligence attributes and four operational benefits. The final sub-step of the ANP calculation relates to the calculation of a limit super-matrix by the *Super Decisions* (*Step Five* of ANP approach). The results of the average limiting super-matrix with the relative importance and final weights of each intelligence indicator of IBMS were summarised in Table 7.5.

	GOAL	**ECE**	**OEE**	**UC**	**S&R**	**AUT**	**BIB**	**CCD**	**MMI**
GOAL	0	0	0	0	0	0	0	0	0
ECE	0	0	0	0	0	0.1621	0.1762	0.1718	0.2095
OEE	0	0	0	0	0	0.3266	0.2748	0.3421	0.3508
UC	0	0	0	0	0	0.2155	0.4004	0.1982	0.2842
S&R	0	0	0	0	0	0.2958	0.1486	0.2879	0.1556
AUT	**0.2762**	0.3463	0.3662	0.2407	0.3661	0	0	0	0
BIB	**0.1656**	0.1828	0.1297	0.2988	0.1418	0	0	0	0
CCD	**0.3272**	0.2614	0.2735	0.2910	0.2518	0	0	0	0
MMI	**0.2310**	0.2095	0.2305	0.1695	0.2403	0	0	0	0

Note: The ‘GOAL’ here is the selection of the most intelligent IBMS; CE = enhanced cost effectiveness; OEE = improved operational effectiveness and energy efficiency; S&R=increased safety and reliability; UC = improved user comfort and productivity; AUT = autonomy; BIB = bio-inspired behaviour; CCD = controllability of complicated dynamics; and MMI = man-machine interaction.

Figure 7.16: Super-matrix ‘E’ Compiled from Matrices A and B for the Linkages of the Intelligent Attributes of the IBMS and Operational Benefits

Table 7.5: The Final Weights of IBMS Intelligence Indicators

Intelligence attributes and indicators of IBMS	Normalised value of category from the average limiting super-matrix	The relative weight of indicator (from matrix 10-13)	The final weight of indicator (ANP)
AUT	**0.3288**		
AL		0.3437	**0.1130**
SD		0.3477	**0.1143**
YT		0.3086	**0.1015**
CCD	**0.2764**		
ALMS		0.1543	**0.0427**
RCI		0.0932	**0.0258**
ACML		0.1208	**0.0334**
AES		0.2184	**0.0604**
ML		0.1880	**0.0520**
MHVAC		0.2253	**0.0623**
MMI	**0.2115**		
RG		0.1148	**0.0243**
APOAF		0.1605	**0.0339**
SOS		0.1812	**0.0383**
GR		0.2098	**0.0444**
RC		0.3337	**0.0706**
BIB	**0.1833**		
AOF		0.4659	**0.0854**
PAC		0.5341	**0.0979**

Note: AUT = autonomy; BIB = bio-inspired behaviour; CCD = controllability of complicated dynamics; and MMI = man-machine interaction; AL = adaptive limiting control algorithm; SD = self-diagnostic of operation deviations; YL = year-round time schedule operation; AOF = provide adaptive control algorithms based on seasonal changes; PAC = automatically adapt to daily occupied space changes; ALMS = ability to link multiple standalone building control systems from a variety of manufacturers; RCI = remote control via internet; CML = ability to connect multiple locations; AES = alarms and events statistics; MHVAC = control and monitor HVAC equipments; ML = control and monitor lighting time schedule / zoning operation; RG = reports generation and output of statistical and trend profiling of controls and operations; APOAF = ability to provide operational and analytical functions; SOS = single operation system/ platform for multiple location supervision; GR = graphical representation and real-time interactive operation action icons; and, RC = run continually with minimal human supervision.

7.5 DATA ANALYSIS AND RESULTS

Comparing the Findings of the First and ANP Surveys

This section summarises the major findings obtained from the AHP-ANP survey, and contrasts them with the results of the general survey. Table 7.6 summarises the results of the weights and rankings of individual intelligence indicators of all seven building control systems calculated by the ANP method. Contrasting the relative importance of the intelligence indicators of the IBMS in the two surveys of this study indicates that the ANP results are slightly different from the general survey. In the general survey, *'ability to link multiple standalone building control systems from a variety of manufacturers'* was judged as the most 'suitable' intelligence indicator of the IBMS. Surprisingly, the importance of this factor declined to eleventh most suitable in the ANP survey. Possibly, the ability of the IBMS to link other building systems was perceived by the experts as a basic intelligent feature. This is consistent with the recent view of practitioners like Tay *et al*. (2002) that the ability of linking control systems from multiple manufacturers is considered as a basic feature of the IBMS, making it an inadequate indicator for discriminating between the intelligent levels of various systems. Instead, experts in the ANP survey suggested that *'self-diagnostic of operation deviations'* and '*adaptive limiting control algorithm*' were the first and second most 'suitable' intelligence indicators respectively. This indicates that an 'intelligent' IBMS should possess the capability of detecting the deviations in its operation and self-adjusting in order to solve any problems. When the changes in plant dynamics are large, unpredictable or over the limits, the adaptive controller should be able to learn the operating conditions of the plant and the control system by observing the response to changes in set points or in external disturbances in order to protect the system against parameter estimates and prevent poor control performance in unpredictable situations (CIBSE, 2000b). In the ANP survey, experts also considered the suitability of '*year-round time schedule operation*' (ranked 3rd) as an intelligence indicator. This implied that an intelligent IBMS should be able to operate and schedule building services automatically in response to changing temperature, solar radiation, humidity, etc., all over the year.

Table 7.6: A Summary of the Relative Importance of Individual Intelligence Indicators of Seven Key Building Control Systems in the ANP Survey

Indicators	Weight	Ranking	Indicators	Weight	Ranking
Integrated Building Management System			**HVAC Control System (cont.)**		
(IBMS)			**AUT**		
AUT			SD	0.0462	10
AL	0.1130	2	**CCD**		
SD	0.1143	1	OCM	0.1343	3
YT	0.1015	3	INTF	0.1393	2
CCD			**MMI**		
ALMS	0.0427	11	DAT	0.0774	7
RCI	0.0258	15	PPR	0.0892	4
ACML	0.0334	14	GR	0.0847	5
AES	0.0604	8	**BIB**		
ML	0.0520	9	UNVC	0.2012	1
MHVAC	0.0623	7			
MMI			**Digital Addressable Lighting Control System**		
RG	0.0243	16	**(DALI)**		
APOAF	0.0339	13	**CCD**		
SOS	0.0383	12	PD	0.0895	7
GR	0.0444	10	CIL	0.1309	5
RC	0.0706	6	INTF	0.1338	4
BIB			**MMI**		
AOF	0.0854	5	DAT	0.1153	6
PAC	0.0979	4	PPSC	0.2063	1
			BIB		
Telecom and Data System (ITS)			SLI	0.1771	2
CCD			AUTLS	0.1471	3
IMS	0.1980	3			
TCCD	0.3063	2	**Security Monitoring and Access**		
MMI			**Control System (SEC)**		
FHTP	0.3177	1	**AUT**		
SLTC	0.1781	4	SP	0.3855	1
			CCD		
Addressable Fire Detection and Alarm			DP	0.0520	7
System (AFA)			CAISP	0.1034	4
AUT			INTSY	0.0513	8
ADA	0.1764	2	INTF	0.0614	6
SDF	0.1264	4	**MMI**		
STS	0.1462	3	RC	0.1200	3
CCD			DAT	0.1014	5
ICSD	0.0883	5	PSSU	0.1250	2
INTF	0.0373	9			
INTSS	0.0279	10	**Smart & Energy Efficient Lift System (LS)**		
INTHVAC	0.0588	6	**AUT**		
INTLS	0.0448	7	AE	0.2602	1
INTLG	0.0439	8	ONDL	0.1482	2
MMI			**CCD**		
RC	0.2501	1	ACPTP	0.1236	4
			ONIA	0.0681	7
HVAC Control System			INTF	0.0563	8
AUT			**MMI**		
AL	0.0306	11	DAT	0.1347	3
ITS	0.0825	6	PSSE	0.1107	5
ETS	0.0647	8	HED	0.0981	6
AFD	0.0498	9			

Examination of the survey results also indicates that there were variations in the relative importance of the intelligence indicators of ITS in the two surveys. The importance of indicator *'integrated multiple network and service provider'* declined from being the most suitable indicator in the first survey to third in the ANP survey. For the network system to function effectively, experts probably expected that every network system in the intelligent building should be at least capable of supporting a wide variety of communication services without major modification to circuits or switches (Smith, 2002). Thus, it makes this indicator relatively less representative as the most 'suitable' intelligent measure of the ITS. Further comparisons of the survey results illustrate that the second and third most 'suitable' intelligence indicators of ITS in the general survey: *'fixed hub/terminal port installed'* and *'transmission capacity control and diversion'* improved to the first and second most 'suitable' in the ANP survey. From the experts' perspectives, an intelligent network system should not only contain fixed terminal ports to allow flexible connections and expansion of the system network, but it should also be able to deal with message prioritisation, diversion and avoid message collision when several devices are attempting to transmit concurrently.

Regarding the HVAC control system, the results of the general survey suggested *'pre-programmed responses and zoning control'* as the most 'suitable' intelligence indicator. However, its importance declined to the fourth in the ANP survey. The most 'suitable' position was replaced by the indicator *'utilise natural ventilation control'*. From the results, it reflects that experts considered that an intelligent HVAC control system should possess the function of utilising natural ventilation, which not only helps reduce the electricity cost and consumption, but also promotes the image of environmental-friendliness of the building. This finding is consistent with the view of

Rousseau and Mathews (1993) that ‘energy efficiency of HVAC systems is getting more important concern in intelligent building’. On the other hand, the results of the ANP survey further confirmed the suitability of *‘interface with EMS, BAS, or IBMS’* as one of the intelligence indicator for HVAC control system. This indicator was equally ranked as the second most ‘suitable’ in both surveys. This confirms that an ‘intelligent’ HVAC control system should have a desirable interface with the building management system (Alcalá *et al.*, 2006). Another intelligence indicator *‘operational control mechanism’* was judged as the third most ‘suitable’ by the experts in the ANP survey. According to So and Chan (1999), there is a range of artificially intelligent controls for an HVAC system, including computer vision control, neural network control, static fuzzy logic based control and self learning fuzzy logic based control. No matter which type(s) of control model the HVAC system adapted, the ultimate aim is to improve response rate, save energy and reduce operating and maintenance costs.

Further analysis of the survey results found that the suitability of *‘run continually with minimal human supervision’* as an intelligence indicator of the AFA system improved from being the fifth most ‘suitable’ in the general survey to the most ‘suitable’ in the ANP survey. This is consistent with the view of Thuillard *et al.* (2001) that an ‘intelligent’ fire detection system should have high sensitivity of catching real danger situations and sending command signal for actuation with minimum human intervention and supervision. In addition, the suitability of *‘self-test of sensors, detectors and control points’* also improved from being the eighth in the general survey to the third in the ANP survey. This showed that self-testing of the status of the addressable detectors and sensors, and self-recognition of a breakdown in the system, are indispensable to an ‘intelligent’ AFA system (Song and Hong, 2007). Furthermore, the suitability of *‘alarm* *deployment algorithm within the building and notification to Fire Department'* and *'self-diagnostic analysis for false alarm reduction'* as two 'suitable' intelligence indicators for AFA systems was further confirmed in the ANP survey. They were perceived as the second and fourth most 'suitable' intelligence indicators by the experts.

Investigating the 'suitability' of the intelligence indicators for the SEC system interestingly found that *'sabotage proof'* was considered as the top intelligence indicator in the ANP survey. It was ranked as the fourth most 'suitable' in the first survey. Perhaps the improvement in its overall ranking is due to increasing worries by the experts over the protection of building premises from sabotage by the terrorists in recent years. As a front-line of detecting the presence of any unauthorised people in protected areas of a building, the SEC system and its components must be able to resist physical damage and modification. In addition, *'pre-scheduled set-up'* improved from being the eighth in the general survey to the second most 'suitable' in the ANP survey, which suggested an intelligent SEC system should be allowed for pre-scheduling to facilitate the monitoring and control process during the special events and normal routines. Interestingly, the two top intelligence indicators in the general survey: *'configurable to accurately implement the security policies for the premises'* and *'interface with other systems'*, declined to being the fourth and eighth most 'suitable' in the ANP survey. Possibly, there were other indicators considered more 'suitable' by the experts, and these two intelligent features were perceived by the experts as fundamental functions of many current 'intelligent' SEC systems. Thus, the suitability of these two indicators declined.

The survey results further indicated that *'auto-controlled navigation at emergency'* was ranked as the most 'suitable' indicators for the evaluation of the degree of intelligence of the Smart and Energy Efficient Lift System (LS) in both the general and ANP surveys. However, another indicator, *'human engineering design'*, declined from being the second most important indicator in the general survey to sixth in the ANP survey. Experts found that the human engineering design of in-car lifts was less reflective of an 'intelligent' lift system, as such design (i.e. voice announcement, fit for disables, lighting, and floor display up/down) can already be found in many current intelligent lift systems. Instead, experts considered that *'on-line data logging'* function of the LS are more 'suitable' to reflect the distinctive intelligent performance of the lift control system (ranked the second most suitable in the ANP test). Data logging is essential in facilitating routine maintenance and as a verification of and basis for improvement to a design (CIBSE, 2000a). It provides useful information for the intelligent control of operations. Prior to the execution of any control algorithm, adequate information showing the current status of each lift car within the lift system must be recovered.

Finally, the investigation of the system intelligence of the DALI system concluded that *'pre-programmed response and control'* was judged as the most 'suitable' intelligence indicator. It was improved from being the fifth most 'suitable' to the first in the ANP survey. The timer control system allows switching the whole lighting installation on and off at predetermined times. It can also be programmed to send signals to switch on or off selected luminaries at certain times during the day or in response to the presence of people detected by the occupancy detectors (Society of Light and Lighting, 2002). *'Sensing the light intensity and angle of projection/solar radiation'* was considered as the second most 'suitable' intelligence indicator in both the general and ANP surveys.

As stated in literature, one of the most crucial considerations in DALI system design relates to its system energy consumption (Society of Light and Lighting, 2002). The survey results supported that an ‘intelligent’ DALI system should be capable of enhancing energy efficiency and adjusting the electric lighting needed by sensing the light intensity and solar radiation. If daylight is sufficient, lights would be switched off, and, when needed, switched on again.

Comparing the Relative Importance of Indicators in the AHP and ANP methods

In this study, a combination of the AHP and ANP methods was used for the development of system intelligence analytical models. The AHP determined the relative importance of the intelligence attributes and indicators in the model, while the ANP super-matrix incorporated the influence of interdependent relationships between the intelligence attributes of each intelligent building control system and the building’s operational benefits. This implies that the prioritisation (either an increase or decrease of the weighting) of the intelligence indicators would possibly be different with (i.e., ANP method) or without (i.e., AHP method) the consideration of the interdependent relationships between intelligence attributes and operational benefits of the intelligent building, which would possibly lead to an improvement or decline of final ranking of the indicators.

Contrasting the networked ANP with the hierarchical AHP model by applying both to the evaluation of the intelligence indicators, the resulting outcomes of the normalised relative weights of the intelligence indicators obtained from the ANP and AHP models are varied. Table 7.7 compares and distinguishes the relative weightings and priorities of the individual indicators obtained from the ANP and the AHP. Two remarkable differences appeared in the intelligence indicators of AFA and DALI systems. In AFA, *'run continually with minimal human supervision'* improved from being the fourth most 'suitable' by using the AHP methods (without considering the interdependent relationship) to the most 'suitable' indicator by using the ANP approach (with interdependent relationships taken into consideration). Similarly, the DALI indicator *'pre-programmed responses and control'* improved from being the third most 'suitable' under the AHP to the most 'suitable' under the ANP. The remaining intelligence indicators in the seven intelligent building systems had different weights under the methods of the ANP and the AHP, but their overall ranking were not varied dramatically.

Further comparison of the relative weightings of indicators obtained from the AHP and the ANP indicates that some of the indicators under the same intelligence attribute groups became more dominant when the interdependent relationships with a building's operational benefits were taken into consideration (for example, '*autonomy (AUT)*' and *'bio-inspired behaviour (BIB)'* of IBMS). This implies that both AUT and BIB are more significant intelligence attributes after experts examined and investigated the interrelationships with each operational benefit. This difference implied that the interdependent relationships influenced and altered the original hierarchical ratings by the experts. The network-analysis approach allows a more comprehensive consideration of the system intelligence as it not only tries to deliberate on the intelligent properties, but also takes the operational benefits brought by the intelligent system into account. The results of the survey confirm that a building's operational benefits exert a considerable degree of influence on the importance of the intelligence indicators of the intelligent building systems *(The hypothesis H4 is supported).*

7.6 CHAPTER SUMMARY

This chapter presented the development of suitable intelligence indicators and developed analytical decision models for evaluating the system intelligence of seven key building control systems in the intelligent building. A general survey was first undertaken to elicit 'suitable' intelligence indicators for use in system intelligence measurement in different building control systems. The survey results found that 'autonomy' was not judged as a key intelligence attribute in reflecting the degree of system intelligence of the ITS and DALI systems *(H3 is not fully supported).* The chapter then put forward the use of the ANP together with the AHP for the development of an analytical model for system intelligence evaluation. Data was collected from nine intelligent building experts in the property development and building services sectors. The findings obtained from the ANP (with the consideration of interdependent relationships) were discussed and compared with the results obtained by the AHP approach (without the consideration of interdependent relationships) based on the same set of data obtained. The survey analysis illustrated that a building's operational benefits exert a considerable degree of influence on the importance of the intelligence indicators *(H4 is supported).* In the next chapter, the practicality of the system intelligence models will be examined. The models will also be validated through the judgements of a group of independent intelligent building experts.

Table 7.7: Comparison of the Relative Importance of Individual Intelligence Indicators from the AHP and the ANP

Indicators	Weight (Ranking) of ANP	Weight (Ranking) of AHP
Integrated Building Management System (IBMS)		
AUT		
AL	0.1130 (2)*	0.0977 (2)
SD	0.1143 (1)*	0.0988 (1)
YT	0.1015 (3)*	0.0878 (4)
CCD		
ALMS	0.0427 (11)	0.0496 (10)*
RCI	0.0258 (15)	0.0300 (15)*
ACML	0.0334 (14)	0.0388 (13)*
AES	0.0604 (8)	0.0702 (8)*
ML	0.0520 (9)	0.0604 (9)*
MHVAC	0.0623 (7)	0.0724 (7)*
MMI		
RG	0.0243 (16)	0.0260 (16)*
APOAF	0.0339 (13)	0.0364 (14)*
SOS	0.0383 (12)	0.0411 (12)*
GR	0.0444 (10)	0.0476 (11)*
RC	0.0706 (6)	0.0757 (6)*
BIB		
AOF	0.0854 (5)*	0.0780 (5)
PAC	0.0979 (4)*	0.0895 (3)
Telecom and Data System (ITS)		
CCD		
IMS	0.1980 (3)*	0.1927 (3)
TCCD	0.3063 (2)*	0.2981 (2)
MMI		
FHTP	0.3177 (1)	0.3263 (1)*
SLTC	0.1781 (4)	0.1830 (4)*
Addressable Fire Detection & Alarm System		
AUT		
ADA	0.1764 (2)	0.2339 (1)*
SDF	0.1264 (4)	0.1676 (3)*
STS	0.1462 (3)	0.1939 (2)*
CCD		
ICSD	0.0883 (5)*	0.0658 (5)
INTF	0.0373 (9)*	0.0278 (9)
INTSS	0.0279 (10)*	0.0208 (10)
INTHVAC	0.0588 (6)*	0.0438 (6)
INTLS	0.0448 (7)*	0.0334 (7)
INTLG	0.0439 (8)*	0.0327 (8)
MMI		
RC	0.2501 (1)*	0.1802 (4)
HVAC Control System		
AUT		
AL	0.0306 (11)	0.0358(11)*
ITS	0.0825 (6)	0.0968 (4)*
ETS	0.0647 (8)	0.0759 (5)*
AFD	0.0498 (9)	0.0585 (6)*
HVAC Control System (cont.)		
AUT		
SD	0.0462 (10)	0.0542 (9)*
CCD		
OCM	0.1343 (3)	0.1435 (3)*
INTF	0.1393 (2)	0.1498 (2)*
MMI		
DAT	0.0774 (7)*	0.0498 (10)
PPR	0.0892 (4)*	0.0575 (7)
GR	0.0847 (5)*	0.0546 (8)
BIB		
UNVC	0.2012 (1)	0.2244 (1)*
Digital Addressable Lighting Control System (DALI)		
CCD		
PD	0.0895 (7)*	0.0852 (7)
CIL	0.1309 (5)*	0.1247 (5)
INTF	0.1338 (4)*	0.1274 (4)
MMI		
DAT	0.1153 (6)*	0.0933 (6)
PPSC	0.2063 (1)*	0.1670 (3)
BIB		
SLI	0.1771 (2)	0.2198 (1)*
AUTLS	0.1471 (3)	0.1825 (2)*
Security Monitoring and Access Control System (SEC)		
AUT		
SP	0.3855 (1)	0.5057 (1)*
CCD		
DP	0.0520 (7)*	0.0385 (7)
	0.1034 (4)*	0.0766 (5)
INTSY	0.0513 (8)*	0.0380 (8)
INTF	0.0614 (6)*	0.0455 (6)
MMI		
RC	0.1200 (3)*	0.1024 (3)
DAT	0.1014 (5)*	0.0866 (4)
PSSU	0.1250 (2)*	0.1067 (2)
Smart & Energy Efficient Lift System (LS)		
AUT		
AE	0.2602 (1)	0.2791 (1)*
ONDL	0.1482 (2)	0.1590 (2)*
CCD		
ACPTP	0.1236 (4)	0.1342 (3)*
ONIA	0.0681 (7)	0.0740 (7)*
INTF	0.0563 (8)	0.0612 (8)*
MMI		
DAT	0.1347 (3)*	0.0943 (5)
PSSE	0.1107 (5)*	0.0835 (6)
HED	0.0981 (6)*	0.1148 (4)

Note: * represents a higher weighting score between the ANP and AHP approaches

CHAPTER 8

APPLICATION AND VALIDATION OF MODELS

“Model validation is the process of ensuring that the mathematical model adequately captures the relationships between the model inputs and outputs. Modelling the past often is a useful aid to model validation, even though the purpose of the model is to predict future behaviour. Managers should pay a key role in model validation because they have the best understanding of how the real process works. A useful model is one that supports the manager’s understanding of the decision, not one that contradicts this understanding.”

(Bell, 1999: 22)

8.1 INTRODUCTION

In Chapter 6 and 7, the general conceptual selection models and system intelligence analytic models for the seven key intelligent building control systems were established and tested. However, as Cusack (1984) points out, to apply the developed models with confidence, the models must be tested and validated. Thus, this chapter is organised to examine the effectiveness of the models which were developed in Chapter 6 and 7 respectively.

Prior to the model validation, the developed conceptual models are first transformed to the practical models by adding two components: developing the rating scores and assessment methods for each of the intelligence indicators, and establishing an aggregation formula for overall scores for each candidate building control system. Examples of real-life practical building control systems are employed to illustrate the models' applicability. The models are validated through the comparison between the expert's preferences and the model's ranking of the proposed building system options. Statistical analysis is further employed to test the correlation between the experts' and models' scores.

8.2 RESEARCH PART ONE – SELECTION EVALUATION MODELS

Prior to applying and validating the selection evaluation models developed in Chapter 6, two process steps were initiated to move the developed models from experimental and theoretical framework formulations to being capable of practical application. These two steps include the establishment of the ratings of each of the indicators, and the aggregation of the weighted ratings.

8.2.1 Construction of Practical Models

Rating the Intelligent Building Control Systems on CSC

One of the important steps in transforming the conceptual selection model to a practical model is to evaluate and select candidate intelligent building control systems according to their CSC. To rate a building control system, assessment methods need to be established for rating each CSC. The appropriate rating methods were first developed from a bibliographic review, including industry guidebooks (e.g., CIBSE, 2000a, 2000b, 2003 and 2004) and previous scoring approaches for intelligent buildings (e.g., AIIB, 2001 and 2004). The adequacy of the proposed evaluative methods and scales were then verified and judged by a few appropriate experts, all experienced members of the industry, who were found from referrals by the experts in the AHP survey in Research Part One. The verification of the rating systems and scales by experts has been undertaken in many previous studies (Ling *et al*., 2003; Chan, 1995; Nkado, 1992; Skitmore and Marsden, 1988), since experts are able to provide suitable advice on the ratings.

With respect to the rating scales, Ling (1998) argues that the percentile score (i.e., scale of 0 to 100) might be less appropriate for the rating of attributes for the model as the boarder scale leads to problems in deciding the rating score. Ling also maintains that the normalised scale (i.e., scale of 0 to 1) is too narrow, and raters may have difficulty rating attributes in decimals. In this study, a rating scale of 0 to 5 is used as the standard summated rating score for all rating methods for the building control systems. For example, 0 represents the ‘extremely poor’ or the lowest ability level of the proposed option of building control system to fulfil a particular CSC, and 5 represents the ‘excellent’ or the highest ability level.

After development of the proposed rating scales and scoring methods, they were checked and revised according to experts’ suggestions. Finally, experts generally expressed their comfort over the quantitative CSC scoring system. A total of 27 assessment methods were established for rating the CSC for the seven building control systems in this study. All assessment methods are designed with a range of rating scores from 0 to 5, except for Method A4 where only scores of either 5 marks (compliance with code) or 0 marks (non-compliance with the code) are assigned, depending on whether the candidate building control system is in compliance with the regulation or code. The assessment methods and their rating scores are delineated in Appendix C1, p.386.

Aggregation of Weights and Ratings

The second step for the construction of practical selection evaluation models involves the aggregation of the scores of all relevant CSC to produce one overall score for each of the proposed system options (Ling *et al*., 2003). To calculate the aggregate score, the important weights (*w*) of each relevant CSC, which were developed in the AHP survey in the Chapter 6, are multiplied by the ratings (*r*) for the corresponding CSC that the system options obtained from the raters, to derive the weighted scores. All the weighted ratings of the CSC of an individual building control system are summed up to produce an aggregate selection score (Score_{SE}). Table 8.1 delineates the assessment methods and illustrates the aggregation of weights and ratings (i.e., in the third and fourth columns) for each CSC. The evaluation is conducted by assigning a rating of the system option (in the fourth column), from 0 to 5, based on its actual ability in fulfilling the particular requirements of the CSC. For each CSC, the rating is multiplied by the weights to obtain a weighted score (i.e., the fifth column of Table 8.1). Consequently, the mathematical expression for the aggregate selection score (Score_{SE}) of a building control system is given in the following equation:

$$Score_{SE} = (\sum w_{CSC_1} \times r_{CSC_1}) + (\sum w_{CSC_2} \times r_{CSC_2}) + (\sum w_{CSC_3} \times r_{CSC_3})... + (\sum w_{CSC_n} \times r_{CSC_n})$$

(Eq.8.1)

where, w_{CSC1}, w_{CSC2}, $w_{\text{CSC3},...}w_{\text{CSCn}}$ represent the weight of the CSC; and, r_{CSC1}, r_{CSC2}, $r_{\text{CSC3},...}r_{\text{CSCn}}$ represent the rating given to the CSC of a candidate building control system.

Table 8.1: Assessment Methods of Different CSC of the Building Control Systems

Intelligent Building Control Systems, CSC	**Assessment Method(s)** $^{\Delta}$	**Indicators' weight (GP) from AHP (*w*)**	**Options' rating by experts (*r*)**	**Score (*w*r*)**
Integrated Building Management System (IBMS)				
Reliability and stability	A2	0.3510	$r_{IBMSSC1}$	0.351* $r_{IBMSSC1}$
Operation and maintenance costs	A1	0.3455	$r_{IBMSSC2}$	0.345* $r_{IBMSSC2}$
Integrated and interface with service control systems	A3	0.1345	$r_{IBMSSC3}$	0.134* $r_{IBMSSC3}$
Efficiency and accuracy	A1	0.1690	$r_{IBMSSC4}$	0.169* $r_{IBMSSC4}$
Telecom & Data System (ITS)				
Reliability and stability	A2	0.2090	r_{ITSSC1}	0.209* r_{ITSSC1}
Further upgrade of system	A1	0.1270	r_{ITSSC2}	0.127* r_{ITSSC1}
Operation and maintenance costs	A1	0.4240	r_{ITSSC3}	0.424* r_{ITSSC1}
Service life	A1	0.1230	r_{ITSSC4}	0.123* r_{ITSSC1}
Transmission rate of data	A1	0.1170	r_{ITSSC5}	0.117* r_{ITSSC1}
Addressable Fire Detection and Alarm (AFA) System				
Compliance with the code of minimum fire service installations or equipment	A4	0.3050	r_{AFASC1}	0.305* r_{AFASC1}
Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	A4	0.2400	r_{AFASC2}	0.240* r_{AFASC2}
Operation and maintenance costs	A1	0.2380	r_{AFASC3}	0.238* r_{AFASC3}
System response time and survivability	A5	0.0550	r_{AFASC4}	0.055* r_{AFASC4}
Further upgrade of system	A1	0.0370	r_{AFASC5}	0.037* r_{AFASC5}
Automatic detection of fire, gas and smoke	A1	0.0700	r_{AFASC6}	0.070* r_{AFASC6}
Service life	A1	0.0550	r_{AFASC7}	0.055* r_{AFASC7}
HVAC Control System				
Service life	A1	0.0540	$r_{HVACSC1}$	0.054* $r_{HVACSC1}$
Control of predict mean vote (PMV)	A6	0.0760	$r_{HVACSC2}$	0.076* $r_{HVACSC2}$
Operation and maintenance costs	A1	0.1120	$r_{HVACSC3}$	0.112* $r_{HVACSC3}$
Control of indoor air quality (IQA)	A7	0.0990	$r_{HVACSC4}$	0.099* $r_{HVACSC4}$
Total energy consumption	A8	0.1980	$r_{HVACSC5}$	0.198* $r_{HVACSC5}$
Integrated by IBMS	A9	0.0570	$r_{HVACSC6}$	0.057* $r_{HVACSC6}$
System reliability and stability	A10	0.1230	$r_{HVACSC7}$	0.123* $r_{HVACSC7}$
Minimisation of plant noise	A11	0.0860	$r_{HVACSC8}$	0.086* $r_{HVACSC8}$
Interface with other building control systems	A12	0.0440	$r_{HVACSC9}$	0.044* $r_{HVACSC9}$
Initial costs	A1	0.0750	$r_{HVACSC10}$	0.075* $r_{HVACSC10}$
Adequate fresh air changes	A13	0.0760	$r_{HVACSC11}$	0.076* $r_{HVACSC11}$

Note: $^{\Delta}$ Details of different assessment methods (Method A1 to A27) for the CSC are summarised in Appendix C1, p.386

Table 8.1: Assessment Methods of Different CSC of the Building Control Systems (cont.)

Intelligent Building Control Systems, CSC	**Assessment Method(s) Δ**	**Indicators' weight (GP) from AHP (*w*)**	**Options' rating by experts (*r*)**	**Score (*w*r*)**
Digital Addressable Lighting Control System (DALI)				
Operation and maintenance costs	A1	0.2670	$r_{DALISC1}$	0.267* $r_{DALISC1}$
Interface with other building control systems	A12	0.0300	$r_{DALISC2}$	0.030* $r_{DALISC2}$
Integrated by IBMS	A9	0.0340	$r_{DALISC3}$	0.034* $r_{DALISC3}$
Permanent artificial lighting average power density	A24	0.0410	$r_{DALISC4}$	0.041* $r_{DALISC4}$
Further upgrade of system	A1	0.0360	$r_{DALISC5}$	0.036* $r_{DALISC5}$
Service life	A1	0.0470	$r_{DALISC6}$	0.047* $r_{DALISC6}$
Ease of control	A25	0.3120	$r_{DALISC7}$	0.312* $r_{DALISC7}$
Total energy consumption	A26	0.1910	$r_{DALISC8}$	0.191* $r_{DALISC8}$
Automatic control and adjustment of lux level	A27	0.0420	$r_{DALISC9}$	0.042* $r_{DALISC9}$
Security Monitoring and Access System (SEC)				
Time needed for public announcement of disasters	A5	0.0920	r_{SECSC1}	0.092* r_{SECSC1}
Operation and maintenance costs	A1	0.1960	r_{SECSC2}	0.196* r_{SECSC2}
Time needed to report a disastrous event to the building management	A5	0.1130	r_{SECSC3}	0.113* r_{SECSC3}
Interface with other building control systems	A12	0.0910	r_{SECSC4}	0.091* r_{SECSC4}
Integrated by IBMS	A9	0.0970	r_{SECSC5}	0.097* r_{SECSC5}
Service life	A1	0.0860	r_{SECSC6}	0.086* r_{SECSC6}
Further upgrade of system	A1	0.0860	r_{SECSC7}	0.086* r_{SECSC7}
Initial costs	A1	0.1400	r_{SECSC8}	0.140* r_{SECSC8}
Time for total egress	A14	0.0990	r_{SECSC9}	0.099* r_{SECSC9}
Smart and Energy Efficient Lift System (LS)				
Mean time between failures	A15	0.0460	r_{LSSC1}	0.046* r_{LSSC1}
Service life	A1	0.0230	r_{LSSC2}	0.023* r_{LSSC2}
Waiting time	A16	0.0530	r_{LSSC3}	0.053* r_{LSSC3}
Maximum interval time	A17	0.3020	r_{LSSC4}	0.302* r_{LSSC4}
Total energy consumption	A18	0.1490	r_{LSSC5}	0.149* r_{LSSC5}
Acceleration and deceleration control	A19	0.0450	r_{LSSC6}	0.045* r_{LSSC6}
Journey time	A20	0.0400	r_{LSSC7}	0.040* r_{LSSC7}
Integrated by IBMS	A9	0.0210	r_{LSSC8}	0.021* r_{LSSC8}
Interface with other building control systems	A12	0.0180	r_{LSSC9}	0.018* r_{LSSC9}
Operation and maintenance costs	A1	0.1245	r_{LSSC10}	0.125* r_{LSSC10}
Minimisation of in-car noise	A21	0.0490	r_{LSSC11}	0.049* r_{LSSC11}
Adequate fresh air changes	A22	0.0515	r_{LSSC12}	0.052* r_{LSSC12}
Minimisation of in-car vibration	A23	0.0500	r_{LSSC13}	0.050* r_{LSSC13}
Automatic and remote control	A1	0.0280	r_{LSSC14}	0.028* r_{LSSC14}

Note: Δ Details of different assessment methods (Method A1 to A27) for the CSC are summarised in Appendix C1,p.386

Application of the Selection Evaluation Models

This study contains seven system selection evaluation models for seven different key building control systems. A full explanation and illustration of the applicability of all models may need input efforts similar to those efforts for the development and examination of the building system selection evaluation models in the preceding chapter (Chapter 6). It would be interminable for the focus of this thesis to try to illustrate and present the applicability of all seven developed models. For the sake of brevity, it focuses on demonstrating the applicability of the selection evaluation model of the HVAC control system.

In this study, two real HVAC control system candidates were used for demonstration. These two examples were supplied and assessed by a senior executive of a local M&E engineering consultancy. Prior to the employment for model application, the fulfilment of the CSC by the two system options needs to be checked. Those candidates which fail to meet all their relevant CSC should not be evaluated further, and those which meet the listed CSC should be allowed to be evaluated based on the model. In this study, the brands of the HVAC control system and their manufacturers were not disclosed in order to secure the confidentiality of the information providers and to prevent the intention of any guesses. Instead, fictitious names (i.e. System A and System B) were assigned. In brief, System A is manufactured by a U.S building control system manufacturer, and it has a special feature of monitoring, measuring and managing all HVAC applications from one centralised location. System B is produced by a European building control system manufacturer, and it shares similar features and functions with System A.

A score from 0 to 5 was assigned to each intelligence indicator based on the assessment methods as shown in Table 8.1. For instance, the expert judged that System A (score '4') had a more stable and reliable system performance than System B (score '3'). Finally, the systems' alternative ratings are input into the selection evaluation model, and the aggregate scores are calculated. This case study suggested that System A (4.0700) has a higher aggregate selection score than System B (3.7540), which in turn suggested that System A should be selected. Table 8.2 summarises the judgements of the expert on the CSC scores of both HVAC control system alternatives.

Table 8.2: Illustrative Computations for the Aggregate Selection Scores of Two HVAC Control System Candidates

CSC	**Selection Factors**	**Indicator's weight**	**HVAC System A**		**HVAC System B**	
		(AHP)	Score*	Weight	Score*	Weight
Service life	Work Efficiency	0.0540	4	0.2160	4	0.2160
Control of predict mean vote (PMV)	User Comfort	0.0760	4	0.3040	4	0.3040
Operation and maintenance costs	Cost Effectiveness	0.1120	4	0.4480	3	0.3360
Control of indoor air quality (IQA)	User Comfort	0.0990	5	0.4950	4	0.3960
Total energy consumption	Environmental Related	0.1980	4	0.7920	4	0.7920
Integrated by IBMS	Work Efficiency	0.0570	5	0.2850	4	0.2280
System reliability and stability	Work Efficiency	0.1230	4	0.4920	3	0.3690
Minimisation of plant noise	User Comfort	0.0860	3	0.2580	3	0.2580
Interface with other building control systems	Work Efficiency	0.0440	4	0.1760	4	0.1760
Initial costs	Cost Effectiveness	0.0750	4	0.3000	5	0.3750
Adequate fresh air changes	User Comfort	0.0760	4	0.3040	4	0.3040
			Weighted Mean (Score_{SE}) =	**4.0700**		**3.7540**

Note: CSC weights were normalised. The indicators were rated based on a scale of 0-5 based on the ability in fulfilling the requirement of each CSC. Maximum score = 5.0000.
* The building system options were assessed by a senior executive of M&E engineering consultancy in Hong Kong

The aggregate selection score of two proposed HVAC control systems can also be graphically presented in form of radar diagram plots (Figure 8.1). The grey line ('maximum') in the radar diagram represents the maximum score of each of the CSC of the HVAC control system. The black solid line and dotted line represent the aggregate selection scores for System A and B respectively. The same approach could also be applied to the computations of the aggregate selection scores **(Score$_{SE}$**) for other building control systems.

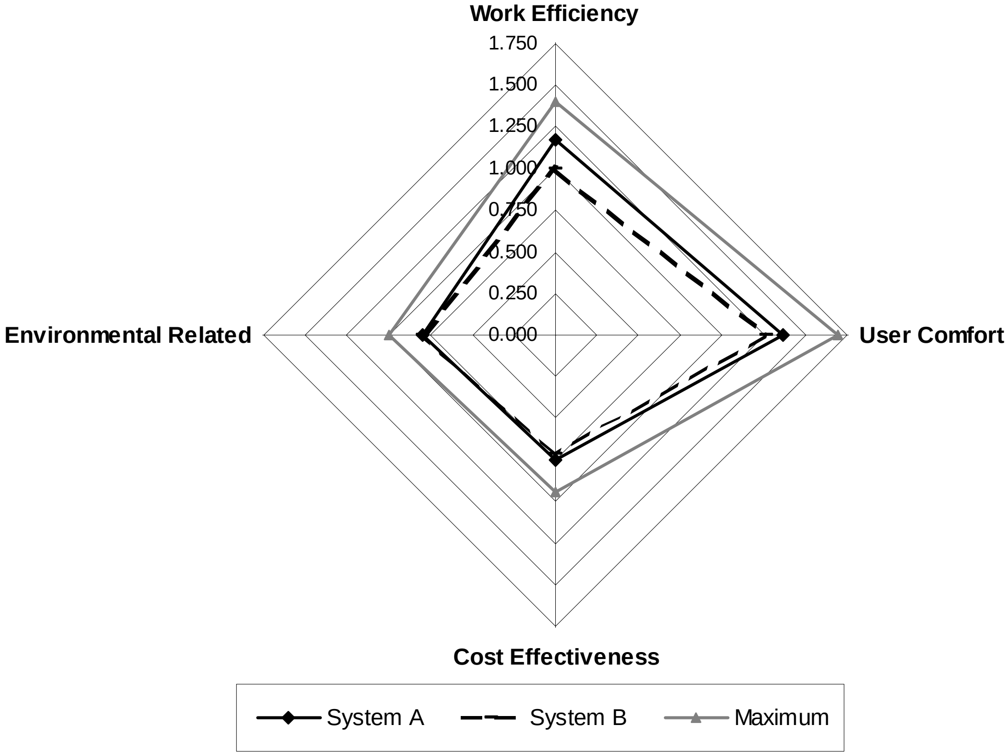


Figure 8.1: Radar Diagram Plot of the Aggregate Selection Scores (Score$_{SE}$) of the Proposed HVAC Control Systems

8.2.2 Model Validation

Model validation is undertaken to examine the models' robustness, and to ascertain the effectiveness of selection evaluation models. In this study, the validities of the models were tested using a number of experts who have extensive intelligent building development and design experience. In order to avoid any bias on their judgement, it was assured that the experts invited for the model validation process did not participate in either the general or AHP surveys in Chapter 6. The experts selected for this validation exercise were highly experienced members of the industry who were recommended by the experts in the AHP survey. A total of eight experts were short-listed and finally five of them (MVEX1 to MVEX5) expressed their willingness to participate in the validation process and to be interviewed. Three respondents were not willing to participate in this validation exercise because of their limited experience in the decision making and selection of the intelligent building control systems or because of a lack of time.

The validation of models with small expert samples has been undertaken and reported in previous research. For example, in their empirical study, Ling *et al.* (2003) invited six building contractors with extensive design and building project experience to validate their Consultant Selection Model. In other research studies, for example, Bracket *et al.* (2007a and 2007b) had eight experts validate a model of assessing the enrichment value of enrichment materials for pigs.

As discussed in the Chapter 5, two consecutive approaches are employed for validating the models. The models' relative ranking of each pair of the building control system alternatives was first compared with the experts' order of preference. Then, scores of system alternatives given by the model and judged by the experts were checked for their similarities by correlation analysis.

Comparison between Experts' Preference and Models' Ranking

The model validation first required each of the five experts to supply and nominate two candidates for each of the seven building control systems (i.e., 14 alternatives should be nominated in total) that they had come across and were most familiar with in their past experience of intelligent building design and development. A written questionnaire (the fifth questionnaire as shown in Appendix A5, p.354) was used to elicit the experts' judgement. Structured interviews were arranged with each of the experts to brief them of the models developed for the study and to guide them for the completion of the model validation questionnaire. In order to ensure sufficient time for the expert to consider and select the right building system candidates for validation exercises, each participated expert was given about one to two weeks for the data preparation prior to the survey interview day. Each pair of system alternatives was then compared between the experts' preference and the model's ranking on the day of the survey interview. To protect confidentiality and to avoid any guesses of the building system brands, the names and details of the products were not shown in this thesis.

In this survey, each expert was invited to indicate a preference for each pair of building system options they supplied using the questionnaire survey. The model validation questionnaire was designed comprising three parts. Part one sought respondents' details to obtain their profile. This included a description of the building system alternatives they used for the survey. Part two of the questionnaire invited the experts to assign an overall score from 0 to 10 (i.e., 0 to 4 represent ‘poor’; 5 represents ‘average’; 6 and 7 represent ‘good’; 8 represents ‘very good’; and, 9 and 10 represent ‘excellent’) for each alternative. A standard 10-point rating scale was adopted (Ling *et al.*, 2003) to allow the experts to assign each alternative a global score, based on its overall ability and performance. Then, in Part three of the questionnaire, they were invited to evaluate the same alternatives by using the Selection Models as described in Table 8.1. In this part, experts were asked to give a score for the level of ability or performance of each building system alternative on a scale between 0 and 5 based on the assessment methods A1 to A27 as delineated in Appendix C1 (p.386). Finally, a total of 31 cases, comprising 30 different brands of building control systems were nominated and compared by the experts. The building control system alternatives in the same manufacturers, especially in the IBMS and LS, were repeatedly nominated by different experts, implied the popularity and reputation of these products in the building product market.

Table 8.3 summarises the experts’ global selection preference scores and the models’ aggregate selection scores of each pair of building control system alternatives. The results indicate that majority of the models’ aggregate scores order in the same way as the experts’ preference in all but four of the 31 cases (87%). In the four exceptional cases, equal global scores were assigned on both options by the experts as shown in Table 8.3.

Table 8.3: Experts' Global Scores and Models' Aggregate Scores for the Intelligent Building Control System Options

Expert reference	Proposed system options	Models' aggregate scores (Ranking of scores)	Experts' global score (Ranking of scores)
MVEX1	MVEX1-IBMS1	4.3510 (1)	7 (1)
	MVEX1-IBMS2	3.8655 (2)	6 (2)
	MVEX1-ITS1	3.6680 (2)	6 (2)
	MVEX1-ITS2	3.9940 (1)	7 (1)
	MVEX1-AFA1	4.1820 (2)	6 (2)
	MVEX1-AFA2	4.3440 (1)	8 (1)
	MVEX1-HVAC1	4.0940 (1)	8 (1)
	MVEX1-HVAC2	3.8010 (2)	7 (2)
	MVEX1-DALI1	3.8810 (1)	8 (1)
	MVEX1-DALI2	3.3670 (2)	6 (2)
	MVEX1-SEC1	3.5720 (2)	6 (2)
	MVEX1-SEC2	3.7740 (1)	7 (1)
	MVEX1-LS1	3.9623 (1)	8 (1)
	MVEX1-LS2	3.4529 (2)	6 (2)
MVEX2	MVEX2-IBMS1	4.3510 (2)	8 *
	MVEX2-IBMS2	4.5200 (1)	8 *
	MVEX2-ITS1	3.7910 (2)	6 (2)
	MVEX1-ITS2	3.9080 (1)	8 (1)
	MVEX2-AFA1	4.3500 (2)	6 (2)
	MVEX2-AFA2	4.5450 (1)	9 (1)
	MVEX2-HVAC1	3.6960 (2)	7 (2)
	MVEX2-HVAC2	3.8070 (1)	8 (1)
	MVEX2-SEC1	3.7690 (1)	7 (1)
	MVEX2-SEC2	3.4780 (2)	5 (2)
	MVEX2-LS1	3.8505 (2)	7 (2)
	MVEX2-LS2	4.0513 (1)	8 (1)
MVEX3	MVEX3-IBMS1	4.1690 (1)	8 (1)
	MVEX3-IBMS2	4.0000 (2)	7 (2)
	MVEX3-AFA1	4.4900 (1)	8 *
	MVEX3-AFA2	4.4200 (2)	8 *
	MVEX3-HVAC1	3.3860 (2)	6 (2)
	MVEX3-HVAC2	3.9480 (1)	8 (1)
	MVEX3-DALI1	3.7250 (2)	7 (2)
	MVEX3-DALI2	4.0640 (1)	8 (1)
	MVEX3-SEC1	4.0920 (1)	8 (1)
	MVEX3-SEC2	3.7180 (2)	7 (2)
	MVEX3-LS1	4.1183 (1)	8 (1)
	MVEX3-LS2	4.0208 (2)	8 (2)
MVEX4	MVEX4-IBMS1	4.0000(1)	7 (1)
	MVEX4-IBMS2	3.6545 (2)	6 (2)
	MVEX4-ITS1	4.0000 (1)	8 (1)
	MVEX4-ITS2	3.7500 (2)	6 (2)
	MVEX4-AFA1	4.5300 (1)	8 (1)
	MVEX4-AFA2	4.4200 (2)	7 (2)
	MVEX4-HVAC1	4.0000 (1)	8 (1)
	MVEX4-HVAC2	3.5030 (2)	7 (2)
	MVEX4-DALI1	3.6440 (2)	6 (2)
	MVEX4-DALI2	3.7330 (1)	7 (1)
	MVEX4-SEC1	3.2800 (1)	7 (1)
	MVEX4-SEC2	3.1110 (2)	5 (2)
	MVEX4-LS1	3.5733 (2)	7 (2)
	MVEX4-LS2	3.9268 (1)	8 (1)
	MVEX5-LS2	3.6473 (2)	7 (2)

Table 8.3: Experts' Global Scores and Models' Aggregate Scores for the Intelligent Building Control System Options (cont.)

Expert reference	Proposed system options	Models' aggregate scores (Ranking of scores)	Experts' global score (Ranking of scores)
MVEX5	MVEX5-IBMS1	4.1690 (2)	7 (2)
	MVEX5-IBMS2	4.3035 (1)	9 (1)
	MVEX5-AFA1	4.5450 (1)	8 (1)
	MVEX5-AFA2	4.2520 (2)	7 (2)
	MVEX5-HVAC1	4.1230 (2)	8 *
	MVEX5-HVAC2	4.3970 (1)	8 *
	MVEX5-SEC1	4.2050 (2)	8 *
	MVEX5-SEC2	4.2910 (1)	8 *
	MVEX5-LS1	3.7648 (1)	8 (1)
	MVEX5-LS2	3.6473 (2)	7 (2)

Note: * Same score was assigned by the expert on the overall ability or performance of the building control systems

Correlation Analysis between Scores of Experts and Models

Having compared and contrasted the models' aggregate scores with the preference of the experts, further model validation testing is required to check whether the models' aggregate selection scores (column 3 of Table 8.3) were correlated with the expert global selection scores (column 4 of Table 8.3). The Pearson product-moment correlation coefficient (*r*) and the Spearman rank order correlation coefficient (*rho*) are employed to ascertain the strength and direction of the relationship between the global scores by the experts, and the aggregate scores of the selection model (de Vaus, 2002). The correlation analysis was conducted in the SPSS. Table 8.4 summarises the results of the Pearson correlation coefficient (*r*) and Spearman's *rho* between the models' aggregate scores and the experts' global scores for selection of each of the building control system options.

Table 8.4: Summary of Correlation Coefficient Results between the Experts' Global Selection Scores and Models' Aggregate Selection Scores of the Intelligent Building Control System Options

Options of Intelligent Building Control Systems	Correlation Coefficient	
	Pearson's *r*	Spearmen's *rho*
Integrated Building Management System (IBMS)	0.769*	0.751 $^{\Delta}$
Telecom and Data System (ITS)	0.821$^{\Delta}$	0.833 $^{\Delta}$
Addressable Fire Detection and Alarm System (AFA)	0.771*	0.750 $^{\Delta}$
Heating Ventilation Air-conditioning (HVAC) Control System	0.834*	0.874*
Digital Addressable Lighting Control System (DALI)	0.893 $^{\Delta}$	0.956*
Security Monitoring and Access Control System (SEC)	0.833*	0.871*
Smart and Energy Efficient Lift System (LS)	0.857*	0.811*

Note: * Correlation is significant at the 0.01 level (2-tailed);
$^{\Delta}$ Correlation is significant at the 0.05 level (2-tailed)

The analysis results indicate a moderate to high correlation between all experts' scores and the scores generated by the models. At the significance level of 0.01 or 0.05, the values of the Spearman's *rho* range from 0.751 to 0.956, while the values of the Pearson's *r* range from 0.769 to 0.893 for all building system categories in this study (Table 8.4). According to de Vaus (2002), correlations with absolute values that range from about 0.01 to 0.09 are referred as 'trivial'; 0.10 to 0.29 as 'low to moderate'; 0.30 to 0.49 as 'moderate to substantial'; 0.50 to 0.69 as 'substantial to very strong'; 0.70 to 0.89 as 'very strong' and 0.90 to 0.99 as 'near perfect'. This generally implies 'very strong' relationships between the experts' and models' selection scores.

8.3 RESEARCH PART TWO – SYSTEM INTELLIGENCE ANALYTIC MODELS

This section focuses on the application and validation of the system intelligence analytic models. A total of seven system intelligence analytical models for the seven key intelligent building control systems, which were based on the views of intelligent building experts and professionals in Hong Kong, were developed and refined along with the findings from the general and AHP-ANP surveys conducted in Chapter 7. This section is also organised to first demonstrate the applicability of the models with examples of real-life practical building control systems, followed by the experts' validation.

8.3.1 Model Construction

Methodology for System Intelligence Appraisal

Similar to the model construction in Research Part One, the first step for the transformation of the conceptual model to the applicable one was to identify and develop rating scales and assessment methods (Ling *et al*. 2003) for each of the intelligence indicators. The rating scale was designed to facilitate the evaluation of the degree of intelligence of the building control systems. The summated rating scales, which ranged from 0 to 5, were further adopted in this part of model construction. Similar to the model construction process for Selection Evaluation Models, the identification of the proposed assessment methods for the intelligence indicators was derived from a review of building services guidebooks and rating indices. The proposed assessment methods were then commented on and verified by two industry experts who participated in the ANP survey. Some minor refinements were made on the assessment methods according to their comments and suggestions. Finally, eight rating methods (i.e., Methods B1 to B8), all with a scale ranging from 0 to 5, were developed. Table 8.5 maps these assessment methods to different intelligence indicators. The details of intelligence indicator assessment methods are delineated in Appendix C2 (p.390).

Having developed the assessment methods and scoring systems for the model, the next process step required for performing system intelligence analysis was to aggregate the scores to produce one overall score for each building control systems. The score for each intelligence indicator is obtained by multiplying the weights (*w*) of each intelligence indicator (developed in Chapter 7) with the ratings (*r*) that each proposed building system obtained for the corresponding indicators. All individual scores of the intelligence indicators under the same building control system are then summed up to produce an aggregate system intelligence score. In this case, the mathematical expression for the aggregate system intelligence score, named System Intelligence Score (Score_{SI}), is given as follows:

$$Score_{SI} = (\sum w_{II1} \times r_{II1}) + (\sum w_{II2} \times r_{II2}) + (\sum w_{II3} \times r_{II3}) ... + (\sum w_{IIn} \times r_{IIn}) \quad \text{(Eq.8.2)}$$

where, w_{II1}, w_{II2}, $w_{II3...}w_{IIn}$ represent the weights of the intelligence indicators; and, r_{II1}, r_{II2}, $r_{II3...}r_{IIn}$ represent the rating given to the building control system option for the intelligence indicators.

This section demonstrates the computation of the System Intelligence Score (Score_{SI}) of the building control systems using the intelligence indicators encapsulated within the analytical models. The second part of research of this thesis also contains seven system intelligence models. A full explanation and illustration of the applicability of all models is cumbersome. Thus, only two real IBMS candidates were selected for demonstrating their assessment procedures and application. The brand names were all fictitious and the product information was undisclosed to prevent any commercial conflicts.

The systems were nominated and assessed by the same M&E engineering consultancy executive in section 8.2.1. The first IBMS alternative (i.e., System C) is developed by a European manufacturer and contains unique features of peer-to-peer operation with a flexible and remote alarm management system. The second IBMS alternative (i.e., System D) is produced by a US manufacturer with similar system features as System C. A score from 0 to 5 was assigned to each intelligence indicator based on assessment methods as stated in Table 8.5. Table 8.6 summarised the judgements of the expert on the intelligent performance of Systems C and D. In this example, although the aggregate system intelligence score (Score_{SI}) of man-machine interaction (MMI) was higher in System D, System C had higher aggregate scores in another two intelligence attributes: autonomy (AUT) and controllability for complicated dynamics (CCD). In accordance with the MCDM, the system alternative with the highest aggregate system intelligence score would be the option with the highest level of 'intelligence'. Finally, the demonstration results indicated that System C (3.8351) had a higher aggregate system intelligence score than System D (3.6333). The results can also be graphically depicted and illustrated in the form of radar diagram plots as in Figure 8.2. The same methodology could be applied to the computations of the aggregate system intelligence score for other building control systems.

Table 8.5: Rating Methods of Different Intelligence Indicators

Intelligent Building Control Systems, *Intelligence attributes,* and indicators	**Assessment method(s)▲**	**Indicators' weight from ANP (*w*)**	**Options' rating by experts (*r*)**	**Score (*w*r*)**
Integrated Building Management System (IBMS)				
AUT				
Adaptive limiting control algorithm (AL)	B1	0.0916	r_{IBMSA1}	$0.0916{*}\ r_{IBMSA1}$
Self-diagnostic of operation deviations (SD)	B1	0.0926	r_{IBMSA2}	$0.0926{*}\ r_{IBMSA2}$
Year-round time schedule operation (YT)	B1	0.0822	r_{IBMSA3}	$0.0822{*}r_{IBMSA3}$
CCD				
Ability to link multiple standalone building control systems from a variety of manufacturers (ALMS)	B1,B2	0.0464	r_{IBMSC1}	$0.0464{*}r_{IBMSC1}$
Remote control via internet (RCI)	B1	0.0280	r_{IBMSC2}	$0.0280{*}r_{IBMSC2}$
Ability to connect multiple locations (ACML)	B1	0.0363	r_{IBMSC3}	$0.0363{*}r_{IBMSC3}$
Alarms and events statistics (AES)	B1	0.0657	r_{IBMSC4}	$0.0657{*}r_{IBMSC4}$
Control/ monitor lighting time schedule/zoning (ML)	B1,B2	0.0565	r_{IBMSC5}	$0.0565{*}r_{IBMSC5}$
Control and monitor HVAC equipments (MHVAC)	B1,B2	0.0677	r_{IBMSC6}	$0.0677{*}r_{IBMSC6}$
MMI				
Reports generation and output of statistical and trend profiling of controls and operations (RG)	B1	0.0276	r_{IBMSM1}	$0.0276{*}r_{IBMSM1}$
Ability to provide operational & analytical functions (APOAF)	B1	0.0386	r_{IBMSM2}	$0.0386{*}r_{IBMSM2}$
Single operation system/ platform for multiple location supervision (SOS)	B1	0.0436	r_{IBMSM3}	$0.0436{*}r_{IBMSM3}$
Graphical representation and real-time interactive operation action icons (GR)	B1	0.0505	r_{IBMSM4}	$0.0505{*}r_{IBMSM4}$
Run continually with minimal human supervision (RC)	B1,B3	0.0803	r_{IBMSM5}	$0.0803{*}r_{IBMSM5}$
BIB				
Analyse operation function parameters (AOF)	B1	0.0896	r_{IBMSB1}	$0.0896{*}r_{IBMSB1}$
Provide adaptive control algorithms based on seasonal changes (PAC)	B1	0.1028	r_{IBMSB2}	$0.1028{*}r_{IBMSB2}$
Telecom & Data System (ITS)				
CCD				
Integrate multiple network or service providers (IMS)	B1	0.1773	r_{ITSC1}	$0.1773{*}r_{ITSC1}$
Transmission capacity control & diversion (TCCD)	B1	0.2743	r_{ITSC2}	$0.2743{*}r_{ITSC2}$
MMI				
Fixed hub/terminal port installed (FHTP)	B1	0.3514	r_{ITSM1}	$0.3514{*}r_{ITSM1}$
System life & turn-round complexity (SLTC)	B1	0.1970	r_{ITSM2}	$0.1970{*}r_{ITSM2}$
Addressable Fire Detection & Alarm (AFA) System				
AUT				
Alarm deployment algorithm within the building and notification to Fire Department (ADA)	B1,B6	0.2081	r_{AFAA1}	$0.2081{*}r_{AFAA1}$
Self-diagnostic analysis for false alarm reduction (SD)	B1	0.1492	r_{AFAA2}	$0.1492{*}r_{AFAA2}$
Self test of sensors, detectors and control points (STS)	B1	0.1725	r_{AFAA3}	$0.1725{*}r_{AFAA3}$
CCD				
Integration & control of sensors, detectors, fire-fighting equipment (ICSD)	B1,B7	0.0718	r_{AFAC1}	$0.0718{*}r_{AFAC1}$
Interface with EMS, BAS or IBMS (INTF)	B1,B2	0.0303	r_{AFAC2}	$0.0303{*}r_{AFAC2}$
Interact with security systems (INTSS)	B1,B7	0.0227	r_{AFAC3}	$0.0227{*}r_{AFAC3}$
Interact with HVAC systems (INTHVAC)	B1,B7	0.0478	r_{AFAC4}	$0.0478{*}r_{AFAC4}$
Interact with lift systems (INTLS)	B1,B7	0.0365	r_{AFAC5}	$0.0365{*}r_{AFAC5}$
Interact with lighting/emergency generator sys. (INTLG)	B1,B7	0.0358	r_{AFAC6}	$0.0358{*}r_{AFAC6}$
MMI				
Run continually with minimal human supervision (RC)	B1,B3	0.2252	r_{AFAM1}	$0.2252{*}r_{AFAM1}$
HVAC Control System				
AUT				
Adaptive limiting control algorithm (AL)	B1	0.0263	r_{HVACA1}	$0.0263{*}r_{HVACA1}$
Sensing the internal temperature and humidity, and auto-adjustment of systems (ITS)	B1	0.0709	r_{HVACA2}	$0.0709{*}r_{HVACA2}$
Sensing of external temperature and humidity, and auto-adjustment of systems (ETS)	B1	0.0556	r_{HVACA3}	$0.0556{*}r_{HVACA3}$

Note: ▲Details of different assessment methods (Method B1 to B8) for the intelligence indicators are delineated in Appendix C2, p.390

Table 8.5: Rating Methods of Different Intelligence Indicators (cont.)

Intelligent Building Control Systems, *Intelligence attributes,* and indicators	**Assessment method(s)** ▲	**Indicators' weight from ANP (*w*)**	**Options' rating by experts (*r*)**	**Score (w*r)**
HVAC Control System (cont.)				
AUT				
Automated fault detection (AFD)	B1	0.0429	r_{HVACA4}	$0.0429*r_{HVACA4}$
Self-diagnosis (SD)	B1	0.0397	r_{HVACA5}	$0.0397*r_{HVACA5}$
CCD				
Operation control mechanism (OCM)	B1,B4	0.1356	r_{HVACC1}	$0.1356*r_{HVACC1}$
Interface with EMS, BAS or IBMS (INTF)	B1,B2	0.1407	r_{HVACC2}	$0.1407*r_{HVACC2}$
MMI				
Provide management staff with database & analytical tools for operation & service evaluation (DAT)	B1	0.0659	r_{HVACM1}	$0.0659*r_{HVACM1}$
Pre-programmed responses and zoning control (PPR)	B1	0.0760	r_{HVACM2}	$0.0760*r_{HVACM2}$
Graphical representation and real-time interactive operation action icons (GR)	B1	0.0721	r_{HVACM3}	$0.0721*r_{HVACM3}$
BIB				
Utilise natural ventilation control (UNVC)	B1,B5	0.2742	r_{HVACB1}	$0.2742*r_{HVACB1}$
Digital Addressable Lighting Control (DALI) System				
CCD				
Presence detection (PD)	B1	0.0812	r_{DALIC1}	$0.0812*r_{DALIC1}$
Control of individual luminaries, groups of luminaries or lighting zone (CIL)	B1,B4	0.1189	r_{DALIC2}	$0.1189*r_{DALIC2}$
Interface with EMS, BAS or IBMS (INTF)	B1,B7	0.1215	r_{DALIC3}	$0.1215*r_{DALIC3}$
MMI				
Provide database and analytical tools for operation and service evaluation (DAT)	B1	0.1051	r_{DALIM1}	$0.1051*r_{DALIM1}$
Pre-programmed response and control (PPSC)	B1	0.1881	r_{DALIM2}	$0.1881*r_{DALIM2}$
BIB				
Sensing light intensity, angle of projection & solar radiation (SLI)	B1,B7	0.2104	r_{DALIB1}	$0.2104*r_{DALIB1}$
Automatic lighting or shading controls (AUTLS)	B1	0.1747	r_{DALIB2}	$0.1747*r_{DALIB2}$
Security Monitoring & Access Control (SEC) System				
AUT				
Sabotage proof (SP)	B1	0.4735	r_{SECA1}	$0.4735*r_{SECA1}$
CCD	B1			
Dynamic programming (DP)	B1	0.0395	r_{SECC1}	$0.0395*r_{SECC1}$
Configurable to accurately implement the security policies for the premises (CAISP)	B1	0.0785	r_{SECC1}	$0.0785*r_{SECC1}$
Interface with communication network/ phone system (INTSY)	B1,B7	0.0390	r_{SECC2}	$0.0390*r_{SECC2}$
Interface with EMS, BAS or IBMS (INTF)	B1,B7	0.0467	r_{SECC3}	$0.0467*r_{SECC3}$
MMI				
Run continually with minimal human supervision (RC)	B1, B3	0.1118	r_{SECM1}	$0.1118*r_{SECM1}$
Provide database/ analytical tools for operation & service evaluation (DAT)	B1	0.0945	r_{SECM2}	$0.0945*r_{SECM2}$
Pre-scheduled set up (PSSU)	B1	0.1165	r_{SECM3}	$0.1165*r_{SECM3}$
Smart and Energy Efficient Lift System (LS)				
AUT				
Auto-controlled navigation at emergency (AE)	B1	0.2910	r_{LSA1}	$0.2910*r_{LSA1}$
On-line data logging (ONDL)	B1	0.1658	r_{LSA2}	$0.1658*r_{LSA2}$
CCD				
Accommodate passenger traffic pattern changes (ACPTP)	B1	0.1293	r_{LSC1}	$0.1293*r_{LSC1}$
On-line investigation and analysis of lift activity (ONIA)	B1	0.0713	r_{LSC2}	$0.0713*r_{LSC2}$
Interface with EMS, BAS or IBMS (INTF)	B1,B7	0.0589	r_{LSC3}	$0.0589*r_{LSC3}$
MMI				
Provide database and analytical tools for operation and service evaluation (DAT)	B1	0.0914	r_{LSM1}	$0.0914*r_{LSM1}$
Pre-scheduled of special events & normal routines (PSSE)	B1	0.0810	r_{LSM2}	$0.0810*r_{LSM2}$
Human engineering design (HED)	B1	0.1112	r_{LSM3}	$0.1112*r_{LSM3}$

Note: ▲ Details of different assessment methods (Method B1 to B8) for the intelligence indicators are delineated in Appendix C2, p.390

Table 8.6: An Example of the Computations for the Aggregate System Intelligence Score (Score_{SI}) of Two IBMS Candidates

Intelligence Indicators (Attribute Group)	**Indicator's weight (ANP)**	**IBMS System C**		**IBMS System D**	
		Score	Weight*	Score	Weight*
AL (AUT)	0.0916	4	0.3664	3	0.2748
SD (AUT)	0.0926	4	0.3704	4	0.3704
YT (AUT)	0.0822	4	0.3288	3	0.2466
ALMS(CCD)	0.0464	4	0.1856	4	0.1856
RCI(CCD)	0.028	5	0.1400	4	0.1120
ACML (CCD)	0.0363	4	0.1452	4	0.1452
AES(CCD)	0.0657	5	0.3285	3	0.1971
MHVAC(CCD)	0.0677	4	0.2708	4	0.2708
ML(CCD)	0.0565	4	0.2260	3	0.1695
RG(MMI)	0.0276	3	0.0828	5	0.1380
APOAF(MMI)	0.0386	3	0.1158	4	0.1544
SOS(MMI)	0.0436	4	0.1744	5	0.2180
GR(MMI)	0.0505	4	0.2020	5	0.2525
RC(MMI)	0.0803	4	0.3212	4	0.3212
AOF(BIB)	0.0896	3	0.2688	3	0.2688
PAC(BIB)	0.1028	3	0.3084	3	0.3084
	Weighted Mean (Score_{SI}) =		**3.8351**		**3.6333**

Note: Intelligence indicators weights were normalised. The indicators were rated based on a scale of 0-5 based on their existence and level of functions/services. Maximum score of SIS = 5.0000;
* The building system options were assessed by a senior executive of M&E engineering consultancy in Hong Kong

8.3.2 Model Validation

The same five experts who assisted in validating the selection evaluation models in Research Part One (i.e., MVEX1 to MVEX5) were further invited to validate the system intelligence analytic models. All experts accepted our invitation and were willing to participate in the validation process and be interviewed. The relative rankings of the different alternatives of building control systems were compared with the order of preference from the experts. Then, the study verified how similar the experts' and models' scores were.

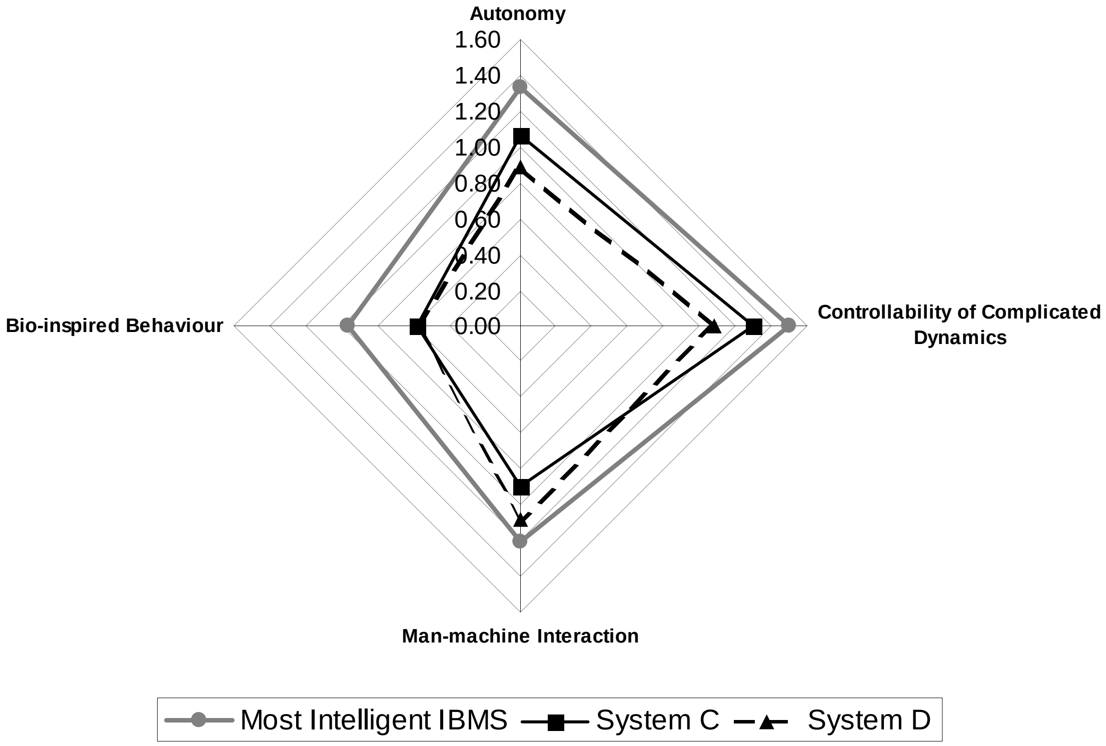


Figure 8.2: Radar Diagram Plot of the System Intelligence Score (Score$_{SI}$) of the Proposed IBMS Options

Comparison between Models' Relative Rankings and Experts' Order of Preferences

To obtain information from the experts about their opinions and judgements of the system intelligence of the candidate building control systems, another model validation questionnaire (the sixth questionnaire as shown in Appendix A6, p.364) was designed. Individual structured interviews were set up to provide guidance for the completion of the questionnaire. Each expert was asked to use the same set of control system candidates they nominated and proposed in the selection evaluation models validation exercises. A score from 0 to 10 (i.e., 0 to 4 represent 'poor'; 5 represents 'average'; 6 and 7 represent 'good'; 8 represents 'very good'; and, 9 and 10 represent 'excellent') were again assigned for each alternative based on their overall intelligent performance or degree of intelligence. Then, the experts were invited to evaluate the same set of alternatives by using the system intelligent analytic models as described in Table 8.5. A weighting score between 0 (extremely poor) and 5 (excellent) based on the assessment methods B1 to B8 in Appendix C2 (p.390) were assigned to reflect the degree of each of the nominated building control system candidates in fulfilling each intelligence indicator. Table 8.7 summarises the experts' global preference scores and models' aggregate scores of each candidate building control system. The results indicate that 27 models' aggregate scores order are in the same way as the experts' preference (87%).

Results of Correlation Coefficient between the Experts' Global System Intelligence Scores and Model's Aggregate System Intelligence Scores

After the comparison of the rankings, the model's aggregate scores (column 3 of Table 8.7) were further correlated with the expert global scores (column 4 of Table 8.7). Table 8.8 summarises the results of the Pearson correlation coefficient (*r*) and Spearman's *rho* between the models' aggregated scores and the experts' global scores for each of the key building control systems.

The analysis results indicate a high correlation between all experts' scores and the scores generated by the models with respect to the degree of intelligence. The values of Spearman's *rho* ranged from 0.812 to 0.890, while the values of Pearson's *r* ranged from 0.771 to 0.847 (Table 8.8). This implies a 'very strong' relationship between the experts' and models' system intelligence scores of the seven building control systems in general (de Vaus, 2002).

Table 8.7: Summary of Experts' Global System Intelligence Scores and Models' Aggregate System Intelligence Score

Expert reference	Proposed system options	Models' aggregate scores (Ranking of scores)	Experts' global score (Ranking of scores)
MVEX1	MVEX1-IBMS1	4.2074 (1)	8 (1)
	MVEX1-IBMS2	3.7100 (2)	7 (2)
	MVEX1-ITS1	3.9803 (2)	7 (2)
	MVEX1-ITS2	4.4516 (1)	8 (1)
	MVEX1-AFA1	3.5886 (2)	8 (2)
	MVEX1-AFA2	3.9996 (1)	9 (1)
	MVEX1-HVAC1	3.9736 (1)	8 (1)
	MVEX1-HVAC2	3.5696 (2)	7 (2)
	MVEX1-DALI1	4.5332 (1)	8 (1)
	MVEX1-DALI2	3.7669 (2)	7 (2)
	MVEX1-SEC1	3.9215 (2)	8 (2)
	MVEX1-SEC2	4.2625 (1)	9 (1)
	MVEX1-LS1	4.0361 (1)	8 (1)
	MVEX1-LS2	3.5395 (2)	6 (2)
MVEX2	MVEX2-IBMS1	3.6098 (2)	6 (2)
	MVEX2-IBMS2	3.9534 (1)	7 (1)
	MVEX2- ITS1	3.8030 (2)	7 *
	MVEX1- ITS2	4.1773 (1)	7 *
	MVEX2- AFA1	3.4591 (2)	6 (2)
	MVEX2- AFA2	3.4633 (1)	8 (1)
	MVEX2- HVAC1	3.3004 (2)	6 (2)
	MVEX2- HVAC2	3.5989 (1)	7 (1)
	MVEX2-SEC1	3.8737 (1)	7 (1)
	MVEX2-SEC2	3.3535 (2)	6 (2)
	MVEX2-LS1	3.6496 (2)	7 (2)
	MVEX2-LS2	4.1108 (1)	8 (1)
MVEX3	MVEX3-IBMS1	3.7852 (1)	8 (1)
	MVEX3-IBMS2	3.4866 (2)	7 (2)
	MVEX3-AFA1	3.6125 (1)	9 (1)
	MVEX3-AFA2	3.0656 (2)	6 (2)
	MVEX3-HVAC1	4.0285 (2)	7 (2)
	MVEX3-HVAC2	4.1155 (1)	8 (1)
	MVEX3-DALI1	3.6309 (2)	7 (2)
	MVEX3-DALI2	4.2023 (1)	8 (1)
	MVEX3-SEC1	4.1035 (1)	8 (1)
	MVEX3-SEC2	3.7890 (2)	6 (2)
	MVEX3-LS1	3.8703 (1)	8 *
	MVEX3-LS2	3.8579 (2)	8 *

Note: * Same score was assigned by the expert on the overall ability or performance of the building control systems

Table 8.7: Summary of Experts' Global System Intelligence Scores and Models' Aggregate System Intelligence Score (cont.)

Expert reference	**Proposed system options**	**Models' aggregate scores (Ranking of scores)**	**Experts' global score (Ranking of scores)**
MVEX4	MVEX4-IBMS1	4.0176 (1)	9 (1)
	MVEX4-IBMS2	3.6403 (2)	7 (2)
	MVEX4-ITS1	4.7257 (1)	8 (1)
	MVEX4-ITS2	4.2546 (2)	7 (2)
	MVEX4-AFA1	3.2973 (1)	7 (1)
	MVEX4-AFA2	3.2078 (2)	6 (2)
	MVEX4-HVAC1	3.8105 (1)	7 (1)
	MVEX4-HVAC2	3.1931 (2)	6 (2)
	MVEX4-DALI1	3.5788 (2)	7 (2)
	MVEX4-DALI2	3.9081 (1)	8 (1)
	MVEX4-SEC1	4.0857 (1)	8 (1)
	MVEX4-SEC2	3.7495 (2)	7 (2)
	MVEX4-LS1	3.3315 (2)	6 (2)
	MVEX4-LS2	4.1108 (1)	8 (1)
MVEX5	MVEX5-IBMS1	4.0575 (2)	9 *
	MVEX5-IBMS2	4.2664 (1)	9 *
	MVEX5-AFA1	3.4336 (1)	8 (1)
	MVEX5-AFA2	2.8443 (2)	6 (2)
	MVEX5-HVAC1	3.4870 (2)	6 (2)
	MVEX5-HVAC2	3.8220 (1)	8 (1)
	MVEX5-SEC1	3.7890 (2)	6 (2)
	MVEX5-SEC2	3.8270 (1)	7 (1)
	MVEX5-LS1	4.5320 (1)	8 *
	MVEX5-LS2	4.3495 (2)	8 *

Note: * Same score was assigned by the expert on the overall ability or performance of the building control systems

Table 8.8: Summary of Correlation Coefficient Results between the Scores of System Intelligence by the Experts and Models

Intelligent Building Control Systems	**Correlation Coefficient**	
	Pearson's *r*	**Spearmen's *rho***
Integrated Building Management System (IBMS)	0.771*	0.820*
Telecom and Data System (ITS)	0.838*	0.828*
Addressable Fire Detection and Alarm (AFA) System	0.818*	0.864*
Heating Ventilation Air-conditioning (HVAC) Control System	0.845*	0.854*
Digital Addressable Lighting Control (DALI) System	0.827 $^{\Delta}$	0.878 $^{\Delta}$
Security Monitoring and Access Control (SEC) System	0.847*	0.890*
Smart and Energy Efficient Lift System (LS)	0.820*	0.812*

Note: * Correlation is significant at the 0.01 level (2-tailed); $^{\Delta}$ Correlation is significant at the 0.05 level (2-tailed)

8.4 DISCUSSIONS

This chapter is a continuation of the development of refined conceptual models for the intelligent building control systems for selection evaluation and system intelligence analysis in Chapters 6 and 7 respectively, which aims to demonstrate the practicability and validity of the developed models. The validation works undertaken in this chapter indicate that the aggregate scores from both selection evaluation models and system intelligence analytic models provide a foundation for comparison and ranking so that a rational decision can be developed. The works attempt to model experts' decision making when they evaluate the selection and analyse the degree of intelligence of different building control system candidates. The developed models provide systematic and structural methods to evaluate each candidate against the weighted CSC or intelligence indicators. The building control system's ability, performance and the degree of intelligence can be assured by selecting the most suitable or appropriate options.

Using the models for selecting and analysing intelligent properties of the building control system alternatives enables the users to know and understand the relative strengths and weaknesses of each candidate on each individual CSC and intelligence indicator. This provides the users or project participants to comprehend the nature of the control system candidates. This helps them to develop measures to improve the features in which the proposed building system candidates are weak. With the development of practical models, they provide mechanisms to assist practitioners in evaluating selection decisions and facilitating the intelligence performance appraisal of the building control systems. Industry practitioners can rely less on the general or global impression of the building system options, which may be biased, erratic, and inaccurate. The development of a methodical way to analyse the building system alternatives can reduce any guessing, and finally minimise the making of subjective and biased decisions.

Comparing experts' opinion with the results of the models showed that the models developed in both parts generally indicate a similar order as the preference of the experts' rankings. The results of models' validation suggested 'very strong' correlation between the experts and the scores generated by the developed models (including the selection evaluation models and the system intelligence analytic models). For the selection evaluation models, the values of Pearson's *r* ranged from 0.769 to 0.893, which implied a high correlation between the model and expert opinion. The high correlation was also found between all experts' scores and the scores generated by the system intelligence analytic models, where the values of *r* were ranged from 0.771 to 0.847.

Despite the high correlation between two sets of scores in this study, it should be noted that there is still a basic distinction between the models and the reality. Bracke *et al.* (2007a) argue that the opinions of experts are the result of a rather intuitive and instantaneous process which only indirectly relate to scientific findings, while modelling involves a systematic, step-by-step, analytic procedure transforming available information into a clear assessment model. Thus, it should be clear that the model cannot be equated with the opinion of the modeller or any experts. Variations between the models' and experts' scores do not imply failures of the models. In fact, any deviations can be considered for further analysis and model upgrading (Bracke *et al*., 2007a). Cusack (1984) also maintained that models are not expected to be completely accurate and that complete accuracy is difficult to achieve in reality. Instead, a model can at best only represent a logical deduction drawn from an imperfect set of assumptions. Perhaps, a possible explanation of the high correlation between the experts and the models in this study could be that the model was properly developed.

Although the models provide an ordered list reflecting expert opinions on the building control systems selection and intelligent performance evaluation, the importance rating and the weights calculated may not be applicable to all intelligent building projects as the control systems in some projects may have unique requirements and may have to satisfy special needs. The user can alter the weight to reflect more accurately their unique project requirements. Despite this, this model remains the initial attempt which enables the users to evaluate the available system options for the commercial intelligent building in Hong Kong. Moreover, a special feature of the use of the MCDM or multi-attribute value technique (MAVT) is the compensatory which means the high scores in some attributes compensate for low scores in other attributes (Ling *et al*., 2003). For example, in evaluating the level of intelligence of two IBMS options, an expert may give a very low score on one of the intelligence indicators (e.g. adaptive limiting control algorithm) of one IBMS, but this option may still obtain a higher aggregate score than another IBMS based on the high scores in other attributes. Thus, it is suggested that the users should check the score for each of the indicators to avoid unintentionally selecting a system alternative with an unwanted weakness. Another limitation of the developed models is that the users or project participants would not be able to evaluate proposed building systems if they are new and have not been used in any building project in the past.

8.5 CHAPTER SUMMARY

This chapter presented step-by-step processes for testing the effectiveness of the selection evaluation models and system intelligence analytic models of seven key building control systems of the intelligent building. The chapter first transformed the developed models from the theoretical frameworks to the practical application. Two real-life practical examples of building control systems were used to demonstrate the practicability of the selection evaluation models and system intelligence analytic models. Then, all models were validated to check their robustness. The models were tested for whether they could simulate the decisions of the experienced intelligent building experts. Effectiveness and robustness of the models were finally discussed.

CHAPTER 9

CONCLUSIONS, CONTRIBUTIONS AND RECOMMENDATIONS

"A set of recommendations is provided for possible future research and an identification of area where the study can be extended in scope or where the empirical or theoretical support may be obtained to increase certainty. It is a guide to how you see further development of the science, made desirable by the need to verify or build on the outcome of your study."

(Runeson and Skitmore, 1999: 74)

9.1 INTRODUCTION

In the introductory chapter, it was stated that the studies of this thesis originated with five specific research objectives: (1) developing general conceptual selection evaluation models for the seven key building control systems of the intelligent building; (2) formulating general conceptual frameworks for system intelligence analysis for the same seven intelligent building control systems; (3) examining the conceptual models in both aspects by means of multiple surveys; (4) transforming the tested conceptual models to the applicable models; and finally, (5) testing the models' effectiveness by experts' validation. This chapter is organised to summarise the findings and results of the analysis undertaken in the previous chapters in the context of these objectives. The references of the research hypotheses to the theoretical and empirical findings are first discussed. This is followed by a brief summary of the major points of the thesis. Achievements and contributions of this research, both to the literature and the industry, are presented. To conclude, the limitations of the research together with the areas of future research are addressed.

9.2 RELEVANCE OF THE RESEARCH HYPOTHESES

In Chapter 1, four hypotheses (H1 to H4) which formed the foundation of the research as the theoretical and empirical investigation for this thesis were presented. The first two hypotheses which related to the selection of the building control systems which were investigated in the Research Part One (in Chapter 6), while the last two hypotheses focused on the system intelligence evaluation of the building control systems which were dealt with in the Research Part Two (in Chapter 7). This section reviews how accurately these four hypotheses have predicted the major findings of the research.

The first hypothesis (H1) predicts that *' the critical selection criteria (CSC) affecting the selection of each of the building control systems in the intelligent building differs, reflecting their distinctive and unique roles'*. To validate the research H1, a general survey in the first half of Chapter 6 was first employed to identify a list of critical selection criteria (CSC) for the building control systems by a group of building practitioners and professionals. A simple rating method was adopted to calculate the mean scores for determining the importance level of the tested selection criteria, while the t-test was used to compare and elicit the CSC. The data set used for empirical analysis contained 71 respondents. The survey revealed that although the operating and maintenance costs and service life are two common CSC for the building control systems, their relative importance or ranking varies from one building control system to another. Additionally, it is suggested in the survey that each building control system is influenced by different and unique sets of CSC depending on the distinctive features of the building control system in the intelligent building. In general, four building control systems including HVAC, SEC, LS and DALI, have more than eight identified CSC, which suggested that these building control systems could not be merely justified by a few selection criteria due to their complexity. While safety concern is more important to the selection of the addressable fire detection and alarm (AFA) system, criteria of user comfort is more influential in HVAC control system selection. Details of the pertinent findings of CSC for each of the seven building control systems will be discussed in the following section 9.3.2. The results and findings of the first survey in Chapter 6 generally upheld H1.

The second hypothesis (H2) suggests that the criteria of each proposed set of CSC exert a considerable degree of influence on determining the building control system. For this hypothesis to be validated, an AHP questionnaire was undertaken for testing in the second half of the Chapter 6. The AHP approach was chosen since it was important to collect data from some experts who were highly experienced in intelligent building design and development, particularly with rich experience in the building control systems selection. Furthermore, a large sample size seemed inappropriate in this study as the intelligent building is a new form of building development which is yet to mature. The AHP is an analytical method which permits a small group of survey population. Thus, the AHP is helpful in collecting and analysing data from a small group of experienced experts. Justification of the use of AHP was discussed in Chapter 5. Following the expert justification in the AHP survey, H2 may be regarded as justified since no single CSC is dominant amongst all building control systems in this survey. Comparing the groups of CSC in each of the building control systems, it was revealed that selection criteria under *Work Efficiency* is considered most significant in the selection of IBMS, ITS, and SEC systems, while the criteria of *User Comfort* is more significant in selecting the HVAC control and DALI systems. In the LS and AFA systems, the criteria of *Safety Related* are more dominant. The survey results suggested the relative importance of the CSC of each building control system for choosing each of the apposite system alternatives differently and substantially. In fact, the AHP survey affirms, through the penetrating insights of the intelligent building experts, the importance of the CSC identified in the general survey.

The third and fourth hypotheses address the issue of the system intelligence of the building controls systems. The third hypothesis predicted that in the evaluation of the degree of system intelligence of the building control systems in the intelligent building, autonomy and human-machine interaction would be considered as two common intelligence attributes, and controllability for complicated dynamics and bio-inspired behaviour would be regarded as two specific intelligence attributes depending on the system's operational characteristics. For this hypothesis to be validated, a general survey was employed in Chapter 7 to calculate the mean scores of each proposed intelligence attribute and indicator. A statistical t-test was further employed to compare the importance of the tested elements. The survey findings indicated that the autonomy was less considered by the building practitioners as a common attribute that could represent the degree of system intelligence in the ITS and DALI systems. Instead, the results showed that the ability to control complicated dynamics and to enhance interaction between human and systems should be emphasised in intelligent communication networks and lighting control systems. The findings concluded that only five intelligent building control systems were confirmatory to H3.

The last hypothesis (H4) suggests that the operational benefits of the intelligent building exert a considerable degree of influence on the importance of intelligence indicators for measuring the degree of system intelligence of the building control systems. To verify this hypothesis (H4), a questionnaire survey combining the AHP and ANP methods was conducted in Chapter 7. The ANP was proposed in this survey as it can provide a more generalised model in multi-criteria decision-making that takes interdependent relationships into consideration. In this survey, the interdependencies between the intelligence attributes of intelligent building systems and the operational benefits were investigated. The relative importance of all intelligence indicators were analysed and calculated by both the AHP and ANP approaches, and the results revealed that prioritisation of the intelligence indicators with (i.e. ANP method) or without (i.e. AHP method) the consideration of the interdependent relationships between intelligence attributes and operational benefits of the intelligent building were different. The resulting outcomes of the normalised relative weights of the intelligence indicators obtained from the ANP and AHP were varied, and the consideration of interdependencies resulted in either an improvement or decline of relative importance and final ranking of the indicators. This difference implies that the interdependent relationships (considering the operational benefits of intelligent building) would influence and alter the original hierarchical ratings. The network-analysis approach allows a more comprehensive consideration of the system intelligence as it not only tries to deliberate on the intelligent properties, but also takes the operational benefits brought by the intelligent system into account.

9.3 CONTRIBUTIONS TO KNOWLEDGE

This study provides a number of theoretical contributions and achievements to the body of intelligent building research. The major contribution of this thesis is the development of both conceptual and applicable models for building control system selection evaluation, and intelligence performance analysis. These works not only signify building control system selection and intelligence evaluation practices in local intelligent building industry, but also embody the theory of selection evaluation and system intelligence analysis through the establishment of the relevant models.

9.3.1 Accomplishing the Research Objectives

As stated earlier, this study originated with five specific research objectives. A chain of systematised research activities were designed and undertaken to achieve the objectives. The general conceptual models for selection evaluation and system intelligence appraisal for the seven identified building control systems were first formulated accordingly by an amalgamation of previous empirical research and theories (i.e., the first and second objective). A list of proposed selection criteria and intelligence indicators for each of the building control systems were developed from an extensive bibliographic review (in Chapter 3 and 4).

After the development of the conceptual models, each conceptual selection evaluation and system intelligence analytic model was tested and refined by two consecutive surveys (i.e., the third objective). The survey method was considered as an advantageous research strategy for determining the conceptual models based on the research strategy of Yin (1994) as stated in Chapter 5. A general survey and an AHP survey were first adopted in Chapter 6 to examine the first two hypotheses of this research, while another two consecutive surveys including a general survey and a survey combining the AHP and ANP approaches were used in Chapter 7 to test the third and fourth hypotheses. To move all tested conceptual models from experimental and theoretical framework formulations to practical applications (i.e., the fourth objective), two process steps were undertaken in Chapter 8 to establish ratings of each of the system options on each of the indicators, and to aggregate the weighted ratings. Examples of real candidate intelligent building control systems were employed to demonstrate the models' practicability. In order to ascertain the effectiveness of the models (i.e., the fifth objective), the validation was undertaken by comparing the experts' preference and models' rankings of the candidate building control systems, and testing the correlations between the experts' scores and models' scores (in Chapter 8). The Pearson correlation coefficient and the Spearman rank correlation coefficient were employed to examine the correlation between experts' preference and the models' rankings.

9.3.2 Summary of Findings and Achievements of Research Part One

As noted in Chapter 3, the present intelligent building research lacks a sound theoretical framework on the selection of building control systems. The first part of research in this thesis (Research Part One) provides an extension review of the present theory of building control systems selection. The following is a list of the pertinent findings and achievements of Research Part One (mainly in Chapter 6), including the accounts for all hypotheses supported:

- A total of 59 CSC were identified for seven different building control systems. Amongst all CSC, both *'service life'* and *'operating and maintenance costs'* are perceived as common CSC to the majority of the building control systems in this study. In specific, *'operating and maintenance costs'* is ranked as the top CSC in ITS, AFA, and SEC systems, and is considered as either second or third CSC for the remaining building control systems.

- Reflect their distinctive features in the intelligent building, there are different sets of CSC affecting the decision on selecting each of the intelligent building control systems. For the HVAC control system, *'total energy consumption'* is perceived as top CSC, followed by the *'system reliability and stability'*, and *'operating and maintenance costs'*, while the top three CSC of the IBMS are *'system reliability and stability'*, *'operating and maintenance costs'*, and *'efficiency and accuracy'*. In the ITS, *'operating and maintenance costs'* is considered as the top CSC, followed by *'reliability and stability'* and *'further upgrade of system'*.
- Safety performance is considered as the key concern in the selection of AFA and LS systems. The top CSC of the AFA system are *'compliance with the code of minimum fire service installations or equipment'* and *'compliance with the code for inspection, testing and maintenance of fire service installations and equipment'*, followed by the *'operating and maintenance costs'* and a number of work efficiency criteria (i.e., *'automatic detection of fire, gas and smoke'*, *'system response time and survivability'*, *'service life'*, and, *'further upgrade of system'*). For the LS, *'mean time between failures'* is perceived as the prime CSC, followed by *'total energy consumption'* and *'operating and maintenance costs'* as the second and third concerns.
- User comfort is considered as the most important factor in selecting the DALI system. *'Ease of control'* is considered as the most important CSC, while the *'total energy consumption'* and *'operating and maintenance costs'* are considered as the second and third top CSC.

- The study found that technological factors are considered less critical in the selection of the intelligent building control systems. Instead, the results generally suggested that the optimum building control systems should be able to ensure efficiency, enhance user comfort and cost effectiveness (discussed in Chapter 6). The result is consistent with the views of DEGW *et al*. (1992) that a true intelligent building does not need to be a building with purely advanced technologies.

9.3.3 Summary of Findings and Achievements of Research Part Two

In this thesis, the second part of research (i.e., Research Part Two) focuses on the evaluation of the degree of system intelligence of the same seven building control systems. The proposed models provide an inclusive investigation of the system intelligence as it does not only test the suitability of different intelligence indicators, but also examines the impacts of the interdependencies between the intelligence attributes and the building's operational benefits. The major findings and achievement are listed as follows:

- The interpretation of 'intelligence' is different from one intelligent building control system to another, which implies that each building control system performs in a non-unique way and contains unique measures of system intelligence. In the IBMS, the top three intelligence indicators – *'self-diagnostic of operation deviations'; 'adaptive limiting control algorithm';* and, *'year-round time schedule performance'* – are all under the attribute of 'autonomy'. This indicates that an 'intelligent' IBMS should possess the capability of detecting the deviations in its operation and self-adjusting these problems. On the other hand, an intelligent network system (ITS) should contain fixed terminal ports to allow flexible connection and expansion of the system network. It should also be able to deal with message prioritisation, diversion and avoid message collision when several devices are attempting to transmit concurrently.

- An 'intelligent' HVAC control system should possess the function of utilising natural ventilation, and be able to interface with the EMS, BAS, or IBMS. The *'operational control mechanism'* is also perceived as an indispensable part of an intelligent HVAC control system. On the other hand, four top intelligence indicators for an intelligent AFA system include: *'run continually with minimal human supervision'*; *'alarm deployment algorithm within the building and notification to Fire Department'*; *'self-test of sensors, detectors and control points'*; and, *'self-diagnostic analysis for false alarm reduction'*.
- The top rank of *'sabotage proof'* and *'pre-scheduled set-up'* suggests that an intelligent SEC system must be able to resist physical damage and modification, and allow for pre-scheduling to facilitate the monitoring and control process during special events and normal routines. For the Smart and Energy Efficient Lift System (LS), the top four intelligence indicators include *'auto-controlled navigation at emergency'*, *'on-line data logging'*, *'providing management staff with database and analytical tools for operation and service evaluation'* and *'accommodating changes of passenger traffic pattern'*. In addition, for the DALI system, *'pre-programmed response and control'* is considered as the top intelligence indicator, followed by the *'sensing the light intensity and angle of projection/solar radiation'*.
- In this study, the findings suggested that 'autonomy' is less suitable in representing the degree of system intelligence for the ITS and DALI systems.

- Contrasting the networked ANP with the hierarchy AHP model by applying both to the system intelligence evaluation, the resulting outcomes of the normalised relative weights of the intelligence indicators obtained from the ANP and AHP are varied. The ANP provides the decision maker with a more accurate and realistic score of system intelligence. This difference implied that the interdependent relationships influenced and altered the original hierarchical ratings by the experts.

In summary, the whole research process required a series of interview and discussions, as well as the combination of experience and knowledge of the intelligent building field. Without applying a multi-criteria approach (i.e., the AHP and ANP), it is difficult to overcome the problem of the qualitative nature of selection evaluation or intelligence measurement that makes it hard to assess the selection decision and compare the degree of intelligence of different control system candidates. Structured and systematic research activities and analysis can provide users a detailed investigation on the problem, and help reduce the risk of making poor decisions or evaluations.

9.4 POSSIBLE CONTRIBUTIONS TO THE INDUSTRY

In this thesis, the development of CSC and intelligence indicators might not only lead to a more comprehensive appreciation of the intelligent building control systems selection, but might also help to build a better understanding of what intelligent features or properties are needed for optimum building control systems. With the establishment of applicable models in Chapter 8, the aggregate selection scores (Score_{SE}) and system intelligence score (Score_{SI}) can be calculated for the proposed building control system alternatives, providing a basis for comparison and ranking so that the rational decisions may be made. The models are intended to structure the decision maker's mind by providing a systematic prioritisation of alternative options so as to lessen the dependence on human expertise and judgement. The design teams do not need to rely on their global impression of the building control system options, in which the decision may be subjective, unreliable and inaccurate. This can reduce the possibility of biased selection decisions. Apart from the aggregate scores, the individual scores are also calculated. The calculation of the CSC enables the relative strengths and weaknesses of each building control system candidate, on individual CSC, to be known to the design team.

From a commercial perspective, the establishment of aggregate system intelligence scores provides a way that allows developers or design teams to estimate the building control system products using the index to manifest their intelligence superiority. It provides a benchmark to measure the degree of intelligence of one control system candidate against another. Building control system consumers are provided with an alternative approach to compare and contrast several building control system products from the viewpoint of intelligence (Schreiner, 2000; and Meystel and Messina, 2000).

The fact that the conceptual frameworks in the two research parts of this thesis lead us to these results and conclusions suggests that the overall objective of the research has been successfully achieved. The contributions, both theoretical and practical, of this thesis are briefly summarised and illustrated in Figure 9.1

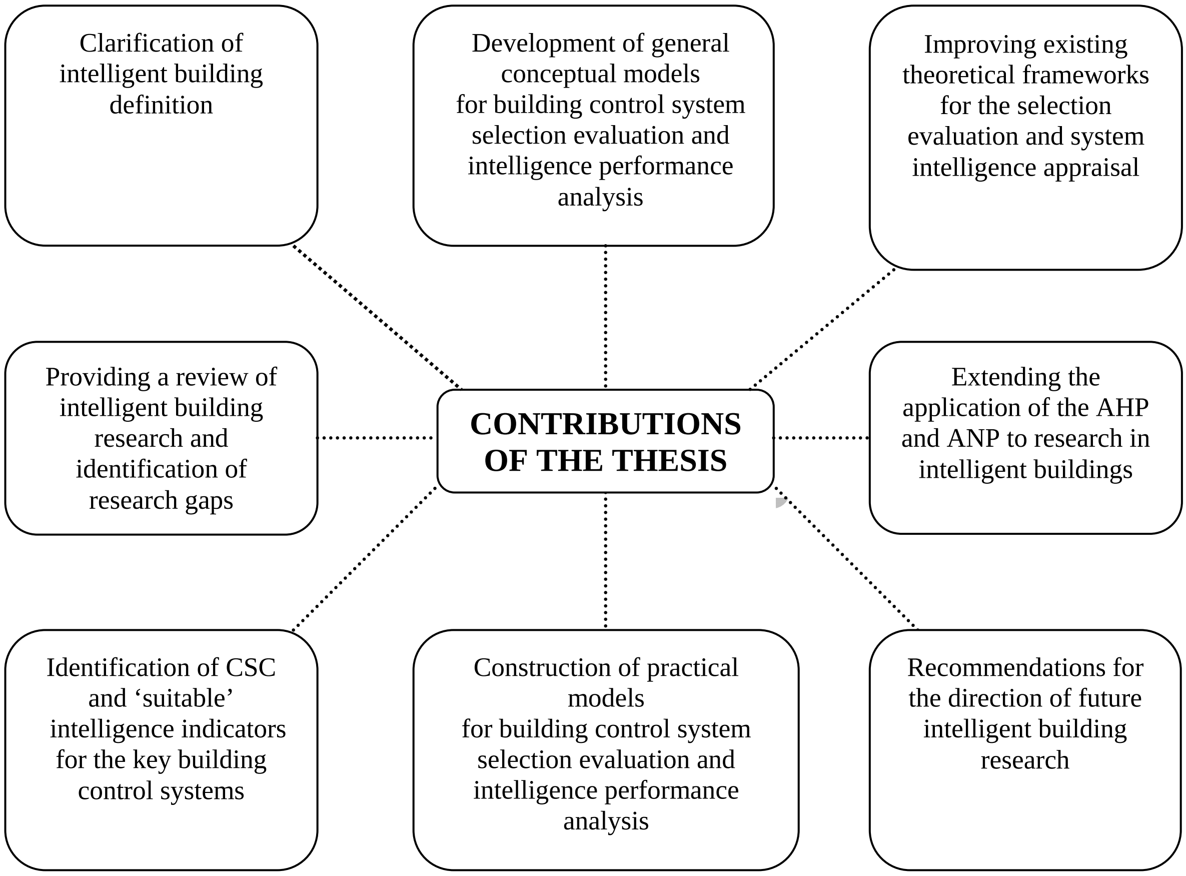


Figure 9.1: Theoretical and Practical Contributions of this PhD Thesis

9.5 RESEARCH LIMITATIONS

Although the research has generally achieved the specific objectives stated in Chapter 1, the nature of the work and the focus of research have meant that the analysis has had to be of a general nature so that the major elements (i.e. CSC and intelligence indicators) of the building control systems could be outlined. Such generality has meant that some of the issues have not received attention and in-depth analysis in this research.

This research was deliberately limited to an investigation of seven of the most general building control systems in the intelligent building since it would be too difficult, for the focus of PhD research, to try to identify all specific building control systems in the intelligent building. Furthermore, the scope of this research is confined to the investigation of building control systems in the commercial intelligent building (i.e., office). The uses and requirements of building control systems depend on the building types (for example, office buildings, residential towers, shopping malls, hospitals and airport buildings) and their ultimate usages (Ancevic, 1997). This implies that the identified CSC and intelligence indicators identified in this research might not be generalised to all types of intelligent buildings. This thesis also has focused on the practices of the intelligent building control systems selection evaluation and system intelligence assessment among the experts and professionals in the context of Hong Kong. The models' effectiveness in other countries will be ascertained when they have been claimed as broadly received.

The research methodology adopted in this thesis also imposed its own limitation. First, the size of the sample of this research was limited. Since the intelligent building industry is new and developing, a large sample of professionals was not available. Only a very limited number of experts could be identified for the surveys. The major group of experts were the design consultants (i.e., M&E engineers), together with a small number of developers and facility managers. As a result, the statistical testing on causal relationships is not conducted and feasible in this study because of the limited sample size. The inherently small sample size also implies that the claims of representation of the wider population cannot be established.

Based on the problems in obtaining an adequate size of samples, the AHP and ANP were employed in this research to collect data and prioritise the elements. However, a limitation in using the AHP or ANP as a method of analysis is that each of the enhancements to the analytic model leads to an increased number of pair-wise comparisons that need to be completed (Meade and Sarkis, 1998). Complexity increases exponentially with the number of indicators or criteria and their interdependence (Wolfslehner *et al.*, 2005). This requires more calculations and the formation of additional comparison matrices, and eventually requires significant time resources and efforts for completion from an application perspective. In order to maintain some parsimony for ease of exposition, the interdependence of same level components (i.e. interdependent relationships among intelligence indicators or CSC) was not considered and examined in the AHP and ANP methods in this research. The non-linear interdependent relationships between each CSC and intelligence indicators on the same hierarchy level were not investigated. In the first part of this research, the CSC were structured in the AHP approach with no consideration for the relationships amongst the CSC on the same level. Similarly, the examination of the relative importance of intelligence indicators in the Research Part Two also merely consider the interdependencies between the intelligence attributes and the operational benefits of intelligent building control systems, without the consideration of interdependence amongst the intelligence indicators in the same level. Future study could examine the interdependencies in the CSC and intelligence indicators because this relationship would possibly have implications for the results of the models.

Furthermore, the AHP and ANP pair-wise comparisons of elements can only be subjectively performed, and thus their accuracies always depend on the knowledge and experience of the raters on the issues and its field (Yurdakul, 2003). In fact, preference modelling of the human decision makers is often uncertain in many cases, and it is also relatively difficult for the decision maker to provide exact numerical values for the comparison ratios (Mikhailov and Singh, 2003). A natural way to cope with uncertain judgement is to express the comparison ratio as intervals or fuzzy sets, which incorporate the vagueness of human thinking. However, the AHP approach only copes with crisp comparison ratios. The interval and fuzzy prioritisation methods cannot be further used in the matrix calculation of the ANP (Meade and Sarkis, 1998; and, Mikhailow and Singh, 2003).

Finally, based on the continually changing and evolving character of information technology, building control systems with novel intelligent features develop from time to time. New innovative features and properties mean that new intelligence indicators or CSC might be added. This implies that the models developed in this thesis can be validated at least to a yearly time span, but it is subjected to the nature of changes in the environment including technological advancement and changes of users' tastes (Skitmore, 1989).

9.6 RECOMMENDATIONS FOR FURTHER RESEARCH

It is important that research in building control system evaluation continues so that a better understanding of the intelligent building continues to develop. This study has set down the foundation for a meticulous examination of the building control systems in their selection evaluation and system intelligence analysis, including the development of conceptual frameworks and practical models. Numerous possibilities are suggested for extending and elaborating upon the research undertaken.

1) The current dearth of research in the area of the selection evaluation and intelligence appraisal for the intelligent building control system means that there is sizeable scope for undertaking further studies. Research methodology employed in this thesis can be used as a basis for model development work. Further research could be undertaken by refining the models or developing similar models in related areas. Similar empirical work of this study can be extended and further developed in other countries, for other building control systems, or in other types of intelligent building. Some new variables may be added into the model.

2) A larger sample would help for improving the extent to which these models represent human decision making processes. Future study should also include the building occupants as part of the survey sample because they are the end-users of the intelligent building. For example, the factors that the end-users adopt for assessing and comparing the usefulness of intelligent building control systems can be investigated. Their feedback provides a better understanding and reflection on the actual performance (or degree of intelligence) of the building control systems.

3) No research has yet been conducted in this thesis into the interdependent relationships between each CSC or intelligence indicators of each building control system on the same level. This research extension provides a better insight into the

impacts of the interdependencies of the decision of selection evaluation and the intelligence appraisal of the building control systems.

4) As mentioned in the research limitations, the ANP approach is restricted in the use of interval and fuzzy prioritisation methods in the matrix calculation. A fuzzy extension of the ANP is proposed in further study so that the uncertain human preferences can be used as input information in the decision making process. The application of software and group decision support systems can minimise the difficulties in implementing this technique. An example of decision support systems includes a fuzzy preference programming method (Mikhailov and Singh, 2003) for tackling the problems of imprecise and uncertain human comparison judgments.

To conclude, as the intelligent building technologies continuously evolve and develop into the foreseen future, the selection evaluation and system intelligence analysis of the building control systems will continuously be seen as an area of interest to explore and investigate.

9.7 CHAPTER SUMMARY

This chapter presented an outline of the major research findings, achievements and contributions provided by this thesis. The chapter was first organised to discuss the hypotheses of the research, which form the basis of the investigation with reference to the theoretical findings. Then, the theoretical and practical contributions provided by this research were summarised. Finally, limitations of this research were highlighted and suggestions for future work in this field were given.

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APPENDIX A

SAMPLE OF SURVEY QUESTIONNAIRES (A1-A6)

APPENDIX A1: QUESTIONNAIRE FOR THE GENERAL SURVEY (RESEARCH PART ONE)

Questionnaire Survey (Round 1)

Critical Selection Criteria of the Building Control Systems for the Commercial Intelligent Building

INSTRUCTIONS

This survey focuses on the identification of the critical selection criteria (CSC) for seven most common building control systems in the commercial intelligent buildings. They include:

1. Integrated Building Management System (IBMS);
2. Telecom and Data System (ITS);
3. Addressable Fire Detection and Alarm System (AFA);
4. Heating, Ventilation and Air-Conditioning (HVAC) Control System;
5. Digital Addressable Lighting Control System (DALI);
6. Security Monitoring and Access Control System (SEC); and,
7. Smart and Energy Efficient Lift System (LS).

This questionnaire consists of three parts (Part 1 and 2). Part 1 requires the respondent to rank the importance of the each proposed selection criteria for each of the seven building control systems. Part 2 asks respondent's details and background for reference.

Please indicate the relative importance of each proposed selection criterion by ticking ('√') the appropriate box **(REMARK: The importance is scaled as: 1 - not important at all; 2 – unimportant; 3 – neutral; 4 – important; 5 – extreme important)**. You are also welcome to add in additional intelligence indicators.

Upon completion, please return the completed questionnaire to the address below or send to email address: xxxxxxxxr@polyu.edu.hk **within 21 days**.

All collected data will be kept strictly confidential and anonymous, and they will be used for academic research purposes ONLY. Thank you

Johnny WONG, PhD Candidate
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PART I: RELATIVE IMPORTANCE OF THE SELECTION CRITERIA

1. INTEGRTAED BUILDING MANAGEMENT SYSTEM (IBMS)

Purpose: To integrate all essential building services systems to provide an overall strategic management in all aspects with the capacity to systematic analysis and report the building performance and connect with multiple site/location to give corporation a portfolio view of the situation. It also aims to provide automatic functional control and maintain the building's normal daily operation (Note: in present time when IBMS has been upgraded to include many functions of building automation system)

	SCALE				
	Not Important at all	**Unimportant**	**Neutral**	**Important**	**Extreme Important**
	1	**2**	**3**	**4**	**5**
Work Efficiency					
• Grade/level of system	☐	☐	☐	☐	☐
• Integration/interface with service control systems	☐	☐	☐	☐	☐
• Compliance with standard	☐	☐	☐	☐	☐
• Compatible with different network protocols	☐	☐	☐	☐	☐
• System reliability and stability	☐	☐	☐	☐	☐
• Efficiency and accuracy	☐	☐	☐	☐	☐
• Further upgrade of system	☐	☐	☐	☐	☐
• Frequency of maintenance	☐	☐	☐	☐	☐
• Remote monitoring and control	☐	☐	☐	☐	☐
• Service life	☐	☐	☐	☐	☐
Others	☐	☐	☐	☐	☐
Cost Effectiveness					
• Initial costs (including purchase, delivery and fixing costs)	☐	☐	☐	☐	☐
• Operating and maintenance costs (including disposal cost)	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

2. TELECOM AND DATA SYSTEM (TS)

Purpose: To provide effective and efficient information transmission and exchange inside and outside building

	SCALE				
	Not Important at all	Unimportant	Neutral	Important	Extreme Important
	1	2	3	4	5
Work Efficiency					
• Transmission rate	☐	☐	☐	☐	☐
• System reliability and stability	☐	☐	☐	☐	☐
• Electromagnetic compatibility	☐	☐	☐	☐	☐
• Provision of fibre digital data interface (FDDI)	☐	☐	☐	☐	☐
• Further upgrade of system	☐	☐	☐	☐	☐
• Service life	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Cost Effectiveness					
• Initial costs	☐	☐	☐	☐	☐
• Operating and maintenance costs	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Technological Related					
• Existence of advanced IT system	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

3. ADDRESSABLE FIRE DETECTION AND ALARM SYSTEM (AFA)

Purpose: To provide effective fire detection, control and fighting.

	SCALE				
	Not Important at all 1	Unimportant 2	Neutral 3	Important 4	Extreme Important 5
Work Efficiency					
• Ability of automatic detection of flame/smoke/gas	☐	☐	☐	☐	☐
• Remote control	☐	☐	☐	☐	☐
• System response time and survivability	☐	☐	☐	☐	☐
• Comprehensive scheme of preventive maintenance	☐	☐	☐	☐	☐
• Service life	☐	☐	☐	☐	☐
• Further upgrade of system	☐	☐	☐	☐	☐
• System interface with other building systems	☐	☐	☐	☐	☐
• Integration with IBMS	☐	☐	☐	☐	☐
• *Others:*	☐	☐	☐	☐	☐
Safety Related					
• Compliance with the code of minimum fire service installations or equipment	☐	☐	☐	☐	☐
• Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Technological Related					
• Artificial intelligent (AI) based supervisory control	☐	☐	☐	☐	☐
• System modernization	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Cost Effectiveness					
• Initial costs	☐	☐	☐	☐	☐
• Operating and maintenance costs	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

4. HEATING, VENTILATION AND AIR-CONDITIONING (HVAC) CONTROL SYSTEM

Purpose: To enhance thermal comfort, humidity control, adequate ventilation, and to control IAQ.

	SCALE				
	Not Important at all	Unimportant	Neutral	Important	Extreme Important
	1	2	3	4	5
Environmental Related					
• Energy recycling	☐	☐	☐	☐	☐
• Total energy consumption	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
User Comfort					
• Control of predict mean vote (PMV)	☐	☐	☐	☐	☐
• Control of indoor air quality (IQA)	☐	☐	☐	☐	☐
• Optimum overall thermal transfer value (OTTV)	☐	☐	☐	☐	☐
• Provision of adequate fresh air changes	☐	☐	☐	☐	☐
• Minimisation of noise level from ventilation and A/C	☐	☐	☐	☐	☐
• Control of odour	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Work Efficiency					
• System reliability and stability	☐	☐	☐	☐	☐
• Detection of refrigerant leakage	☐	☐	☐	☐	☐
• Detection of condensate drain water leakage	☐	☐	☐	☐	☐
• Service life	☐	☐	☐	☐	☐
• Further upgrade of system	☐	☐	☐	☐	☐
• System interface with other building systems	☐	☐	☐	☐	☐
• Integration with IBMS	☐	☐	☐	☐	☐
Others	☐	☐	☐	☐	☐
Technological Related					
• Artificial intelligent (AI) based supervisory control	☐	☐	☐	☐	☐
• System modernization	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Cost Effectiveness					
• Initial costs	☐	☐	☐	☐	☐
• Operating and maintenance costs	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

5. DIGITAL ADDRESSABLE LIGHTING CONTROL SYSTEM (DALI)

Purpose: To provide overall illumination for all tenants and adequate lighting for public areas, and enhancing efficient lighting usage and energy conservation.

	SCALE				
	Not Important at all	Unimportant	Neutral	Important	Extreme Important
	1	2	3	4	5
Environmental Related					
- Permanent artificial lighting average glare index	☐	☐	☐	☐	☐
- Permanent artificial lighting average lux level	☐	☐	☐	☐	☐
- Total energy consumption	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
User Comfort					
- Adequate daylighting	☐	☐	☐	☐	☐
- Ventilation for excessive heat from lighting	☐	☐	☐	☐	☐
- Minimisation of noise from luminaries	☐	☐	☐	☐	☐
- Ease of control	☐	☐	☐	☐	☐
- Acceptable average colour temperature	☐	☐	☐	☐	☐
- Suitable colour rendering	☐	☐	☐	☐	☐
- Suitable glare level	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Work Efficiency					
- Permanent artificial lighting average power density	☐	☐	☐	☐	☐
- Uniformity of lux level	☐	☐	☐	☐	☐
- Automatic control and adjustment of lux level	☐	☐	☐	☐	☐
- Frequency of system maintenance	☐	☐	☐	☐	☐
- Service life	☐	☐	☐	☐	☐
- Further upgrade of system	☐	☐	☐	☐	☐
- System interface with other building systems	☐	☐	☐	☐	☐
- Integration with IBMS	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Technological Related					
- Artificial intelligent (AI) based supervisory control	☐	☐	☐	☐	☐
- System modernization	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Cost Effectiveness					
- Initial costs	☐	☐	☐	☐	☐
- Operating and maintenance costs	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

6. SECURITY MONITORING AND ACCESS CONTROL SYSTEM (SEC)

Purpose: To provide surveillance and access control to detect unauthorized entry and enhance security and safety inside the building.

	SCALE				
	Not Important at all 1	Unimportant 2	Neutral 3	Important 4	Extreme Important 5
Work Efficiency					
• Time needed for public announcement of disasters	☐	☐	☐	☐	☐
• Time needed to report disastrous event to building management	☐	☐	☐	☐	☐
• Time for total egress	☐	☐	☐	☐	☐
• Connectivity of CCTV system to security control system	☐	☐	☐	☐	☐
• Amount of monitored exits and entrances	☐	☐	☐	☐	☐
• Comprehensive scheme of preventive maintenance	☐	☐	☐	☐	☐
• Service life	☐	☐	☐	☐	☐
• Further upgrade of system	☐	☐	☐	☐	☐
• System interface with other building systems	☐	☐	☐	☐	☐
• Integration with IBMS	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Technological Related					
• Artificial intelligent (AI) based supervisory control	☐	☐	☐	☐	☐
• System modernization	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Cost Effectiveness					
• Initial costs	☐	☐	☐	☐	☐
• Operating and maintenance costs	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

7. SMART AND ENERGY EFFICIENT LIFT SYSTEM (LS)

Purpose: To transport passengers to the desired floor quickly, safety, and with comfort.

	SCALE				
	Not Important at all	Unimportant	Neutral	Important	Extreme Important
	1	2	3	4	5
Environmental Related					
- Total energy consumption	☐	☐	☐	☐	☐
- In-car and lobby noise control	☐	☐	☐	☐	☐
- Machine room noise control	☐	☐	☐	☐	☐
- Maximum allowable electrical power	☐	☐	☐	☐	☐
- Total harmonics distortion (THD) of motor drive systems	☐	☐	☐	☐	☐
- Regeneration into supply system	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
User Comfort					
- Control of acceleration and deceleration	☐	☐	☐	☐	☐
- Average illumination	☐	☐	☐	☐	☐
- Provision of adequate air change	☐	☐	☐	☐	☐
- Minimisation of in-car noise level	☐	☐	☐	☐	☐
- Minimisation of in-car vibration level	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Work Efficiency					
- Maximum interval time	☐	☐	☐	☐	☐
- Handling capacity	☐	☐	☐	☐	☐
- Journey time	☐	☐	☐	☐	☐
- Waiting time	☐	☐	☐	☐	☐
- Frequency of servicing and repair	☐	☐	☐	☐	☐
- Efficiency of drive and control system	☐	☐	☐	☐	☐
- Automatic and remote monitoring	☐	☐	☐	☐	☐
- Service life	☐	☐	☐	☐	☐
- Further upgrade of system	☐	☐	☐	☐	☐
- System interface with other building systems	☐	☐	☐	☐	☐
- Integration with IBMS	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Safety Related					
- Time to identify trapped passengers without a mobile phone	☐	☐	☐	☐	☐
- Mean time between failures per month	☐	☐	☐	☐	☐
- Safety regulations compliance	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

Technological Related					
- Artificial intelligent (AI) based supervisory control	☐	☐	☐	☐	☐
- System modernization	☐	☐	☐	☐	☐
- Architectural design/ image	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐
Cost Effectiveness					
- Initial costs (including purchase, delivery and fixing costs)	☐	☐	☐	☐	☐
- Operating and maintenance costs (including disposal cost)	☐	☐	☐	☐	☐
Others:	☐	☐	☐	☐	☐

PART 2: PERSONAL PROFILE

1. Name of respondent:______________________________

2. Your gender: ☐ Male ☐ Female

3. Your title/ work type:______________________________

4. Year of experience:______________________________

5. What is your highest attainment in education?

   ☐ High school graduate ☐ Diploma ☐ Bachelor degree ☐ Masters degree
   ☐ Doctorate degree ☐ Other(s), please specify:______________

6. What is your age group?

   ☐ Below 25 ☐ 25 to 34 ☐ 35-44 ☐ 45-55 ☐ 55 or above

7. Have you participated in any types of intelligent building project (i.e. design, construction, or decision making) in your current or previous experience?

   ☐ YES ☐ NO

8. If your answer to the above question is 'Yes', would you like to participate our second stage questionnaire survey in the future?

   ☐ YES ☐ NO

9. Your contact details:

   Corresponding address: ______________________________

   ____

   Email account: ______________________________

Thank you so much for your kind participation in this survey.

~END~

APPENDIX A2: QUESTIONNAIRE FOR THE AHP SURVEY (RESEARCH PART ONE)

Questionnaire Survey (Round 2)

Weighting and Ranking of Selection Criteria of the Intelligent Building Control Systems

INTRODUCTION

This questionnaire aims at obtaining information from experts about their experience in selecting intelligent building control systems. It is divided into two parts (Part I: Pair-wise Comparison of Critical Selection Criteria (CSC), and Part II: Personal Profile). It may require less than 30 minutes for completion. Those who want for a report by post, please state your name and address in the returned questionnaire. All data provided will be kept in the strictest confidence and will only be used to produce aggregated statistics. These data will not be made available to any third party and will be destroyed after the completion of the thesis. Before providing your opinions, please read the instruction on the following two pages carefully.

All collected data will be kept strictly confidential and anonymous, and they will be used for academic research purposes ONLY. Thank you

Please kindly completed the questionnaire and return to the following address by post within 21 days. Thank you very much for your participation.

Johnny WONG (PhD Candidate)
Department of Building and Real Estate
The Hong Kong Polytechnic University
Hunghom, Kolwoon
Hong Kong

INSTRUCTION

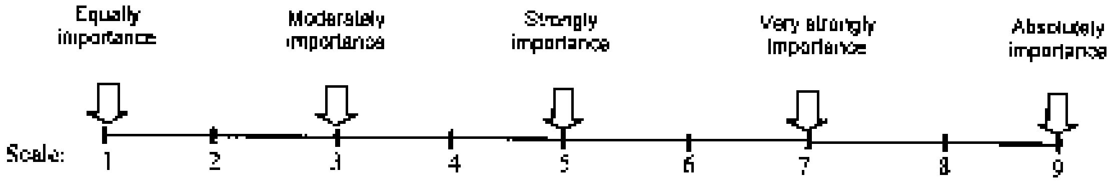
This part is designed based on the results of first survey of our study. It is intended to prioritize the selection factors and criteria of intelligent building control systems. This section employs the 'pair-wise comparison' concept (developed by Saaty, 1980) to prioritize some elements within each judgment matrix, which is simple and easy to complete.

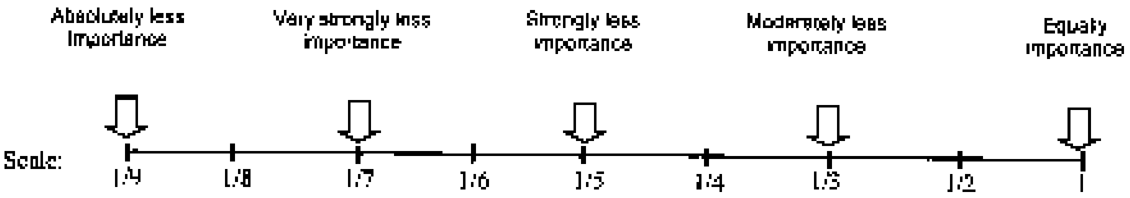
The following concepts are provided for your reference which may be useful for providing your answers:

Pair-wise Comparison	Pair-wise comparison is to compare two items at one time for the purpose of generating more information for analysis. However it is very sensitive in detecting the consistency of your answers. So, please fill in your answers in a logical sequence. For example, suppose there are three items to compare (i.e. A, B and C). If A is 3 times more important than B

	while B is 2 times more important than C, then A will be 6 times more important than C. If someone puts that C is 2 times more important than A, this becomes a violation of logical sequence and an inconsistency value will be computed using the consistency ratio method. If someone puts that A is 2 times more important than C, this sounds logical but a low consistency will be computed since A should be 6 times more important than C.
Intelligent Building	A dynamic and responsive architecture that provides occupants with productive, cost effective, and environmentally approved conditions through a continuous interaction amongst its four basic elements: places (fabrics; structure; facilities), processes (automation; control; systems), people (services, users); and management (maintenance, performance), and the interrelation between them.
Intelligent Building Control Systems	It refers to the major building control systems operated in intelligent building. This study includes seven key building systems which includes Integrated Building Management System (IBMS); Telecom and Data System (ITS); Heating Ventilation Air-Conditioning Control System (HVAC); Addressable Fire Detection and Alarm System (AFA); Security Monitoring and Access Control System (SEC); Smart and Energy Efficient Lift System (LS); and Digital Addressable Lighting Control System (DALI).
Integrated Building Management System (IBMS)	This system integrates all essential building services systems to provide an overall strategic management in all aspects with the capacity to systematic analysis and report the building performance and connect with multiple site/location to give corporation a portfolio view of the situation. It also aims to provide automatic functional control and maintain the building's normal daily operation. In present time when IBMS has been upgraded to include many functions of building automation system (BAS).
Telecom and Data System (ITS)	This system provides information and communication network linkage inside and outside the building through wireless network, fibre optic network, or other advanced network system.
Addressable Fire Detection and Alarm System (AFA)	It refers to the fire detection, fighting and resistance system of the building. Examples of components include automatic fire alarms, sensors, detectors, etc.
Heating Ventilation Air-Conditioning (HVAC) Control System	An HVAC system is comprised by all the components of the appliance used to condition the interior air of a building. This system is needed to provide the occupants with a comfortable and productive working environment which satisfies their physiological needs. Examples of HVAC components include sensors, controllers, and monitoring programs
Digital Addressable Lighting Control System (DALI)	The illumination system in intelligent building to provide overall illumination for all tenants and adequate lighting for public areas, and enhancing efficient lighting usage and energy conservation.
Security Monitoring and Access Control System (SEC)	This system aims to enhance safety and security of the building through the interaction of different safety and security components or devices, for example: sensors, detectors, alarm, CCTV surveillance system, and access control system, etc
Smart and Energy Efficient Lift System (LS)	It aims to transport passengers to the desired floor quickly, safety, and with comfort.

Please note your answer should be provided according to the following rating scale:





Explanations of the above rating scale:

1	The two items are equally important
3	The left (row) item is more important to a moderate extent when compared to the column item
5	The left item is more important to a large extent when compared to the column item
7	The left item is more important to a very large extent when compared to the column item
9	The left item is more important to an absolutely large extent when compared to the column item
2, 4, 6, 8	An intermediate value between two adjacent judgments
1/3	The left (row) item is less important to a moderate extent when compared to the column item
1/5	The left item is less important to a large extent when compared to the column item
1/7	The left item is less important to a very large extent when compared to the column item
1/9	The left item is less important to an absolutely large extent when compared to the column item
1/2, 1/4, 1/6, 1/8	An intermediate value between two adjacent judgments

Only one answer for each paired comparison. **Those boxes marked with 'xxx' are <u>no need</u> to fill in any answers.** Taking the questions on the IBMS1 as an example:

ILLUSTRATED EXAMPLE:

IBMS1: Please compare the degree of impact of the following main factors on the selection of the IBMS.

This answer shows that 'Work Efficiency' is moderately important (scale '3') than 'Cost Effectiveness' as a main factor for IBMS selection

Main Factors	Work Efficiency	Cost Effectiveness (O&M Costs)
Work Efficiency	xxx	3
Cost Effectiveness (O&M Costs)	xxx	xxx

After answering question IBMS1 (rating the main selection factors), we now rate the level of importance of various selection criteria under the factor (i.e. 'Work Efficiency') in affecting IBMS selection.

IBMS2: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	System reliability and stability	Integration and interface with services control systems	Efficiency and accuracy
System reliability and stability	xxx	3	[redacted]
Integration and interface with services control systems	xxx	xxx	1/6
Efficiency and accuracy	xxx	xxx	xxx

It shows that 'reliability' is moderately important (scale '3') than 'capability of integrating systems' as a criterion in affecting the IBMS selection

It means that 'reliability' is slightly less important (scale '1/2') than 'efficiency' as a criterion in affecting IBMS selection

Compared to 'efficiency', 'capability of integrating systems' is very strongly to absolutely less important (scale '1/6') in affecting IBMS selection

<u>Please ensure the consistency in your answers in the questionnaire</u>

Please proceed to the following to begin the survey.

PART I: PAIR-WISE COMPARISON OF CRITICAL SELECTION CRITERIA

SYSTEM 1: INTEGRATED BUILDING MANAGEMENT SYSTEM (IBMS)

IBMS1: Please compare the degree of impact of the following main factors on the selection of the IBMS

Main Factors	Work Efficiency	Cost Effectiveness (O&M costs)
Work Efficiency	xxx	
Cost Effectiveness (O&M Costs[1])	xxx	xxx

Note 1: Operating and maintenance costs refer to the costs of running, operating, maintaining and disposing of the building components

IBMS2: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	System reliability and stability	Integration and interface with services control systems	Efficiency and accuracy
System reliability and stability	xxx		
Integration and interface with services control systems	xxx	xxx	
Efficiency and accuracy	xxx	xxx	xxx

SYSTEM 2: TELECOM AND DATA SYSTEM (ITS)

ITS1: Please compare the degree of impact of the following main factors on the selection of the ITS

Main Factors	Work Efficiency	Cost Effectiveness (O&M Costs)
Work Efficiency	xxx	
Cost Effectiveness (O&M Costs)	xxx	xxx

ITS2: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	System reliability and stability	Further upgrade of system	Service life	Transmission rate of data
System reliability and stability	xxx			
Further upgrade of system	xxx	xxx		
Service life	xxx	xxx	xxx	
Transmission rate of data	xxx	xxx	xxx	xxx

SYSTEM 3: ADDRESSABLE FIRE DETECTION AND ALARM SYSTEM (AFA)

AFA1: Please compare the degree of impact of the following main factors on the selection of AFA

Main Factors	**Work Efficiency**	**Cost Effectiveness** (O&M Costs)	**Safety**
Work Efficiency	xxx		
Cost Effectiveness (O&M Costs)	xxx	xxx	
Safety	xxx	xxx	xxx

AFA2: Please compare the degree of importance of the following selection criteria under the factor of '**Safety**'.

Selection Criteria	Compliance with the code of minimum fire service installations or equipment	Compliance with the code for inspection, testing and maintenance of fire service installations and equipment
Compliance with the code of minimum fire service installations or equipment	xxx	
Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	xxx	xxx

AFA3: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	System response time and survivability	Further upgrade of system	Automatic detection of fire, gas and smoke	Service life
System response time and survivability	xxx			
Further upgrade of system	xxx	xxx		
Automatic detection of fire, gas and smoke	xxx	xxx	xxx	
Service life	xxx	xxx	xxx	xxx

SYSTEM 4: HVAC CONTROL SYSTEM

HVAC1: Please compare the degree of impact of the following main factors on the selection of HVAC control system.

Main Factors	**Work Efficiency**	**User Comfort**	**Environmental** (Total energy consumption)	**Cost Effectiveness**
Work Efficiency	xxx			
User Comfort	xxx	xxx		
Environmental (Total energy consumption)	xxx	xxx	xxx	
Cost Effectiveness	xxx	xxx	xxx	xxx

HVAC2: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	Service life	System reliability and stability	Integrated by IBMS	Interface with other building control systems
Service life	xxx			
System reliability and stability	xxx	xxx		
Integrated by IBMS	xxx	xxx	xxx	
Interface with other building control systems	xxx	xxx	xxx	xxx

Note 2: Compatibility refers to the level of one building system would be compatible with other building systems in order to work and cooperate together to perform a function.

HVAC3: Please compare the degree of importance of the following selection criteria under the factor of **'User Comfort'**.

Selection Criteria	Control of predict mean vote[3]	Control of indoor air quality[4]	Minimisation of plant noise	Adequate fresh air changes
Control of predict mean vote	xxx			
Control of indoor air quality	xxx	xxx		
Minimisation of plant noise	xxx	xxx	xxx	
Adequate fresh air changes	xxx	xxx	xxx	xxx

Note 3: Predict mean vote is a measure for the thermal comfort of the occupants incorporating relative humidity and mean radiant temperature

4. Indoor air quality is defined as air in which there are no contaminants at harmful concentrations and with which a substantial majority of the people are satisfied

HVAC4: Please compare the degree of importance of the following selection criteria under the factor of **'Cost Effectiveness'**

Selection Criteria	Initial costs	O&M costs
Initial costs	xxx	
O&M costs	xxx	xxx

SYSTEM 5: DIGITAL ADDRESSABLE LIGHTING CONTROL SYSTEM (DALI)

DALI1: Please compare the degree of impact of the following main factors on the selection of the DALI.

Main Factors	Work Efficiency	User Comfort (Ease of control)	Environmental (Total energy consumption)	Cost Effectiveness (O&M costs)
Work Efficiency	xxx			
User Comfort (Ease of control)	xxx	xxx		
Environmental (Total energy consumption)	xxx	xxx	xxx	
Cost Effectiveness (O&M costs)	xxx	xxx	xxx	xxx

DALI2: Please compare the degree of importance of the following selection criteria under the factor of **'Work Efficiency'**.

Selection Criteria	Interface with other building control systems	Integrated by IBMS	Permanent artificial lighting average power density	Further upgrade of system	Service life	Automatic control and adjustment of lux level
Interface with other building control systems	xxx					
Integrated by IBMS	xxx	xxx				
Permanent artificial lighting average power density	xxx	xxx	xxx			
Further upgrade of system	xxx	xxx	xxx	xxx		
Service life	xxx	xxx	xxx	xxx	xxx	
Automatic control and adjustment of lux level	xxx	xxx	xxx	xxx	xxx	xxx

SYSTEM 6: SECURITY MONITORING AND ACCESS CONTROL SYSTEM (SEC)

SEC1: Please compare the degree of impact of the following main factors on the selection of SEC.

Main Factors	**Work Efficiency**	**Cost Effectiveness**
Work Efficiency	xxx	
Cost Effectiveness	xxx	xxx

SEC2: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	Time needed for public announcement of disasters	Time needed to report a disastrous event to building management	Interface with other building control systems	Integrated by IBMS	Service life	Further upgrade of system	Time for total egress
Time needed for public announcement of disasters	xxx						
Time needed to report a disastrous event to building management	xxx	xxx					
Interface with other building control systems	xxx	xxx	xxx				
Integrated by IBMS	xxx	xxx	xxx	xxx			
Service life	xxx	xxx	xxx	xxx	xxx		
Further upgrade of system	xxx	xxx	xxx	xxx	xxx	xxx	
Time for total egress	xxx	xxx	xxx	xxx	xxx	xxx	xxx

SEC3: Please compare the degree of importance of the following selection criteria under the factor of '**Cost Effectiveness**'.

Selection Criteria	Initial costs	O&M costs
Initial costs	xxx	
O&M costs	xxx	xxx

SYSTEM 7: SMART AND ENERGY EFFICIENT LIFT SYSTEM (LS)

LS1: Please compare the degree of impact of the following main factors on the selection of the LS.

Main Factors	**Work Efficiency**	**User Comfort**	**Safety** (Mean time between failures)	**Environmental** (Total energy consumption)	**Cost Effectiveness** (O&M costs)
Work Efficiency	xxx				
User Comfort	xxx	xxx			
Safety (Mean time between failures)	xxx	xxx	xxx		
Environmental (Total energy consumption)	xxx	xxx	xxx	xxx	
Cost Effectiveness (O&M costs)	xxx	xxx	xxx	xxx	xxx

LS2: Please compare the degree of importance of the following selection criteria under the factor of '**Work Efficiency**'.

Selection Criteria	Service life	Waiting time	Maxi interval time	Journey time	Integrated by IBMS	Interface with other bldg control systems	Automatic and remote control
Service life	xxx						
Waiting time	xxx	xxx					
Maximum interval time	xxx	xxx	xxx				
Journey time	xxx	xxx	xxx	xxx			
Integrated by IBMS	xxx	xxx	xxx	xxx	xxx		
Interface with other building control systems	xxx	xxx	xxx	xxx	xxx	xxx	
Automatic and remote control	xxx	xxx	xxx	xxx	xxx	xxx	xxx

LS3: Please compare the degree of importance of the following selection criteria under the factor of '**User Comfort**'.

Selection Criteria	Minimisation of in-car noise	Acceleration and deceleration control	Adequate in-car fresh air changes	Minimisation of in-car vibration
Minimisation of in-car noise	xxx			
Acceleration and deceleration control	xxx	xxx		
Adequate in-car fresh air changes	xxx	xxx	xxx	
Minimisation of in-car vibration	xxx	xxx	xxx	xxx

PART II: PERSONAL PROFILE

Name of respondent:________________

Your title/ work type:________________

Year of experience:________________

You have completed the Questionnaire.

Thank you very much for your kind assistance and help.

- END -

APPENDIX A3: QUESTIONNAIRE FOR THE GENERAL SURVEY (RESEARCH PART TWO)

Questionnaire Survey (Round I)

Measuring the Degree of 'Intelligence' of the Building Control Systems

INSTRUCTIONS

This survey intends to elicit and identify the most 'suitable' intelligence indicators for 7 common building control systems in the commercial intelligent buildings, including:

1. Integrated Building Management System (IBMS);
2. Telecom and Data System (TDS);
3. Heating Ventilation Air-Conditioning (HVAC) Control System;
4. Addressable Fire Detection and Alarm System (AFA);
5. Security Monitoring and Access Control System (SEC);
6. Smart and Energy Efficient Lift System (LS); and,
7. Digital Addressable Lighting Control System (DALI).

This questionnaire is structured in 7 sub-sections based on the building control systems described above. The proposed intelligence indicators are grouped under four (4) intelligence attributes, which are extracted from the literature. The four intelligence attributes listed are outlined for your evaluation:

- **Autonomy:** Abilities on performing self-operative functions.
- **Controllability for Complicated Dynamics:** Abilities on performing interactive operative functions.
- **Man-machine Interaction:** Abilities on interfacing with operator and working staff.
- **Bio-inspired Behaviour:** Abilities on interact with the built environment and the services provided.

Within each of the above attributes, specific functional characteristics are stated. You are invited to mark your answer with '☒' for each of these characteristics according to the following scale [***1= Not suitable; 2= Less suitable; 3= Suitable; 4= More suitable; and, 5= Most suitable***] for measuring the suitability of the system 'intelligence' measures for each of the building control systems. You are also welcome to put in additional intelligence indicators, if necessary.

Please answer the questions based on actual building control systems and their operation status that your company owns/ designs/ manages. Upon completion, please return the completed questionnaire to the address below or send to email address: xxxxxxxxx@polyu.edu.hk **within 21 days**.

All collected data will be kept strictly confidential and anonymous, and they will be used for academic research purposes ONLY. Thank you

Johnny WONG, PhD Candidate
Department of Building and Real Estate,
The Hong Kong Polytechnic University, Hung Hom, Kowloon

PART I: PERSONAL PROFILE

1. Name of respondent:____

2. Your title/ work type:____

3. Year of experience:____

4. Are you currently, recently and directly, involved in the intelligent building development specially relating to the design and decision on the building control systems and components?

   ☐ YES (Go to Q.5) ☐ NO (Go to Q.6)

5. Your experience of intelligent building development/ management / operation (Please cross or tick the following):

   ☐ commercial/retail
   ☐ commercial/recreational
   ☐ residential/single block-villa
   ☐ others (Please specify:)
   ☐ commercial/office
   ☐ industrial/warehouse
   ☐ residential/complex
   ☐ commercial/hotel-resort
   ☐ industrial/manufacturing

6. Do you have an extensive knowledge of the intelligent building technologies?

   ☐ YES ☐ NO

7. Would you like to participate in further survey in this research?

   ☐ YES ☐ NO

8. Corresponding address:____

9. Email account:____

PART 2: IDENTIFICATION OF THE MOST "SUITABLE" INTELLIGENT INDICATORS

1. INTEGRATED BUILDING MANAGEMENT SYSTEM (IBMS)

Purpose: To integrate all essential building services systems to provide an overall strategic management in all aspects with the capacity to systematic analysis and report the building performance and connect with multiple site/location to give corporation a portfolio view of the situation. It also aims to provide automatic functional control and maintain the building's normal daily operation (Note: in present time when IBMS has been upgraded to include many functions of building automation system)

	SCALE				
	Not Suitable	Less Suitable	Suitable	More Suitable	Most Suitable
	1	2	3	4	5
Autonomy					
• Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
• Self-diagnostic of operation deviations	☐	☐	☐	☐	☐
• Year-round time schedule operation	☐	☐	☐	☐	☐
Comments:					
Controllability for Complicated Dynamics					
• Ability to link multiple standalone building control systems from a variety of manufacturers (interoperability)	☐	☐	☐	☐	☐
• Remote control via internet	☐	☐	☐	☐	☐
• Ability to connect multiple locations	☐	☐	☐	☐	☐
• Alarms and events statistics	☐	☐	☐	☐	☐
• Control and monitor HVAC equipments on sequence control, time scheduling, thermal comfort, ventilation, fault recovery operations	☐	☐	☐	☐	☐
• Control and monitor lighting time schedule / zoning operation	☐	☐	☐	☐	☐
• Control and monitor security system interlock operation with "other services"	☐	☐	☐	☐	☐
• Control and monitor fire detection interlock operation with "other services"	☐	☐	☐	☐	☐
• Control and monitor vertical transportation operation.	☐	☐	☐	☐	☐
Comments:					
Man-machine Interaction					
• Web based interface to any location and wireless terminal for functional access (i.e. PALM, pocket PC, mobile phone)	☐	☐	☐	☐	☐
• Reports generation and output of statistical and trend profiling of controls and operations	☐	☐	☐	☐	☐
• Ability to provide operational and analytical functions for totalized building performance review	☐	☐	☐	☐	☐
• Single operation system/ platform for multiple location supervision	☐	☐	☐	☐	☐
• Graphical representation and real-time interactive operation action	☐	☐	☐	☐	☐

icons					
• Run continually with minimal human supervision	☐	☐	☐	☐	☐
Comments:					
Bio-Inspired Behaviour					
▪ Analyse operation function parameters to select the best and effective operation logic to run the building services systems over time	☐	☐	☐	☐	☐
• Automatically adapt to daily occupied space changes to control building services systems	☐	☐	☐	☐	☐
• Provide adaptive control algorithms based on seasonal changes to control building services systems (i.e. outdoor temperature, humidity, time of sun rise/sun set)	☐	☐	☐	☐	☐
Comments:					

2. TELECOM AND DATA SYSTEM (TDS)

Purpose: To provide effective and efficient information transmission and exchange inside and outside building

	SCALE				
	Not suitable	Less Suitable	Suitable	More Suitable	Most Suitable
	1	2	3	4	5
Autonomy					
▪ Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
▪ Self-diagnosis to detect the timeworn parts	☐	☐	☐	☐	☐
Comments:					
Controllability for Complicated Dynamics					
• Integrate multiple network or service providers	☐	☐	☐	☐	☐
• Transmission capacity control and diversion	☐	☐	☐	☐	☐
• All digital system	☐	☐	☐	☐	☐
Comments					
Man-machine Interaction					
• Fixed hub/terminal port installed for flexibility connections and expansions	☐	☐	☐	☐	☐
• System life and turn-round complexity	☐	☐	☐	☐	☐
▪ End-user terminal provisions	☐	☐	☐	☐	☐
Comments:					
Bio-Inspired Behaviour					
• Interactive voice system	☐	☐	☐	☐	☐
• Transmission/processing analysis	☐	☐	☐	☐	☐
Comments:					

3. HEATING VENTILATION AIR CONDITIONING CONTROL SYSTEM (HVAC)

Purpose: To enhance thermal comfort, humidity control, adequate ventilation, and to control IAQ.

	SCALE				
	Not suitable	Less Suitable	Suitable	More Suitable	Most Suitable
	1	2	3	4	5
Autonomy					
• Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
• Sensing the internal temperature and humidity, and auto-adjustment of systems	☐	☐	☐	☐	☐
• Sensing of external temperature and humidity, and auto-adjustment of systems	☐	☐	☐	☐	☐
• Automated fault detection	☐	☐	☐	☐	☐
• Self-diagnosis to detect the timeworn parts	☐	☐	☐	☐	☐
Comments:					
Controllability for Complicated Dynamics					
• Operation control mechanism to achieve efficient power consumption	☐	☐	☐	☐	☐
• Interface with Energy Management System, Building Automation System and/or Integrated Building Management System	☐	☐	☐	☐	☐
• Interact with lighting and sun-blinds systems	☐	☐	☐	☐	☐
Comments:					
Man-machine Interaction					
• Provide management staff with database and analytical tools for operation and service evaluation	☐	☐	☐	☐	☐
• Pre-programmed responses and zoning control	☐	☐	☐	☐	☐
• Graphical representation and real-time interactive operation action icons	☐	☐	☐	☐	☐
Comments:					
Bio-inspired Behaviour					
• Adaptive to occupancy work pattern	☐	☐	☐	☐	☐
• Utilise natural ventilation control to reduce air-conditioning power consumption	☐	☐	☐	☐	☐
Comments:					

4. ADDRESSABLE FIRE DETECTION AND ALARM SYSTEM (AFA)

Purpose: To provide effective fire detection, control and fighting.

	SCALE				
	Not suitable	Less Suitable	Suitable	More Suitable	Most Suitable
	1	2	3	4	5
Autonomy					
• Alarm deployment algorithm within the building and notification to Fire Department	☐	☐	☐	☐	☐
• Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
• Self-diagnostic analysis for false alarm reduction	☐	☐	☐	☐	☐
• Self test of sensors, detectors and control points	☐	☐	☐	☐	☐
• Self-diagnosis to detect the timeworn parts	☐	☐	☐	☐	☐
Comments:					
Controllability for Complicated Dynamics					
• Integration and control of sensors, detectors, fire-fighting equipment	☐	☐	☐	☐	☐
• Interface with Energy Management System, Building Automation System and/or Integrated Building Management System	☐	☐	☐	☐	☐
• Interact with security systems	☐	☐	☐	☐	☐
• Interact with HVAC systems	☐	☐	☐	☐	☐
• Interact with lift systems	☐	☐	☐	☐	☐
• Interact with emergency generator systems	☐	☐	☐	☐	☐
Comments:					
Man-machine Interaction					
• Run continually with minimal human supervision	☐	☐	☐	☐	☐
• Provide management staff with database and analytical tools for operation and service evaluation	☐	☐	☐	☐	☐
• Provide access for tenants and occupants concurrent information of the services provision	☐	☐	☐	☐	☐
• Pre-scheduled of special events and incidents	☐	☐	☐	☐	☐
Comments:					
Bio-inspired Behaviour					
• Analysis of alarm and false alarm events patterns	☐	☐	☐	☐	☐
Comments:					

5. SECURITY MONITORING AND ACCESS CONTROL SYSTEM (SEC)

Purpose: To provide surveillance and access control to detect unauthorized entry and enhance security and safety inside the building.

	SCALE				
	Not suitable 1	Less Suitable 2	Suitable 3	More Suitable 4	Most Suitable 5
Autonomy					
- Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
- Sabotage proof to resist physical damage and modification	☐	☐	☐	☐	☐
- Self-diagnosis to detect the timeworn parts	☐	☐	☐	☐	☐
Comments:					
Controllability for Complicated Dynamics					
- Dynamic programming (routing, time schedule, monitoring sequence, control reaction, etc.)	☐	☐	☐	☐	☐
- Configurable to accurately implement the security policies for the premises	☐	☐	☐	☐	☐
- Interface with other system, e.g. communication network, phone system, etc	☐	☐	☐	☐	☐
- Interface with Energy Management System: Building Automation System and/or Integrated Building Management System	☐	☐	☐	☐	☐
- Multiple detection or verification mechanism	☐	☐	☐	☐	☐
Comments:					
Man-machine Interaction					
- Run continually with minimal human supervision	☐	☐	☐	☐	☐
- Provide management staff with database and analytical tools for operation and service evaluation	☐	☐	☐	☐	☐
- Provide access for tenants and occupants concurrent information of the services provision	☐	☐	☐	☐	☐
- Pre-scheduled set up of special events and normal routines:	☐	☐	☐	☐	☐
Comments:					
Bio-inspired Behaviour					
- Human behaviour analysis and diagnostic	☐	☐	☐	☐	☐
- Adaptive to demands in high traffic or occupancy situations	☐	☐	☐	☐	☐
Comments:					

6. SMART AND ENERGY EFFICIENT LIFT SYSTEM (LS)

Purpose: To transport passengers to the desired floor quickly, safety, and with comfort.

	SCALE				
	Not suitable	Less Suitable	Suitable	More Suitable	Most Suitable
	1	2	3	4	5
Autonomy					
▪ Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
▪ Auto-controlled navigation at emergency (with remote override)	☐	☐	☐	☐	☐
▪ On-line data logging facilitating routine maintenance	☐	☐	☐	☐	☐
▪ Self-diagnosis to detect the timeworn parts	☐	☐	☐	☐	☐
Comments					
Controllability for Complicated Dynamics					
▪ Accommodate changes of passenger traffic pattern (up peak/ down peak)	☐	☐	☐	☐	☐
▪ Remote monitoring	☐	☐	☐	☐	☐
▪ On-line investigation and analysis of lift activity	☐	☐	☐	☐	☐
▪ Interface with Energy Management System, Building Automation System and/or Integrated Building Management System	☐	☐	☐	☐	☐
Comments:					
Man-machine Interaction					
▪ Human engineering design to facilitate convenience of passengers (i.e. voice announcement, fit for disables, lighting, floor display up/down, etc)	☐	☐	☐	☐	☐
▪ Provide management staff with database and analytical tools for operation and service evaluation (i.e. levelling performance)	☐	☐	☐	☐	☐
▪ Provide access for tenants and occupants concurrent information of the services provision	☐	☐	☐	☐	☐
▪ Pre-scheduled of special events and normal routines	☐	☐	☐	☐	☐
Comments:					
Bio-inspired Behaviour					
▪ User designation, verification and specific control (static sectoring or dynamic sectoring)	☐	☐	☐	☐	☐
▪ Integration with building usage schedule for travel programming	☐	☐	☐	☐	☐
Comments:					

7. DIGITAL ADDRESSABLE LIGHTING CONTROL SYSTEM (DALI)

Purpose: To provide overall illumination for all tenants and adequate lighting for public areas, and enhancing efficient lighting usage and energy conservation.

	SCALE				
	Not suitable 1	Less Suitable 2	Suitable 3	More Suitable 4	Most Suitable 5
Autonomy					
• Adaptive limiting control algorithm (e.g. max/min threshold limiter, fault-tolerance adaptation)	☐	☐	☐	☐	☐
• Monitoring capabilities that lamp performance and hours run can be logged	☐	☐	☐	☐	☐
• Self-diagnosis to detect the timeworn parts	☐	☐	☐	☐	☐
Comments:					
Controllability for Complicated Dynamics					
• Adaptive to occupancy work schedule	☐	☐	☐	☐	☐
• Presence detection (i.e. dimmable occupancy sensor, access triggered control)	☐	☐	☐	☐	☐
• Control of individual luminaries, groups of luminaries or lighting zone	☐	☐	☐	☐	☐
• Interface with Energy Management System, Building Automation System and/or Integrated Building Management System	☐	☐	☐	☐	☐
Comments:					
Man-machine Interaction					
• Provide management staff with database and analytical tools for operation and service evaluation	☐	☐	☐	☐	☐
• Provide access for tenants and occupants concurrent information of the services provision	☐	☐	☐	☐	☐
• Pre-programmed response and control	☐	☐	☐	☐	☐
• User interface via internet/intranet or remote control	☐	☐	☐	☐	☐
Comments:					
Bio-inspired Behaviour					
• Provide multiple level and control mode for occupants to program custom-mode settings	☐	☐	☐	☐	☐
• Sensing the light intensity and angle of projection and solar radiation to maximise natural light/reduce lighting power (i.e. photoelectric switching and dimming controls)	☐	☐	☐	☐	☐
• Automatic lighting or shading controls	☐	☐	☐	☐	☐
Comments:					

Thank you for completing the questionnaire. We appreciate your time.

~ END ~

APPENDIX A4: QUESTIONNAIRE FOR THE AHP-ANP SURVEY (RESEARCH PART TWO)

Questionnaire Survey (Round 2)

System Intelligence of Intelligent Building Systems

INTRODUCTION

This research study intends to investigate and evaluate the system intelligence of the key building systems especially in the commercial type of intelligent building (IB). Previous survey (Round 1) was designed to elicit a group of suitable indicators to assess the intelligent level of key IB systems. In this survey (Round 2), we aim to prioritize these identified indicators (i.e. by pair-wise comparison), and to investigate the interdependent relationships between the intelligence attributes of each building control systems and the operational benefits of the intelligent building.

Your inputs are tremendously valuable and we do hope that you can participate in this final survey. It would be much appreciated if you could spend around 30 minutes to complete and return the completed questionnaire by sending it to email address: xxxxxxxxn@polyu.edu.hk within **21 days**. Should you have any queries, please feel free to contact Mr. Johnny Wong at 2766 xxxx. Thank you again for your time and efforts on this research.

INSTRUCTION:

- Each section in this survey consists of a number of question sets. Each question within a question set asks you to compare two factors/criteria at a time (i.e. pair-wise comparisons) with respect to a third factor/criterion.

- Please read each question carefully before giving your opinions/answers, and answer according to the following rating scale:

1	–	the two factors are **equally important**;
2 on the left (right)	–	the left (right) factor is more important to **a small extent** than the right (left) factor;
3 on the left (right)	–	the left (right) factor is more important to a **moderate extent** than the right (left) factor;
4 on the left (right)	=	an intermediate value between 3 and 5;
5 on the left (right)	=	the left (right) factor is more important to a **larger extent** than the right (left) factor;
6 on the left (right)	–	an intermediate value between 5 and 7;
7 on the left (right)	=	the left (right) factor is more important to a **very large extent** than the right (left) factor,
8 on the left (right)	–	an intermediate value between 7 and 9; and,
9 on the left (right)	=	the left (right) factor is more important to **an absolutely large extent** than the right (left) factor.

- The definitions of intelligence attributes are provided for your reference:

  Autonomy (AUT): abilities to allow minimum human intervention as much as possible during execution of task.

  Controllability for complicated dynamics (CCD): a very complicated dynamic system is well-controlled.

  Man-machine interaction (MMI): abilities to make the human users to feel more comfortable and use-friendly.

  Bio-inspired behaviour (BIB): abilities on interact with the built environment and the services provided.

EXAMPLE:

The question asks you to compare the relative importance two intelligence attributes with respect to an 'intelligent' integrated building management system (IBMS): 'autonomy' versus 'controllability for complicated dynamics'. A '9' on the right (9☒) means 'autonomy' is absolutely less important compared to 'controllability for complicated dynamics', and a '9' on the left (9☒) means that 'autonomy' is absolutely more important compared to 'controllability for complicated dynamics'. A '1' means equal importance.

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD

Note: AUT = Autonomy; CCD = Controllability for complicated dynamics

In above demonstration, we put in 5☒ on the right that 'autonomy' is less important than 'controllability for complicated dynamics' as an attribute to an optimum IBMS with a value of 1/5.

SYSTEM 1: INTEGRATED BUILDING MANAGEMENT SYSTEM (IBMS)

Relative importance of the following **intelligence attributes** with respect to an 'intelligent' IBMS

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Note: AUT = Autonomy; CCD = Controllability for complicated dynamics; MMI = Man-machine interaction; BIB = Bio-inspired behaviour

Relative importance of the following intelligence measures (or indicators) with respect to **autonomy** attribute

Column 1		Column 2
Adaptive limiting control algorithm	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self-diagnostic of operation deviations
Adaptive limiting control algorithm	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Year-round time schedule operation
Self-diagnostic of operation deviations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Year-round time schedule operation

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics** attribute

Column 1		Column 2
Link multiple standalone bldg. control systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Remote control via internet
Link multiple standalone bldg. control systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Ability to connect multiple locations
Link multiple standalone bldg. control systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Alarms & events statistics
Link multiple standalone bldg. control systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor HVAC equipments

Link multiple standalone bldg. control systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor lighting time schedule
Remote control via internet	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Ability to connect multiple locations
Remote control via internet	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Alarms & events statistics
Remote control via internet	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor HVAC equipments
Remote control via internet	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor lighting time schedule
Ability to connect multiple locations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Alarms & events statistics
Ability to connect multiple locations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor HVAC equipments
Ability to connect multiple locations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor lighting time schedule
Alarms & events statistics	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor HVAC equipments
Alarms & events statistics	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor lighting time schedule
Control & monitor HVAC equipments	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control & monitor lighting time schedule

Relative importance of the following intelligence measures (or indicators) with respect to **man-machine interaction** attribute

Column 1		Column 2
Reports generation, output of statistical, trend profiling of controls & operations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Provide operational and analytical functions for totalized building performance review
Reports generation, output of statistical, trend profiling of controls & operations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Single operation system/ platform for multiple location supervision
Reports generation, output of statistical, trend profiling of controls & operations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Graphical representation and real-time interactive operation action icons

Reports generation, output of statistical, trend profiling of controls & operations	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Run continually with minimal human supervision
Provide operational and analytical functions for totalized building performance review	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Single operation system/ platform for multiple location supervision
Provide operational and analytical functions for totalized building performance review	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Graphical representation and real-time interactive operation action icons
Provide operational and analytical functions for totalized building performance review	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Run continually with minimal human supervision
Single operation system/ platform for multiple location supervision	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Graphical representation and real-time interactive operation action icons
Single operation system/ platform for multiple location supervision	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Run continually with minimal human supervision
Graphical representation and real-time interactive operation action icons	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Run continually with minimal human supervision

Relative importance of the following intelligence measures (or indicators) with respect to **bio-inspired behaviour** attribute

Column 1		Column 2
Analyse operation function parameters to select the best & effective operation logic	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Provide adaptive control algorithms based on seasonal changes

Relative importance of the intelligence attributes of IBMS in generating the operational benefit of **increased safety and reliability**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the intelligence attributes of IBMS in generating the operational benefit of **improved cost effectiveness**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the intelligence attributes of IBMS in generating the operational benefit of **better user comfort**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the intelligence attributes of IBMS in generating the operational benefit of **improved operational effectiveness and efficiency**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the operational benefits respect to the **autonomy** attributes of an IBMS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Note: S&R = Increased safety and reliability; ECE = Enhanced cost effectiveness; UC = Improved user comfort, OEE = Improved operational effectiveness & efficiency

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of an IBMS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of an IBMS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC

S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **bio-inspired behaviour** attribute of an IBMS

Column 1		**Column 2**
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECE
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

SYSTEM 2: TELECOM AND DATA SYSTEM (ITS)

Relative importance of the following **intelligence attributes** with respect to an "intelligent" ITS

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics** attribute

Column 1		**Column 2**
Integrate multiple network or service providers	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Transmission capacity control and diversion

Relative importance of the following intelligence measures (or indicators) with respect to **man-machine interaction** attribute

Column 1		**Column 2**
Fixed hub/terminal port installed for flexibility connections and expansions	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	System life and turn-round complexity

Relative importance of the following intelligence attributes of ITS in generating the operational benefit of **increased safety and reliability**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of ITS in generating the operational benefit of **improved cost effectiveness**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of ITS in generating the operational benefit of **better user comfort**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of ITS in generating the operational benefit of **improved operational effectiveness and efficiency**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of ITS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of ITS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

SYSTEM 3: HVAC CONTROL SYSTEM

Relative importance of the following **Intelligence attributes** with respect to an 'intelligent' HVAC control system

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the following intelligence measures (or indicators) with respect to **autonomy** attribute

Column 1		Column 2
Adaptive limiting control algorithm	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Sensing the internal temperature and humidity, & auto-adjustment of systems
Adaptive limiting control algorithm	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Sensing the external temperature and humidity, & auto-adjustment of systems
Adaptive limiting control algorithm	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Automated fault detection
Adaptive limiting control algorithm	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self-diagnosis to detect the timeworn parts
Sensing the internal temperature and humidity, & auto-adjustment of systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Sensing the external temperature and humidity, & auto-adjustment of systems

Sensing the internal temperature and humidity, & auto-adjustment of systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Automated fault detection
Sensing the internal temperature and humidity, & auto-adjustment of systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self-diagnosis to detect the timeworn parts
Sensing the external temperature and humidity, & auto-adjustment of systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Automated fault detection
Sensing the external temperature and humidity, & auto-adjustment of systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self-diagnosis to detect the timeworn parts
Automated fault detection	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self-diagnosis to detect the timeworn parts

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics** attribute

Column 1		Column 2
Operation control mechanism to achieve efficient power consumption	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS

Relative importance of the following intelligence measures (or indicators) with respect to **man-machine interaction** attribute

Column 1		Column 2
Provide management staff with database and analytical tools for operation and service evaluation	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Pre-programmed responses and zoning control
Provide management staff with database and analytical tools for operation and service evaluation	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Graphical representation and real-time interactive operation action icons
Pre-programmed responses and zoning control	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Graphical representation and real-time interactive operation action icons

Relative importance of the following intelligence attributes of HVAC control system in generating the operational benefit of **increased safety and reliability**

Column 1																		Column 2
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	CCD
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
MMI	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB

Relative importance of the following intelligence attributes of HVAC control system in generating the operational benefit of **improved cost effectiveness**

Column 1																		Column 2
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	CCD
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
MMI	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB

Relative importance of the following intelligence attributes of HVAC control system in generating the benefit of **better user comfort**

Column 1																		Column 2
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	CCD
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
MMI	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB

Relative importance of the following intelligence attributes of HVAC control system in generating the operational benefit of **improved operational effectiveness and efficiency**

Column 1																		Column 2
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	CCD
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
AUT	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	MMI
CCD	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB
MMI	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	BIB

Relative importance of the operational benefits respect to **autonomy** attribute of HVAC control system

Column 1																		Column 2
S&R	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	ECE
S&R	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	UC
S&R	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	OEE
ECE	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	UC
ECE	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	OEE
UC	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	OEE

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of HVAC control system

Column 1																		Column 2
S&R	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	ECE
S&R	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	UC
S&R	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	OEE
ECE	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	UC
ECE	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	OEE
UC	9☐	8☐	7☐	6☐	5☐	4☐	3☐	2☐	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of HVAC control system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECE
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **bio-inspired behaviour autonomy** attribute of HVAC control system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECE
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

SYSTEM 4: ADDRESSABLE FIRE DETECTION AND ALARM (AFA) SYSTEM

Relative importance of the following **intelligence attributes** with respect to an "intelligent" AFA system

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence measures (or indicators) with respect to **autonomy** attribute

Column 1		Column 2
Alarm deployment algorithm within the building and notification to Fire Dept.	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self-diagnostic analysis for false alarm reduction
Alarm deployment algorithm within the building and notification to Fire Dept.	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self test of sensors, detectors and control points
Self-diagnostic analysis for false alarm reduction	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Self test of sensors, detectors and control points

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics** attribute

Column 1		Column 2
Control of sensors, detectors, fire-fighting equipment	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS
Control of sensors, detectors, fire-fighting equipment	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with security systems

Control of sensors, detectors, fire-fighting equipment	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with HVAC systems
Control of sensors, detectors, fire-fighting equipment	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with lift systems
Control of sensors, detectors, fire-fighting equipment	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with emergency generator systems
Interface with EMS, BAS and/or IBMS	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with security systems
Interface with EMS, BAS and/or IBMS	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with HVAC systems
Interface with EMS, BAS and/or IBMS	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with lift systems
Interface with EMS, BAS and/or IBMS	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with emergency generator systems
Interact with security systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with HVAC systems
Interact with security systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with lift systems
Interact with security systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with emergency generator systems
Interact with HVAC systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with lift systems
Interact with HVAC systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with emergency generator systems
Interact with lift systems	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interact with emergency generator systems

Relative importance of the following intelligence attributes of AFA system in generating the operational benefit of **increased safety and reliability**

Column 1		**Column 2**
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of AFA system in generating the operational benefit of **improved cost effectiveness**

Column 1		**Column 2**
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of AHA system in generating the operational benefit of **better user comfort**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of AHA system in generating the operational benefit of **improved operational effectiveness** and **efficiency**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the operational benefits respect to **autonomy** attribute of AHA system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of AHA system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of AHA system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

SYSTEM 5: SECURITY MONITORING AND ACCESS CONTROL SYSTEM (SEC)

Relative importance of the following **intelligence attributes** with respect to an "intelligent" SEC system

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics attribute**

Column 1		Column 2
Dynamic programming	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Configurable to accurately implement the security policies for the premises
Dynamic programming	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with other system (network system)

Dynamic programming	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS
Configurable to accurately implement the security policies for the premises	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with other system (network system)
Configurable to accurately implement the security policies for the premises	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS
Interface with other system (network system)	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS

Relative importance of the following intelligence measures (or indicators) with respect to **man-machine interaction** attribute

Column 1		Column 2
Run continually with minimal human supervision	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Provide database and analytical tools for operation and service evaluation
Run continually with minimal human supervision	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Pre-scheduled set up of special events and normal routines;
Provide database and analytical tools for operation and service evaluation	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Pre-scheduled set up of special events and normal routines;

Relative importance of the following intelligence attributes of SEC system in generating the operational benefit of **increased safety and reliability**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of SEC system in generating the operational benefit of **improved cost effectiveness**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of SEC system in generating the operational benefit of better **user comfort**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of SEC system in generating the operational benefit of **improved operational effectiveness and efficiency**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the operational benefits respect to **autonomy** attribute of SEC system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of SEC system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of SEC system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

SYSTEM 6: SMART AND ENERGY EFFICIENT LIFT SYSTEM (LS)

Relative importance of the following **intelligence attributes** with respect to an "intelligent" LS

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence measures (or indicators) with respect to **autonomy** attribute

Column 1		Column 2
Auto-controlled navigation of emergency (with remote override)	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	On-line data logging facilitating routine maintenance

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics** attribute

Column 1		Column 2
Accommodate changes of passenger traffic pattern	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	On-line investigation and analysis of lift activity

Accommodate changes of passenger traffic pattern	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS
On-line investigation and analysis of lift activity	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS

Relative importance of the following intelligence measures (or indicators) with respect to **man-machine interaction** attribute

Column 1		Column 2
Human engineering design to facilitate convenience of passengers	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Provide database and analytical tools for operation and service evaluation
Human engineering design to facilitate convenience of passengers	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Prescheduled of special events and normal routines
Provide database and analytical tools for operation and service evaluation	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Prescheduled of special events and normal routines

Relative importance of the following intelligence attributes of LS in generating the operational benefit of **increased safety and reliability**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of LS in generating the operational benefit of **improved cost effectiveness**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of LS in generating the operational benefit of **better user comfort**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the following intelligence attributes of LS system in generating the operational benefit of **improved operational effectiveness and efficiency**

Column 1		Column 2
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	CCD
AUT	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI

Relative importance of the operational benefits respect to **autonomy** attribute of LS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	FCC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of LS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECE
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of LS

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECE
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECE	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

SYSTEM 7: DIGITAL ADDRESSABLE LIGHTING CONTROL SYSTEM (DALI)

Relative importance of the following **intelligence attributes** with respect to an 'intelligent' DALI system

Column 1		Column 2
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the following intelligence measures (or indicators) with respect to **controllability of complicated dynamics** attribute

Column 1		Column 2
Presence detection	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Control of individual luminaries, groups of luminaries or lighting zone
Presence detection	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS
Control of individual luminaries, groups of luminaries or lighting zone	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Interface with EMS, BAS and/or IBMS

Relative importance of the following intelligence measures (or indicators) with respect to **man-machine interaction** attribute

Column 1		Column 2
Provide database and analytical tools for operation and service evaluation	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Pre-programmed response and control

Relative importance of the following intelligence measures (or indicators) with respect to **bio-inspired behaviour** attribute

Column 1		Column 2
Sensing the light intensity/ angle of projection/ solar radiation to maximise natural light & reduce lighting power	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	Automatic lighting or shading controls

Relative importance of the following intelligence attributes of DALI system in generating the operational benefit of **increased safety and reliability**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the following intelligence attributes of DALI system in generating the operational benefit of **improved cost effectiveness**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the following intelligence attributes of DALI system in generating the operational benefit of **better user comfort**

Column 1		Column 2
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the following intelligence attributes of DALI system in generating the operational benefit of **improved operational effectiveness** and **efficiency**

Column 1		**Column 2**
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	MMI
CCD	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB
MMI	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	BIB

Relative importance of the operational benefits respect to **controllability of complicated dynamics** attribute of DALI system

Column 1		**Column 2**
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **man-made interaction** attribute of DALI system

Column 1		Column 2
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

Relative importance of the operational benefits respect to **bio-inspired behaviour** attribute of DALI system

Column 1		**Column 2**
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	ECC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
S&R	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	UC
ECC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE
UC	9☐ 8☐ 7☐ 6☐ 5☐ 4☐ 3☐ 2☐ 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐	OEE

All collected data will be kept strictly confidential and anonymous, and they will be used for academic research purposes ONLY.

Thank you for completing the questionnaire. We appreciate your time.

~End~

APPENDIX A5: QUESTIONNAIRE FOR THE VALIDATION OF MODELS DEVELOPED IN RESEARCH PART ONE

VALIDATION OF THE
SELECTION EVALUATION MODELS
FOR INTELLIGENT BUILDING CONTROL SYSTEMS

INSTRUCTIONS

The main objective of this survey is to collect data for validating the selection evaluation models of seven key intelligent building control systems, which were generated through the collaboration of 71 industry practitioners and 9 experts in intelligent building field in Hong Kong.

All collected data will be kept strictly confidential and anonymous, and they will be used for academic research purposes ONLY.

This model validation survey includes three parts (Part 1, 2 and 3):

Part 1: Before answering the questions, we invite you to nominate 2 real building system alternatives for each of the seven intelligent building control systems. Please make sure that you have come across and are familiar with the nominated building systems in your past experience of intelligent building design or development. The seven building control systems which were covered in this study include:

- Integrated Building Management System (IBMS);
- Telecom and Data System (ITS);
- Heating Ventilation Air-Conditioning (HVAC) Control System;
- Addressable Fire Detection and Alarm System (AFA);
- Security Monitoring and Access Control System (SEC);
- Smart and Energy Efficient Lift System (LS); and,
- Digital Addressable Lighting Control System (DALI).

Part 2: After identifying the building system alternatives, you are invited to rank ordered of them according to your preference based on their overall ability and performance. The ranking is based on the following scale (scale 0-10):

0	1	2	3	4	5	6	7	8	9	10
Poor					**Average**	**Good**		**Very Good**	**Excellent**	

Part 3: You are further invited to evaluate the ability level of each nominated building control system option to fulfil each **critical selection criteria (CSC)** requirements of the models. The rating/assessment methods are varied for each CSC is appended for your reference, but a rating scale of 0 to 5 was commonly used, ***unless otherwise specified***.

PART 1: BASIC INFORMATION

Personal Information of Respondent:

1. Name of respondent: ______________________________
2. Position: ______________________________
3. Year of experience: ______________________________
4. Number of intelligent building projects participated : ______________
5. Company/entity: ______________________________

Names and Information of the Building Control System Options:

Integrated Building Management System (IBMS)

Option 1

Option 2 ______________________________

Telecom and Data System (ITS)

Option 1 ______________________________

Option 2 ______________________________

Heating Ventilation Air-Conditioning Control System (HVAC)

Option 1 ______________________________

Option 2 ______________________________

Addressable Fire Detection and Alarm System (AFA)

Option 1 ______________________________

Option 2 ______________________________

Security Monitoring and Access Control System (SEC)

Option 1 ______________________________

Option 2 ______________________________

Smart and Energy Efficient Lift System (LS)

Option 1 ______________________________

Option 2 ______________________________

Digital Addressable Lighting Control System (DALI)

Option 1 ______________________________

Option 2 ______________________________

PART 2: EXPERT'S PERFERENCE OF BUILDING SYSTEM CONTROL ALTERNATIVES

In this part, please choose from a global rating score of 0 to 10 (i.e., 0 to 4 represent 'poor'; 5 represents 'average'; 6 and 7 represent 'good'; 8 represents 'very good'; and, 9 and 10 represent 'excellent') to represent the overall ability and performance of each nominated building control systems in the intelligent building.

Intelligent Building Control Systems	**Global Score**
Integrated Building Management System (IBMS)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Telecom and Data System (ITS)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Heating Ventilation Air-Conditioning Control System (HVAC)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Addressable Fire Detection and Alarm System (AFA)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Security Monitoring and Access Control System (SEC)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Smart and Energy Efficient Lift System (LS)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Digital Addressable Lighting Control System (DALI)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

PART 3: EVALUATION BASED ON THE SELECTION MODELS

In this part, please choose from 0 to 5 (where the rating methods are specified in Appendix*) to assess each nominated system alternative on each of the CSC of the selection models.

** Please note that, except for the first and second CSC in AFA that, the assessment is based on either 'full compliance' (5 marks) or 'non-compliance' (0 mark).

1. Integrated Building Management System (IBMS)

Critical Selection Criteria (CSC)	Rating Methods*	IBMS Option 1	IBMS Option 2
Reliability and stability	Method A2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Integrated and interface with service control systems	Method A3	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Efficiency and accuracy	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

2. Telecom and Data System (ITS)

Critical Selection Criteria (CSC)	Rating Methods*	ITS Option 1	ITS Option 2
Reliability and stability	Method A2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Further upgrade of system	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Service life	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Transmission rate of data	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

3. Heating Ventilation Air-Conditioning Control System (HVAC)

Critical Selection Criteria (CSC)	Rating Methods*	HVAC Option 1	HVAC Option 2
Service life	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Control of predict mean vote (PMV)	Method A6	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Control of indoor air quality (IQA)	Method A7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Total energy consumption	Method A8	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Integrated by IBMS	Method A9	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
System reliability and stability	Method A10	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Minimisation of plant noise	Method A11	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

Interface with other building control systems	Method A12	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Initial costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Adequate fresh air changes	Method A13	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

4. Addressable Fire Detection and Alarm System (AFA)

Critical Selection Criteria (CSC)	**Rating Methods***	**AFA Option 1**	**AFA Option 2**
Compliance with the code of minimum fire service installations or equipment	Method A4 **	⓪ ⑤	⓪ ⑤
Compliance with the code for inspection, testing and maintenance of fire service installations and equipment	Method A4 **	⓪ ⑤	⓪ ⑤
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
System response time and survivability	Method A5	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Further upgrade of system	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Automatic detection of fire, gas and smoke	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Service life	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

5. Security Monitoring and Access Control System (SEC)

Critical Selection Criteria (CSC)	**Rating Methods***	**SEC Option 1**	**SEC Option 2**
Time needed for public announcement of disasters	Method A5	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Time needed to report a disastrous event to the building management	Method A5	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with other building control systems	Method A12	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Integrated by IBMS	Method A9	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Service life	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Further upgrade of system	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Initial costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Time for total egress	Method A14	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

6. Smart and Energy Efficient Lift System (LS)

Critical Selection Criteria (CSC)	Rating Methods*	LS Option 1	LS Option 2
Mean time between failures	Method A15	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Service life	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Waiting time	Method A16	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Maximum interval time	Method A17	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Total energy consumption	Method A18	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Acceleration and deceleration control	Method A19	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Journey time	Method A20	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Integrated by IBMS	Method A9	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with other building control systems	Method A12	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Minimisation of in-car noise	Method A21	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Adequate fresh air changes	Method A22	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Minimisation of in-car vibration	Method A23	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Automatic and remote control	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

7. Digital Addressable Lighting Control System (DALI)

Critical Selection Criteria (CSC)	Rating Methods*	DALI Option 1	DALI Option 2
Operation and maintenance costs	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with other building control systems	Method A12	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Integrated by IBMS	Method A9	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Permanent artificial lighting average power density	Method A24	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Further upgrade of system	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Service life	Method A1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Ease of control	Method A25	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Total energy consumption	Method A26	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Automatic control and adjustment of lux level	Method A27	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

Thank you for participation. We appreciate your time.

~ END ~

*APPENDIX: Rating Methods and Measurement Scales for the CSC

CSC Rating Methods	**Measurement Scales**
Method A1	Rating is based on the ability level of the intelligent building system to fulfil a specific CSC. The rating scales range from 0 to 5: 5 marks (Excellent), 4 marks (Good), 3 marks (Fair), 2 marks (Poor), 1 mark (Very Poor), and 0 mark (Extremely Poor)
Method A2	The frequency of major breakdown of the building systems (i.e., 10% of whole business of the whole building has to halt due to major breakdown). The assessment was based on the breakdown frequency from 5 marks (once/year or less), 4 marks (twice/year), 3 marks (3-5 times/year or less), 2 marks (6-8 times /year or less), 1 mark (9-11 times /year or less), to 0 mark (once/month of more)
Method A3	Rating is based on the percentage of permanently installed devices under control and monitoring (i.e., by IBMS). The rating scales range from 0 to 5. 5 marks (100%), 4 marks (100-80%), 3 marks (80-60%), 2 marks (60-40%), 1 mark (40-20%), and 0 mark (lower than 20%)
Method A4 **	Rating is based on whether the AFA system in compliance with local regulations. The Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (1998) and the Code of Practices for Fire Resisting Construction (1996) are two codes of practice issued by the Fire Services Department of HKSAR. The rating scale in this part is only based on 5 marks (Full compliance) and 0 mark (non-compliance)
Method A5	The assessment is based on the average response and report time for public announcement and to building management of disasters. The rating scales range from 0 to 5: 5 marks (5 seconds or shorter), 4 marks (5 to 30 seconds), 3 marks (30 to 60 seconds), 2 marks (60 to 90 seconds), 1 mark (90 to 120 seconds), and 0 mark (120 seconds or longer)
Method A6	PMV related to the overall percentage of thermal dissatisfaction and it depends on air temperature, mean radiant temperature, relative air velocity, relative humidity, human metabolic rate and clothing insulation level. This assess whether the HVAC control system is able to provide a lowest PMV. The assessment is based ISO Standard 7730 for human comfort (ISO, 1995). The most optimal thermal comfort level is resulted when a PMV value is equal to zero. The numerical figure with its range between +3 (hot) and -3 (cold). The rating scales range from 0 to 5; 5 marks (PMV at 0), 4 marks (PMV at between 0 and +1/-1), 3 marks (PMV at lower than +1/-1 and higher than +2/-2), 2 marks (PMV at +2/-2), 1 mark (PMV at lower than +2/-2 and higher than +3/-3), and 0 mark (PMV at +3/-3)
Method A7	The assessment is based the Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places which was published by the Indoor Air Quality Management Group of HKSAR Government in November 1999. The IQA contains the following 6 items: (1) dry bulb temperature lower than 25.5C; (2) relative humidity less than 70%; (3) air movement less than 0.3m/s; (4) CO level less than 10000 μg/m; (5) CO_2 lower than 1000ppm; and. (6) radon level to be lower than $200Bq/m^3$. This evaluate whether the HVAC control system has the ability to

maintain a reasonable IAQ level.

The rating scales range from 0 to 5: 5 marks (full compliance of 6 items), 4 marks (failures of 1-2 items amongst items 1, 2, and 3), 3 marks (failure of 1-2 items amongst items 4, 5, and 6), 2 marks (failure of items 1, 2, and 3), 1 mark (failure of items 4, 5 and 6), and 0 mark (completely non-compliance)

Method A8 The energy consumption by HVAC system is rated based on GFA of the building.

The rating scales range from 5 marks (60 kWh/year/m^2 or below): 4 marks (60-130 kWh/year/m^2 or below), 3 marks (130 kWh/year/m^2 or below), 2 marks (130-140 kWh/year/m^2 or below), 1 mark (140-150 kWh/year/m^2 or below), to 0 mark (150 kWh/year/m^2 or above)

Method A9 The assessment is based on the percentage of standalone building control systems were linked by IBMS.

The rating scales range from 0 to 5: 5 marks (100%-81%), 4 marks (80%-61%), 3 marks (60%-41%), 2 marks (40%-21%), 1 mark (20% -1%), and 0 mark (lower than 1%)

Method A10 The assessment is based on the frequency breakdown of the proposed HVAC systems (i.e., average mean time between failures, MTBF).

The rating scales range from 0 to 5, 5 marks (MTBF=3 months or above), 4 marks (MTBF=3-2.5 months), 3 marks (MTBF=2.5-2 months), 2 marks (MTBF=2-1.5 months), 1 mark (MTBF=1.5-1 month), and 0 mark (MTBF=1 month or below)

Method A11 This related to the control of noise level in the HVAC system.

The assessment was based on the noise level from 5 marks (NC 45 or below), 4 marks (NC 45 -50), 3 marks (NC 50-55), 2 marks (NC 55 -60), 1 mark (NC 60 -65), to 0 mark (NC 65 or above)

Method A12 Based on the level and scope of system interface.

The rating scales range from 0 to 5: 5 marks (100%), 4 marks (100-80%), 3 marks (80-60%), 2 marks (60-40%), 1 mark (40-20%), and 0 mark (lower than 20%)

Method A13 Amount of air change per second provided for the occupants. Inadequate fresh air would lead to uncomfortable feeling, and too much fresh air consumes unnecessary energy.

Rating methods: 5 marks (9.5 litres/s/occupant), 4 marks (between 9.49 to 7.75 litres/s/occupant and 9.49 to 10.75 litres/s/occupant), 3 marks (between 7.76 to 5.76 litres/s/occupant and 10.76 to 11.99 litres/s/occupant), 2 marks (between 5.75 to 3.26 litres/s/occupant and 12 to 13.74 litres/s/occupant), 1 mark (between 3.25 to 1.01 litres/s/occupant and 13.75 to 14.99 litres/s/occupant), and 0 mark (more than 15 litres/s/occupant or less than 1 litres/s/occupant)

Method A14 The assessment is based on the total time span for all building occupants to arrive at safe location after receiving the general alarms from the public address system is estimated.

The rating scales range from 0 to 5: 5 marks (10 minutes or less), 4 marks (10-15 minutes), 3 marks (15-20 minutes), 2 marks (25-20 minutes), 1 mark (30 to 25 minutes), and 0 mark (30 minutes or longer)

Method A15 The reliability and stability of the lift system inside the intelligent building. This is measured by the mean time between any two failures of any lifts or escalators with the whole system.

The rating scales range from 0 to 5: 5 marks (6 months or above), 4 marks (4.5-6 months), 3 marks (3-4.5 months), 2 marks (1.5-3 months), 1 mark (1-1.5 month), and 0 mark (1 month or below)

Method A16 The assessment is based on the expected average time taken for a passenger to wait for the arrival of the appropriate car at the lift lobby.

The rating scales range from 0 to 5: 5 marks (30 seconds or shorter), 4 marks (50 seconds to 31 seconds), 3 marks (70 seconds to 51 seconds), 2 marks (90 seconds to 71 seconds), 1 mark (110 to 90 seconds), and 0 mark (more than 110 seconds)

Method A17 The assessment is based on the time required for the next car to arrive at the main terminal after the previous car has arrived at the main terminal. The value measurement is extracted from the Code of Practice (COP) for Energy Efficiency of Lift and Escalator Installations issued by Electrical and Mechanical Service Department (EMSD) of HKSAR in 2000.

The rating scales range from 0 to 5: 5 marks (22.5 seconds or shorter), 4 marks (26.25 seconds to 22.5 seconds), 3 marks (30 seconds to 26.25 seconds), 2 marks (47.5 seconds to 30 seconds), 1 mark (65 to 47.5 seconds), and 0 mark (more than 65 seconds)

Method A18 The assessment can be measured in two ways: the average power consumption with passengers (WP) (measured in kJ per passenger per m) and without passengers (W/O P) (measured in J/kg).

The rating scales range from 0 to 5: 5 marks (WP: 2 kg/passenger/m or less; W/O P: 50 J/kg or less); 4 marks (WP: 2.1-3.25 kg/passenger/m; W/O P: 51-163 J/kg), 3 marks (WP: 3.25-4.50 kg/passenger/m; W/O P: 163-275 J/kg), 2 marks (WP: 5.75-4.50 kg/passenger/m; W/O P: 387-275 J/kg), 1 mark (WP: 7-5.75 kg/passenger/m; W/O P: 500-387 J/kg), and 0 mark (WP: 7 kg/passenger/m or more; W/O P: 500 J/kg or more)

Method A19 The assessment is based on the comfort feeling of the common occupants if both acceleration and deceleration are being kept below a value about one sixth of the gravitational acceleration, i.e., 9.8 m/s^2.

The rating scales range from 0 to 5: 5 marks (0.8 m/s^2 or less), 4 marks (1.85- 0.8 m/s^2), 3 marks (2.9-1.85 m/s^2), 2 marks (3.95-2.9 m/s^2), 1 mark (3.95-5 m/s^2), and 0 mark (5 m/s^2 or more)

Method A20 The assessment is based on the expected average time a passenger needs to take from the moment of entering the car to the moment of leaving the lift car.

The rating scales range from 0 to 5: 5 marks (40 seconds or shorter), 4 marks (60 seconds to 41 seconds), 3 marks (80 seconds to 61 seconds), 2 marks (100 seconds to 81 seconds), 1 mark (120 to 101 seconds), and 0 mark (more than 120 seconds)

Method A21 The assessment is based on the measurement by eh EVA-625 recorder with a microphone placed 1 meter above the car floor at the middle of the car when the empty car is travelling upward from the bottom floor to the top floor of the zone.

The rating scales range from 0 to 5: 5 marks (45 dBA or lower), 4 marks (55.5 dBA to 45 dBA), 3 marks (66 dBA to 55.5 dBA), 2 marks (73 dBA to 66 dBA), 1 mark (80 dBA to73 dBA), and 0 mark (more than 80 dBA)

Method A22 The amount of air change per hour inside lift cars.

This is judged based on the rating scales of 0 to 5: 5 marks (20 AC/hr or above), 4 marks (17.5 to 20 AC/hr), 3 marks (15 to 17.5 AC/hr), 2 marks (12.5 to 15 AC/hr), 1 mark (10 to 12.5 AC/hr), and 0 mark (lower than 10 AC/hr)

Method A23 The assessment is based on the lift car horizontal (HVL) and vertical vibration limits (VVL).

The rating scales range from 0 to 5: 5 marks (HVL: 0.04m/s^2; VVL: 9.80m/s^2), 4 marks (HVL: 0.06-0.04m/s^2; VVL: 9.84-9.80m/s^2), 3 marks (HVL: 0.08-0.06m/s^2; VVL: 9.88-9.84m/s^2), 2 marks (HVL: 0.12-0.08m/s^2; VVL: 9.92-9.88m/s^2), 1 mark (HVL: 0.15-0.12m/s^2; VVL: 9.95-9.92m/s^2), and 0 mark (HVL: 0.15 m/s^2 or higher; VVL: 9.95m/s^2 or higher)

Method A24 The assessment is extracted from the Code of Practice for Energy Efficiency of Lighting Installations published by EMSD (1998).

The rating scales range from 0 to 5: 5 marks (25 W/m^2 or above), 4 marks (28-25 W/m^2), 3 marks (32-28 W/m^2), 2 marks (36-32 W/m^2), 1 mark (40-36 W/m^2), and 0 mark (Above 40 W/m^2)

Method A25 The assessment is based on the extent and level of automatic control.

The rating scales range from 0 to 5: 5 marks (100% automatic control), 4 marks (80% automatic control), 3 marks (60% automatic control), 2 marks (40% automatic control), 1 mark (20% automatic control), and 0 mark (manual control)

Method A26 The energy consumption can be measured on the average efficacy of all lamps of the lighting systems. This was rated based on the ratio of the total lumen output of a lamp to the total electric power input to it.

The rating scales range from 0 to 5: 5 marks (50 lm/W or above); 4 marks (37.5 to 50 lm/W), 3 marks (25-37.5 lm/W), 2 marks (12.5-25 lm/W), 1 mark (5-12.5 lm/W), and 0 mark (5 lm/W or below)

Method A27 The assessment was based on the existence and level of automatic control and adjustment of lux level.

The rating scales range from 0 to 5: 5 marks (100% automatic control), 4 marks (80% automatic control), 3 marks (60% automatic control), 2 marks (40% automatic control), 1 mark (20% automatic control), and 0 mark (manual control)

APPENDIX A6: QUESTIONNAIRE FOR THE VALIDATION OF MODELS DEVELOPED IN RESEARCH PART TWO

VALIDATION OF THE SYSTEM INTELLIGENT ANALYTIC MODELS

INSTRUCTIONS

This survey aims to validate the analytic models of seven key building control systems, which were generated through the collaboration of 44 industry practitioners and 9 experts in intelligent building field in Hong Kong. To validate these models, it is important to receive your opinion.

All collected data will be kept strictly confidential and anonymous, and they will be used for academic research purposes ONLY.

This model validation survey includes three parts (Part 1, 2 and 3):

Part 1:
Before answering the questions, we invite you to nominate 2 real building control system options for each of the seven intelligent building control systems. Please make sure that you have come across and are familiar with the nominated building control systems in your past experience of intelligent building design or development. The seven intelligent building control systems which were covered in this study include:

- Integrated Building Management System (IBMS);
- Telecom and Data System (ITS);
- Heating Ventilation Air-Conditioning Control System (HVAC);
- Addressable Fire Detection and Alarm System (AFA);
- Security Monitoring and Access Control System (SEC);
- Smart and Energy Efficient Lift System (LS); and,
- Digital Addressable Lighting Control System (DALI).

NOTES: If you have participated in our survey of 'Validation of the Selection Evaluation Models for Building Control System' before, please use the same set of building control system alternatives for this survey.

Part 2: After identifying the building control system options, you are invited to rank ordered of them according to your preference in terms of their overall level of intelligence, or *intelligent performance*. The ranking is based on the following scale (scale 0-10):

0	1	2	3	4	5	6	7	8	9	10
Poor					Average	Good		Very Good	Excellent	

Part 3: You are further invited to judge the intelligent performance of each of the building system control options you named based on the intelligence indicators of the models. The

rating/assessment method and scoring system is appended for your reference. Generally, a rating scale of 0 to 5 is used.

PART 1: BASIC INFORMATION

Personal Information of Respondent:

1. Name of respondent:____
2. Position:____
3. Year of experience:____
4. Number of intelligent building projects participated :______________
5. Company/entity:____

PART 2: EXPERT'S PERFERENCE OF BUILDING CONTROL SYSTEM OPTIONS

In this part, please choose from a global rating score of 0 to 10 (i.e., 0 to 4 represent 'poor'; 5 represents 'average'; 6 and 7 represent 'good'; 8 represents 'very good'; and, 9 and 10 represent 'excellent') to represent the overall intelligent performance of each option of the seven listed building control systems

Intelligent Building Control Systems	Global Score
Integrated Building Management System (IBMS)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Telecom and Data System (ITS)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Heating Ventilation Air-Conditioning Control System (HVAC)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Addressable Fire Detection and Alarm System (AFA)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Security Monitoring and Access Control System (SEC)	
Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Smart and Energy Efficient Lift System (LS)	

Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Digital Addressable Lighting Control System (DALI)

Option 1	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
Option 2	⓪ ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

PART 3: EVALUATION BASED ON THE SYSTEM INTELLIGENCE ANALYTIC MODELS

In this part, please choose from 0 to 5 (where the rating methods are specified in Appendix*) to assess the alternatives of the same seven listed building control systems based on the intelligence indicators of the developed analytic models.

I. Integrated Building Management System (IBMS)

Intelligent Properties/ Functions	Rating Methods*	IBMS Option 1	IBMS Option 2
Adaptive limiting control algorithm (AL)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Self-diagnostic of operation deviations (SD)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Year-round time schedule operation (YT)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Ability to link multiple standalone building control systems from a variety of manufacturers (ALMS)	Method B2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Remote control via internet (RCI)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Ability to connect multiple locations (ACML)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Alarms and events statistics (AES)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Control and monitor lighting time schedule / zoning operation (ML)	Method B2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Control and monitor HVAC equipments (MHVAC)	Method B2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Reports generation and output of statistical and trend profiling of controls and operations (RG)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Ability to provide operational and analytical functions (APOAF)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Single operation system/ platform for multiple location supervision (SOS)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Graphical representation and real-time interactive operation action icons (GR)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

Run continually with minimal human supervision (RC)	Method B3	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Analyse operation function parameters (AOF)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Provide adaptive control algorithms based on seasonal changes (PAC)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

2. Telecom and Data System (ITS)

Intelligent Properties/ Functions	Rating Methods*	IBMS Option 1	IBMS Option 2
Integrate multiple network or service providers (IMS)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Transmission capacity control & diversion (TCCD)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Fixed hub/terminal port installed (FHTP)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
System life & turn-round complexity (SLTC)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

3. Heating Ventilation Air-Conditioning Control System (HVAC)

Intelligent Properties/ Functions	Rating Methods*	IBMS Option 1	IBMS Option 2
Adaptive limiting control algorithm (ALCA)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Sensing the internal temperature and humidity, and auto-adjustment of systems (ITS)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Sensing of external temperature and humidity, and auto-adjustment of systems (ETS)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Automated fault detection (AFD)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Self-diagnosis (SD)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Operation control mechanism (OCM)	Method B4	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with EMS, BAS or IBMS (INTF)	Method B2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Provide management staff with database & analytical tools for operation & service evaluation (DAT)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Pre-programmed responses and zoning control (PPR)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Graphical representation and real-time interactive operation action icons (GR)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Utilise natural ventilation control (UNVC)	Method B5	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

4. Addressable Fire Detection and Alarm System (AFA)

Intelligent Properties/ Functions	Rating Methods*	IBMS Option 1	IBMS Option 2
Alarm deployment algorithm within the building and notification to Fire Department (ADA)	Method B6	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Self-diagnostic analysis for false alarm reduction (SD)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Self test of sensors, detectors and control points (STS)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Integration and control of sensors, detectors, fire-fighting equipment (ICSD)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with EMS, BAS or IBMS (INTF)	Method B2	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interact with security systems (INTSS)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interact with HVAC systems (INTHVAC)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interact with lift systems (INTLS)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interact with lighting and emergency generator systems (INTLG)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Run continually with minimal human supervision (RC)	Method B3	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

5. Security Monitoring and Access Control System (SEC)

Intelligent Properties/ Functions	Rating Methods*	IBMS Option 1	IBMS Option 2
Sabotage proof (SP)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Dynamic programming (DP)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Configurable to accurately implement the security policies for the premises (CAISP)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with other system, e.g. communication network, phone system, etc (INTSY)	Method B8	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with EMS, BAS or IBMS (INTF)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Run continually with minimal human supervision (RC)	Method B3	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Provide database and analytical tools for operation and service evaluation (DAT)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Pre-scheduled set up (PSSU)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

6. Smart and Energy Efficient Lift System (LS)

Intelligent Properties/ Functions	**Rating Methods***	**IBMS Option 1**	**IBMS Option 2**
Auto-controlled navigation at emergency (AE)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
On-line data logging (ONDL)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Accommodate changes of passenger traffic pattern (ACPTP)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
On-line investigation and analysis of lift activity (ONIA)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with EMS, BAS or IBMS (INTF)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Provide database and analytical tools for operation and service evaluation (DAT)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Pre-scheduled of special events and normal routines (PSSE)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Human engineering design (HED)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

7. Digital Addressable Lighting Control System (DALI)

Intelligent Properties/ Functions	**Rating Methods***	**IBMS Option 1**	**IBMS Option 2**
Presence detection (PD)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Control of individual luminaries, groups of luminaries or lighting zone (CIL)	Method B4	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Interface with EMS, BAS or IBMS (INTF)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Provide database and analytical tools for operation and service evaluation (DAT)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Pre-programmed response and control (PPSC)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Sensing the light intensity and angle of projection and solar radiation (SLI)	Method B7	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤
Automatic lighting or shading controls (AUTLS)	Method B1	⓪ ① ② ③ ④ ⑤	⓪ ① ② ③ ④ ⑤

Thank you for participation. We appreciate your time.

~ END ~

*APPENDIX: Rating Methods and Measurement Scales for the Intelligence Indicators

Rating Methods	**Measurement Scales**
Method B1	The assessment was based on the existence and level of intelligent functions or properties. The rating scales range from 0 to 5: from 5 marks (Excellent), 4 marks (Good), 3 marks (Fair), 2 marks (Poor), 1 mark (Very Poor), and 0 mark (Extremely Poor)
Method B2	The assessment was based on the percentage of standalone building control systems were linked by IBMS. The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39%-20%), and 0 mark (lower than 20%)
Method B3	The assessment is based on the number of human intervention (per month): 1 time or below to 30 times or above. The rating scales range from 0 to 5: from 5 marks (1 time or below), 4 marks (1 to 7 times), 3 marks (8 to 15 times), 2 marks (16-22 times), 1 mark (23-29 times), and 0 mark (30 times or above)
Method B4	The assessment was based on the existence and level of automatic control. The rating scales range from 0 to 5: from 5 marks (100% automatic control), 4 marks (80% automatic control), 3 marks (60% automatic control), 2 marks (40% automatic control), 1 mark (20% automatic control), and 0 mark (manual control)
Method B5	The assessment was based on the percentage of natural ventilation used compared to the mechanical ventilation. The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39%-20%), and 0 mark (lower than 20%)
Method B6	The assessment was based on the average response/ report time to building management and Fire Dept: (5 seconds or shorter to 2 minutes or longer). The rating scales range from 0 to 5: from 5 marks (5 seconds or shorter), 4 marks (between 5 seconds and 45 seconds), 3 marks (between 45 seconds and 90 seconds), 2 marks (between 90 seconds and 2 minutes), 1 mark (2 minutes to 3 minutes), and 0 mark (3 minutes or longer)
Method B7	The assessment was based on the percentage of permanently installed devices under control and monitoring (by IBMS). The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39% -20%), and 0 mark (lower than 20%)
Method B8	The assessment was based on the level and scope of system interface. The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39% -20%), and 0 mark (lower than 20%)

APPENDIX B

MATRICES DEVELOPED FOR THE CALCULATION OF RELATIVE IMPORTANCE OF INTELLIGENCE INDICATORS FOR THE BUILDING CONTROL SYSTEMS (B1–B6)

APPENDIX B: MATRICES DEVELOPED FOR THE CALCULAION OF RELATIVE IMPORTANCE OF INTELLIGENCE INDICATORS FOR THE BUILDING CONTROL SYSTEMS

The following matrices list the eigenvectors of usable responses of the AHP-ANP questionnaire survey in Research Part Two for the calculation of the final weights of intelligence indicator for the intelligent building control systems. The matrices for the relative importance of intelligence indicators of IBMS have been discussed in Chapter 7.

B1: Telecom and Data System (ITS)

Matrix of intelligence attributes with respect to the decision problem (the overall intelligence of ITS)

GOALS	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CCD	0.7500	0.5000	0.8571	0.7500	0.1667	0.1429	0.5000	0.5000	0.2500	**0.4907**
MMI	0.2500	0.5000	0.1429	0.2500	0.8333	0.8571	0.5000	0.5000	0.7500	**0.5093**

Matrix of intelligence attributes with respect to enhanced cost effectiveness

ECE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CCD	0.2000	0.2000	0.8333	0.6667	0.5000	0.5000	0.5000	0.5000	0.6667	**0.5074**
MMI	0.8000	0.8000	0.1667	0.3333	0.5000	0.5000	0.5000	0.5000	0.3333	**0.4926**

Matrix of intelligence attributes with respect to improved operational effectiveness and energy efficiency

OEE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CCD	0.1667	0.1429	0.8000	0.7500	0.5000	0.5000	0.6667	0.8000	0.8000	**0.5696**
MMI	0.8333	0.8571	0.2000	0.2500	0.5000	0.5000	0.3333	0.2000	0.2000	**0.4304**

Matrix of intelligence attributes with respect to improved user comfort and productivity

UC	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CCD	0.1667	0.2000	0.8333	0.5000	0.3333	0.2500	0.3333	0.2500	0.2500	**0.3463**
MMI	0.8333	0.8000	0.1667	0.5000	0.6667	0.7500	0.6667	0.7500	0.7500	**0.6537**

Matrix of intelligence attributes with respect to increased system safety and reliability

S&R	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CCD	0.1667	0.2000	0.7500	0.8000	0.5000	0.6667	0.7500	0.6667	0.5000	**0.5556**
MMI	0.8333	0.8000	0.2500	0.2000	0.5000	0.3333	0.2500	0.3333	0.5000	**0.4444**

Matrix of operational benefits with respect to the controllability of complicated dynamics attribute

CCD	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
ECE	0.3125	0.2965	0.1770	0.2855	0.0784	0.1634	0.1293	0.1273	0.1977	**0.1964**
OEE	0.3125	0.3122	0.1338	0.3462	0.2585	0.2781	0.5039	0.3119	0.3453	**0.3114**
UC	0.3125	0.3279	0.1444	0.1635	0.1241	0.1634	0.1001	0.2804	0.2093	**0.2028**
S&R	0.0625	0.0634	0.5448	0.2048	0.5390	0.3951	0.2667	0.2804	0.2477	**0.2894**

Matrix of operational benefits with respect to the man-machine interaction attribute

MMI	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
ECE	0.3125	0.3034	0.1338	0.2711	0.0819	0.1194	0.0689	0.1224	0.0997	**0.1681**
OEE	0.3125	0.3213	0.1770	0.4338	0.1903	0.2009	0.3587	0.2270	0.3701	**0.2880**
UC	0.3125	0.3034	0.1444	0.1529	0.1725	0.4598	0.1713	0.4236	0.1850	**0.2584**
S&R	0.0625	0.0719	0.5448	0.1422	0.5553	0.2199	0.4011	0.2270	0.3452	**0.2855**

Matrix of intelligence indicators with respect to the controllability of complicated dynamics attribute

CCD	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
IMS	0.1667	0.6667	0.2500	0.5000	0.2000	0.2500	0.5000	0.5000	0.5000	**0.3926**
TCCD	0.8333	0.3333	0.7500	0.5000	0.8000	0.7500	0.5000	0.5000	0.5000	**0.6074**

Matrix of intelligence indicators with respect to the man-machine interaction attribute

MMI	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
FHTP	0.5000	0.6667	0.5000	0.8000	0.8333	0.8000	0.6667	0.5000	0.5000	**0.6407**
SLTC	0.5000	0.3333	0.5000	0.2000	0.1667	0.2000	0.3333	0.5000	0.5000	**0.3593**

Results of super-matrix

	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
CCD	0.1771	0.1818	0.7832	0.6958	0.4750	0.4703	0.6330	0.5378	0.5840	**0.5042**
MMI	0.8229	0.8182	0.2168	0.3042	0.5250	0.5297	0.3670	0.4622	0.4160	**0.4958**

B2: Addressable Fire Detection and Alarm System (AFA)

Matrix of intelligence attributes with respect to the decision problem (the overall intelligence of AFA)

GOALS	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.7143	0.6000	0.3333	0.7396	0.7010	0.7143	0.7010	0.4433	0.4126	**0.5955**
CCD	0.1429	0.2000	0.3333	0.1666	0.1929	0.1429	0.1929	0.3875	0.2599	**0.2243**
MMI	0.1429	0.2000	0.3333	0.0938	0.1061	0.1429	0.1061	0.1692	0.3275	**0.1802**

Matrix of intelligence attributes with respect to enhanced cost effectiveness

ECE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5000	0.5499	0.5499	0.7396	0.3333	0.3333	0.4000	0.5000	0.3333	**0.4710**
CCD	0.2500	0.2098	0.2403	0.1666	0.3333	0.3333	0.4000	0.2500	0.3333	**0.2796**
MMI	0.2500	0.2403	0.2098	0.0938	0.3333	0.3333	0.2000	0.2500	0.3333	**0.2493**

Matrix of intelligence attributes with respect to improved operational effectiveness and energy efficiency

OEE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5000	0.5000	0.3333	0.5954	0.4000	0.3108	0.4934	0.4000	0.3875	**0.4356**
CCD	0.2500	0.2500	0.3333	0.2764	0.4000	0.4934	0.3108	0.4000	0.1692	**0.3203**
MMI	0.2500	0.2500	0.3333	0.1283	0.2000	0.1958	0.1958	0.2000	0.4433	**0.2441**

Matrix of intelligence attributes with respect to improved user comfort and productivity

UC	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5000	0.5499	0.5000	0.6608	0.2500	0.2500	0.1634	0.2000	0.1840	**0.3620**
CCD	0.2500	0.2098	0.2500	0.2081	0.2500	0.2500	0.2970	0.2000	0.2318	**0.2385**
MMI	0.2500	0.2403	0.2500	0.1311	0.5000	0.5000	0.5396	0.6000	0.5842	**0.3995**

Matrix of intelligence attributes with respect to increased system safety and reliability

S&R	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5000	0.5499	0.5396	0.5954	0.4286	0.7142	0.4579	0.5000	0.4126	**0.5220**
CCD	0.2500	0.2098	0.2970	0.2764	0.4286	0.1429	0.4161	0.2500	0.3275	**0.2887**
MMI	0.2500	0.2403	0.1634	0.1282	0.1428	0.1429	0.1260	0.2500	0.2599	**0.1893**

Matrix of operational benefits with respect to the autonomy attribute

AUT	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.2761	0.1404	0.1140	0.1719	0.1209	0.0931	0.1205	0.1250	0.2087	**0.1523**
OEE	0.1381	0.3300	0.2852	0.1887	0.2925	0.2794	0.4182	0.3750	0.2994	**0.2896**
UC	0.1953	0.1996	0.0982	0.0696	0.1029	0.1103	0.1906	0.1250	0.2530	**0.1494**
S&R	0.3905	0.3300	0.5026	0.5699	0.4837	0.5172	0.2707	0.3750	0.2389	**0.4087**

Matrix of operational benefits with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1953	0.1250	0.1090	0.2158	0.1824	0.0723	0.1222	0.0793	0.2046	**0.1451**
OEE	0.2761	0.3750	0.2968	0.1959	0.2251	0.2015	0.4435	0.5008	0.3383	**0.3170**
UC	0.3905	0.1250	0.1090	0.1079	0.0878	0.1154	0.1222	0.1400	0.1692	**0.1519**
S&R	0.1381	0.3750	0.4852	0.4804	0.5047	0.6108	0.3121	0.2799	0.2879	**0.3860**

Matrix of operational benefits with respect to the man-machine interaction attribute

MMI	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
ECE	0.1381	0.1253	0.0750	0.1605	0.1386	0.0954	0.1368	0.1436	0.1571	**0.1300**
OEE	0.1953	0.3065	0.1469	0.2562	0.1948	0.1601	0.1608	0.2260	0.3191	**0.2184**
UC	0.2761	0.2349	0.2258	0.1357	0.1571	0.4673	0.3512	0.4588	0.2810	**0.2875**
S&R	0.3905	0.3333	0.5523	0.4476	0.5095	0.2772	0.3512	0.1716	0.2428	**0.3640**

Matrix of intelligence indicators with respect to the autonomy attribute

AUT	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
ADA	0.7608	0.7143	0.0823	0.1005	0.1111	0.5000	0.3333	0.6000	0.3333	**0.3929**
STS	0.1576	0.1429	0.6026	0.4664	0.4444	0.2500	0.3333	0.2000	0.3333	**0.3256**
SDF	0.0816	0.1429	0.3150	0.4331	0.4444	0.2500	0.3333	0.2000	0.3333	**0.2815**

Matrix of intelligence indicators with respect to the controllability of complicated dynamics attribute

CCD	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
INTF	0.1031	0.1164	0.2630	0.0781	0.0820	0.0590	0.0866	0.2357	0.0910	**0.1239**
ICSD	0.2984	0.2475	0.0341	0.4594	0.4450	0.1824	0.4479	0.1759	0.3482	**0.2932**
INTLG	0.0947	0.1295	0.0848	0.1230	0.1254	0.2508	0.1147	0.1030	0.2876	**0.1459**
INTHVAC	0.2045	0.2088	0.2545	0.1767	0.1797	0.2186	0.1752	0.2476	0.0910	**0.1952**
INTLS	0.2045	0.1922	0.1368	0.1230	0.1254	0.2052	0.1231	0.1398	0.0910	**0.1490**
INTSS	0.0949	0.1055	0.2269	0.0399	0.0425	0.0839	0.0525	0.0980	0.0910	**0.0928**

Results of super-matrix

	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.5000	0.5332	0.4824	0.6273	0.3880	0.3794	0.4026	0.3933	0.3343	**0.4489**
CCD	0.2500	0.2233	0.2943	0.2505	0.3880	0.4032	0.3516	0.2931	0.2551	**0.3010**
MMI	0.2500	0.2435	0.2233	0.1223	0.2240	0.2174	0.2458	0.3137	0.4106	**0.2501**

B3: Heating, Ventilation and Air-conditioning (HVAC) Control System

Matrix of intelligence attributes with respect to the decision problem (the overall intelligence of HVAC)

GOALS	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.6359	0.5346	0.3674	0.1653	0.2282	0.4827	0.1394	0.2414	0.0965	**0.3213**
BIB	0.0430	0.0728	0.1142	0.4091	0.0875	0.2756	0.4547	0.1534	0.4094	**0.2244**
CCD	0.1605	0.1963	0.3959	0.3219	0.5602	0.1006	0.3205	0.3718	0.2047	**0.2925**
MMI	0.1605	0.1963	0.1225	0.1038	0.1241	0.1412	0.0855	0.2335	0.2895	**0.1619**

Matrix of intelligence attributes with respect to enhanced cost effectiveness

ECE	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.2179	0.2242	0.4335	0.1653	0.2282	0.4598	0.3397	0.2857	0.3726	**0.3030**
BIB	0.0613	0.0678	0.1241	0.4091	0.0875	0.1194	0.1405	0.1429	0.0863	**0.1377**
CCD	0.3604	0.2915	0.3110	0.3219	0.5602	0.2009	0.2390	0.2857	0.2457	**0.3129**
MMI	0.3604	0.4165	0.1314	0.1038	0.1241	0.2199	0.2808	0.2857	0.2954	**0.2464**

Matrix of intelligence attributes with respect to improved operational effectiveness and energy efficiency

OEE	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.1741	0.2024	0.4359	0.1609	0.2740	0.2979	0.3835	0.3509	0.2986	**0.2865**
BIB	0.0871	0.1100	0.0951	0.3511	0.1045	0.2095	0.1119	0.1091	0.1041	**0.1425**
CCD	0.1231	0.1020	0.3270	0.3511	0.4717	0.2463	0.2947	0.3509	0.3244	**0.2879**
MMI	0.6157	0.5856	0.1419	0.1369	0.1498	0.2463	0.2099	0.1891	0.2729	**0.2831**

Matrix of intelligence attributes with respect to improved user comfort and productivity

UC	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.4607	0.4943	0.3880	0.1881	0.1072	0.1614	0.1192	0.1033	0.1876	**0.2455**
BIB	0.0598	0.0721	0.1120	0.5003	0.4535	0.4640	0.5453	0.5087	0.3310	**0.3385**
CCD	0.1901	0.1804	0.3880	0.2300	0.1972	0.1677	0.1303	0.1207	0.2407	**0.2050**
MMI	0.2894	0.2532	0.1120	0.0816	0.2421	0.2069	0.2052	0.2673	0.2407	**0.2109**

Matrix of intelligence attributes with respect to increased system safety and reliability

S&R	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.1591	0.2346	0.3805	0.1186	0.2598	0.4874	0.3000	0.3015	0.2894	**0.2812**
BIB	0.0531	0.0735	0.1344	0.5216	0.0808	0.0956	0.1000	0.1100	0.1750	**0.1493**
CCD	0.4611	0.1700	0.3902	0.2320	0.5194	0.2085	0.3000	0.3584	0.2462	**0.3206**
MMI	0.3266	0.5219	0.0949	0.1278	0.1400	0.2085	0.3000	0.2301	0.2894	**0.2488**

Matrix of operational benefits with respect to the autonomy attribute

AUT	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
ECE	0.1092	0.1233	0.1211	0.1391	0.4202	0.1337	0.1682	0.1293	0.1427	**0.1652**
OEE	0.5093	0.4705	0.4881	0.3521	0.1092	0.4946	0.3833	0.4099	0.2853	**0.3891**
UC	0.2676	0.2810	0.2745	0.4382	0.2693	0.1534	0.1069	0.1197	0.0863	**0.2219**
S&R	0.1139	0.1252	0.1163	0.0706	0.2013	0.2183	0.3416	0.3411	0.4857	**0.2238**

Matrix of operational benefits with respect to the bio-inspired behaviour attribute

BIB	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1626	0.1530	0.0905	0.1434	0.1236	0.0867	0.1594	0.1393	0.1055	**0.1293**
OEE	0.4247	0.4328	0.4224	0.2524	0.1886	0.1994	0.2262	0.1318	0.1501	**0.2698**
UC	0.3091	0.3060	0.3652	0.5023	0.5409	0.5831	0.5104	0.5897	0.6203	**0.4808**
S&R	0.1036	0.1082	0.1219	0.1019	0.1469	0.1308	0.1040	0.1392	0.1241	**0.1201**

Matrix of operational benefits with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1626	0.1859	0.1567	0.1553	0.1682	0.1028	0.2761	0.1069	0.1724	**0.1652**
OEE	0.1698	0.1967	0.1967	0.3182	0.5780	0.5393	0.3905	0.3416	0.3570	**0.3431**
UC	0.5942	0.5339	0.5560	0.4491	0.1284	0.1135	0.1381	0.1682	0.2353	**0.3241**
S&R	0.0734	0.0835	0.0906	0.0775	0.1254	0.2444	0.1953	0.3833	0.2353	**0.1676**

Matrix of operational benefits with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.4012	0.3923	0.3976	0.1281	0.2087	0.1070	0.1953	0.1294	0.1351	**0.2327**
OEE	0.4199	0.4117	0.3976	0.3414	0.2530	0.4155	0.2761	0.2512	0.3569	**0.3470**
UC	0.0763	0.0785	0.0846	0.4471	0.2389	0.2926	0.3905	0.4493	0.3085	**0.2629**
S&R	0.1026	0.1175	0.1202	0.0834	0.2994	0.1849	0.1381	0.1701	0.1995	**0.1573**

Matrix of intelligence indicators with respect to the autonomy attribute

AUT	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ALCA	0.0759	0.0933	0.0395	0.0426	0.0562	0.1010	0.0560	0.1111	0.4286	**0.1116**
AFD	0.2576	0.2581	0.2365	0.0969	0.1508	0.1572	0.1163	0.2222	0.1429	**0.1821**
ETS	0.1513	0.1105	0.3481	0.3535	0.2190	0.2605	0.3195	0.2222	0.1429	**0.2364**
ITS	0.2576	0.2581	0.2066	0.3938	0.4536	0.4260	0.3497	0.2222	0.1429	**0.3012**
SD	0.2576	0.2801	0.1693	0.1132	0.1204	0.0553	0.1585	0.2222	0.1429	**0.1688**

Matrix of intelligence indicators with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
INTF	0.6667	0.7500	0.5000	0.6667	0.5000	0.2500	0.5000	0.5000	0.2500	**0.5093**
OCM	0.3333	0.2500	0.5000	0.3333	0.5000	0.7500	0.5000	0.5000	0.7500	**0.4907**

Matrix of intelligence indicators with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
GR	0.3333	0.3333	0.6548	0.1429	0.5396	0.4286	0.1634	0.3333	0.1047	**0.3371**
PPR	0.3333	0.3333	0.2499	0.2857	0.2970	0.4286	0.2970	0.3333	0.6370	**0.3550**
DAT	0.3333	0.3333	0.0953	0.5714	0.1634	0.1429	0.5396	0.3333	0.2583	**0.3079**

Results of super-matrix

	EXB1	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.2592	0.2805	0.4123	0.1706	0.2190	0.3140	0.2846	0.2492	0.2748	**0.2738**
BIB	0.0700	0.0860	0.1102	0.4447	0.1852	0.2496	0.2356	0.2437	0.1858	**0.2012**
CCD	0.2342	0.1773	0.3532	0.2794	0.4300	0.2116	0.2390	0.2697	0.2680	**0.2736**
MMI	0.4366	0.4562	0.1243	0.1052	0.1658	0.2248	0.2408	0.2374	0.2714	**0.2514**

B4: Security Monitoring and Access Control System (SEC)

Matrix of intelligence attributes with respect to the decision problem (the overall intelligence of SEC)

GOALS	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5000	0.5000	0.3333	0.7418	0.7049	0.2583	0.7153	0.5396	0.2583	**0.5057**
CCD	0.2500	0.2500	0.3333	0.1830	0.2109	0.1047	0.1870	0.1634	0.1047	**0.1986**
MMI	0.2500	0.2500	0.3333	0.0752	0.0841	0.6370	0.0977	0.2970	0.6370	**0.2957**

Matrix of intelligence attributes with respect to enhanced cost effectiveness

ECE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.4000	0.4286	0.5936	0.7418	0.7049	0.2583	0.4126	0.2403	0.3333	**0.4571**
CCD	0.2000	0.1429	0.2493	0.1830	0.2109	0.1047	0.3275	0.2098	0.3333	**0.2179**
MMI	0.4000	0.4286	0.1571	0.0752	0.0841	0.6370	0.2599	0.5499	0.3333	**0.3250**

Matrix of intelligence attributes with respect to improved operational effectiveness and energy efficiency

OEE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.2970	0.2857	0.2493	0.6000	0.4286	0.2600	0.7153	0.5000	0.5499	**0.4318**
CCD	0.1634	0.1429	0.1571	0.2000	0.4286	0.4130	0.1870	0.2500	0.2098	**0.2391**
MMI	0.5396	0.5714	0.5936	0.2000	0.1428	0.3270	0.0977	0.2500	0.2403	**0.3292**

Matrix of intelligence attributes with respect to improved user comfort and productivity

UC	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.2970	0.2970	0.2970	0.1220	0.3333	0.2000	0.2500	0.2403	0.1571	**0.2437**
CCD	0.1634	0.1634	0.1634	0.3196	0.3333	0.2000	0.2500	0.2098	0.2493	**0.2280**
MMI	0.5396	0.5396	0.5396	0.5584	0.3333	0.6000	0.5000	0.5499	0.5936	**0.5282**

Matrix of intelligence attributes with respect to increased system safety and reliability

S&R	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.4934	0.5000	0.5000	0.2599	0.3333	0.2500	0.4000	0.5000	0.3275	**0.3960**
CCD	0.3108	0.2500	0.2500	0.4126	0.3333	0.5000	0.4000	0.2500	0.4126	**0.3466**
MMI	0.1958	0.2500	0.2500	0.3275	0.3333	0.2500	0.2000	0.2500	0.2599	**0.2574**

Matrix of operational benefits with respect to the autonomy attribute

AUT	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1634	0.1634	0.1573	0.2740	0.4326	0.2950	0.1172	0.1243	0.1760	**0.2115**
OEE	0.1634	0.1634	0.1385	0.1285	0.2377	0.2050	0.1939	0.3786	0.2810	**0.2100**
UC	0.2781	0.2780	0.2395	0.0595	0.1606	0.1060	0.1939	0.1957	0.2455	**0.1952**
S&R	0.3952	0.3952	0.4647	0.5380	0.1691	0.3940	0.4950	0.3014	0.2975	**0.3833**

Matrix of operational benefits with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1976	0.1976	0.1856	0.3916	0.1096	0.1270	0.1351	0.0997	0.2096	**0.1837**
OEE	0.1682	0.1682	0.1481	0.1776	0.4385	0.1630	0.3569	0.3452	0.2463	**0.2458**
UC	0.3952	0.3952	0.4276	0.1532	0.1866	0.1930	0.1995	0.1850	0.2463	**0.2646**
S&R	0.2390	0.2390	0.2387	0.2776	0.2653	0.5170	0.3085	0.3701	0.2978	**0.3059**

Matrix of operational benefits with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.3257	0.2370	0.2290	0.1796	0.1436	0.1140	0.1405	0.1713	0.2093	**0.1944**
OEE	0.3564	0.3400	0.3630	0.2368	0.1716	0.1370	0.1237	0.1713	0.1977	**0.2331**
UC	0.1243	0.1357	0.1060	0.2368	0.4588	0.4100	0.4150	0.4666	0.3453	**0.2998**
S&R	0.1936	0.2873	0.3020	0.3468	0.2260	0.3390	0.3208	0.1908	0.2477	**0.2727**

Matrix of intelligence indicators with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CAISP	0.3905	0.4950	0.2500	0.6439	0.4150	0.2482	0.5896	0.2500	0.1876	**0.3855**
DP	0.1381	0.1173	0.2500	0.2157	0.1237	0.0947	0.2261	0.2500	0.3310	**0.1941**
INTF	0.2761	0.1939	0.2500	0.0820	0.3208	0.3561	0.0922	0.2500	0.2407	**0.2291**
INTSY	0.1953	0.1939	0.2500	0.0584	0.1405	0.3010	0.0922	0.2500	0.2407	**0.1913**

Matrix of intelligence indicators with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
PSSU	0.2970	0.3333	0.3333	0.3333	0.2970	0.5584	0.3333	0.3333	0.4286	**0.3608**
DAT	0.1634	0.3333	0.3333	0.3333	0.5396	0.1220	0.3333	0.3333	0.1429	**0.2927**
RC	0.5396	0.3333	0.3333	0.3333	0.1634	0.3196	0.3333	0.3333	0.4286	**0.3464**

Results of super-matrix

	EXB1	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.3762	0.3858	0.4150	0.4367	0.4595	0.2398	0.4348	0.3876	0.3340	**0.3855**
CCD	0.2132	0.1820	0.2092	0.2983	0.3284	0.3430	0.3046	0.2326	0.3022	**0.2682**
MMI	0.4105	0.4322	0.3758	0.2650	0.2121	0.4172	0.2606	0.3798	0.3638	**0.3463**

B5: Digital Addressable Lighting Control System (DALI)

Matrix of intelligence attributes with respect to the decision problem (the overall intelligence of DALI)

GOALS	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
BIB	0.2970	0.5499	0.1998	0.1429	0.6370	0.5695	0.3333	0.3333	0.5584	**0.4024**
CCD	0.5396	0.2403	0.6833	0.4286	0.2583	0.0974	0.3333	0.3333	0.1220	**0.3373**
MMI	0.1634	0.2098	0.1169	0.4286	0.1047	0.3331	0.3333	0.3333	0.3196	**0.2603**

Matrix of intelligence attributes with respect to enhanced cost effectiveness

ECE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
BIB	0.4000	0.2098	0.1998	0.1428	0.1428	0.2000	0.1428	0.3333	0.1634	**0.2150**
CCD	0.2000	0.5499	0.6833	0.4286	0.4286	0.4000	0.4286	0.3333	0.2970	**0.4166**
MMI	0.4000	0.2403	0.1169	0.4286	0.4286	0.4000	0.4286	0.3333	0.5396	**0.3684**

Matrix of intelligence attributes with respect to improved operational effectiveness and energy efficiency

OEE	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
BIB	0.1634	0.1634	0.1744	0.1429	0.1260	0.1396	0.1428	0.2000	0.1220	**0.1527**
CCD	0.2970	0.2970	0.6337	0.4286	0.4579	0.3326	0.4286	0.4000	0.3196	**0.3994**
MMI	0.5396	0.5396	0.1919	0.4286	0.4161	0.5278	0.4286	0.4000	0.5584	**0.4478**

Matrix of intelligence attributes with respect to improved user comfort and productivity

UC	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
BIB	0.5714	0.6483	0.2098	0.5000	0.6483	0.5695	0.6000	0.6908	0.6483	**0.5652**
CCD	0.2857	0.2297	0.5499	0.2500	0.2297	0.0974	0.2000	0.1488	0.1220	**0.2348**
MMI	0.1429	0.1220	0.2403	0.2500	0.1220	0.3331	0.2000	0.1604	0.2297	**0.2000**

Matrix of intelligence attributes with respect to increased system safety and reliability

S&R	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
BIB	0.2500	0.2500	0.2500	0.1429	0.2599	0.2318	0.1260	0.2000	0.2000	**0.2123**
CCD	0.5000	0.5000	0.5000	0.4286	0.4126	0.5842	0.4579	0.4000	0.4000	**0.4648**
MMI	0.2500	0.2500	0.2500	0.4286	0.3275	0.1840	0.4161	0.4000	0.4000	**0.3229**

Matrix of operational benefits with respect to the bio-inspired behaviour attribute

BIB	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.2042	0.1716	0.1121	0.1755	0.1846	0.0924	0.1886	0.0657	0.1360	**0.1479**
OEE	0.2416	0.2426	0.1349	0.1755	0.1626	0.2078	0.1236	0.1304	0.1202	**0.1710**
UC	0.3857	0.3432	0.5048	0.5741	0.5620	0.5684	0.5409	0.6202	0.5598	**0.5177**
S&R	0.1684	0.2426	0.2482	0.0749	0.0908	0.1314	0.1469	0.1837	0.1840	**0.1634**

Matrix of operational benefits with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.2322	0.1682	0.0894	0.1896	0.1692	0.1237	0.1020	0.0865	0.1457	**0.1452**
OEE	0.2322	0.1976	0.3741	0.4448	0.2879	0.4150	0.5050	0.4084	0.3727	**0.3597**
UC	0.3952	0.3952	0.2451	0.2581	0.2046	0.1405	0.1281	0.0967	0.2048	**0.2298**
S&R	0.1404	0.2390	0.2914	0.1076	0.3383	0.3208	0.2649	0.4084	0.2767	**0.2653**

Matrix of operational benefits with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.2761	0.3012	0.2884	0.1634	0.2857	0.1381	0.1404	0.1000	0.2463	**0.2155**
OEE	0.3905	0.4100	0.2300	0.2310	0.2857	0.2761	0.1650	0.3000	0.2036	**0.2769**
UC	0.1381	0.1179	0.3709	0.4901	0.2857	0.3905	0.4950	0.3000	0.3465	**0.3261**
S&R	0.1953	0.1709	0.1107	0.1155	0.1429	0.1953	0.1996	0.3000	0.2036	**0.1815**

Matrix of intelligence indicators with respect to the bio-inspired behaviour attribute

BIB	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUTLS	0.6667	0.6667	0.1667	0.2500	0.1667	0.6667	0.5000	0.5000	0.5000	**0.4537**
SLI	0.3333	0.3333	0.8333	0.7500	0.8333	0.3333	0.5000	0.5000	0.5000	**0.5463**

Matrix of intelligence indicators with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
CIL	0.2970	0.3333	0.3484	0.4286	0.1429	0.6000	0.3333	0.4000	0.4433	**0.3696**
INTF	0.1634	0.3333	0.5821	0.4286	0.5714	0.2000	0.3333	0.4000	0.3875	**0.3777**
PD	0.5396	0.3333	0.0695	0.1429	0.2857	0.2000	0.3333	0.2000	0.1692	**0.2526**

Matrix of intelligence indicators with respect to the man-machine interaction attribute

MMI	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
PPSC	0.6667	0.6667	0.8571	0.6667	0.5000	0.7500	0.5000	0.5000	0.6667	**0.6415**
DAT	0.3333	0.3333	0.1429	0.3333	0.5000	0.2500	0.5000	0.5000	0.3333	**0.3585**

Results of super-matrix

	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
BIB	0.3587	0.3364	0.2078	0.2978	0.3386	0.3264	0.3140	0.3892	0.3487	**0.3242**
CCD	0.3049	0.3743	0.5806	0.3511	0.3630	0.3066	0.3473	0.3033	0.2568	**0.3542**
MMI	0.3365	0.2893	0.2116	0.3511	0.2984	0.3670	0.3387	0.3075	0.3944	**0.3216**

B6: Smart and Energy Efficient Lift System (LS)

Matrix of intelligence attributes with respect to the decision problem (the overall intelligence of LS)

GOALS	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.5396	0.3333	0.3333	0.7049	0.2499	0.3331	0.7153	0.4000	0.3333	**0.4381**
CCD	0.1634	0.3333	0.3333	0.2109	0.6548	0.0974	0.0977	0.2000	0.3333	**0.2694**
MMI	0.2970	0.3333	0.3333	0.0841	0.0953	0.5695	0.1870	0.4000	0.3333	**0.2925**

Matrix of intelligence attributes with respect to enhanced cost effectiveness

ECE	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.5396	0.5396	0.4126	0.4444	0.3333	0.3333	0.3333	0.3333	0.5000	**0.4188**
CCD	0.1634	0.1634	0.2599	0.1112	0.3333	0.3333	0.3333	0.3333	0.2500	**0.2535**
MMI	0.2970	0.2970	0.3275	0.4444	0.3333	0.3333	0.3333	0.3333	0.2500	**0.3277**

Matrix of intelligence attributes with respect to improved operational effectiveness and energy efficiency

OEE	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.5000	0.5499	0.5499	0.4742	0.2498	0.2000	0.7153	0.4000	0.6000	**0.4710**
CCD	0.2500	0.2098	0.2098	0.3764	0.6549	0.2000	0.0977	0.2000	0.2000	**0.2665**
MMI	0.2500	0.2403	0.2403	0.1494	0.0953	0.6000	0.1870	0.4000	0.2000	**0.2625**

Matrix of intelligence attributes with respect to improved user comfort and productivity

UC	EXB1	EXB2	EXB3	EXB4	EXB5	EXB6	EXB7	EXB8	EXB9	Mean Weight
AUT	0.5000	0.6000	0.6000	0.2098	0.1220	0.1604	0.2500	0.1634	0.4126	**0.3354**
CCD	0.2500	0.2000	0.2000	0.2403	0.3196	0.1488	0.2500	0.2970	0.2599	**0.2406**
MMI	0.2500	0.2000	0.2000	0.5499	0.5584	0.6908	0.5000	0.5396	0.3275	**0.4240**

Matrix of intelligence attributes with respect to increased system safety and reliability

S&R	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5396	0.5499	0.5396	0.3333	0.3333	0.3333	0.3333	0.4000	0.4126	**0.4194**
CCD	0.1634	0.2098	0.1634	0.3333	0.3333	0.0972	0.3333	0.4000	0.2599	**0.2549**
MMI	0.2970	0.2403	0.2970	0.3333	0.3333	0.5695	0.3333	0.2000	0.3275	**0.3257**

Matrix of operational benefits with respect to the autonomy attribute

AUT	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1381	0.1173	0.0993	0.1057	0.2537	0.0783	0.0820	0.0800	0.1131	**0.1186**
OEE	0.1953	0.1939	0.1404	0.2148	0.1673	0.4621	0.2422	0.3490	0.2769	**0.2491**
UC	0.2761	0.1939	0.1986	0.1891	0.2445	0.2511	0.3678	0.1781	0.3050	**0.2449**
S&R	0.3905	0.4950	0.5617	0.4904	0.3345	0.2085	0.3080	0.3929	0.3050	**0.3874**

Matrix of operational benefits with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.1684	0.1129	0.1284	0.2036	0.2530	0.1041	0.1250	0.0987	0.1692	**0.1515**
OEE	0.2416	0.1707	0.1575	0.3465	0.2994	0.2986	0.3750	0.4946	0.2879	**0.2969**
UC	0.2042	0.1707	0.2952	0.2036	0.2389	0.2729	0.1250	0.0985	0.2046	**0.2015**
S&R	0.3857	0.5457	0.4189	0.2463	0.2087	0.3244	0.3750	0.3082	0.3383	**0.3501**

Matrix of operational benefits with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ECE	0.3181	0.3235	0.1059	0.1429	0.2761	0.1038	0.0955	0.1713	0.1405	**0.1864**
OEE	0.3857	0.4310	0.1636	0.2857	0.1381	0.0970	0.2085	0.1713	0.2390	**0.2355**
UC	0.1141	0.0864	0.4476	0.2857	0.3905	0.5436	0.4875	0.4667	0.3397	**0.3513**
S&R	0.1821	0.1591	0.2829	0.2857	0.1953	0.2556	0.2085	0.1907	0.2808	**0.2267**

Matrix of intelligence indicators with respect to the autonomy attribute

AUT	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AE	0.6667	0.5000	0.5000	0.6667	0.8000	0.8000	0.5000	0.5000	0.8000	**0.6370**
ONDL	0.3333	0.5000	0.5000	0.3333	0.2000	0.2000	0.5000	0.5000	0.2000	**0.3630**

Matrix of intelligence indicators with respect to the controllability of complicated dynamics attribute

CCD	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
ACPTP	0.5000	0.3333	0.4545	0.7396	0.2970	0.6833	0.3333	0.4286	0.7143	**0.4982**
ONIA	0.2500	0.3333	0.0909	0.0938	0.5396	0.1169	0.3333	0.1429	0.1429	**0.2271**
INTF	0.2500	0.3333	0.4545	0.1666	0.1634	0.1998	0.3333	0.4286	0.1429	**0.2747**

Matrix of intelligence indicators with respect to the man-machine interaction attribute

MMI	**EXB1**	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
DAT	0.1634	0.2000	0.0769	0.6250	0.6337	0.6250	0.3333	0.3333	0.5396	**0.3923**
HED	0.2970	0.4000	0.4615	0.1365	0.1744	0.1365	0.3333	0.3333	0.2970	**0.2855**
PSSE	0.5396	0.4000	0.4615	0.2385	0.1919	0.2385	0.3333	0.3333	0.1634	**0.3222**

Results of super-matrix

	EXB1	**EXB2**	**EXB3**	**EXB4**	**EXB5**	**EXB6**	**EXB7**	**EXB8**	**EXB9**	**Mean Weight**
AUT	0.5208	0.5564	0.5446	0.3608	0.2540	0.2300	0.4043	0.3302	0.4747	**0.4084**
CCD	0.2045	0.2005	0.1910	0.2915	0.3960	0.1646	0.2422	0.2998	0.2425	**0.2481**
MMI	0.2747	0.2431	0.2644	0.3477	0.3500	0.6054	0.3535	0.3700	0.2828	**0.3435**

APPENDIX C

ASSESSMENT METHODS AND MEASUREMENT SCALES FOR THE CSC AND INTELLIGENCE INDICATORS OF THE INTELLIGENT BUILDING CONTROL SYSTEMS (C1 & C2)

APPENDIX C1: ASSESSMENT METHODS AND MEASUREMENT SCALES FOR THE CSC

CSC Assessment Methods	Measurement Scales
Method A1	The extent of the intelligent building system to fulfil a specific CSC. The rating scales range from 0 to 5: 5 marks (Excellent), 4 marks (Good), 3 marks (Fair), 2 marks (Poor), 1 mark (Very Poor), and 0 mark (Extremely Poor)
Method A2	The frequency of major breakdown of the building systems (i.e., 10% of whole business of the whole building has to halt due to major breakdown). The assessment was based on the breakdown frequency from 5 marks (once/year or less), 4 marks (twice/year), 3 marks (3-5 times/year or less), 2 marks (6-8 times /year or less), 1 mark (9-11 times /year or less), to 0 mark (once/month of more)
Method A3	The percentage of permanently installed devices under control and monitoring (i.e., by IBMS). The rating scales range from 0 to 5: 5 marks (100%), 4 marks (100-80%), 3 marks (80-60%), 2 marks (60-40%), 1 mark (40-20%), and 0 mark (lower than 20%)
Method A4	The extent of the AFA system in compliance with local regulations. The Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (1998) and the Code of Practices for Fire Resisting Construction (1996) are two codes of practice issued by the Fire Services Department of HKSAR. The rating scale in this part is only based on 5 marks (Full compliance) and 0 mark (non-compliance)
Method A5	The average response and report time for public announcement and to building management of disasters. The rating scales range from 0 to 5: 5 marks (5 seconds or shorter), 4 marks (5 to 30 seconds), 3 marks (30 to 60 seconds), 2 marks (60 to 90 seconds), 1 mark (90 to 120 seconds), and 0 mark (120 seconds or longer)
Method A6	PMV related to the overall percentage of thermal dissatisfaction and it depends on air temperature, mean radiant temperature, relative air velocity, relative humidity, human metabolic rate and clothing insulation level. This assess whether the HVAC control system is able to provide a lowest PMV. The assessment is based ISO Standard 7730 for human comfort (ISO, 1995). The most optimal thermal comfort level is resulted when a PMV value is equal to zero. The numerical figure with its range between +3 (hot) and -3 (cold). The rating scales range from 0 to 5: 5 marks (PMV at 0), 4 marks (PMV at between 0 and +1/-1), 3 marks (PMV at lower than +1/-1 and higher than +2/-2), 2 marks (PMV at +2/-2), 1 mark (PMV at lower than +2/-2 and higher than +3/-3), and 0 mark (PMV at +3/-3)
Method A7	The assessment is based the Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places which was published by the Indoor Air Quality Management Group pf HKSAR Government in November 1999. The IQA contains the following 6 items: (1) dry bulb temperature lover than 25.2C; (2) relative humidity less than 70%; (3) air movement less than 0.3m/s; (4) CO level less than 10000 µg/m; (5) CO_2 lower than 1000ppm; and, (6) radon level to be lower than $200Bq/m^3$. This evaluate whether the HVAC control system has the ability to maintain a reasonable IAQ level. The rating scales range from 0 to 5: 5 marks (full compliance of 6 items), 4 marks (failure of 1-2 items amongst items 1, 2, and 3), 3 marks (failure of 1-2 items amongst items 4, 5, and 6), 2 marks (failure of items 1, 2, and 3), 1 mark (failure of items 4, 5 and 6), and 0 mark (completely non-compliance)

CSC Assessment Methods	Measurement Scales
Method A8	The amount of energy consumption by HVAC system. It is rated based on GFA of the building. The rating scales range from 5 marks (60 kWh/year/m² or below); 4 marks (60-130 kWh/year/m² or below), 3 marks (130 kWh/year/m² or below), 2 marks (130-140 kWh/year/m² or below), 1 mark (140-150 kWh/year/m² or below), to 0 mark (150 kWh/year/m² or above)
Method A9	The percentage of standalone building control systems were linked by IBMS. The rating scales range from 0 to 5: 5 marks (100%-81%), 4 marks (80%-61%), 3 marks (60%-41%), 2 marks (40%-21%), 1 mark (20% -1%), and 0 mark (lower than 1%)
Method A10	The assessment is based on the frequency breakdown of the proposed HVAC systems (i.e., average mean time between failures, MTBF). The rating scales range from 0 to 5, 5 marks (MTBF=3 months or above), 4 marks (MTBF=3-2.5 months), 3 marks (MTBF=2.5-2 months), 2 marks (MTBF=2-1.5 months), 1 mark (MTBF=1.5-1 month), and 0 mark (MTBF=1 month or below)
Method A11	This related to the control of noise level in the HVAC system. The assessment was based on the noise level from 5 marks (NC 45 or below), 4 marks (NC 45 -50), 3 marks (NC 50-55), 2 marks (NC 55 -60), 1 mark (NC 60 -65), to 0 mark (NC 65 or above)
Method A12	The level and scope of system interface. The rating scales range from 0 to 5: 5 marks (100%), 4 marks (100-80%), 3 marks (80-60%), 2 marks (60-40%), 1 mark (40-20%), and 0 mark (lower than 20%)
Method A13	Amount of air change per second provided for the occupants. Inadequate fresh air would lead to uncomfortable feeling, and too much fresh air consumes unnecessary energy. Rating methods: 5 marks (9.5 litres/s/occupant), 4 marks (between 9.49 to 7.75 litres/s/occupant and 9.49 to 10.75 litres/s/occupant), 3 marks (between 7.76 to 5.76 litres/s/occupant and 10.76 to 11.99 litres/s/occupant), 2 marks (between 5.75 to 3.26 litres/s/occupant and 12 to 13.74 litres/s/occupant), 1 mark (between 3.25 to 1.01 litres/s/occupant and 13.75 to 14.99 litres/s/occupant), and 0 mark (more than 15 litres/s/occupant or less than 1 litres/s/occupant)
Method A14	The total time span for all building occupants to arrive at safe location after receiving the general alarms from the public address system is estimated. The rating scales range from 0 to 5: 5 marks (10 minutes or less), 4 marks (10-15 minutes), 3 marks (15-20 minutes), 2 marks (25-20 minutes), 1 mark (30 to 25 minutes), and 0 mark (30 minutes or longer)
Method A15	The reliability and stability of the lift system inside the intelligent building. This is measured by the mean time between any two failures of any lifts or escalators with the whole system. The rating scales range from 0 to 5: 5 marks (6 months or above), 4 marks (4.5-6 months), 3 marks (3-4.5 months), 2 marks (1.5-3 months), 1 mark (1 -1.5 month), and 0 mark (1 month or below)
Method A16	The expected average time taken for a passenger to wait for the arrival of the appropriate car at the lift lobby. The rating scales range from 0 to 5: 5 marks (30 seconds or shorter), 4 marks (50 seconds to 31 seconds), 3 marks (70 seconds to 51 seconds), 2 marks (90 seconds to 71 seconds), 1 mark (110 to 90 seconds), and 0 mark (more than 110 seconds)

CSC Assessment Methods	Measurement Scales
Method A17	The time required for the next car to arrive at the main terminal after the previous car has arrived at the main terminal. The value measurement is extracted from the Code of Practice (COP) for Energy Efficiency of Lift and Escalator Installations issued by Electrical and Mechanical Service Department (EMSD) of HKSAR in 2000. The rating scales range from 0 to 5: 5 marks (22.5 seconds or shorter), 4 marks (26.25 seconds to 22.5 seconds), 3 marks (30 seconds to 26.25 seconds), 2 marks (47.5 seconds to 30 seconds), 1 mark (65 to 47.5 seconds), and 0 mark (more than 65 seconds)
Method A18	The assessment can be measured in two ways: the average power consumption with passengers (WP) (measured in kJ per passenger per m) and without passengers (W/O P) (measured in J/kg). The rating scales range from 0 to 5: 5 marks (WP: 2 kg/passenger/m or less; W/O P: 50 J/kg or less); 4 marks (WP: 2.1-3.25 kg/passenger/m; W/O P: 51-163 J/kg), 3 marks (WP: 3.25-4.50 kg/passenger/m; W/O P: 163-275 J/kg), 2 marks (WP: 5.75-4.50 kg/passenger/m; W/O P: 387–275 J/kg), 1 mark (WP: 7-5.75 kg/passenger/m; W/O P: 500-387 J/kg), and 0 mark (WP: 7 kg/passenger/m or more; W/O P: 500 J/kg or more)
Method A19	The assessment is based on the comfort feeling of the common occupants if both acceleration and deceleration are being kept below a value about one sixth of the gravitational acceleration, i.e., 9.8 m/s^2. The rating scales range from 0 to 5: 5 marks (0.8 m/s^2 or less), 4 marks (1.85- 0.8 m/s^2), 3 marks (2.9-1.85 m/s^2), 2 marks (3.95-2.9 m/s^2), 1 mark (3.95-5 m/s^2), and 0 mark (5 m/s^2 or more)
Method A20	The expected average time a passenger needs to take from the moment of entering the car to the moment of leaving the lift car. The rating scales range from 0 to 5: 5 marks (40 seconds or shorter), 4 marks (60 seconds to 41 seconds), 3 marks (80 seconds to 61 seconds), 2 marks (100 seconds to 81 seconds), 1 mark (120 to 101 seconds), and 0 mark (more than 120 seconds)
Method A21	The assessment is based on the measurement by the EVA-625 recorder with a microphone placed 1 meter above the car floor at the middle of the car when the empty car is travelling upward from the bottom floor to the top floor of the zone. The rating scales range from 0 to 5: 5 marks (45 dBA or lower), 4 marks (55.5 dBA to 45 dBA), 3 marks (66 dBA to 55.5 dBA), 2 marks (73 dBA to 66 dBA), 1 mark (80 dBA to73 dBA), and 0 mark (more than 80 dBA)
Method A22	The amount of air change per hour inside lift cars. This is judged based on the rating scales of 0 to 5: 5 marks (20 AC/hr or above), 4 marks (17.5 to 20 AC/hr), 3 marks (15 to 17.5 AC/hr), 2 marks (12.5 to 15 AC/hr), 1 mark (10 to 12.5 AC/hr), and 0 mark (lower than 10 AC/hr)
Method A23	The assessment is based on the lift car horizontal (HVL) and vertical vibration limits (VVL). The rating scales range from 0 to 5: 5 marks (HVL: 0.04m/s^2; VVL: 9.80m/s^2), 4 marks (HVL: 0.06-0.04m/s^2; VVL: 9.84-9.80m/s^2), 3 marks (HVL: 0.08-0.06m/s^2; VVL: 9.88-9.84m/s^2), 2 marks (HVL: 0.12-0.08m/s^2; VVL: 9.92-9.88m/s^2), 1 mark (HVL: 0.15-0.12m/s^2; VVL: 9.95-9.92m/s^2), and 0 mark (HVL: 0.15 m/s^2 or higher; VVL: 9.95m/s^2 or higher)
Method A24	The assessment is extracted from the Code of Practice for Energy Efficiency of Lighting Installations published by EMSD (1998). The rating scales range from 0 to 5: 5 marks (25 W/m^2 or above), 4 marks (28-25 W/m^2), 3 marks (32-28 W/m^2), 2 marks (36-32 W/m^2), 1 mark (40-36 W/m^2), and 0 mark (Above 40 W/m^2)

CSC Assessment Methods	Measurement Scales
Method A25	The extent and level of automatic control. The rating scales range from 0 to 5: 5 marks (100% automatic control), 4 marks (80% automatic control), 3 marks (60% automatic control), 2 marks (40% automatic control), 1 mark (20% automatic control), and 0 mark (manual control)
Method A26	The energy consumption can be measured on the average efficacy of all lamps of the lighting systems. This was rated based on the ratio of the total lumen output of a lamp to the total electric power input to it. The rating scales range from 0 to 5: 5 marks (50 lm/W or above); 4 marks (37.5 to 50 lm/W), 3 marks (25-37.5.lm/W), 2 marks (12.5-25 lm/W), 1 mark (5-12.5 lm/W), and 0 mark (5 lm/W or below)
Method A27	The existence and level of automatic control and adjustment of lux level. The rating scales range from 0 to 5: 5 marks (100% automatic control), 4 marks (80% automatic control), 3 marks (60% automatic control), 2 marks (40% automatic control), 1 mark (20% automatic control), and 0 mark (manual control)

APPENDIX C2: ASSESSMENT METHODS AND MEASUREMENT SCALES FOR THE INTELLIGENCE INDICATORS

Intelligence Indicators Assessment Methods	Measurement Scales
Method B1	The existence and level of intelligent functions or properties. The rating scales range from 0 to 5: from 5 marks (Excellent), 4 marks (Good), 3 marks (Fair), 2 marks (Poor), 1 mark (Very Poor), and 0 mark (Extremely Poor)
Method B2	The percentage of standalone building control systems were linked by IBMS. The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39% -20%), and 0 mark (lower than 20%)
Method B3	The assessment is based on the number of human intervention (per month): 1 time or below to 30 times or above. The rating scales range from 0 to 5: from 5 marks (1 time or below), 4 marks (1 to 7 times), 3 marks (8 to 15 times), 2 marks (16-22 times), 1 mark (23-29 times), and 0 mark (30 times or above)
Method B4	The existence and level of automatic control. The rating scales range from 0 to 5: from 5 marks (100% automatic control), 4 marks (80% automatic control), 3 marks (60% automatic control), 2 marks (40% automatic control), 1 mark (20% automatic control), and 0 mark (manual control)
Method B5	The percentage of natural ventilation used compared to the mechanical ventilation. The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39% -20%), and 0 mark (lower than 20%)
Method B6	The average response/ report time to building management and Fire Dept: [5 seconds or shorter to 2 minutes or longer]. The rating scales range from 0 to 5: from 5 marks (5 seconds or shorter), 4 marks (between 5 seconds and 45 seconds), 3 marks (between 45 seconds and 90 seconds), 2 marks (between 90 seconds and 2 minutes), 1 mark (2 minutes to 3 minutes), and 0 mark (3 minutes or longer)
Method B7	The percentage of permanently installed devices under control and monitoring (by IBMS). The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39% -20%), and 0 mark (lower than 20%)
Method B8	The level and scope of system interface. The rating scales range from 0 to 5: from 5 marks (100%), 4 marks (99%-80%), 3 marks (79%-60%), 2 marks (59%-40%), 1 mark (39%-20%), and 0 mark (lower than 20%)

APPENDIX D

PUBLICATIONS OF THE AUTHOR

APPENDIX D: PUBLICATIONS OF THE AUTHOR

Refereed Journal Papers (Arising From the Thesis):

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APPENDIX E

GLOSSARY OF TERMS

APPENDIX E: GLOSSARY OF TERMS

Note: Letters in parenthesis refer to abbreviation used in the paragraph and/or Appendices

Addressable Fire Detection and Alarm System (AFA) – a system for the detection of the occurrence of the fire accidents (including gas and smoke) within the building in order to maintain the safety of the occupants in the buildings.

Analytic Hierarchy Process (AHP) - a decision making theory, developed by Thomas L. Saaty (1980), which aims at handling a large number of decision factors and providing a systematic procedure for ranking many decision variables.

Analytic Network Process (ANP) – an advanced version of the Analytic Hierarchy Process (AHP), which enables users to consider dependencies and interdependencies between all attributes, both within one particular level and also across levels.

Autonomy (AUT) - the abilities of performing self-operative functions

Bio-inspired Behaviour (BIB) - the system's capability of performing bio-inspired behavioural traits, and the system's ability to interact with the building environment and the services provided

Controllability for Complicated Dynamics (CCD) - the ability to perform interactive operative functions and is able to make a very complicated dynamic system well-controlled

Consistency – The compatibility of a matrix of the ratios constructed from a principal right eigenvector with the matrix of judgments from which it is derived.

Control hierarchy – A hierarchy of criteria and subcriteria for which priorities are derived in the usual way with respect to the goal of the system being considered

Digital Addressable Lighting Control System (DALI) – A system for the control of the intensity of a plurality of lights operating entirely by digital means.

Eigenvector – The weight vector for the comparison matrix at the criteria level in the AHP or ANP method

Fault tolerance - the ability of a system to avoid failure after faults in the system’s design/implementation had caused errors

Global priority (GP) - the importance of an element with respect to the focus of the decision problem

Heating, Ventilation and Air-conditioning (HVAC) Control System – A system provides a flexible control of heating, ventilation and air conditioning (HVAC) for enclosed areas.

Intelligent building (IB) – a building type which provides for innovative and adaptable assemblies of technologies in appropriate physical, environmental and organizational settings, to enhance worker productivity, communication and overall human satisfaction

Integrated Building Management System (IBMS) - the core system of intelligent building which aims to provide automatic functional control and to maintain the building’s normal daily operation.

Interoperability – the ability to link multiple standalone building control systems from a variety of manufacturers

Local priority (LP) - the importance, or priority, of an element in a certain level with respect to an element in a level immediately above it

Lux – The International System of Units of illuminance, the total luminous flux incident on a surface, per unit area, is a measure of the intensity of the incident light, wavelength-weighted by the luminosity function to correlate with human brightness perception.

Man-machine Interaction (MMI) - the abilities of an intelligent system to interface with operator and working staff, which make the human users feel more comfortable and the system more user-friendly

Matrix – A tabular representation of the interrelatiomships between the variables in a network.

Predict Mean Vote (PMV) - the overall percentage of thermal dissatisfaction and it depends on air temperature, mean radiant temperature, relative air velocity, relative humidity, human metabolic rate and clothing insulation level.

Remote override – map a control surface item to a specific reason parameter or function

Self-diagnosis – the process of self-correction or self-compensation of short-term stable systematic errors using long-term stable reference quantities and special algorithms.

Security Monitoring and Access Control System (SEC) – A system designed to anticipate, recognise and appraise a crime risk and to initiate actions to remove or reduce that risk.

Smart and Energy Efficient Lift System (LS) – a system designed to provide a higher handling capacity, improved riding comfort and a better man-machine interface.

Super-matrix – a partitioned or ‘overall’ matrix, where each sub-matrix is composed of a set of relationships between and within the levels as represented by the decision-maker’s model, which allows for a resolution of interdependencies that exist among the elements of a system

Telecom and Data System (ITS) – a system to generate, process, store and transmit information in the intelligent building.

Threshold limiter - an accuracy limit threshold based upon the proximity of the receive signal frequency to the transceiver operating frequency, a maximum correction threshold based upon a predetermined maximum frequency correction limit.