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Quality Function Deployment for Buildable and Sustainable Construction

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Abbreviations

A&A	Additions and alterations
AHP	Analytic hierarchy process
AMEP	Architectural, mechanical, electrical, and plumbing
BC	Buildability criteria
BCA	Building and construction authority
BDAS	Buildable design appraisal system
BL	Concrete blockwall
BN	Bayesian network
C&S	Civil and structural
CAS	Constructability appraisal system
CBR	Case-based reasoning
CL	Claybrick wall
CMSM	Construction method selection model
CP	Code of practice
CR	Criteria room
CS	Cast in situ wall
CW	Curtain wall
DM	Decision maker
DSS	Decision support system
EC	Economic criteria
ELECTRE	Elimination Et Choix Traduisant la Réalité or elimination and choice translating reality
EN	Environmental criteria
ESD	Environmental sustainable design
ETTV	Envelope thermal transfer value
FG	Fixed-glass wall
FR	Fuzzy techniques for prioritizing the design alternatives room
GFA	Gross floor area
GM	Green mark
GMS	Green mark scheme
HOBSB	House of quality of sustainability and buildability

HOQ	House of quality
IAQ	Indoor air quality
IMMPS	Interactive method for measuring preassembly and standardization
KBDSS	Knowledge-based decision support system
KBS	Knowledge-based system
KM	Knowledge management
KM-C	Knowledge management of the criteria system
KM-M	Knowledge management of the materials and designs system
KM-R	Knowledge management of relationships between the criteria and design alternatives system
KMS	Knowledge management system
M&E	Mechanical engineering
MADM	Multiattribute decision-making
MCDM	Multicriteria decision-making
MODM	Multiobjective decision-making
MOLP	Multiobjective linear programming
MR	Building envelope materials and designs room
PC	Precast wall
PM	Project management
PPMOF	Preassembly, modularization, and offsite fabrication
PR	Preference list room
PSSM	Prefabrication strategy selection method
QFD	Quality function deployment
QS	Quantity surveyor
RBR	Rule-based reasoning
RC	Reinforced concrete
RR	Relationships between the criteria and the building envelope materials and designs room
RTTV	Roof thermal transfer value
SBI	Sustainability and buildability index
SC	Shading coefficient
SC	Social criteria
SD	Shading device
SFC	Structural frame selection
SI	Severity index
SPSS	Statistical packages for the social sciences
SS	Singapore standard
STC	Sound transmission class
TBP	Total building performance
TOPSIS	Technique for order preference by similarity to ideal solution
UML	Unified modeling language
VOC	Voice of customer
WG	Window glazing
WWR	Window-to-wall ratio

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Abstract

Success of a private high-rise residential building project is tied with the assessment and selection of building envelope materials and designs that can satisfy requirements of the stakeholders of the project. These requirements typically refer to the criteria for achieving sustainability and buildability in building envelope design. Although it has been found that sustainability and buildability in the building industry have gained more importance in recent years, designers seem to be unable to grasp the concept of sustainability and buildability collectively.

Apart from this problem, a building design team also faces several decision-making problems when assessing building envelope materials and designs for a private high-rise residential building in the early design stage. These decision-making problems include inadequate consideration of requirements, inadequate consideration of possible materials and designs, lack of efficiency and consistency in making decisions of the team, lack of communication and integration among members of the team, subjective and uncertain requirements, and disagreement between members of the team. Undoubtedly, these problems can cause significant adverse impacts to a project.

In response to these two main problems, two objectives are set out in this book. The first objective is to identify underlying factors of the criteria for the assessment of the building envelope materials and designs based on the Institutional Theory framework. This aims to support the building professionals to realize the importance of sustainability and buildability when assessing building envelope materials and designs. To achieve this objective, survey and questionnaire are selected as the research design and method of data collection, respectively. The results from factor analysis reveal that the criteria can be grouped into four major factors which are the environmental, economic, social, and buildability factors. These findings provide the building professionals with a more concise and defined structure of sustainability and buildability, thereby leading to a better way to determine an optimal balance between environmental, economic, social, and buildability issues related to the building envelope design.

The second objective of this book is to develop the knowledge-based decision support system quality function deployment (KBDSS-QFD) tool to facilitate the design team to mitigate the decision-making problems identified as a whole. Based on the pilot study and semi-structured interviews, the book automates the tool by comprehensively integrating the house of quality for sustainability and buildability (HOQSB), knowledge management system (KMS), fuzzy set theory, and user interface together. To fulfill the second objective, case study and group interview are selected as the research design and method of data collection, respectively. The book applies three case studies of different design teams to use the KBDSS-QFD tool developed, and each team consists of an architect, civil and structural (C&S) engineer, and mechanical and electrical (M&E) engineer. The results from the qualitative framework analysis through the group interviews show that the tool has the potential to mitigate the decision-making problems as a whole. The contributions of using this automated KBDSS-QFD tool include not only mitigating the decision-making problems but also improving overall project management with respect to cost, time, and quality goals of a project.

Keywords Building envelope materials and designs · Sustainability · Buildability · Design team · Decision-making problems · Decision support system · Quality function deployment · Knowledge-based system · Fuzzy set theory · Project management

Chapter 1
Introduction

1.1 Introduction

This chapter presents the background (Sect. 1.2), significance of the issue (Sect. 1.3), and the aim (Sect. 1.4) of this book. This is followed by describing the research problems (Sect. 1.5), research objectives (Sect. 1.6), and knowledge gaps (Sect. 1.7). The chapter then highlights the research scope (Sect. 1.8), research strategy (Sect. 1.9), and structure of the book (Sect. 1.10).

1.2 Background

Building envelope systems, as the interface between interior space and the exterior environment, generally serve the function of weather and pollution exclusion and thermal and sound insulation (Kibert 2008). Their performance affects occupant comfort and productivity, energy use and running costs, strength, stability, durability, fire resistance, aesthetics appeal of a building, etc. (Chew 2009; Chua and Chao 2010a). A thoughtful building envelope design can make a building work more effectively for its builders and occupants as part of stakeholders of a project (Boecker et al. 2009). The success of a project is tied to the assessment and selection of building envelope materials and designs that can satisfy the requirements of stakeholders. These requirements typically refer to important criteria for achieving sustainability and buildability in building envelope design (Singhaputtangkul et al. 2011a).

Sustainability can be seen as the balance between social and economic activities and the environment (Bansal 2005), while buildability refers to the ability to construct a building efficiently, economically, and to agreed quality levels from its construction resources (Low et al. 2008c). In Singapore, sustainability of building envelope design is assessed by the green mark scheme (GMS) in the form of the

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GM score (BCA 2010a), while buildability of building envelope design is evaluated through the buildable design appraisal system (BDAS) and constructability appraisal system (CAS) by determining the buildability score and constructability score, respectively (BCA 2011a). It is imperative that all the scores mentioned of a given building meet the minimum requirements before approval of building plans (BCA 2010a, 2011a). However, it was found that building professionals, particularly architects and engineers, seem to be unable to grasp the abstract concept of' sustainability and buildability when conducting the assessment of the building envelope materials and designs in the early design stage (Wong et al. 2006).

Apart from this problem, notwithstanding the fact that the building envelope materials and designs in Singapore have to comply with sustainability and buildability regulations, this compliance does not guarantee the satisfaction of the stakeholders because these regulations do not cover all key requirements of the stakeholders (Azhar and Brown 2009; Singhaputtangkul et al. 2011a). This is because the assessment of the building envelope materials and designs for private high-rise residential buildings in the early design stage requires a large amount of information and involves considerations from the builders, especially architects and engineers, as part of a design team (Singhaputtangkul et al. 2011b). Undoubtedly, from the literature reviews and a pilot study, this assessment appears to be affected by a number of decision-making problems, for example, inadequate consideration of requirements, lack of communication between the parties, subjective and uncertain requirements, and so on. These decision-making problems can cause significant adverse impacts to a project such as delays, increase in expenses, increase in manpower of a building project, and poor professional relationship (Arain and Low 2005; Fryer 2004). Hence, there is a need to mitigate these problems when the design team makes the decisions for the assessment of the building envelope materials and designs in the early design stage.

1.3 Significance of Issue

The construction industry, because of its fragmented nature, has tended to separate practitioners with different expertise and disciplines. This demarcation feature seems to reduce the productivity of a project, and possibly cause difficulties for building professionals (Wong et al. 2006). These issues are evident in the assessment of building envelope materials and designs for private high-rise residential buildings where decisions related to the assessment not only involve several project requirements, but also require inputs and intuitive judgments from a number of the building professionals (Brock 2005; Carmody et al. 2007).

Consequently, in spite of the implementation of numerous regulations and standards to promote sustainable and buildable designs, the concept of sustainability and buildability has not been much appreciated by architects and engineers (Boecker et al. 2009; Yang et al. 2003). One of the major barriers is the inability of architects and engineers to grasp the concept of sustainability and buildability collectively when assessing the building envelope materials and designs. Significantly, this may impede the decision-making process to deliver a more sustainable and buildable building envelope design in the early design stage (Salazar and Brown 1988).

In addition to the above-mentioned problem, the design team consisting of architects and engineers seem to encounter a number of decision-making problems when assessing the building envelope materials and design. In principle, each building organization has its goals, and achieves these goals through the use of resources such as people, materials, money, and the performance of managerial functions including planning, organizing, directing, and controlling. To carry out these functions, decision-makers (DMs) are engaged to participate in a continuous process of making decisions (Reilly 2001). Wason (1978) suggested that people are often poor at reasoning and also found that much of the time people do not reason logically. Wason and Evans (1975) found that DMs' judgments in making difficult decisions require systematic decision analysis to provide structure and guidance for thinking systematically about hard or difficult decisions. These difficult decisions are typically made up of four common decision-making problems as shown in Fig. 1.1.

First, a decision can be difficult because of its complexity. This makes it hard to keep all of the issues in mind at one time due to cognitive limitation. Second, making a decision may encounter difficulties because of the inherent uncertainty in a situation. Therefore, the decision must be made without knowing exactly what these uncertain values will be, especially, in the early design stage. Third, a DM may be interested in working toward multiple objectives, but progress in one direction may impede progress in others. Lastly, a decision may be difficult if different perspectives of DMs lead to different conclusions. In fact, even from a single perspective, slight changes in certain inputs may lead to different choices. This source of difficulty is particularly pertinent when more than one person is involved in making the decision (Reilly 2001; Yang et al. 2003). In addition, DMs may also disagree on the uncertainty or value of the various inputs and outputs (Pedrycz et al. 2011).

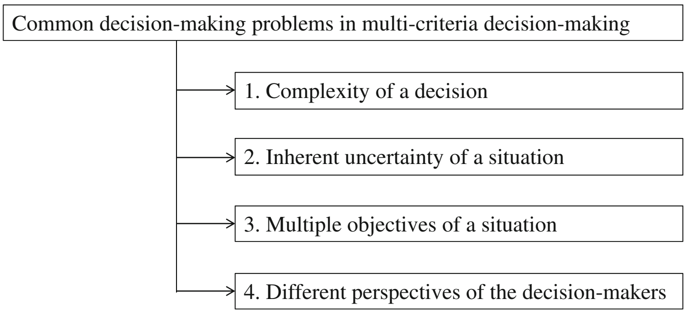


Fig. 1.1 Common decision-making problems in multicriteria decision-making

These four major considerations as a whole contribute to a number of the decision-making problems faced by architects and engineers when assessing the building envelope design in the early design stage. A pilot study (see Appendix A) and literature reviews suggested that there are six major decision-making problems affecting the assessment of the building envelope materials and designs in the early design stage as described in the following sections.

1. **Inadequate consideration of requirements**

Inadequate consideration of requirements is a major cause for poor performance in construction projects (Ibbs and Allen 1995). For instance, because of inadequate consideration of project requirements, designers may not be able to develop a comprehensive design, which may lead to numerous adverse impacts during different project phases (El-Alfy 2010). Singhaputtangkul et al. (2011a) found that inadequate consideration of project requirements tends to lead to redesigning activities, particularly when new assessment criteria have to be additionally considered. These activities can cause progress delay, project delay, increase in expenses, increase in manpower needed of a building project, etc. (Fryer 2004). Furthermore, Singhaputtangkul et al. (2011b) highlighted this problem by showing an example that if the building material that requires more complex construction methods was selected on a basis of enhancing the energy performance of a building solely, in the situation where there was a mismatch between the methods of construction and workers' skill sets, the safety performance of a project could be affected (Singhaputtangkul et al. 2011b).

2. **Inadequate consideration of possible materials and designs**

The field of building envelope design and engineering is quite established, while new building envelope materials and systems are being developed on a continual basis. El-Alfy (2010), Makenya and Soronis (1999) reported that most architects and engineers usually select materials drawn from their personal collection of literature and their knowledge of what is available in the local and international market, and frequently use short cuts based on their experience in order to save time. In addition, most architects and engineers preferred to stick to familiar products, have a strong preference for certain materials and components used previously, and typically refuse to use new products unless they are unavoidable. As a result, this may reduce a number of the alternative materials and designs that could satisfy the requirements of the stakeholders.

3. **Lack of efficiency and consistency**

Efficiency is typically represented in the form of time, cost, or effort to accurately complete a decision-making activity (Charnes et al. 1978), while consistency refers to agreement or accordance between current and previously made decisions (Martino et al. 2008). Efficiency and consistency are an important consideration in group decision making because a group must strive not only to achieve immediate results, but also to acquire the capability to continue to obtain consistent results in the future and ensure that these are efficient results (Argandona 2008).

Unsurprisingly, due to the complexity of most decision-making problems, previous studies have suggested that lack of efficiency and consistency is a major problem in making decisions in a team (Davenport and Prusak 1998; McMahon et al. 2004). There are numerous sources of this problem. Based on the pilot study, in the area of building envelope design, one of these sources is the absence of an organized knowledge management system (KMS), which is the systematic and active management of ideas, information, and knowledge residing in an organization's employees.

For instance, in the absence of an established KMS, if there is only one designer who knows about stone cladding design, and if this designer leaves a design team, there will likely be an absence of such distinctive knowledge. Conversely, if he stays, the design team may always depend on his decisions on stone cladding design. Both the situations seem to have a significant impact on efficiency and consistency in making decisions in the team. Notwithstanding this example, designers also have limited knowledge, or sometimes are not aware of some design and construction knowledge from other multifunctional team members (Fischer 1991). Consequently, the absence of the KMS to store and organize important knowledge would affect efficiency and consistency in making decisions in the design team.

4. **Lack of communication and integration between designers**

In building design, communication and integration play a vital role in connecting and combining ideas of designers from different parties together during design processes. The principle of communication involves a sequential mode from the sender encoding the channel of communication to the receiver decoding the same channel (Low and T'ng 1998). Integration refers to the task of bringing works of designers together to make a harmonious whole (Mantel et al. 2008). In the context of early stage design management, these two concepts seem to be correlated (Kibert 2008). Effective communication and integration during the early design stage of a project provides the potential for designers to give their clients best value-for-money designs (Yang 2004). Nevertheless, when the project is complex involving inputs and works from several DMs, the intricate process of coordinating and integrating such inputs and works becomes more difficult (Mantel et al. 2008; Sidney 1986).

Lack of communication and integration is recognized as a major problem not only during the design development stage but also during the entire project development cycle. In particular, communication and integration among the designers are often fraught with difficulties and are seldom linked to design outcomes (Low and T'ng 1998). The barriers in communications render the achievement of an appropriate design difficult as well as a time-consuming process (Low and T'ng 1998; Marsot 2005). Additionally, previous studies have pointed out that poor communication and integration faced by building professionals typically lead to unclear instructions, additional work, delay in progress, poor professional relations, and poor quality of design solutions (Austina et al. 2002; Kagioglou 2000).

5. **Subjective and uncertain requirements**

Practical building design depends heavily on intuitive thinking and professional expertise that usually have a large variation of shades of gray as opposed to black and white colors (Malek 1996). It was noted that, while assessing and selecting the building envelope materials and designs require a process to program large amount of information, in many cases, crisp data are often inadequate to model real-world problems related to building design (Yang 2004). This could be due to various reasons; for example, subjective estimation and perception, incomplete knowledge, or the complexity of studied systems (Chakraborty 2002). Under these vague and uncertain circumstances, DMs seem to be unable to estimate their preferences with an exact numerical input (Lam et al. 2010). This appears to affect management of tradeoffs between these subjective, conflicting, and uncertain criteria and makes the problem related to subjective and uncertain requirements one of the major decision-making problems faced by architects and engineers when assessing the building envelope materials and designs.

6. **Disagreement between members of the team**

Nutt (1993) defines “decision making” as a process made up of stages carried out to set directions, identify solutions, evaluate courses of action, and implement a preferred plan. The effectiveness of a group decision process has become an increasingly important organizational concern. This strategy is based on the assumption that decisions made by groups of employees with diversified expertise will be higher in quality than those made by employees with more homogeneous backgrounds (Jacksons 1992; Low and T’ng 1998). A common organizational response to this consideration is to design cross-functional teams, combining representatives of different organizational functions to ensure diversity in knowledge and perspectives (Stasser and Titus 1985).

Nevertheless, these heterogeneous groups exhibit additional problems, as multicriteria group decision making involves many complex and conflicting aspects intrinsic to human individuality and human nature. One of these problems is disagreement between members of a team (Low and T’ng 1998). According to Phillips and Phillips (1993), group work offers a multitude of advantages to an organization through sharing information, generating ideas, making decisions, and reviewing the effects of decisions. Ideally, the group should reach a “better” decision than an individual because the collective knowledge is typically greater than an individual’s knowledge. In real situations, when a set of experts takes part in the decision process, it is quite natural that, initially, their opinions disagree. Unsettled disagreement can possibly cause disputes within a party, disputes among parties, poor professional relations, and ambiguous design details (Behfar et al. 2008; Fryer 2004; Robey et al. 1991).

When dealing with multicriteria group decision-making problems, a decision aid tool can help to overcome difficulties faced by team members by providing a more structured decision-making framework (Boudreau 1989). A decision support system (DSS) as a sophisticated form of the decision aid tool enables members of a team to consider more factors that can affect building designs during the decision-making process, and to conduct more thorough decision analysis (Ling 1998). Among several decision aid tools, quality function deployment (QFD) is regarded as a highly effective tool to systematically structure difficult decision-making processes (Low and Yeap 2001; PMI 2008). Using a QFD approach also helps in producing more accurate decisions by focusing on several aspects and criteria based on customer's needs (Mallon and Mulligan 1993).

Previous studies therefore have adopted the QFD approach by integrating it with either fuzzy techniques or KMS to develop a QFD-based DSS to deal with problems in the building industry. In brief, Crow (2002) found that applying the QFD approach can reduce disagreement among designers over what is important at each stage of the product development process. This is because the QFD tool systematically guides the experts to focus on the critical items that affect the success of the product. Yang et al. (2003) developed a fuzzy QFD tool and suggested that fuzzy set theory integrated into the QFD tool can capture inherent impreciseness and vagueness of design inputs and facilitate making decisions in a design team.

Among several decision-making techniques, for example Bayesian Network, TOPSIS, and AHP, the fuzzy set theory has been found to be more useful when the decision-making process is subject to inherent uncertainty and involves various alternatives. A main benefit of the fuzzy set theory lies in its ability to deal with diverse types of uncertainty through the use of fuzzy linguistic terms (Pedrycz and Gomide 1998). Notwithstanding its difficulties in choosing fuzzy linguistic functions, fuzzification functions, and defuzzification functions, a fuzzy system provides a more flexible, economical and reliable way to utilize the knowledge and experience of building professionals (Yang 2004).

The fuzzy set theory has also been applied to develop techniques to seek a consensus among members of a team when making group decisions. One of these is a fuzzy consensus scheme (Pedrycz et al. 2011). Similar to a Delphi technique, the fuzzy consensus scheme adopts the principle that allows experts to improve their decisions through a number of review cycles to revise their replies. However, a main benefit of the Delphi technique lies in anonymity of team members, while, conversely, success of the fuzzy consensus scheme ties with an open discussion of all the team members. With this in mind, the fuzzy consensus scheme appears to be more useful for a team dealing with complex problems where face-to-face discussion among individual experts is needed, such as in building design.

In addition to integrating the QFD approach with the fuzzy set theory, there are studies combing the QFD approach with a KMS. For example, Hsu et al. (2011) integrated the QFD approach with a KMS to improve efficiency in identifying customer requirements. This seems to suggest that integration of the QFD tool with the fuzzy set theory and KMS together may be able to form a DSS for mitigating the decision-making problems identified in this book as a whole and for improving quality of design outcomes. Details of the literature reviews related to decision-making techniques and development of the tool is provided in Chap. 2.

1.4 Aim of the Book

The main aim of this book is to develop a knowledge-based decision support system quality function deployment (KBDSS-QFD) tool by integrating the QFD approach with the fuzzy set theory and KMS to facilitate the design team in mitigating the decision-making problems at once. In brief, the QFD approach would play a role to structure the decision-making process of assessment of building envelope materials and designs. This would facilitate identification of customer requirements in terms of criteria and design alternatives as well as prioritization of such requirements and alternatives.

In parallel, the KMS is established to store relevant knowledge of the requirements and alternative. It aims to enhance consistency and efficiency in making decision of the DM. The QFD tool integrated with this KMS would also improve communication among the DMs as the DMs can immediately access to the knowledge when making decisions. The tool is also embedded with the fuzzy set theory to allow DMs to translate the vagueness of their feeling and recognition of both the requirements and alternatives into a decision model. In this regard, making decisions through integration of the fuzzy set theory and KMS would mitigate the decision-making problem related to subjective requirements faced by the DMs. Furthermore, the fuzzy consensus scheme as introduced earlier is applied in this book as part of the KBDSS-QFD tool to mitigate disagreements related to perspectives toward importance of criteria and satisfactions of alternatives among the DMs.

1.5 Research Problems

Considering the background and significance of the research issues, the research problems of this book are set out below:

1. What is the concept behind the assessment of the building envelope materials and designs?
2. How are the decision-making problems faced by the design team in the early design stage mitigated through the use of the KBDSS-QFD tool?

The first research problem points out that there is a need to identify the concept to support the building professionals to achieve sustainability and buildability when assessing the building envelope materials and design. As there are several criteria applied for the assessment, the lack of a concept for sustainability and buildability may have an adverse impact on selection of the building envelope materials and designs. This could also affect performance of a building as well as satisfaction of stakeholders of a project.

The second research problem raises the question regarding a capability of the KBDSS-QFD tool in mitigating the decision-making problems. As the tool would be modeled from the QFD approach integrated with the fuzzy set theory and KMS in the first instance, the impact of the KBDSS-QFD tool on the decision-making problems is unknown. More importantly, although studies have reported effectiveness of integration of the QFD approach with either the fuzzy set theory or KMS, there is still a lack of information regarding integration of the QFD approach and both the fuzzy set theory and KMS, especially to mitigate decision-making problems in building design.

1.6 Research Objectives

The specific objectives of this book are to:

1. Identify the underlying factors that affect sustainability and buildability based on the Institutional Theory.
2. Develop the KBDSS-QFD tool to mitigate the decision-making problems faced by the design team as a whole.

The first objective aims to identify and group the criteria affecting sustainability and buildability when assessing building envelope materials and designs according to their underlying factors. In brief, the criteria would be obtained mainly from the literature review. These criteria would then be grouped to identify the underlying factors as suggested by the Institutional Theory. The Institutional Theory adopts an open system perspective asserting that firms are strongly influenced by their environments, not only by competitive forces and efficiency-based forces at work, but also by socially constructed belief and rule systems (Scott 2008). The underlying factors suggested by this theory would provide the building professionals with a more concise and defined structure of sustainability and buildability, thereby leading to a better way to grasp the abstract concept of the sustainability and buildability requirements of a building envelope design.

At the same time, it has been found that a conventional QFD tool has some drawbacks that need to be addressed before applying the tool to mitigate the decision-making problems identified as a whole. For example, the conventional QFD tool has faced difficulties in dealing with qualitative and subjective decision-making attributes (Bouchereau and Rowlands 2000). With this in mind, the main objective of this book is to modify the conventional QFD tool by integrating this with the fuzzy set theory and KMS to build the automated KBDSS-QFD tool. Improvement of the conventional QFD tool is presented in greater detail in Sects. 2.13 and 2.14. The KBDSS-QFD tool would contribute not only to mitigating the decision-making problems but also to improving the overall project management with respect to cost, time, and quality goals of a project.

1.7 Knowledge Gaps

There are two specific knowledge gaps that this book sets out to fill. The first knowledge gap relates to lack of a comprehensive set of the criteria to assist the building professionals to assess the building envelope materials and designs for achieving sustainability and buildability. Past research has identified the following indicators and attributes to improve sustainability and buildability in the building industry: prefabrication, preassembly, modularization and offsite fabrication (PPMOF), interactive method for measuring preassembly and standardization (IMMPS), prefabrication strategy selection method (PSSM) and construction method selection model (CMSM).

PPMOF was developed to help the stakeholders of a project overcome project challenges and improve performance by using the available opportunities in prefabrication (Song et al. 2005). However, it focuses solely on strategic level analysis and fails to consider each factor objectively, which may therefore produce a biased decision (Chen et al. 2010a). IMMPS brings “softer issues” such as health, safety, sustainability, and effects on management and process into consideration but it is not suitable to apply in the early design stage (Chen et al. 2010a). PSSM was developed to focus on curtain wall systems, mechanical systems, and wall frames (Luo et al. 2008). The latest tool, CMSM, is divided into two sequential levels, strategic and tactical (Chen et al. 2010a). The former is to evaluate prefabrication potential in terms of project characteristics, site conditions, market attributes, and local regulations, while the latter aims to examine project efficiency and explore an optimal strategy across different scenarios. Both PSSM and CMSM take into account only certain sustainability and buildability aspects, so much so that these offer limited support to holistic decision making toward achievement of sustainability and buildability. While these indicators provide some awareness of sustainability and buildability, few are capable of recommending a holistic set of criteria to assist building professionals to deliver sustainable and buildable building envelope designs in the early design stage.

Furthermore, within the area of building envelope design and construction, most studies applied only a few criteria to assess and compare different building envelope materials and designs. For example, Wang et al. (2006) applied multi-objective genetic algorithms to find optimal building envelope designs by considering only costs and environmental impacts of building envelope designs as their main criteria. Kaklauskas et al. (2006) took into account energy savings, indoor climate, and architectural appearance as well as market value as key considerations in evaluating and selecting low-emissivity (E) windows. By comparing various glazing windows and shading devices of building envelope designs, Chua and Chou (2010b) adopted energy performance and cost saving as the main criteria to determine payback periods.

As can be seen, none of the above-mentioned studies considered an exhaustive set of the criteria to assess the building envelope materials and designs. This issue is significant as highlighted earlier that lack of awareness from building professionals to take into account some of the key criteria when conducting the assessment and selection in the early building envelope design stage could lead to undesirable additional cost and time, as well as adverse quality (Fryer 2004; Kibert 2008; Singhaputtangkul et al. 2011a). With this in mind, a more comprehensive set of the criteria should be investigated prior to assessing the building envelope materials and designs toward sustainability and buildability.

Moreover, none of the previous studies discussed theoretical relationships between their criteria and sustainability and buildability. As such, this book applies the Institutional Theory to form a framework to define theoretical roles of sustainability and buildability in making decisions by architects and engineers when assessing the building envelope materials and designs. This framework allows the criteria for assessment of the building envelope materials and designs to be grouped for easier interpretation and better understanding to achieve sustainability and buildability.

The second knowledge gap of this book is associated with ineffectiveness of existing DSSs to mitigate the decision-making problems identified from a holistic view. To be specific, there are studies that developed tailor-made DSSs that possess distinct features to deal with decision-making problems, yet most of these studies focused on mitigating one or a few decision-making problems at the time. As a result, these individual DSSs may be unable to mitigate the decision-making problems identified in this book as a whole; however, their distinct features altogether show the potential to do so. These promising features include the QFD approach, KMS, fuzzy set theory, and fuzzy consensus scheme.

Fazio et al. (1989) presented a prototype knowledge-based system (KBS) to analyze and design building envelope. This system assisted a designer in selecting materials and constructional systems based on energy requirements to a certain degree. Iliescu (2000) proposed a case-based reasoning (CBR) framework for selecting the construction alternatives during the preliminary stage of the building envelope design process. This aimed at finding the most suitable design for a new building envelope to meet the energy requirements of a project. Yang et al. (2003) developed a DSS based on the QFD approach and fuzzy set theory to improve the overall buildability level of a building. It was found that the tool demonstrated its ability in quantitative building evaluation and effective communication and integration for building professionals.

Yan et al. (2005) applied the QFD approach combined with design knowledge hierarchy systems to develop a product conceptualization tool. In their study the system showed its effectiveness in delivering a conceptual design in the early design stage. Arain and Low (2006) developed a KBDSS for management of variation orders for institutional building projects by providing experts with prompt and more consistent responses based on learning from past experience. Hsu et al. (2011) applied the QFD approach combined with a KMS to provide an effective procedure of mining the dynamic trends of customer requirements and engineering characteristics. This system also helped in identifying and improving customer satisfaction and green competitiveness in the marketplace in a more consistent manner. Pedrycz et al. (2011) proposed a fuzzy consensus scheme as part of a fuzzy

DSS to facilitate a team in mitigating disagreement among experts. Parreiras et al. (2012a) further investigated three consensus schemes based on fuzzy models for dealing with inputs of multiple experts in multicriteria decision making. Their study showed the potential of exploiting the capabilities of each group member through the use of these fuzzy consensus schemes.

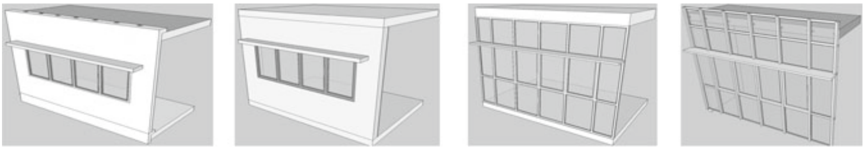
Nevertheless, there is little information about a combination of the QFD tool with the KMS, fuzzy set theory and fuzzy consensus scheme together to form the DSS to facilitate the design team to overcome decision-making problems. To fill this specific knowledge gap, this book develops the KBDSS-QFD tool by integrating the QFD approach with the KMS, fuzzy set theory, and fuzzy consensus scheme to simultaneously deal with all the decision-making problems identified. The results of this book may provide novel research approaches for achievement of such integration. Furthermore, notwithstanding its potential to mitigate decision-making problems, the tool would also assist the design team to make more informed and prompt decisions and consequently to achieve better project management.

1.8 Scope of the Book

As there are several building types such as commercial, industrial, public, and private buildings, the book concentrates on only the new private high-rise residential buildings developed under the design-bid-build procurement mode. In this procurement mode, the key DMs in the design team who are in-charge of development of the building envelopes of the building include only the architect, C&S engineer, and M&E engineer. For the first objective, the main tasks are limited to identifying the comprehensive set of criteria for assessment of the building envelope materials and designs as well as determining their underlying factors based on suggestions from the Institutional Theory framework developed.

For the second objective, with the main aim to mitigate the decision-making problems, the book emphasizes on development of the KBDSS-QFD tool for use by the design team in the early design stage. To be specific, only necessary functions of the tool are built to allow the book to sufficiently evaluate the potential of applying the tool to mitigate the decision-making problems. In parallel, this is also to maintain the scope of program coding within reasonable limits.

Additionally, the knowledge stored in the KMS includes only the knowledge of fundamental building envelope materials of a high-rise residential building in Singapore. These materials are divided into three main categories; namely external wall, window and frame, and shading device. In brief, the external wall category consists of the following six material types as options; namely precast concrete cladding, infilled clay brick, concrete block, cast in situ reinforced concrete (RC), full fixed-glass, and full glass curtain walls. In the window category, the glazing materials include the following four glazing materials types as options, namely clear single glazing, low-E clear single glazing, double clear glazing, and low-E



Precast wall design-based alternative Masonry wall design-based alternative Fixed-glass wall design-based alternative Curtain wall design-based alternative

Fig. 1.2 Four main hypothetical types of the building envelope design alternatives

Precast wall design-based building Masonry wall design-based building Fixed-glass wall design-based building Curtain wall design-based building

Fig. 1.3 Real-life high-rise residential buildings in Singapore

double clear glazing, with use of aluminum as a window frame material. In the shading device category, the book includes horizontal concrete and horizontal aluminum as material options. Furthermore, structural type of a building is limited to a center-cored building or skeleton frame building where the building envelope systems mainly serve as a non-load-bearing function.

With this in mind, only the knowledge related to the fundamental design alternatives as shown in Figs. 1.2 and 1.3 with respect to four basic external walls types which are the precast, masonry and cast in situ, fixed-glass and curtain walls are acquired in this book. Nevertheless, the tool permits future users to add new knowledge of more hybrid design alternatives into the tool for assessment.

1.9 Research Strategy

The research strategy of this book consists of two parallel parts as shown in Fig. 1.4. The first part relates to the first objective of this book. This part comprises three major phases. The first phase starts with conducting preliminary literature reviews to formulate the first research problem and objective. In-depth literature reviews are also carried out to examine important criteria for the assessment of the building envelope materials and designs, and to develop the Institution Theory framework. A pilot study (see Appendix B) is then conducted to fine-tune the related criteria, and the Institution Theory framework is subsequently constructed to form the first research hypothesis of this book.

Next, the second phase highlights the research design and method of data collection for validating the first hypothesis. In brief, survey and survey questionnaire (see Appendix C) are selected as the research design and method of data collection,

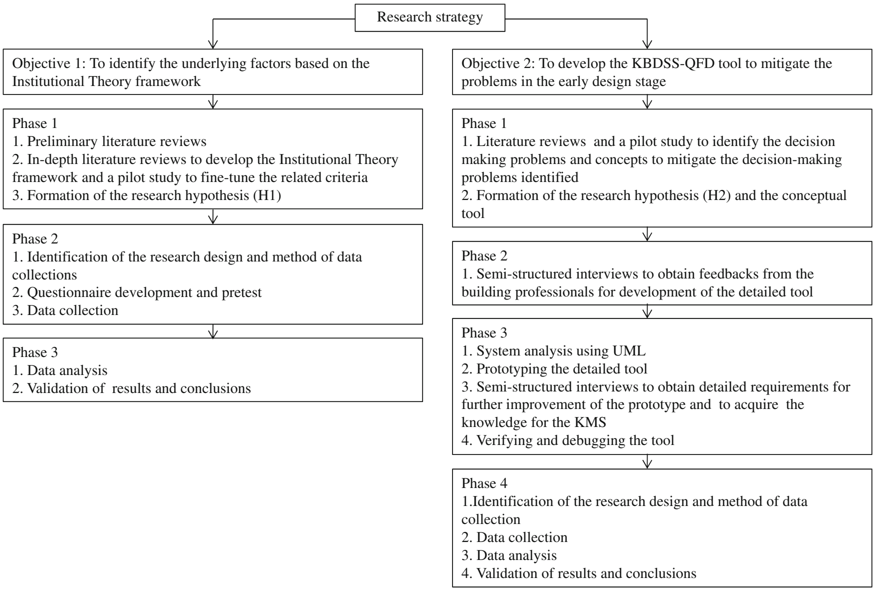


Fig. 1.4 Research strategy of this book

respectively. The last phase of this research strategy part focuses on data analysis and verification of responses from the survey. A main statistical technique of this book is factor analysis; however, ranking analysis and Spearman rank correlation are also applied to gain further in-depth understanding of the responses.

The second part of the research strategy comprises four phases to achieve the second objective of this book. The first phase is based on literature reviews and another set of a pilot study (see Appendix A). These are conducted to identify the decision-making problems faced by architects and engineers when assessing the building envelope materials and designs in the early design stage as well as concepts to mitigate these problems. Findings from both the literature reviews and pilot study lead to formulation of the second research hypothesis of this book and development of a conceptual KBDSS-QFD tool. Next, the second phase involves obtaining feedbacks from architects and engineers for development of a detailed KBDSS-QFD tool through semi-structured interviews (see Appendix D).

In the third phase, the detailed KBDSS-QFD tool is built. A prototype is modeled after this detailed tool. Before prototyping begins, an extensive and thorough system analysis is carried out using the unified modeling language (UML). The prototype is developed using Microsoft Visual Studio, and the KMS is built on Microsoft Access for Windows. Another round of semi-structured interviews (see Appendix E) is also conducted for a final improvement of the prototype with the main purposes to ensure that the prototype can represent the actual expectations of the designers, and to collect and verify the knowledge for the KMS.

The last phase emphasizes the validation of the second hypothesis of this book. In this phase, a case study is selected as the research design, and group interview (see Appendix F) is selected as the method of data collection. Specifically, the book engages three different design teams to test the prototype by applying representative high-rise residential building projects in Singapore. Each design team consists of three different DMs which are an architect, a C&S engineer, and an M&E engineer. After that, the members of each team are interviewed as a group with respect to their perspectives toward applying this prototype to mitigate the decision-making problems. The book then employs qualitative data analysis to analyze findings from the group interviews, and subsequently validates these findings by conducting interviews with the other three building professionals.

1.10 Structure of the Book

This book comprises nine chapters, and Fig. 1.5 presents the flow between the chapters.

This chapter introduces the overview background of this book as well as the significance of the issue. It then presents the aim, research questions, and corresponding research objectives of the book. Next, the knowledge gaps and scope of research are highlighted following by the research strategy and structure of the book.

Chapter 2 reviews the general concepts of decision making and QFD. It also discusses about the customers of QFD and provides the concepts to mitigate the

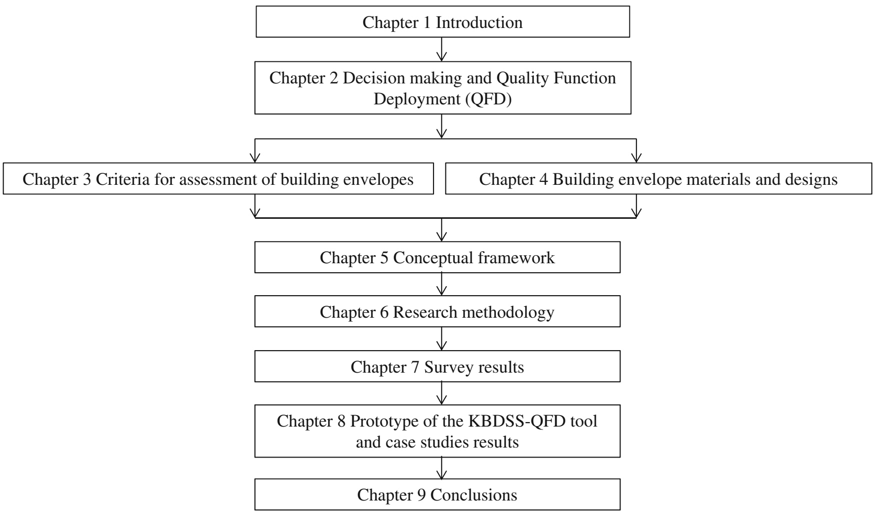


Fig. 1.5 Structure of the thesis

decision-making problems identified. Importantly, this chapter presents a basis to develop the conceptual KBDSS-QFD tool.

Chapter 3 reviews important considerations related to building envelope design. It begins by introducing concepts of total building performance (TBP), sustainability, and buildability. This is followed by identification of the related criteria for the assessment of the building envelope materials and designs.

Chapter 4 examines key aspects of the building envelope materials and designs. These are discussed in regard to design, delivery and handling, construction, and maintenance phases.

Chapter 5 is dedicated to development of the conceptual framework of this book. This conceptual framework integrates the Institutional Theory framework and the KBDSS-QFD tool together. Based on this conceptual framework, two main hypotheses of the book are formulated.

Chapter 6 focuses on the research methodology of the book. This chapter presents the research designs and methods of data collection to test the hypotheses. Detail of data collection and analysis with respect to each hypothesis are also provided.

Chapter 7 presents the findings from the data analysis in relation to the survey. This includes discussion of the characteristics of the responses from the survey as well as findings from factor analysis.

Chapter 8 presents development of the detailed KBDSS-QFD tool and its first prototype. The highlights of this chapter are associated with the four major elements of the tool and how these elements are integrated and modeled for building the prototype. This chapter then explains the steps for using the prototype to facilitate designers to assess the building envelope materials and designs in the early design stage. Lastly, the chapter shows design outcomes from the case studies and findings from the framework analysis.

Chapter 9 summarizes the main findings of this book. In this chapter, the major contributions of the book including academic and practical contributions are underlined. This chapter also discusses the limitations of the research and proposes the recommendations for future research works.

Chapter 2
Decision Making and Quality Function Deployment (QFD)

2.1 Introduction

This chapter first introduces general concepts of decision making (Sect. 2.2), Knowledge management system (KMS) (Sect. 2.3), basic components of knowledge-based decision-support system (KBDSS) (Sect. 2.4), decision making techniques (Sect. 2.5), fuzzy set theory (Sect. 2.6), and consensus scheme (Sect. 2.7). Next, the chapter presents QFD (Sect. 2.8) as a methodology to support group decision making. Benefits of QFD (Sect. 2.9) in several areas with the focus on the use of QFD in the building industry (Sect. 2.10) are then highlighted. This is followed by reviewing the customers of QFD (Sect. 2.11), fundamental components of QFD (Sect. 2.12) and concepts to improve a conventional QFD tool for mitigation of the decision-making problems (Sect. 2.13). The last section discusses development of the conceptual KBDSS-QFD tool (Sect. 2.14) by incorporating all the concepts to mitigate the decision-making problems together.

2.2 Concepts of Decision Making

Decision making is a process of choosing among two or more alternative courses or actions for the purpose of achieving a goal or goals. According to Simon (1977), decision making is directly influenced by several decision styles. Decision style is the manner in which DMs think and react to problems. This refers to the way DMs perceive, their cognitive responses and how values and beliefs vary from individual to individual and from situation to situation. As a result, different groups of DMs make decisions in different ways. Although there is a general process of decision making, it is far from linear. Moreover, in many cases, DMs do not follow the same steps of the process in the same sequence, nor do DMs use all the steps (Simon 1977).

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2.2.1 Human Decision Making

According to Simon (1977, 1991), most human decision making, whether organizational or individual, involves a willingness to settle for a satisfactory solution, "something less than the best". In particular, DMs set up an aspiration, a goal or a desired level of performance and then search the alternatives until one is found to achieve their satisfactory level. The usual reasons for satisfying are time pressures, ability to achieve **optimization**, and recognition that the marginal benefit of a better solution is not worth the marginal cost to obtain it. Essentially, satisfying is a form of **sub-optimization** where there may be a best solution, an optimum, but it would be difficult, if not impossible, to attain.

Importantly, as per Simon (1997)'s idea of bounded rationality, DMs tend to have a limited capacity for rational thinking; these generally construct and analyze a simplified model of a real situation by considering fewer alternatives, criteria, and/or constraints than actually exist. Their behavior with respect to this simplified model seems to be rational. Rationality is bounded not only by limitations on human processing capacities but also by individual differences such as age, education, knowledge and attitudes (Turban et al. 2007).

2.2.2 Group Decision Making

In response to a growing demand for efficiency and flexibility, organizations are implementing teams to do much of the work which is traditionally accomplished by individuals (Boyett and Conn 1992; Katzenbach and Smith 1993). This strategy is based on the assumption that the decisions made by groups of employees with diversified expertise will be higher in quality than those employees with more heterogeneous backgrounds. As such, the group should combine representatives from different organizational functions to ensure diversity in knowledge and experience (Jacksons 1992; Low and T'ng 1998). Mode (1988) concluded that group decision making tends to fall into one of two categories, namely the interactive and noninteractive. The most familiar forms are interactive groups which generally meet face-to-face and have specific agenda and decision objectives.

In complex problems, the interactive group appears to generate a better team decision quality than the noninteractive groups since the first promotes participation and interaction of members of the team. The main shortcoming of the interactive techniques for the discussion group, design team or brainstorming group is "group think" where individual members of the group feel unable to show their concern or to disagree with others. Thus, the group seems to be in unanimous agreement, yet, for a number of reasons, individuals may suppress their dissent. Other shortcomings such as embarrassment fear of rejection and reprisal may also restrict the free expressions of ideas in group.

As most major decisions in medium-sized and large organizations are typically made by groups, inevitably, there are often conflicting objectives in a group decision making setting (Turban et al. 2007). Groups can be of variable size and may include a number of DMs from cross-functional departments or even very often from different organizations. Members of such groups may also have different cognitive styles, personality types and decision styles. Fryer (2004) treated group decision making as discrete events that are distinguishable from many aspects particularly communication, relationships, social behavior, practices, support, rituals, cultures and norms, power, authority, constrained choices, reluctance, conflict, fear, dominance, influences, information, articulation, and persuasiveness as shown in Fig. 2.1. Based on this figure, group decision making is also subject to four controls including task based or tactical control, social socio-emotional control, organizational and cultural control, and emotional control.

In the context of this book, it is important to highlight two main aspects affecting group decision making which are communication and conflict. Argyle (1989) suggested that interaction and communication among group members are important for group cohesiveness which is the degree of solidarity and positive feeling held by individuals towards their group. Group cohesiveness can contribute to greater satisfaction and co-operation among members of the team and, in opposite, may result in lower absenteeism and labour turnover. For example, groups that are too cohesive can suffer a reduced productivity due to the amount of social interaction that may take place. A balance needs to be struck when team members communicate and interact with one another (Fryer 2004).

Low and T'ng (1998) suggested that one of the aspects that support group decision making is conflict. It was mentioned that good group decisions can emerge

Fig. 2.1 Potential factors affecting group decision making

from conflict when disagreement among team members leads to identification and consideration of a variety of decision solutions. Amason (1996) recognized this paradox of conflict as “cognitive” and “affective”. Cognitive conflict occurs with differences in perspective and judgments, helping identify potential problem solutions, while affective conflict, on the other hand, is considered dysfunctional as it tends to be emotional and it aims at a person, not an issue. Cognitive and affective conflicts also tend to occur together. To maintain cognitive conflict, Cline (1994) reported that a very high level of agreement and very too low level of disagreement may likely be subject to “groupthink”. The same study also suggested a few ways of avoiding this which include asking questions, noting an absence of agreement and disagreement, and being aware that the risk of illusory agreement heightens as external stress increases.

2.2.3 Complexities in Group Decision Making

Notwithstanding the common decision-making problems found in multicriteria decision making (MCDM) (see Sect. 1.3), Black and Boal (1994) characterized complexities in group decision making into elements; including (1) numerous complicated linkages among organizational and environmental elements, (2) dynamic and uncertain environments, (3) ambiguity of available information, (4) lack of complete information and (5) conflicts concerning the outcomes of decisions among interested parties. Turban et al. (2007) further compared benefits of working in groups and dysfunctions of the group decision-making process as shown in Table 2.1.

Despite these dysfunctions, the trend towards group decision making has still continued. For one important reason, organizations and projects have become larger and more complex, making it increasingly difficult for one person to reach decision without consulting others who have relevant information or are affected by the outcome (Fryer 2004). Hunt (1992) suggested that groups can be more effective at decision making if, related to the context of this book, a group has its members with a variety of skills and experience, the decision-making process is structured, and clear objectives are given, for example.

To deal with these situations, a computerized DSS, sometimes called a group decision-support system (GDSS), has been found useful. This system is an interactive computer-based system that facilitates the solution of semi-structured and unstructured problems by a group of DMs. Its goal is to support the process of group decision making by providing automation of subprocesses using information technology tools. Main purpose of using this system is to encourage generation of ideas, resolution of conflicts, freedom of expression, etc. (Reilly 2001; Turban et al. 2007). In this book, the DSS and GDSS are used interchangeably.

Table 2.1 Benefits and dysfunctions of working in groups

Benefits	Dysfunctions
Groups are better than individual at understanding complex problems	It is a time-consuming, slow process. This is also subject to inappropriate influences
Working in a group may stimulate creativity	"Groupthink" may lead to poor decisions
A group has more knowledge than any one member	There can be tendency for group members to either dominate the agenda or rely on others
A group may produce synergy during problem solving	Some group members may be afraid to participate, communicate or speak up
Members of a group take ownership of problems and their solutions	There is often nonproductive time, and inappropriate use of information
Members of a group can spot one another's mistakes	There can be attention and concentration blocking

2.2.4 Decision-Making Models

A decision-making model is a simplified representation or abstraction of reality. As it is too complex to describe exactly, it was suggested that much of the complexity is actually irrelevant in solving a specific problem. In general, the decision-making model contains decision variables that describe the alternatives among which a DM must choose, a result variable or a *set* of result variables that describes the objective or goal of the decision-making problem, and uncontrollable variables or parameters that describe the environment (Turban et al. 2007). There are two main approaches for modeling; **normative models** and **descriptive models**. Normative models are the models in which the chosen alternative is demonstrably the best of all possible alternatives, whereas descriptive models describe things as they are or as they are believed to be (Turban et al. 2007).

In other words, *descriptive* study attempts to unearth, and perhaps explain, the actual state of the object at the time of its inspection. In contrast, *normative* study purports to discover ways to improve the object or similar later objects, by pointing out possible improvements for the object of book (Routio 2007; Popper 1959). The normative model appears to represent how designers make decisions. This is because designers start their work in the world of concepts, making their conceptual plans and projects for new products or for improving new activities (Routio 2007). Particularly, the normative model governs that DMs examine possible alternatives and prove that the one selected is indeed the best. This process can be called **optimization.** The main assumption of this model is that humans are economic beings whose objective is to maximize the attainment of goals. Under the bounded rationality idea introduced, the normative model posits that DMs have an order or preference that enables them to optimize the desirability of all consequences of the analysis (Turban et al. 2007).

2.3 Knowledge Management System (KMS)

Knowledge is relatively distinct from data and information. It is considered information which is contextual relevant and actionable. While data, information and knowledge can be viewed as assets of an organization, knowledge provides a higher level of meaning about data and information. It conveys meaning and hence tends to be much more valuable, yet more ephemeral (Hoffer et al. 2002). Furthermore, firms are much larger today than they used to be, and their market becomes more competitive. These fuel the need for better tools for collaboration, communication, and knowledge sharing. Firms therefore must develop strategies to sustain competitive advantage by leveraging their intellectual assets for optimal performance (Berman et al. 2002).

One of these strategies is to establish a KMS. Ariely (2006) classified knowledge as a synonym for *intellectual capital*. Collectively, brand and customer are aspects of intellectual capital, but today's marketplace, the most significant and valuable aspect of intellectual capital is indeed knowledge in all its forms. A KMS can help an organization cope with turnover, rapid change, inconsistency of customer service and downsizing by making the expertise of the organization's human capital widely accessible. In addition, knowledge management is rooted in the concepts of organizational learning and or organizational memory. When members of an organization collaborate and communicate ideas, knowledge is transformed and transferred from individual to individual (Bennet and Bennet 2003; Jasimuddin et al. 2006). A functioning KMS follows six steps in a cycle as shown in Fig. 2.2. The reason for the cycle is that knowledge is dynamically refined over time. The knowledge in a good KMS is never finished because the environment changes over time and the knowledge must be updated to reflect the changes (Allard 2003; Gaines 2003; Turban et al. 2007).

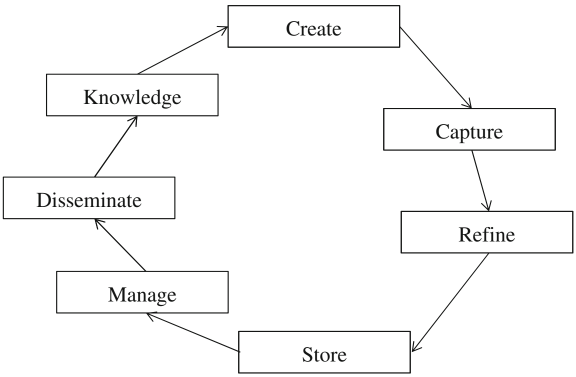

Fig. 2.2 Six steps in the KM cycle

1. Create knowledge
   Knowledge is created as people determine new ways of doing things or develop know-how. Sometimes external knowledge is brought in. Some of these new ways may become best practices.
2. Capture knowledge
   New knowledge must be identified as valuable and be represented in a reasonable way.
3. Refine knowledge
   New knowledge must be placed in context so that it is actionable. This is where human insights must be captured along with explicit facts.
4. Store knowledge
   Useful knowledge must be stored and represented in a reasonable format in a KMS so that others in the organization can access and use it.
5. Manage knowledge
   Similar to a library, a KMS must be kept current. It must be reviewed to verify that it is relevant and accurate.
6. Disseminate knowledge
   Knowledge must be made available in a useful format to anyone in the organization who needs it, anywhere and anytime.

In general, a KMS is a text-oriented DSS; not a knowledge-based management system. A KMS typically do not involve running models to solve problems. A DSS that includes a KMS is often called an intelligent DSS, an expert-support system, an active DSS or a knowledge-based DSS (KBDSS). A KBDSS as the main focus of this book can supply the required expertise for solving some aspects of the problem and provide knowledge that can enhance the operation of a DSS (Turban et al. 2007). There are several ways to integrate knowledge-based expert system and mathematical modeling. These include knowledge-based systems that support parts of the decision process not handled by mathematics, intelligent decision modeling systems to help with developing, applying and managing model database, and decision analytic DSS to integrate uncertainty into the decision-making process (Power and Sharda 2007; Rasmus 2000).

2.4 Components of KBDSS

A KBDSS is a system that can undertake intelligent tasks in a specific domain that is normally performed by highly skilled people (Miresco and Pomerol 1995). The approach is extensively used to deal with problems in the construction industry (Arain 2006). The success of such a system relies on the ability to represent the knowledge for a particular subject (Fischer and Kunz 1995). Fundamentally, a KBDSS can be viewed as having two main environments: the development environment and the consultation environment as illustrated in Fig. 2.3.

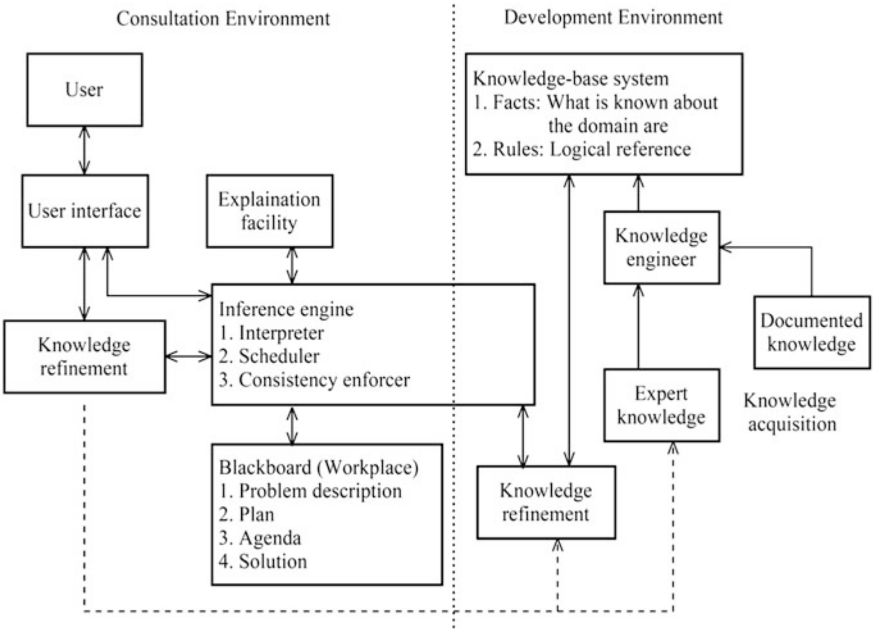

Fig. 2.3 General components of a KBDSS

A KBDSS builder takes the development environment to build the components and systematically puts knowledge into the knowledge base. Users adopt the consultation environment to obtain expert knowledge and advice. These two environments could be separated when a system is complete (Turban et al. 2007). More specifically, Fig. 2.3 also shows that there are four major elements in a KBDSS. These include a knowledge acquisition and knowledge base system, blackboard (workplace), user interface, and inference engine.

2.4.1 Knowledge Acquisition and Knowledge-Based System

Knowledge acquisition is the accumulation, transfer and transformation of problem solving expertise to a computer program for constructing or expanding the knowledge base. Potential sources of knowledge include human experts, textbooks, multimedia documents, databases (public and private), etc. (Arain and Low 2005; Turban et al. 2007). In building a large knowledge-base system, a knowledge engineer or knowledge elicitation expert may need to interact with one or more human experts in building the knowledge-base system. Typically, the knowledge engineer helps the expert structure the problem area by interpreting and integrating human answers to questions, drawing analogies, posing counterexamples and bringing conceptual difficulties to light through the knowledge-based system. In the context of building design, the knowledge associated with design decisions on how design materials and alternatives have an impact on their corresponding criteria can be represented as decision rules (Skibniewski et al. 1997).

Expert systems constitute the most well-known type of rule-based reasoning (RBR) systems (Buchanan and Shortliffe 1984; Gonzalez and Dankel 1993). Rules can easily represent general knowledge about a problem domain in autonomous, relatively small chunks. Their ability to provide explanations for the derived conclusions in a straightforward manner is a vital feature, given that explanations in certain application domains are considered necessary. Although RBRs are subject to difficulties in dealing with missing inputs and knowledge acquisition bottlenecks when the rules are too specific, RBRs do provide a direct consequence of their naturalness and modularity which are useful for DMs (Prentzas and Hatzilygeroudis 2007).

Yang (2004) presented this rule in the IF-THEN format for enhancing buildability of building design. For example, the decision rule used to reason about the relationship between the buildability attribute, "Spatial performance", and the buildable design feature, "the type of structural system", is represented as:

"If the structural system is easily adaptable to the design requirements of,

- individual space layout,
- and aggregating of individual space,
- and provision of convenience and service, of a building,

Then buildability is enhanced".

Another example of the decision rule applied to reason about the relationship between the buildability attribute, "construction equipment and tools", and the design feature, "the type of structural system", is represented as:

"If the construction equipment and tools used to construct the type of structural system

- are highly affordable,
- and have a low maintenance cost,
- and easily fit the constraints of site conditions,
- and support the application of available advanced and innovative technologies,

Then buildability is enhanced".

The other possible way to represent knowledge in building design is case-based reasoning (CBR). For example, Iliescu (2000) proposed a CBR framework for selecting the construction alternatives during the preliminary stage of the building envelope design process. Case-based representations store a large set of previous cases with their solutions in the case base or case library and use them whenever a similar new case has to be dealt with (Prentzas and Hatzilygeroudis 2007). In building design, each building is tailor-made, and, moreover, knowledge in relation to design and construction of each case or building cannot be fully acquired, introducing a large degree of uncertainty (Low and Yeap 2001). With this level of uncertainty, similar cases may not yield similar results.

In addition, as new considerations especially those related to building regulations and design standards are often revised (Singhaputtangkul et al. 2011a), to develop the KBDSS-QFD tool, the CBR approach may require too many cases with in-depth knowledge which seems to be inaccessible and subject to frequent revision. For these reasons, the CBR approach has not been selected for development of the KBDSS-QFD in this book.

2.4.2 Blackboard

The blackboard is an area of working memory for the description of a current problem as specified by input data. It is also used for recording intermediate decisions. Three types of decisions can be recorded on the blackboard: a *plan* such as how to overcome the problem, an *agenda* such as potential actions awaiting execution, and a *solution such as* candidate hypotheses and alternative courses of action that the system has generated thus far.

2.4.3 Inference Engine

The inference engine is a brain of a system. This engine is also known as the control structure or the rule interpreter. The inference engine component is essentially a computer program that provides a methodology based on a certain decision technique(s) for reasoning input data and formulating conclusions. Several decision-making techniques are reviewed in Sect. 2.5. The inference engine provides directions about how to use the system's knowledge by developing the agenda that organizes and controls the steps taken to solve problems whenever consultation takes place.

2.4.4 User Interface

A KBDSS contains a language processor for friendly and problem-oriented communication between the user and the computer. This is known as the user interface. This communication can best be carried out in a natural language. Due to technological constraints, most existing systems use the question-and-answer approach to interact with the user. Sometimes it is supplemented by menus, electronic forms and graphics to enhance communication among members of a team.

2.5 Decision-Making Techniques

Decisions in the real-world contexts are often made in the presence of multiple, conflicting and incommensurate criteria (Goh 2000; Lu et al. 2007). MCDM is one of the most well-known topics for making decisions in such cases. Generally, there are two basic approaches to MCDM problems; namely multiattribute decision making (MADM) and multiobjective decision making (MODM). In a broad sense, the main difference between MODM and MADM is that the former concentrates on continuous decision spaces, primarily on mathematical programming with several objective functions, whereas the latter focuses on problems with discrete decision spaces (Lu et al. 2007).

2.5.1 Multiobjective Decision Making (MODM)

MODM is considered the continuous type of the MCDM. The main characteristics of MODM problems are that DMs need to achieve multiple objectives while these multiple objectives are noncommensurable and may conflict with each other. An MODM model includes a vector of decision variables, objective functions, and constraints. DMs attempt to maximize or minimize the objective functions. Since this problem has rarely a unique solution, DMs are expected to choose a solution from among the set of efficient solutions as alternatives. In most MODM models, the alternatives can be generated automatically by the models. Particularly, each alternative is judged by how close it satisfies an objective or multiple objectives (Nedjah and Mourelle 2005; Pedcryz et al. 2011).

Multiobjective linear programming (MOLP) is one of the most important forms to describe MODM problems, which are specified by linear objective functions that are to be maximized or minimized subject to a set of linear constraints. When formulating MOLP problems, various factors should be reflected in the description of the objective functions and the constraints. Furthermore, these objective functions and constraints involve parameters in which possible values may be assigned by the experts. Such parameters are set at some values in an experimental or subjective manner through the experts' understanding of the nature for the parameters. The standard form of a MOLP problem can be written as shown in Eq. (2.1) (Kahraman and Kaya 2008; Lu et al. 2007).

$$(\text{MOLP}) \begin{cases} \max f(x) = Cx \\ \text{s.t.} x \in X = \{x \in R^n, Ax \leq b, x \geq 0\} \end{cases} \tag{2.1}$$

where C is a $k \times n$ objective function matrix, A is an $m \times n$ constraint matrix, b is an m-vector of right-hand side, and x is an n-vector of decision variables.

Multiobjective optimization using the concept of nondominance requires approximation of the Pareto frontier, i.e. the set of all nondominated solutions (Cohon 1978). To determine the set of all nondominated solutions, the key to solve MOLP problems is to develop their objective functions and constraints. As this book focuses on prioritizing design alternatives in the early design stage where some objectives of the project remain ambiguous, adopting the MOLP may not produce the best solutions. This is because some essential considerations, for instance, aesthetics of design or safety of construction methods, cannot be well expressed in terms of the objective functions and constraints. It was suggested that applying this model seems to be more suitable for the problems that most of their information as well as objective functions can be more clearly addressed (Lu et al. 2007).

2.5.2 Multiattribute Decision Making (MADM)

MADM refers to making preference decisions, including evaluation, prioritization, and selection, over the available alternatives that are characterized by multiple and conflicting attributes. The main feature of MADM is that there are usually a limited number of predetermined alternatives which are associated with a level of achievement of the attributes. In most MADM situations, it is necessary to generate alternatives manually over the available alternatives that are characterized by multiple attributes. Doing this is heavily dependent on the availability and the cost of information, and requires expertise in the problem area (Lu et al. 2007).

In particular, alternatives can be generated with heuristics as well, and be from either individuals or groups. The generation of alternatives may come before or after the criteria for evaluating the alternatives are identified, but the selection of the alternatives should come after that. By taking into consideration all the attributes, the final decision can be made. In addition, the final selection of the alternative is constructed with the help of inter- and intra-attribute comparisons involving management of explicit or implicit tradeoff. Mathematically, a typical MADM problem is modeled as shown in Eq. (2.2).

$$\text{(MADM)}\begin{cases} Select: A_1, A_2, \ldots, A_m \\ \text{s.t.}: C_1, C_2, \ldots, C_n \end{cases} \tag{2.2}$$

which denotes m alternatives, and represents n attributes often called criteria for characterizing a decision situation. The *select* is normally based on maximizing a multiattribute value or utility function elicited from the stakeholders. The basic information involved in this model can be expressed by the matrix D and W as shown in Eq. (2.3).

$$D = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{12} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{\text{m}2} & \dots & x_{mn} \end{bmatrix} \tag{2.3}$$

$$W = [w_1, w_2, \ldots, w_n]$$

where A = $(A_1, A_2, \ldots, A_m)$ are alternatives, $C = (C_1, C_2, \ldots, C_n)$ are attributes with which alternative performances are measured, x_{ij}, $i = 1, \ldots, m$, $j = 1, \ldots, n$, is the rating of alternative A_i with respect to attribute C_j, and w_j is the weight of attribute C_j (Lu et al. 2007).

Some of the MADM techniques widely used include Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination Et Choix Traduisant la Réalité or Elimination and Choice Translating Reality (ELECTRE), Bayesian Network (BN), Analytical Hierarchy Process (AHP), and MADM combined with fuzzy techniques.

2.5.2.1 Topsis

TOPSIS is based on the concept that the ideal alternative has the best level for all criteria, whereas the negative ideal is the one with all the worst criteria values. In other words, the selected best alternative should have the shortest distance from the positive ideal solution in geometrical sense while it has the longest distance from the negative solution (Hwang and Yoon 1981; Wang et al. 2008). This technique assumes that each criterion has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions (Wang et al. 2009). Nevertheless, in the early stage building design where voices of the building professionals cannot be expressed in a precise manner coupled with the fact that calculation outputs of the TOPSIS are shown in the preference order, these considerations may draw some difficulties to the building professionals when interpreting how much their design alternatives are different in a quantitative scale.

2.5.2.2 ELECTRE

ELECTRE is one of the outranking methods. It has been widely adopted to solve MADM problems. ELECTRE families include ELECTRE I, II, III, IV, TRI, and a number of improved ELECTRE methods. The basic concept of the ELECTRE method is associated with outranking relation by using pair-wise comparisons among alternatives with respect to each criterion individually. This technique requires pair-wise comparison of alternatives based on the degree to which evaluation of the alternatives and preference weight confirms or contradicts the pair-wise dominance relationship between the alternatives (Lu et al. 2007; Wang et al. 2009). Nevertheless, similar to TOPSIS, ELECTRE delivers the results in the preference order which may not signal the difference between the alternatives.

2.5.2.3 Bayesian Network (BN)

A Bayesian Network (BN) is a directed acyclic graph over which is defined a probability distribution. BNs are a popular class of graphical probabilistic models for research and application in the field of artificial intelligence. In general, BNs are used to represent a joint probability distribution over a set of variables. This joint probability distribution can be used to calculate the probabilities for any configuration of the variables. In Bayesian inference, the conditional probabilities for the values of a set of unconstrained variables are calculated given fixed values of another set of variables, which are called observations or evidence (Starr and Shi 2004).

There are a number of advantages of working with BNs. Briefly, BNs are effective in facilitating learning about causal relationships between variables (Uusitalo 2007) and can easily be converted into decision-support tools (Marcot et al. 2001). The graphical nature of a BN clearly displays the links between different system components. This would facilitate discussion of the system structure with people from a wide variety of backgrounds and may encourage interdisciplinary discussion and stakeholder participation (Martin et al. 2005). The use of Bayesian inference also allows a BN to be updated, when new knowledge becomes available (Ticehurst et al. 2008).

Nevertheless, while Bayesian models seem to be a useful way to model expert knowledge in several areas, in building design, there are disadvantages in applying BNs in assessment of building envelope materials and designs in the early design stage. To be specific, similar to decision trees, the BN models introduce a difficulty to get experts to agree on their structure of and its nodes that are important to be included when assessing the building envelope materials and designs. This could even lead to disagreements among members of the design team. In addition, elicitation of expert knowledge may require a time-consuming iterative process, to ensure that all experts are comfortable with the nodes, their states and interrelationships in the BN (Pollino 2008).

2.5.2.4 AHP

AHP is widely used to deal with MCDM problems in various domains. It is a decision analysis methodology that calculates ratio-scaled importance of alternatives through pair-wise comparison of evaluation criteria and alternative. The matrix of pair-wise comparisons when there are n criteria at a given level can be formed. AHP processes involve decomposing a complex decision into a hierarchy with goal or objective at the top of the hierarchy, criteria and subcriteria at levels

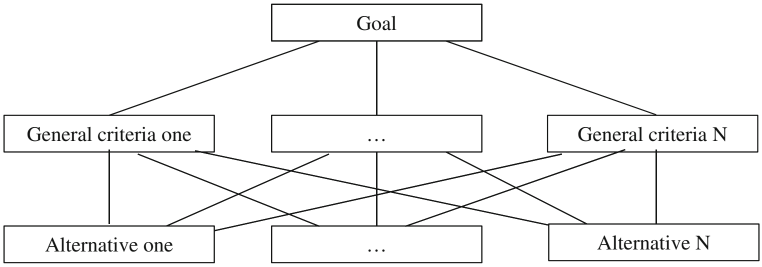

Fig. 2.4 A typical AHP

and sublevels of the hierarchy, and decision alternatives at the bottom of the hierarchy as shown in Fig. 2.4 (Yang 2004).

The AHP has been applied to solve construction-related problems (Armacost et al. 1994; Chen et al. 2011; Skibniewski and Chao 1992). Despite its advantages, the AHP has a few shortcomings under certain conditions. One of these problems is the occurrence of rank reversal (Armacost et al. 1994; Harker and Vargas 1987; Perez et al. 2006). The concept of rank reversal lies in prioritizing the alternatives that may be changed by adding a new alternative or deleting an existing alternative. Another shortcoming of the AHP is the explosion in the number of pair-wise comparisons (Ling 1998; Perez et al. 2006). For instance, if a given layer of the hierarchy includes n elements to be compared, a total of $(n)(n–1)/2$ pair-wise comparisons is required. It is noted that, in decision-making related to building design, not only is a new design alternative often generated, but also the existing alternative is often modified. Thus, accuracy of the pair-wise comparisons would be affected if there are quite many attributes considered within the AHP decision-making processes (Yang 2004).

2.5.2.5 MADM Combined with Fuzzy Techniques

Most of the classic MADM techniques assume that all inputs are expressed in crisp values. However, in a real-world decision situation, the application of the classic multicriteria evaluation methods may encounter serious practical constraints as their inputs are subject to imprecision or vagueness inherent in the information. Specifically, due to the availability and uncertainty of information as well as the vagueness of human feeling and recognition, such as "equally", "moderately", "strongly", "very strongly", "extremely" or "significantly", it is relatively difficult to provide exact numerical values for the criteria as well as to make an exact evaluation and convey the feeling and recognition of objects for DMs (Lu et al. 2007; Pedcrycz et al. 2011).

Fuzzy set theory introduced by Zadeh (1965) shows the potential to overcome this problem by playing a significant role in translating unquantifiable information, incomplete information, nonobtainable information, and partially ignorant facts into the decision model. Since decisions to be made in complex contexts are normally affected by uncertainty, which is essentially from the insufficient and imprecise nature of input data as well as the subjective and evaluative preferences of DMs, the combination of MADM and fuzzy set theory has been increasingly adopted in a variety of both research and professional areas (Lu et al. 2007; Pedrycz et al. 2011; Ross 2010).

2.6 Fuzzy Set Theory

This section discusses how the fuzzy set theory can be adopted to prioritize attributes and alternatives.

2.6.1 Fuzzy Sets

To model real-world decision problems, it is necessary to process large amount of information. Crisp data appear to be inadequate to do so due to various reasons; for example, subjective estimation and perception, incomplete knowledge, or the complexity of the systems studied (Chakraborty 2002). As a result, DMs may unable to estimate their preferences with an exact numerical data. In this situation, a more realistic approach is to use linguistic assessments instead of numerical values (Chen 2000; Zadeh 1975; Zhou et al. 2002). In dealing with the description about vagueness of an object, Zadeh (1965) proposed a membership function associated with each object in the form of a grade of membership (Bellman and Zadeh 1970; Xie et al. 2003).

A fuzzy set A is formally described by a membership function mapping the elements of a universe X to the unit $[0, 1]$ as shown in Eq. (2.4) (Zadeh 1965; Zadeh 1975).

$$A : X \rightarrow [0, 1] \tag{2.4}$$

Any function in accordance with this equation could be qualified to serve as a membership function describing the corresponding fuzzy set (Klir and Yuan 1995; Pedrycz et al. 2011). Hence, a fuzzy set A in X can be represented as a set of ordered pairs of the element x and its membership function, $u_A(x)$, that describes the degree of membership of x in A:

$$A = \left\{ \left(\frac{u_A(x)}{x} | x \in X \right) \right\}$$

Zadeh's (1975) extension principle plays a fundamental role in translating classical set based concepts into their fuzzy set counterparts (Pedrycz and Gomide 1998). According to Ross (1995) and Pedrycz and Gomide (1998), the extension principle is defined as Eq. (2.5).

$$u_B(x) = \max_{y=f(x_1,x_2,\ldots,x_n)}\{\min[u_{A_1}(x), u_{A_2}(x), \ldots, u_{A_n}(x)]\} \tag{2.5}$$

where A_1, A_2, …, A_n are fuzzy sets defined on the universe X_1, X_2, …, X_n, and $B = f(A_1, A_2, \ldots, A_n)$ is the mapping fuzzy sets A_1, A_2, …, A_n.

It is noted that this equation is expressed for a discrete-value function, $f(\cdot)$. If the function is a continuous value expression, the max operator is replaced by the supremum operator (Yang 2004). In addition, fuzzy numbers are a direct application of the extension principle (Dubois and Prade 1980; Ross 1995; Cox 1998; Pedrycz and Gomide 1998). A fuzzy number is a special fuzzy set $F=\left\{\left(\frac{u_F(x)}{x}|x \in X\right)\right\}$ where x takes its value on the real line: R: $-\infty < x < +\infty$ and $u_F(x)$ is a continuous mapping from R to the closed interval [0,1] (Dubois and Prade 1980; Chan et al. 1999).

Fundamentally, there are a number of fuzzy membership functions. These include triangular membership functions, trapezoidal membership, Gaussian membership, generalized bell membership, and sigmoidal membership functions. In this book, one of the most widely used fuzzy set which is the triangular fuzzy set is employed to quantify the qualitative information. The triangular fuzzy number $M = (a, b, c)$, where $a \le b \le c$, has the linear membership function as shown in Eq. (2.6) (Pedrycz and Gomide 1998):

$$\mu_M(x) = \begin{cases} 0, x < a, \quad \text{or} \quad x > c \\ \dfrac{x-a}{b-a}, a \le x \le b \\ \dfrac{c-x}{c-b}, b < x \le c \end{cases} \tag{2.6}$$

where $\mu_M(x)$ is the membership function of the imprecise numerical concepts, such as "close to b", "about b", or "approximately b" (Pedrycz and Gomide 1998).

2.6.2 Basic Operations of Fuzzy Sets

Based on the extension principle explained earlier, for the two triangular fuzzy numbers; $M_1=(a_1, b_1, c_1)$ and $M_2=(a_2, b_2, c_2)$, fuzzy set operations can be divided into addition (Eq. 2.7), subtraction (Eq. 2.8), scalar multiplication (Eq. 2.9), multiplication (Eq. 2.10), division (Eq. 2.11) operations (Dubios and Prade 1980; Cox 1998; Pedrycz and Gomide 2007).

$$\text{Addition} \quad M_1 + M_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \tag{2.7}$$

$$\text{Subtraction} \quad M_1 - M_2 = (a_1 - a_2, b_1 - b_2, c_1 - c_2) \tag{2.8}$$

$$\text{Scalar multiplication} \quad kM_1 = (ka_1, kb_1, kc_1) \tag{2.9}$$

$$\text{Multiplication} \quad M_1 \times M_2 \cong (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2) \tag{2.10}$$

$$\text{Division} \quad M_1 \div M_2 \cong (a_1 \div a_2, b_1 \div b_2, c_1 \div c_2) \tag{2.11}$$

Apart from these operations, another important application of fuzzy numbers is fuzzy ranking which is shown as (Dubois and Prade 1980):

If $a_2 \geq a_1, b_2 \geq b_1, c_2 \geq c_1$, and at least on inequality hold strictly, then $M_2 \succ M_1$, where "$\succ$" mean "is more preferred (important, superior, etc.)".

If $a_2 = a_1$, $b_2 = b_1$, $c_2 = c_1$, then $M_1 = M_2$.

2.6.3 Determining Fuzzy Preference Index

Fuzzy preference index is a sum of products of performance satisfactions of the alternatives and importance weights of the criteria. This section shows how the fuzzy preference index is calculated. The triangular fuzzy numbers are adopted to define the linguistic terms as shown in Fig. 2.5 to assess the weights of the criteria and the performance satisfactions of the alternatives (Lam et al. 2010).

There are three steps in determining the fuzzy preference index of the alternatives (Klir and Yuan 1995; Lam et al. 2010) as illustrated in Fig. 2.6. Based on Eqs. (2.7)–(2.11), the first step is to assess the collective importance weights of the assessment criteria, W_t^C, as shown in Eq. (2.12) where the j DM assigns the importance weight for each criterion. The second step is to determine the collective performance satisfaction of each alternative with respect to each criterion, A_{it}^C. In this step, the j DM assigns the performance satisfaction, A_{ijt}, to the i alternative for the t criterion as shown in Eq. (2.13).

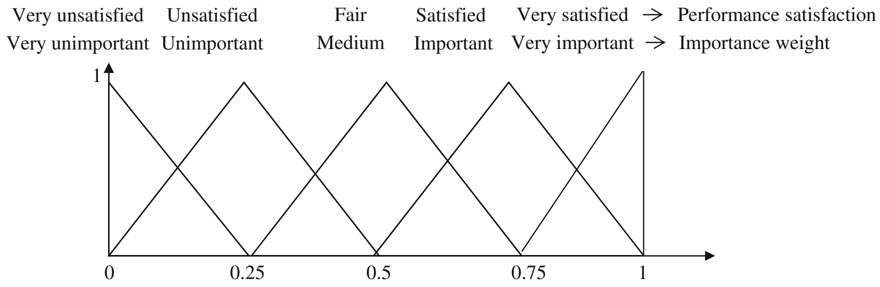

Fig. 2.5 Fuzzy linguistic terms

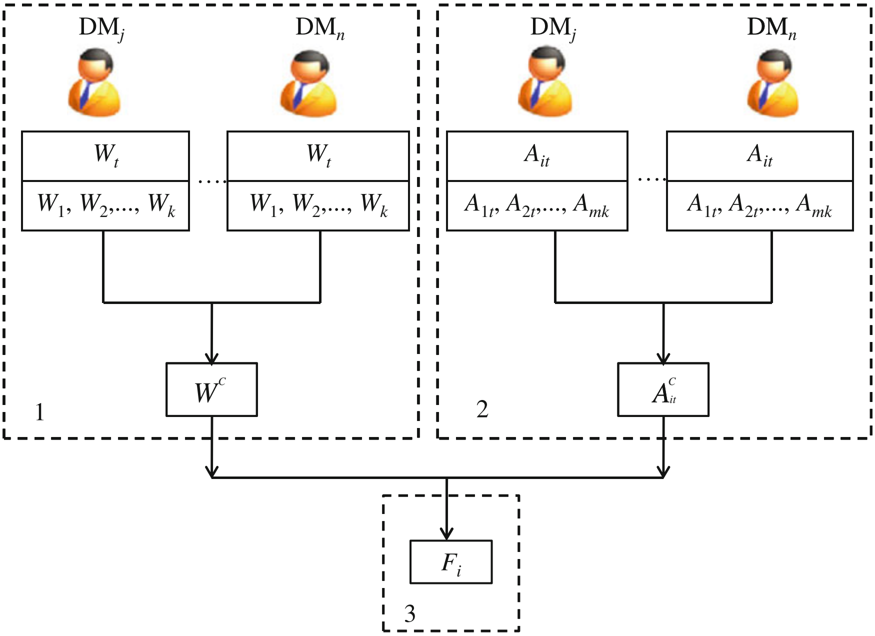

Fig. 2.6 Three steps for calculating the fuzzy inference index

$$W_t^C = \left(\sum_{j=1}^{n} \frac{p_{tj}}{n}, \sum_{j=1}^{n} \frac{q_{tj}}{n}, \sum_{j=1}^{n} \frac{r_{tj}}{n} \right) \tag{2.12}$$

$$A_{it}^C = \left(\sum_{j=1}^{n} \frac{a_{ijt}}{n}, \sum_{j=1}^{n} \frac{b_{ijt}}{n}, \sum_{j=1}^{n} \frac{c_{ijt}}{n} \right) \tag{2.13}$$

where
i (Alternatives) = (1, 2, 3, …, m)
j (DMs) = (1, 2, 3, …, n)
t (Criteria) = (1, 2, 3, …, k)

In addition, according to Fig. 2.5, the triangular fuzzy numbers of the W_t^C and A_{it}^C are given in Table 2.2.

The third step is to determine the fuzzy preference index of each alternative with respect to each criterion, F_{it}, through a fuzzification operation as shown in Eq. (2.14).

Table 2.2 Fuzzy triangular numbers of the weights and satisfactions

Importance weights	Performance satisfactions	$W_t^C = \left(\sum_{j=1}^{n} \frac{p_{tj}}{n}, \sum_{j=1}^{n} \frac{q_{tj}}{n}, \sum_{j=1}^{n} \frac{r_{tj}}{n}\right)$ $A_{it}^C = \left(\sum_{j=1}^{n} \frac{a_{ijt}}{n}, \sum_{j=1}^{n} \frac{b_{ijt}}{n}, \sum_{j=1}^{n} \frac{c_{ijt}}{n}\right)$
Very unimportant	Very unsatisfied	(0, 0, 0.25)
Unimportant	Unsatisfied	(0, 0.25, 0.5)
Medium	Fair	(0.25, 0.5, 0.75)
Important	Satisfied	(0.5, 0.75, 1)
Very important	Very satisfied	(0.75, 1, 1)

Source Adapted from Lam et al. (2010)

$$F_{it} = \sum_{1}^{t} \frac{\left(W_t^C \times A_{it}^C\right)}{W_t^C} \tag{2.14}$$

where
i (Alternatives) = (1, 2, 3, …, m)
t (Criteria) = (1, 2, 3, …, k)

As can be seen, the advantage of the fuzzy set approach over a weighted average approach is that the DMs are allowed to adjust the level of uncertainty of the fuzzy linguistic terms to fit their perspectives. Doing this may or may not affect ranking of the alternatives, but it can have a stronger impact on an overall performance of each alternative.

2.6.4 Translating Fuzzy Number into Crisp Number

For transforming a fuzzy number into a crisp number, x, four commonly used defuzzification methods can be applied. These include max method, centroid method, weighted average method, and mean max method. Also known as the height method, the max scheme is limited to peaked output functions. The weighted average method is frequently used in fuzzy applications since it is one of the more computationally efficient methods. Unfortunately, it is usually restricted to symmetrical output membership functions. Mean max membership, also called middle-of-maxima, is closely related to the weighted average method, except that the locations of the maximum membership can be nonunique for example the maximum membership can be a plateau rather than a single point. The centroid method, also called center of area, center of gravity, is the most prevalent and physically appealing of all the defuzzification methods (Ross 2010).

As can be seen that each has its own strengths and weaknesses (Klir and Yuan 1995), the centroid method is employed in this book for the reason that it is simple and widely used (Chou and Chang 2008; Lam et al. 2010). The controid approach retranslates the fuzzy numbers, W_t, A_{it}, and F_{it}, into crisp numbers by assuming that fuzzy number, $D = (d_1, d_2, d_3)$, can be converted into the crisp number by using Eq. (2.15);

$$x = (d_1 + d_2 + d_3)/3 \tag{2.15}$$

where x is the crisp number.

2.6.5 Translating Fuzzy Number into Fuzzy Linguistic Term

It is assumed that a fuzzy number D is "approximately the linguistic term A", when it has the membership function as shown in Eq. (2.16). As, in this book, $(b - a)$ and $(c - b)$ of each of the linguistic terms are equal to 1, Eq. (2.17) shows the $\mu_A(x)$ representing the possibility that the fuzzy number D is "approximately the linguistic term A" (Cheng 1999; Yang et al. 2003).

$$\mu_A(x) = \begin{cases} 0, x < a, \quad \text{or} \quad x > c \\ \dfrac{x-a}{b-a}, a \le x \le b \\ \dfrac{c-x}{c-b}, b < x \le c \end{cases} \tag{2.16}$$

$$\mu_A(x) = \begin{cases} 0, x < a, \quad \text{or} \quad x > c \\ x - a, a \le x \le b \\ c - x, b < x \le c \end{cases} \tag{2.17}$$

where x is the crisp number transformed by Eq. (2.15)

Furthermore, if it is assumed that the fuzzy set; $A = \left(\sum_{u=1}^{y} \frac{\mu_{A_u}(x)}{A_u}\right)$ could represent the possibility that the fuzzy number B which is "approximately the linguistic terms $A_1, A_2, \ldots, A_y$", the triangular fuzzy number B can be converted into the linguistic terms, A_z, where $1 < z < y$, as shown in Eq. (2.18).

$$\frac{\mu_{A_z}(x)}{A_z} = \max\left(\sum_{u=1}^{y} \frac{\mu_{A_u}(x)}{A_u}\right) \tag{2.18}$$

Calculation examples for Eqs. (2.12)–(2.18) can be found in Chap. 8, Sect. 8.7.

2.7 Consensus Scheme

Multicriteria group decision making involves many complex and conflicting aspects intrinsic to human individuality and human nature. For instance, when a team of DMs takes part in the decision process, their opinions, in many cases, may disagree. Frequently, each member of the group has different information at hand and partially shares the goals of other members (Pedrycz et al. 2011). Cline (1994) found that when groups avoid disagreement or conflict, often called “group think”, the vulnerability of a proposal may be overlooked. In contrast, conflict during discussion can have positive effects on decision making; however, if conflict results in a dispute, outcome of a satisfactory nature may be reduced. Shanteau (2001) also pointed out that, disagreement between domain experts is inevitable and should not be taken as evidence of the incompetence of any expert, but reflection of the way that experts think and a consequence of the type of work they do.

There are several types of decision-making methods that a group may use to seek a satisfying solution; namely authority rule, majority rule, negative minority rule and consensus rule. These methods have their own pros and cons in different scenarios. Authority rule refers to any groups that have a leader who has an authority to make the ultimate decision for a group. Although, the method can generate a final decision fast, it does not encourage maximizing the strengths of the individuals in the group (Lu et al. 2007). Majority rule is presented in some groups when the decisions are made based on a vote for alternatives or individual opinions. This method delivers fast solutions, and follows a clear rule of using democratic participation in the process. However, sometimes, decisions made by this method are not well implemented due to an insufficient period of discussions.

Negative minority rule refers to a rule that holds a vote for the most unpopular alternative and eliminates it. It then repeats this process until only one alternative is left. It was found that this method is slow and sometimes, group members may feel resentful at having their ideas voted as unpopular (Lu et al. 2007). Consensus rule, on the other hand, is based on the rule that all members genuinely agree that the decision is acceptable. With this rule, the decision is discussed and negotiated in the group until everyone affected through understanding, agree with what will be done.

The consensus rule seems to be suitable for building designers since this rule does not force building professionals to accept only high consensus solution, but it allows these to set up minimum acceptance level in regard to their certain task (Lu et al. 2007; Pedrycz et al. 2011). More importantly, although this method is one of the most time-consuming techniques for group decision making, it may be useful to find a balance between two opposite events where experts are not in agreement but do not express this, and where discordant opinions of experts are given, but ignored.

2.7.1 Fuzzy Consensus Scheme

Concordance and consensus indices are essential tools in a fuzzy consensus scheme to measure the degree of compatibility between the triangular fuzzy linguistic terns expressed by DMs. The concordance index is a function that qualifies the level of similarity or correspondence between any pair of opinions. In the fuzzy consensus scheme, the main use of a concordance index is associated with the identification of the least concordant DM in each cycle of the discussion. The consensus index assumes values in the unit interval and is modeled as a function that quantifies how far a group of DMs is from perfect agreement. The value of 1 corresponds to full and unanimous concordance, whereas 0 refers to nonexistent concordance (Garcia-Lapresta 2008).

The concordance index was proposed by Hsu and Chen (1996) and later improved by Lu et al. (2006). It is function of fuzzy distance and fuzzy similarity concepts. The concordance index allows a fair comparison between a pair of fuzzy linguistic terms or fuzzy opinions given by DMs. Hsu and Chen (1996) calculated the similarity of fuzzy opinions as shown in Eq. (2.19).

$$S_w^y\left(F_p^y(X_k), F_p^C(X_k)\right) = \frac{\int_x \left(\min\left\{F_p^y(X_k), F_p^C(X_k)\right\}\right)\mathrm{d}x}{\int_x \left(\max\left\{F_p^y(X_k), F_p^C(X_k)\right\}\right)\mathrm{d}x} \tag{2.19}$$

where the weighted similarity, S_w^y, between the fuzzy number, $F_p^y(\mathrm{X_k})$, provided by the yth DM, and the collective fuzzy number, $F_p^C(X_k)$, which is calculated by Eq. (2.12) and Eq. (2.13). This equation is a similarity measure function proposed by Zwick et al. (1987), which refers to the proportion of the consistent area to the total area. However, it was pointed out by Lu et al. (2006) that this equation needs to incorporate the consideration with respect to the supports of the consistent area and the total area. As a result, a new formula to calculate the similarity between two fuzzy opinions was proposed as shown in Eq. (2.20).

$$S_w^y\left(F_p^y(X_k), F_p^C(X_k)\right) = \frac{\int_x \left(\min\left\{F_p^y(X_k), F_p^C(X_k)\right\}\right)^2\mathrm{d}x}{\int_x \left(\max\left\{F_p^y(X_k), F_p^C(X_k)\right\}\right)^2\mathrm{d}x} \tag{2.20}$$

The distance, D_h, between $F_p^y(X_k)$ and $F_p^C(X_k)$ can be calculated as shown in Eq. (2.21).

$$D_h\left(F_p^y(X_k), F_p^C(X_k)\right) = \frac{1}{2}\left[\int_x^l F_p^y(X_k) - F_p^C(X_k)\mathrm{d}x + d_{\inf}\left(F_p^y(X_k), F_p^C(X_k)\right)\right] \tag{2.21}$$

In Eq. (2.21), the integral, $d_{\inf}$, corresponds to the Hamming distance between $F_p^y(X_k) = \{a_1, a_2, a_3, a_4\}$ and $F_p^C(X_k) = \{b_1, b_2, b_3, b_4\}$, and this term $d_{\inf}$ is given as shown in Eq. (2.22).

$$d_{\inf}\left(F_p^y(X_k), F_p^C(X_k)\right) = \inf\{d(a,b),\, a \in [a_1, a_4],\, b \in [b_1, b_4]\} \tag{2.22}$$

where $d_{\inf}\left(F_p^y(X_k), F_p^C(X_k)\right)$ is the absolute value of the difference between $F_p^y(X_k)$ and $F_p^C(X_k)$.

Finally, the concordance level, S_{FE}^y, between $F_p^y(X_k)$ and $F_p^C(X_k)$ in the form of a linear aggregation of the distance and the weighted similarity metrics is shown in Eq. (2.23) (Lu et al. 2006).

$$\begin{aligned} S_{FE}^y\left(F_p^y(X_k), F_p^C(X_k)\right) = \beta S_w\left(F_p^y(X_k), F_p^C(X_k)\right) \\ + (1-\beta)\left(1 - \widetilde{D}_h\left(F_p^y(X_k), F_p^C(X_k)\right)\right) \end{aligned} \tag{2.23}$$

where the parameter β, defined in the range $0 \le \beta \le 1$, allows S_w to have a certain level of influence on the concordance value.

In Eq. (2.23), the $\widetilde{D}_h$ is the normalized distance calculated as shown in Eq. (2.24) (Ekel et al. 2009).

$$\widetilde{D}_h = \frac{D_h\left(F_p^y(X_k), F_p^C(X_k)\right)}{\max\ \{D_h\}} \tag{2.24}$$

where $\max\{D_h\}$ is the maximum possible distance between two extreme fuzzy linguistic terms as proposed by Bernardes et al. (2009).

This maximum distance depends on the universe of discourse being considered. It is worth mentioning that this normalization usually facilitates to empirically fix β as it guarantees that $0 \le \widetilde{D}_h \le 1$. The consensus level across the group per alternative, $C(X_k)$, can be calculated on the basis of arithmetic average as shown in Eq. (2.25).

$$C(X_k) = \frac{\sum_{y=1}^{\upsilon} S_{FE}^y\left(F_p^y(X_k), F_p^C(X_k)\right)}{\upsilon} \tag{2.25}$$

where v is the total number of the fuzzy numbers in that decision

2.7.2 Guideline Procedure for the Fuzzy Consensus Scheme

In the fuzzy consensus scheme, computational components for executing supervision functions are delegated to a human moderator. It is assumed that the variable *cycle* indicates the current iteration; and the variable *elast* is a vector utilized to store the index of the DM requested to update the opinion at each cycle of discussion. Furthermore, three freezing conditions to freeze the discussion have to be specified, namely *minconsensus*, *maxcycles* and *maxreview*. *Minconsensus* defines the minimum acceptable level of consensus. *Maxcycles* defines the maximum number of the cycles for the discussion to persist. *Maxreviews* stores the maximum number of times that any individual DM can successively be invited by the moderator to review his/her opinion (Pedrycz et al. 2011). With this in mind, the flowchart to guide the consensus scheme is proposed as shown in Fig. 2.7.

This flowchart is explained in the following steps (Pedrycz et al. 2011):

Step 1: Set *cycle* = 1, the weight for each DM $w_j = 1/n$ (j = the number of the DMs = 1, 2, …, n), *minconsensus* = e, *maxcycles* = f, *maxreviews* = g.

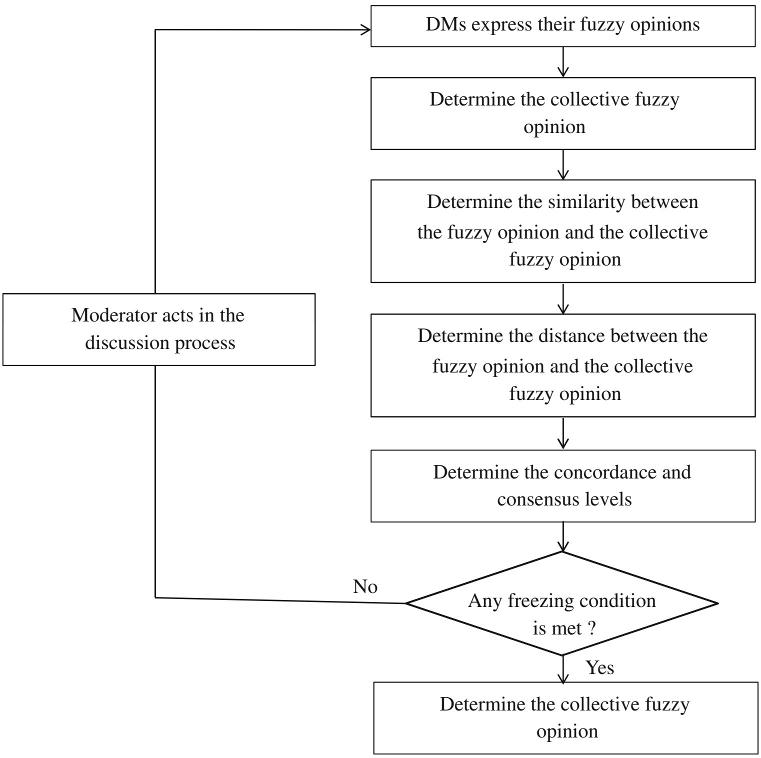

Fig. 2.7 Flowchart to guide the fuzzy consensus scheme

Step 2: Collect the opinion of each DM concerning the criterion, *t*, and the alternative, *i*.
Step 3: Aggregate the individual opinion, $F_p^y(X_k)$, in a temporary collective opinion, $F_p^C(X_k)$ with the use of the fuzzy operations.
Step 4: Calculate the consensus level based on Eq. (2.25).
Step 5: If the maximum number of cycles or a minimum level of consensus is achieved, then go to Step 10, if no freezing condition is met, then go to Step 6.
Step 6: Calculate the concordance level based on Eq. (2.23).
Step 7: Identify the least concordance DM and verify, in vector *elast*, if s/he has been the least concordant DM for the last *maxreviews* cycles. If this is true, repeat step 7 for the second least concordant DM and so on. This is to avoid the same DM being excessively requested.
Step 8: Add 1 to the value of variable *cycle*, store the index of the DM selected in Step 7 in *elast*, and invite this DM to update his/her opinion.
Step 9: Collect the opinion of the selected DM, and then go to Step 3.
Step 10: Interrupt the procedure. The output is the current collective fuzzy opinion.

The fuzzy consensus scheme shares a common principle with the Delphi technique. Both the fuzzy consensus technique and Delphi technique adopt the principle of encouraging experts to revise their decisions based on other replies. However, a main benefit of the Delphi technique lies in anonymity of team members, while, in opposite, success of the fuzzy consensus scheme ties with an open discussion of all team members. With this in mind, the fuzzy consensus scheme appears to be more useful for a team dealing with complex problems where face-to-face discussion among individual experts is needed.

2.8 Introduction to QFD

In making decisions of organizations in any industry, one of the most privileged DMs is the customers. Satisfying their needs and expectations appears to be of utmost importance for the organizations. Many companies have adopted approaches to improve quality of their products to satisfy their customers. Among these approaches, QFD is regarded as a highly effective and structured planning tool to systematically deal with customer demands and to precisely define their requirements (Dikmen et al. 2005; Xie et al. 2003). Using QFD also helps in producing more accurate decisions by focusing on several aspects and criteria based on client's needs (Mallon and Mulligan 1993). As such, a QFD approach has been applied to develop a DSS in many academic areas (Yang 2004). However, QFD is not a simple tool. It can be seen not only as an entire quality system (Govers 2001), but also as a planning process (Day 1993), a mechanism (Sullivan 1986), as well as a methodology (Xie et al. 2003).

QFD was born as a concept to new product development under the umbrella of total quality control in Japan in the late 1960s (Akao 1997). Since its first use, QFD has been adopted by a large number of organizations worldwide, for example, Du Pont, General Motors, IBM, AT&T, Motorola, Philips International, and Texas Instrument (Burn 1994; Chan and Wu 2002; Kathawala and Motwani 1994). It has also been used in several fields, for example, automotive (Dika 1995), education (Bier and Conesky 2001; Hwarng and Teo 2001), healthcare (Foster 2001), and software design (Elboushi and Sherif 1997; Pai 2002).

2.9 Benefits of QFD

QFD's applications have many benefits in reducing the quality-related problems (PMI 2008). These benefits include identification of client needs and expectations, planning, communication, and uncertainty reduction (Tran and Sherif 1995). Precise collection and identification of client needs and expectations are major part of the benefits in using QFD. A QFD methodology can provide a systematic way to collect and identify client needs. These expectations are collected at earlier stages and used to provide the correct design solutions. The QFD methodology has proved to be a helpful method in both collecting and transferring client expectations into design solutions. The methodology can also be used as the project goes on in parallel with the traditional design and construction development processes (Kamara and Anumba 1999).

Adopting the QFD approach can improve project planning as QFD helps to track client demands as well as expectations from the start till the end of the project. Consequently, any possible change can be checked and incorporated in a timely manner. QFD enhances communication and cross-functional participation among project team members by encouraging the members to integrate their work through the use of concurrent procedures and processes so much so that client needs are collected and converted accurately into design targets (Xie et al. 2003). Furthermore, QFD seems to play an important role in reducing uncertainty of a project in several ways. One of these can be seen where early identification of client expectations helps to minimize uncertainty as the project phases develop. Importantly, reduced cycle times regarding redesign and communication are observed with implementation of QFD since QFD project teams thoroughly understand, and are aware of what the teams have to produce from the beginning (Ahmed et al. 2003).

2.10 Use of QFD in the Building Industry

The building industry, to a certain extent, differs from other industries in the sense that many businesses and agencies of varying sizes all come together for one building project. In particular, they work together for a number of years, and then go on to another project with another group of participants. It is noted that construction is more a service industry than a manufacturing or product-based industry. Even though large products are often constructed, a project's success is more dependent on the people involved than a particular piece of equipment, a process, or a patent. A building project that can muster well-organized, skilled, and motivated people, with an effective communication system in place stands a good chance of succeeding (Chew 2009; Gould 2005).

For this reason, many public and private entities have been focusing on establishing strong team building, leadership systems, cross-function communication as well as integrative planning and design (Gould 2005). Furthermore, a building project seems to be relatively unique in that each building is tailor-made to meet the requirements and needs of the customers that, significantly, have to match capability of a project team. Hence, using the QFD approach makes good sense in the building industry (Low and Yeap 2001). In this regard, it has been found that employing QFD as part of construction and building design management is useful. This can be seen in two different project development phases; namely during the early design stage and during the detailed design stage (Dikmen et al. 2005).

2.10.1 Implementing QFD During the Early Design Stage

Previous studies have suggested that using QFD during the early design stage is helpful in several ways. According to Arditi and Lee (2003), QFD was successfully applied to assess corporate service quality performance of design/build (D/B) contractors by owners at the project-planning phase as well as to determine the quality performance of potential firms on their bidding list. Ahmed et al. (2003) confirmed that QFD is useful for civil engineering capital project planning. Yang et al. (2003) developed a fuzzy QFD tool and adopted this as a DSS to evaluate building designs at the early design stage.

Similarly, Low and Yeap (2001) examined the awareness and applicability of the QFD methodology in design and build (D/B) contracts, while Dikmen et al. (2005) employed a fuzzy QFD tool to determine a marketing strategy by identification of expectations of target customer groups in the construction industry. Likewise, Sener and Karsak (2011) developed a fuzzy multiple objective decision framework by integrating fuzzy linear regression and fuzzy multiple objective to achieve target levels of engineering characteristics in QFD. It was found that the inherent fuzziness of functional relationships in QFD modeling promotes fuzzy regression as an effective tool for estimating the relationships between customer needs and engineering characteristics, and among engineering characteristics.

2.10.2 Implementing QFD During the Detailed Design Stage

The QFD approach has been employed in several studies to improve quality of decision making as well as design solutions during the detailed design stage. For instance, Mallon and Mulligan (1993) introduced the construction literature with the QFD methodology and proved the applicability of QFD in the design of a hypothetical renovation project. Huovila et al. (1997) utilized the QFD methodology for finalizing the structural design of an industrial building. By using the QFD methodology, Gargione (1999) developed the design of a building project according to end-user requirements. Furthermore, Kamara and Anumba (2001) adopted the QFD approach for identifying and processing client requirements. This aimed to determine the actual requirements of a building project and to support decision making of building professionals.

2.11 Customers of QFD

In a broad context, the customers of a project are those impacted by a project. For instance, if one party works in collaboration with another party, these two parties will both become the customers of a project (Yang et al. 2003). As such, the customers of QFD in this book are the parties who involve in the early design stage of high-rise residential buildings. It is therefore imperative to understand roles of these parties in the early stage design. Based on the pilot study (see Appendix A), in Singapore, most high-rise residential buildings adopt the design-bid-build procurement method where a developer engages designers to design and prepare contract documents before selection of a contractor.

In this method, architects from an architectural firm lead a design team in design development including building envelope design development. Focusing on the early design stage, the architects receive relevant information regarding the building envelope design development of a project from the developer/owner, and then develop a conceptual building envelope design with help of C&S engineers, and M&E engineers to satisfy requirements of the developer by providing a set of design alternatives. Specifically, the engineers assist the architects by not only finding the building envelope materials and designs that meet requirements of the developer and architects, but also assessing energy efficiency, day-lighting, visual performance of building envelope design alternatives, etc.

After that, the developer selects and finalizes the conceptual design, and then the architects and engineers move on to develop a schematic or detailed building envelope design. At this point, a Quantity Surveyor (QS) firm comes into provide cost estimation, and, in some cases, an Environmental Sustainable Design (ESD) firm may be called on board to help the architects and engineers to assess building performance. The architect, if qualified, can sometimes be appointed as a project manager to manage design and construction development. In other cases, the developer can engage another Project Management (PM) firm to do so. However, the PM firm usually gets involved in the design development after the detailed design stage begins. As a result, the main customers or DMs of the design team in the early design stage for this book include only the architect, C&S engineer and M&E engineer.

2.12 Components of QFD

QFD presents its structure in the form of the House of Quality (HOQ). The HOQ is the most commonly used matrix in the QFD methodology. The fundamental of the HOQ is the belief that products should be designed to reflect customers' demands. The focus in the HOQ is the correlation between the identified customer needs, called WHATs, and the engineering characteristics, called HOWs (Hauser and Clausing 1998).

2.12.1 Structure of the House of Quality

The structure of the HOQ is presented in Fig. 2.8 as the shape of a house containing six rooms.

The left side room is a list of customer requirements, while the right side room is prioritized customer requirements, which reflect the importance of these requirements. The ceiling of the house provides engineering characteristics, sometimes also called technical descriptors or design characteristics. These technical descriptors are provided through engineering requirements, design constraints, and parameters (Xie et al. 2003). The interior or living room holds relationships between the customer requirements and engineering characteristics. In this room, the customer requirements are translated into the engineering characteristics based

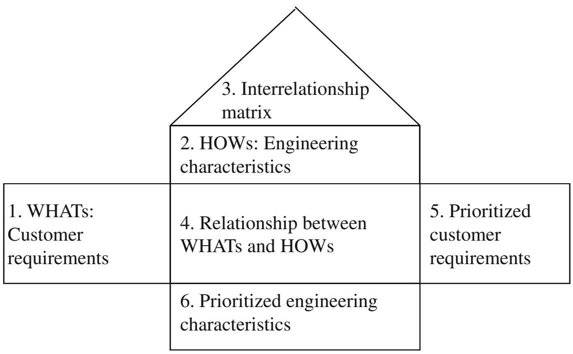

Fig. 2.8 Structure of the (HOQ)

on the relationships stored in the interior room. The roof of the house contains interrelationships between the engineering characteristics to keep tradeoffs between similar and conflicting engineering characteristics. At the foundation of the house, factors, such as technical benchmarking, degree of technical difficulty and target value, can be listed (Xie et al. 2003).

2.12.2 Construction of the HOQ

The steps for construction of the rooms in the HOQ based on Fig. 2.8 are described below: (Low and Yeap 2001; Xie et al. 2003).

Room 1: List of customer requirements (WHATs)
QFD starts with a list of goals/objectives. This room is often referred to as WHATs that customer needs or expects from a particular task. This list of primary customer requirements is usually vague and very general in nature. Further definition is accomplished by defining a new, more detailed list of secondary customer requirements to support the primary customer requirements. In other words, a primary customer requirement may encompass numerous secondary customer requirements.

Room 2: List of engineering characteristics (HOWs) To meet the goal of the HOQ, once the customer needs and expectations are identified, the QFD team must develop the engineering characteristics referring HOWs that can affect one or more of the customer requirements. These engineering characteristics are part of the ceiling and second floor of the HOQ. These characteristics are expressions of the Voice of Customer (VOC) in a technical language. The development process should be continued until every item on the list is actionable. In addition, the list of engineering characteristics can be divided into a hierarchy of several levels of the engineering characteristics.

Room 3: Interrelationship matrix between pairs of HOWs
The roof of the HOQ, called the correlation matrix, is used to identify any interrelationships between pairs of engineering characteristics. It is a triangular table attached to the engineering characteristics. This matrix allows the QFD team to uncover which engineering characteristics are most important because these not only are frequently the result of conflicting customer requirements, but also represent points at which trade-offs must be made. Some of these trade-offs may require high-level managerial decisions, and some are cross-functional area boundaries.

Room 4: Relationship matrix between WHATs and HOWs
This room, called the relationship matrix, provides comparison between the customer requirements and engineering characteristics. The number of comparisons relies on the number of the customer requirements and the number of engineering

characteristics. Doing this early in the development process would shorten the development cycle and lessen the need for future change.

Room 5: Prioritized customer requirements
This room relates to development the prioritized customer requirements by making up a block of columns corresponding to each customer requirement in the HOQ on the right-hand side of the relationship matrix. It should contain calculation algorithms for prioritizing the customer requirements. Examples of these algorithms include linear importance rating, AHP, and fuzzy set rating methods.

Room 6: Prioritized engineering characteristics
The prioritized engineering characteristics room is located below the relationships between WHATs and HOWs room. In this room, the QFD team prioritizes the engineering characteristics based on the relationship matrix and the prioritized customer requirements using the calculation algorithms as well as the interrelationship matrix.

2.13 Improvement on Conventional QFD

A conventional QFD tool promotes identifying the requirements of the stakeholders and design alternatives, minimizing disagreement between members of a design team, and making decisions as a team. It also improves communication and coordination processes among the members to a certain level. QFD is a relatively new approach, but a feasible and useful method in construction (Oswald and Burati 1993; Mallon and Mulligan 1993; Kamara and Anumba 1999; Low and Yeap 2001). Hence, QFD seems to be a promising approach to mitigate the decision-making problems introduced in Sect. 1.3. Nevertheless, the conventional QFD tool appears to have some barriers to do so. These include the difficulty in manually recording the QFD matrix in a paper form (Wolfe 1994), the amount of time to implement it (Cohen 1995), the difficulty in dealing with complex product and conflicting requirements (Prasad 1996), lack of knowledge-based decision-making, the qualitative and subjective decision-making attributes (Bouchereau and Rowlands 2000) and conflicting perceptions and solutions (Gray and Hughes 2001).

In response to these, the book applied the concepts as shown in Fig. 2.9 to improve the conventional QFD tool to achieve mitigation the decision-making problems. This modification results in a conceptual KBDSS-QFD tool of this book. It should be noted that the concepts to mitigate the decision-making problems were derived from the literature reviews, and then preliminarily verified through the pilot study (see Appendix A) conducted with the building professionals who had rich experience in the building envelope design and construction in Singapore.

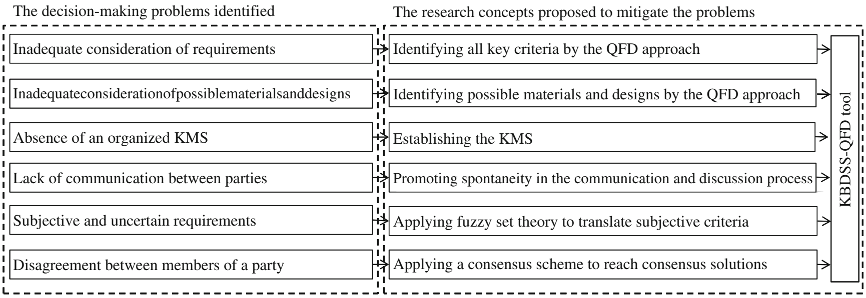

Fig. 2.9 Concepts to improve a conventional QFD tool for mitigation of the decision-making problems

2.13.1 Identifying Key Criteria Using the QFD Approach

Singhaputtangkul et al. (2011a) found that, instead of redesigning the building envelope, when design parameters are changed, or when new assessment criteria have to be additionally considered, it would be better if a comprehensive set of the criteria can be identified before the assessment of the building envelope materials and designs begins. Identifying this set of the criteria would be able to deliver more reliable design and planning leading to optimizing workload, time requirements, and savings on associated costs by reducing variations and repetitive assessment processes (Arian 2005; Mantel et al. 2008; PMI 2008).

In parallel, doing this would also help to remind the architects and engineers to consider procurement-, construction-, and occupation-design inputs for the assessment of the building envelope materials and designs, thereby supporting overall project planning and management (Gould 2005). Notwithstanding the potential of applying the conventional QFD tool to identify project requirements, the concept of identifying the set of the related criteria for the assessment of the building envelope materials and designs was incorporated into the conceptual KBDSS-QFD tool. Briefly, the book provided a comprehensive list of the criteria in the "List of the customer requirements" room in the HOQ of the conceptual KBDSS-QFD tool in an effort to remind the DMs of key criteria and to support them in making more comprehensive criteria selection. This list of the criteria was adopted from the first research objective of this book.

2.13.2 Identifying Possible Materials and Designs Using the QFD Approach

Previous studies, as discussed before, have found the QFD approach useful in identifying engineering characteristics in both the building industry and others. For instance, El-Alfy (2010) suggested that providing a holistic set of the building materials and designs can help to remind the architects and engineers to explore other possible materials and designs. Likewise, Kibert (2008) and Boecker et al. (2009) also found that a thorough assessment of several possible design alternatives plays an important role in achieving green designs. To mitigate the decision-making problem related to inadequate consideration of possible building envelope materials and designs, this book adopted the concept of identifying a possible set of the building envelope materials and designs based on the QFD approach before the designers begin to assess the materials and designs. This concept was incorporated into the “List of the engineering characteristics” room in the HOQ of the conceptual KBDSS-QFD tool. However, as discussed earlier in Sect. 1.8, to keep the scope of the book manageable, only a set of the basic building envelope materials and designs was considered in this book.

2.13.3 Establishing the KMS

Over the past few decades, the industrialized economy has been going through a transformation from being based on natural resources to being based on intellectual assets (Alavi 2000; Tseng and Goo 2005). The knowledge-based economy is a reality (Godin 2006). Firms must develop strategies to sustain competitive advantage by leveraging their intellectual assets for optimal performance such as providing quick response to customer needs (Berman et al. 2002). Among several strategies, establishing a KMS may help the firms to do so by facilitating them to store and retrieve knowledge, improve collaboration, locate knowledge sources, and capture and use knowledge. Arain (2005) and Nevo and Wand (2005) pointed out that applying the KMS can assist experts to remember the past, thereby supporting these in making prompt decisions and increasing consistency of the decision outcomes. In addition, Jennex and Olfman (2003) suggested that the KMS can also capture new knowledge and make it available in its enhanced form.

As such, this book applied the concept of establishing the KMS as discussed in Sect. 2.4 to store relevant knowledge and to create several situational decisions and rules to mitigate the decision-making problem related to lack of efficiency and consistency in making the decisions of the architects and engineers. Establishing such KMS aims at organizing existing knowledge and structuring new knowledge related to the assessment of the building envelope materials and designs (Arain and Low 2006; Turban et al. 2007). The KMS therefore was integrated into the conceptual KBDSS-QFD tool to assist the building professionals in learning from similar situational decisions to make prompt and consistent responses.

According to the structure of the HOQ (see Sect. 2.12), there are three rooms that may need the knowledge supplied by the KMS; namely the “List of the customer requirements (WHATs)”, “List of the engineering characteristics (HOWs)” and “Relationship matrix between the WHATs and HOWs” rooms. The KMS of the conceptual KBDSS-QFD tool thus was modeled in relation to these three rooms in the HOQ. Consequently, the main KMS consists of three subsystems to separately store the knowledge related to the related criteria for the assessment of the building envelope materials and design, building envelope materials and designs, and relationships between the criteria and the materials and designs.

2.13.4 Promoting Spontaneity in the Communication and Integration Process

As a group has more information than any one member, groups seem to be better than individuals at stimulating creativity as well as catching errors. Nevertheless, a major inherent problem of group decision making is that there tends be lack of communication and integration due to poor decision-making structure (Turban et al. 2007). In response to this, making decisions as a group through the use of a computerized DSS based on the QFD approach would strengthen communication, coordination and integration among DMs (Gwangwava and Mhlanga 2011; Yang 2004). In particular, Krishnaswamy and Elshennawy (1992) found that the QFD tool can be applied to develop a DSS for improving the communication inside the organization if it is correctly implemented. Low and T'ng (1998) and Gwangwava and Mhlanga (2011) suggested that the QFD approach is an effective method for enhancing communication and integration between team members. It also provides the means to derive a good understanding of the customer's needs and requirements.

Daws et al. (2009) further highlighted that that QFD may need to be computerized for achieving better communication and integration among members of a group based on it specific tasks. Hence, to mitigate the decision-making problem related lack of communication and integration, this book promoted spontaneity in communication and integration by engaging the architects and engineers to make decisions as a team through a structured and computerized decision-making process (Xie et al. 2003; Yang et al. 2003). This process is guided by the user interface of the conceptual KBDSS-QFD tool developed with respect to Sect. 2.4.

2.13.5 Applying the Fuzzy Set Theory to Translate Subjective Criteria

In a real-world decision situation, it is recognized that human judgment on qualitative criteria is always subjective and imprecise. However, as discussed in Sect. 2.6, the fuzzy set theory introduced by Zadeh (1965) can mitigate this problem by translating unquantifiable information, incomplete information, unavailable information, and partially ignored facts into the decision model. For example, Karsak (2004) developed a multiobjective programming approach that incorporates imprecise and subjective information inherent in a QFD planning process with the use of the fuzzy set theory, and found that this approach was helpful in determining the level of fulfillment of design requirements. Hassan et al. (2010) also showed the applications of their fuzzy QFD tool to handle the subjective assessments.

This book hence integrated the fuzzy set theory as part of a fuzzy inference engine of the conceptual KBDSS-QFD tool to evaluate preferences of the architects and engineers (Lu et al. 2007; Pedrycz et al. 2011; Ross 2010). To be specific, the DMs express their preferences for the criteria and their judgments for the building envelope materials and design alternatives using fuzzy linguistic terms instead of crisp numbers. The fuzzy inference engine then prioritizes the materials and design alternatives, and subsequently delivers a set of satisfied design solutions based on the inputs of the DMs.

2.13.6 Applying the Consensus Scheme to Reach Optimized Consensus Solutions

Notwithstanding the fact that multicriteria group decision making usually involves various complex and conflicting aspects intrinsic to human individuality and human nature, individual DMs of such group also seem to have different information at hand and partially share the goals of other DMs (Ekel et al. 2009; Lu et al. 2007). Disagreement between domain experts seems to be inevitable and should be taken as the way that experts perceive and importantly should not be neglected because these may help a group to identify sources of crucial information for the decision (Shanteau 2001). Among several techniques for seeking consensus solutions among experts, the consensus scheme as discussed in Sect. 2.6 has been recognized by several studies (Bui and Jarke 1986; Jiang and Klein 2000; Madu and Kuei 1995).

In principle, the scheme consists of a systematic and iterative discussion process implemented under supervision of a moderator with the intention of reducing the discordance among opinions (Ekel et al. 2009). Pedcrycz et al. (2011) applied this concept and proposed a fuzzy consensus scheme as described in Sect. 2.7. Parreiras et al. (2012a) found usefulness of applying fuzzy consensus schemes in exploiting the capabilities of each member of the group in a cooperative work. Parreiras et al. (2012b) made use of the fuzzy consensus scheme to regulate the information flow in the discussion and disagreement among the experts. With this in mind, the book adopted the fuzzy consensus scheme as part of the fuzzy inference engine of the conceptual KBDSS-QFD tool to mitigate potential disagreement of opinions among the designers when assessing the building envelope materials and designs (Lu et al. 2007; Pedrycz et al. 2011).

2.14 Development of the Conceptual KBDSS-QFD Tool

Figure 2.10 illustrates the architecture of the conceptual KBDSS-QFD tool incorporated with the concepts to improve the conventional QFD tool for mitigation of the decision-making problems. Overall, there are four major elements in the conceptual KBDSS-QFD tool which include HOQ for Sustainability and Buildability (HOQSB), KMS, fuzzy inference engine, and user interface. Firstly, the HOQSB was developed by modifying the conventional HOQ to facilitate mitigation of the decision-making problems. The HOQSB consists of five rooms which are Criteria room (CR), Building envelope materials and designs room (MR), Relationships between the criteria and the building envelope materials and designs room (RR), Fuzzy techniques for prioritizing the design alternatives room (FR) and Preference list room (PR).

The CR is used to facilitate mitigation of the decision-making problem related to inadequate in consideration of criteria by assisting the DMs in identifying and reminding key criteria for the assessment of the building envelope materials and designs towards sustainability and buildability. The MR is applied to facilitate mitigation of the decision-making problem related to inadequate consideration of possible materials and designs. This room assists the DMs in identifying and reminding possible materials and design alternatives. The RR contains the relationships between the criteria and the design alternatives. This room is organized in a form of a matrix to indicate certain parameters affecting each criterion. The FR is embedded with the fuzzy calculation algorithms operated by the fuzzy inference engine.

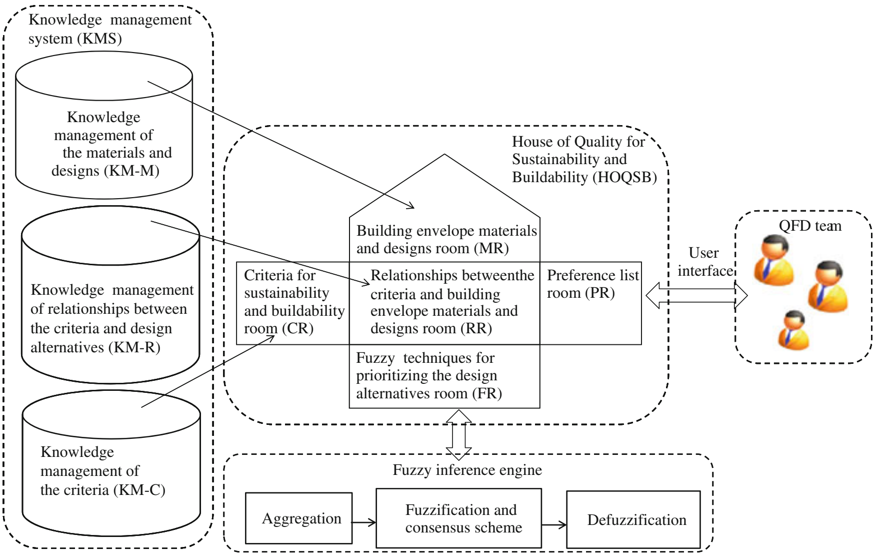

Fig. 2.10 Architecture of the conceptual KBDSS-QFD tool

The PR then delivers the results analyzed from the FR in the form of the preference list of the design alternatives. It is noted that the “Prioritized customer requirements” and “Prioritized engineering characteristics” rooms of the conventional QFD tool as shown in Fig. 2.8 are combined into the FR in the HOQSB of the conceptual KBDSS-QFD tool as shown in Fig. 2.10. This is because, in this book, prioritizing both the customer requirements and engineering characteristics is governed by a single fuzzy inference engine.

In addition, this book establishes the assessment that takes into account the design alternatives that comprise only the materials which are positively correlated. As such, to a large extent, the interrelationship matrix of such materials can be omitted. For example, the design alternatives that comprise concrete shading device and fixed glass wall together are not included in this book to avoid potential conflicts in terms of design and construction between these building envelope materials. This aims to facilitate not only assessment of the building envelope materials and designs but also development of the KBDSS-QFD tool in the first instance. More importantly, although the interrelationship matrix is omitted, the concept of this matrix to reveal potential conflicts in different components of the design alternatives is applied to build the KMS to support the DMs in prioritizing the design alternatives (See Sect. 8.3).

Secondly, to mitigate the decision-making problem related to lack of efficiency and consistency in making the decisions faced by the designers, the KMS was established to organize and structure the knowledge related to the criteria, building envelope materials and designs as well as relationships between the criteria and building envelope materials and designs. The KMS is made of Knowledge management of the criteria system (KM-C), Knowledge management of the materials and designs system (KM-M) and Knowledge management of relationships between the criteria and design alternatives system (KM-R). As shown in Fig. 2.10, the KM-C, KM-M and KM-R of the KMS serve as the database of the CR, MR and RR in the HOQSB, respectively.

Next, the fuzzy inference engine contains the fuzzy techniques to translate subjectivity and uncertainty requirements into quantified numbers. The engine is also equipped with the fuzzy consensus scheme to mitigate disagreement between members of a design team by helping the team to seek optimized consensus solutions that all the members agree. Lastly, the user interface plays a role to operate all the components. This leads the members of the team to communicate and integrate their opinions through a clear and deliberated decision-making process, thereby supporting mitigation of the decision-making problem related to lack of communication and integration among the designers. Importantly, this conceptual KBDSS-QFD tool serves an important basis for development of a detailed KBDSS-QFD tool and its first prototype to be thoroughly discussed in Chap. 8.

2.15 Summary

This chapter reviewed the concepts of decision making, KMS, KBDSS and decision-making techniques, following by introducing the concepts of QFD. In brief, QFD has been regarded by a number of leading organizations as one of the widely used tools to deal with customer requirements in several fields. Previous studies have found that adopting QFD as a tool can effectively identify customer requirements, transfer these into correct design solutions, promote better planning, enhance communication, minimize uncertainty, etc. However, the conventional QFD tool seemed to have some drawbacks. This book improved the conventional QFD tool by incorporating the following concepts: identifying key criteria using the QFD approach, identifying possible materials and designs using the QFD approach, establishing the KMS, promoting spontaneity in the communication and integration process, applying the fuzzy set theory to translate subjective criteria, and applying the consensus scheme to reach optimized consensus solutions. As a result of this modification, the conceptual KBDSS-QFD tool, consisting of the HOQSB, KMS, fuzzy inference engine and user interface, was formed to facilitate development of the detailed KBDSS-QFD tool and its first prototype.

Chapter 3
Criteria for Assessment of Building Envelopes

3.1 Introduction

This chapter examines the criteria for the assessment of the building envelope materials and designs to achieve sustainability and buildability as part of the first objective of the book. This chapter also reviews the relevant knowledge of the criteria to store in the KM-C and KM-R of the KMS. It begins by summarizing concepts of total building performance (TBP) (Sect. 3.2). This is followed by introducing background of sustainability (Sect. 3.3), background of buildability (Sect. 3.4), and criteria for the assessment of the building envelope materials and designs (Sect. 3.5).

3.2 Concepts of Total Building Performance (TBP)

Buildings need to perform their basic functions of building enclosure against environmental degradation through moisture, temperature, air movement, radiation, chemical and biological attacks, or environmental disasters. In addition, these also have to provide interior occupancy requirements and the comfort. Hartkopft et al. (1992) called these needs as TBP. TBP is widely regarded as the whole-building system approach and process in which one is able to fully apply and integrate the values of a building (Low et al. 2008b). From a technical point of view, TBP is often defined as the integration of the different building performance mandates (Hartkopf et al. 1992; Rush 1986).

TBP aims to respond to a set of integrated strategies, which focuses on bringing about utmost efficiency and performance in the construction industry (Rush 1986). It consists of six performance mandates: namely indoor air quality performance (IAQ), visual performance, thermal performance, building integrity performance, spatial performance, and acoustic performance mandates (Hartkopf et al. 1992).

S. Natee et al., *Quality Function Deployment for Buildable and Sustainable Construction*, DOI 10.1007/978-981-287-849-6_3

This section discusses concepts of these performance mandates, and investigates impact of assessment of the building envelope materials and designs on each of these mandates.

3.2.1 Indoor Air Quality Performance

One of the basic functions of a building is to act as a shelter for its occupants and allow these to carry out their respective activities in a conducive environment. Providing a comfortable environment requires incorporating TBP concepts into the enclosed spaces. With increasing expectations, the occupants seem to demand better IAQ associated with ventilation performance of a building. As there are a variety of reasons why poor IAQ can occur, to reduce the possibility of that happening, the IAQ mandate should be taken into consideration during the planning and design stages (Low et al. 2008c).

In particular, there are several aspects that can be controlled and used to enhance good IAQ. These include site planning and design, overall architecture design, ventilation and climate control by both natural and mechanical, materials selection and specifications, construction process and initial occupancy, space planning, and building design envelope (Low et al. 2008c). Although selecting appropriate building envelope materials could affect the IAQ performance mandate, this seems to play a less significant role than design factors. One of the design factors is the size of openings including windows and walls in the building shell affecting the ability to provide good thermal comfort and control of air contaminants. Additionally, due to potential sources of outdoor air contaminants and wind pattern, the building site has to be evaluated with respect to not only the size of the opening, but also the location of the windows and doors, site layout to promote air movement and natural ventilation (Asimakopoulos et al. 2001; Lovell 2010).

3.2.2 Visual Performance

Visual performance refers to lighting performance of a building. Different activities in each part of a building require specific lighting. In visual performance design, there are some important aspects that should be considered. These include, for example, glare, quantities of lighting, natural daylighting, building envelope and building orientation, windows, view, and occupancy factors (age, activities, number of occupants, etc.). Providing good visual comfort should be a priority in rooms that are used for demanding visual tasks (Carmody et al. 2007; Lovell 2010). In almost all environments, the layout of a building should be designed in such a way that direct sunlight will not directly penetrate the working areas. Similarly, the type, size, shape, position, and orientation of openings and interior designs, in conjunction with various control systems, are basic factors affecting the amount and distribution of light (Asimakopoulos et al. 2001). Furthermore, the building envelope may also exert a certain influence over the amount of daylight penetrating the building through its different material properties such as the transmission, diffusion, and color of the materials (Low et al. 2008c).

3.2.3 Thermal Performance

The thermal performance of a building is closely associated with air temperature. Air temperature appears to be the most commonly used indicator to measure the thermal comfort as this seems to be the easiest and most obvious indicator that most people are able to relate to when determining the thermal comfort of a given space (Lovell 2010; Low et al. 2008b). Nevertheless, the environmental conditions required for comfort are not the same for everyone. Air temperature should always be considered in relation to the other environmental and personal factors that contribute to the determination of thermal comfort. These factors include the four environmental factors—air temperature, radiant temperature, air velocity, and humidity, and personal factors. Although these factors may be independent of each other, they can collectively contribute to an occupant's overall thermal comfort (Harriman 2008; Low et al. 2008b).

Furthermore, controlling the energy transfer parameters particularly the envelope thermal transfer value (ETTV), roof thermal transfer value (RTTV), and thermal transmittance (U-value) for roof can enhance the thermal performance of a building (BCA 2010a; Low et al. 2008b). Design parameters of the building envelope, such as site layout and landscaping including orientation and shape of a building as well as material types of the building envelope also have an impact on the thermal performance of a building in several ways (Carmody et al. 2007; Chua and Chou 2010a). Site layout and landscaping influence not only air movements toward the inside of a building, but also shadowing and shading of a building by adjacent buildings. Considering the orientation of a building, north and south openings can be used as a collector of solar heat gains during winter; however, direct radiation should be avoided during summer, while east and west openings increase cooling load during summer as this allows for direct radiation (Asimakopoulos et al. 2001).

Wang et al. (2007) evaluated the thermal performance of facade designs for naturally ventilated buildings in Singapore. Their findings suggested that the thermal transmittance (U-value) of facade materials for the north and south orientation should be less than 2.5 W/m^2 K, whereas the U-value of facade materials for the east and west orientation should be less than 2 W/m^2 K. Furthermore, south-facing facades can provide much comfortable indoor environment than east- and west-facing facades in Singapore. It was also reported that north- and south-facing facades can provide better thermal comfort than west- and east-facing facades and thus should be considered as priority. Specifically, for south-facing facade, the optimum facade design is window-to-wall ratio (WWR) = 0.36 with horizontal shading width more than 300 mm. For north-facing facade, the optimum

Table 3.1 Design guidelines for naturally ventilation and thermal comfort for residential buildings

WWR	East	West	North	South
0.12	$U = 2$ W/m^2 K, Shading = 600 mm	$U = 2$ W/m^2 K, Shading = 600 mm	$U = 2.5$ W/m^2 K, Shading = none	$U = 2.5$ W/m^2 K, Shading = none
0.24	$U = 2$ W/m^2 K, Shading = 600 mm	$U = 2$ W/m^2 K, Shading = 600 mm	$U = 2.5$ W/m^2 K, Shading = 300 mm	$U = 2.5$ W/m^2 K, Shading = 300 mm
0.30	$U = 2$ W/m^2 K, Shading = 1200 mm	$U = 2$ W/m^2 K, Shading = 1200 mm	$U = 2.5$ W/m^2 K, Shading = 300 mm	$U = 2.5$ W/m^2 K, Shading = 300 mm
0.36	$U = 2$ W/m^2 K, Shading = 1200 mm	$U = 2$ W/m^2 K, Shading = 1200 mm	$U = 2.5$ W/m^2 K, Shading = 300 mm	$U = 2.5$ W/m^2 K, Shading = 300 mm

WWR is 0.24 with or without shading. For west-facing facade, the optimum WWR is 0.12 with horizontal shading width more than 1200 mm and for east-facing facade the optimum WWR is 0.24 or 0.12 with horizontal shading width more than 1200 mm. Design guidelines for the natural ventilation and thermal comfort for residential buildings in Singapore are summarized in Table 3.1.

3.2.4 Building Integrity Performance

Building integrity is usually defined as maintaining the material, component, and assembly properties to withstand external and internal forces over time (Hartkopt et al. 1992; Rush 1986). Building integrity should sustain mechanical properties for geometric stability, structural strength and stability, physical properties of water-tightness and air-tightness, and visible properties of color, texture, and surface finish. There are several forces as well as environmental factors that could harm building integrity. These include, for example, moisture, temperature, radiation, light, chemical attack, biological attack, fire, and man-made, and natural disasters (Low et al. 2008b). Enhancing the building integrity performance is one of the major goals in building envelope design. It is important for building façade to be able to withstand water, air, sound, light, view, heat, fire, pollution, security, safety, and explosions. Importantly, these factors can be controlled by selecting an appropriate skin, and all of these factors should be combined in a balanced way (BCA 2004; Bryan 2010; Chew 2009).

3.2.5 Spatial Performance

Spatial performance is referred to as arrangement of space. This arrangement is associated greatly with human work performance. Assessment of the spatial performance involves various subjective parameters. Although there is not much information regarding specifications of the spatial performance in Singapore, there are some guidelines that can assist in spatial performance assessment. These guidelines include achieving psychological requirements, physiological requirements, sociological requirements, and economic requirements (Low et al. 2008a; Robertson and Courtney 2001).

In regard to human occupancy, psychological requirements aim to support individual mental health through appropriate provisions for privacy, interaction, clarity, status, change, etc. Physiological requirements focus on the physical health and safety of the building occupants. Next, sociological requirements refer to supporting the well-being of the community within which the individuals act. In the economical sense, the resources must reap maximum benefits whenever possible. For spatial quality, the economic requirements must be fulfilled through the arrangement of space in a way that the space can maximize the benefit to both the owner as well as the occupants (Lueder 1986; Rush 1986).

3.2.6 Acoustic Performance

Acoustic performance is simply the performance of a building to control sound (Low et al. 2008a). It was found that types of window glazing and wall account for a significant portion in determining the acoustic performance of the building (Bryan 2010). There is also a direct relationship between a window area of opening and its characteristic level of acoustic insulation; larger openings provide poorer acoustic protection (TBPC 2007). Considering the acoustic performance of window glazing, if the sound insulation of the solid or opaque wall of a facade is at least 15 dB higher than that of the glazing, noise transfer through the wall can be ignored. In this regard, noise transmission through windows and other openings alone may be considered (ACC 2011).

The window should be well sealed between the frame and the supporting wall as sound can flank around the window when not properly sealed. Furthermore, opening type of window can affect the acoustic performance of the façade. For example, awning windows with outward opening sashes are preferred to sliding windows as when closed they achieve a positive compression seal against their window frame (ACC 2011). Considering the acoustic performance of wall, there are a number of rating systems for defining the effectiveness of a wall for sound insulation. One of these includes the sound transmission class (STC). STC is the decibel reduction in noise a panel can provide. The higher the STC value, the better is the acoustic performance.

Overall, using different building envelope materials does not affect the IAQ performance much, since the IAQ performance seems to be more dependent on the building envelope design factors particularly building location, layout, landscaping, as well as WWR. In contrast, using appropriate building envelope materials are relatively essential in improving the visual performance of a building. However, this should be conducted in parallel with taking into account the type, size, shape, position, and orientation of openings, and interior designs, in conjunction with various control systems which are the basic factors affecting the amount and distribution of light. Similarly, the thermal performance of a building depends not only on several design parameters of the building envelope, for example, site layout and landscaping, orientation and shape of a building, and the three main guidelines; namely the administrative controls, the engineering controls, and the generic controls, but also properties of the building envelope materials.

Next, enhancing the building integrity performance of a building, to a certain extent, relatively relies on selection of the building envelope materials and designs. In the context of this book, the building integrity performance of the building envelope is associated with various aspects; including water, air, sound, light, heat, fire, pollution, security, safety, and explosions. While the relationships among the building envelope materials and designs and spatial performance seem to be quite limited, the acoustic performance of a building can be influenced by the building envelope materials and designs. The review suggested that selecting appropriate building envelope materials and designs play a significant role in withstanding unwanted sounds coming from outside of a building. In brief, this selection should be based on the acoustic insulating performance, particularly the STC of the wall and window materials, and the quality of jointing and sealing between the window frame and the supporting wall.

Overall, there are four performances that can be largely affected by the building envelope materials and designs in the early design stage; these include the visual, thermal, building integrity, and acoustic performances. As such, these performances become part of the criteria for the assessment of the building envelope materials and designs as discussed in Sect. 3.5.

3.3 Sustainability

Awareness of sustainable development has increased in recent years. In the construction industry, this can be seen where implementation of an energy rating guideline to assess environmental and energy performance of buildings has become more important in many countries (Kibert 2008). This green market has brought major improvements through employing green building practices. Primary drivers cited in the literature for green building adoption include minimizing operating and maintenance costs, increasing employee health, productivity, and satisfaction, improved indoor environment quality, and so on (Ahn and Pearce 2007; Lapinski et al. 2006; Tatari and Kucukvar 2010).

Over the last few decades, a common definition of sustainable development has been developed. It was agreed that the mainstay of sustainability thinking is to strike a balance between three dimensions: environmental, social, and economic impacts of the design as shown in Fig. 3.1 (Bansal 2005). This implies that it is important not only to achieve environmental requirements of the building assessment programs, but also to incorporate the social and economic impacts of building

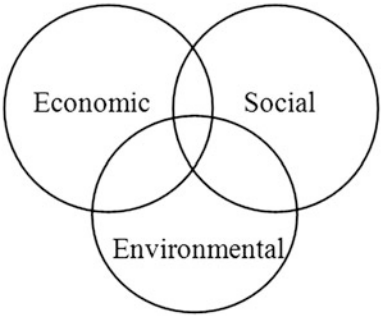

Fig. 3.1 Three dimensions in sustainable development

designs that have on the environment as well as the building organizations themselves (Singhaputtkul et al. 2011b).

There are schemes implemented to evaluate sustainability of building design, for example, BREEM of the United Kingdom, LEED of the United States, CASBEE of Japan, and Green Star of Australia. In Singapore, sustainability of a building is measured by a green mark (GM) score of the green mark scheme (GMS). The GMS is a Code of Practice used for assessing the environmental and energy performance of buildings under the Building Control (Environmental Sustainability) Regulations (2010) (Version 4). This Code of Practice requires all new buildings, additions or extensions to existing buildings, and building works involving major retrofitting to existing buildings with the gross floor area (GFA) equal to or more than 2000 m^2 to meet the requirements of the GMS (BCA 2010a).

As shown in Table 3.2, five categories are evaluated in the GMS; namely energy efficiency, water efficiency, environmental protection, indoor environmental quality, and other green features. The minimum environmental sustainability standard of building works shall have a level of environmental performance that meet the minimum GM score. For either residential or nonresidential buildings, the maximum achievable GM score is 155 points, while the minimum GM score is 50 points (BCA 2010a).

Table 3.2 Categories of the GMS and their corresponding GM scores

Categories		Point allocations
Minimum 30 points	Energy efficiency	87
Minimum 20 points	Water efficiency	14
	Environmental protection	41
	Indoor environmental quality	6
	Other green features: green features and innovations	7
Total points		155

For residential buildings, under the energy-efficient category, the maximum GM score of the building envelope is 15 points. The GM score of the building envelope is defined as a function of the ETTV as shown in Eq. (3.1).

$$\text{GM score of the building envelope} = 75 - (3 \times (\text{ETTV}_{\text{Res}})) \tag{3.1}$$

where $\text{ETTV}_{\text{Res}} \leq 25\,\text{W/m}^2$

The GM score of the building envelope accounts for a significant portion in achieving the Green Mark Awards as shown in Table 3.3. The highest award is the Green Mark Platinum Award for designs with 90 points or above. The remaining awards are the Green Mark Certified, Green Mark Gold, and Green Mark Gold PLUS Awards (BCA 2010a).

As can be seen in Eq. (3.1) where the GM score is a function of the ETTV_{Res}, it is imperative to investigate how this parameter can be calculated. Chua and Chou (2010b) defined the ETTV_{Res} as a measure of the average heat gain into the envelope of a building. This heat gain consists of three components; the heat conduction through opaque wall, the heat conduction through windows, and the solar radiation through windows. The formula in Eq. (3.2) presents these three portions in relation to the three components of the heat gain.

$$\text{ETTV} = \text{TD}_{\text{eq}}(1 - \text{WWR})U_w + \Delta\text{T}(\text{WWR})U_{\text{f}} + \text{SF}(\text{WWR})(\text{CF})(\text{SC}_{\text{f}}) \tag{3.2}$$

where

TD_{eq}	is equivalent temperature difference (°C)
ΔT	is temperature difference (°C)
SF	is solar factor (W/m^2)
WWR	is window-to-wall ratio
U_{w}	is total thermal transmittance of opaque wall (W/m^2 K)
U_{f}	is total thermal transmittance of fenestration system (W/m^2 K)
CF	is solar correction factor
SC_{f}	is shading coefficient of fenestration system

ETTV_{Res} can be calculated as shown in Eq. (3.3) (Chua and Chou 2010b).

$$\begin{aligned}\text{ETTV}_{\text{Res}} = {} & 3.4(1 - \text{WWR})U_{\text{w}_{\text{Heat conduction wall}}} \\ & + 1.3(\text{WWR})U_{\text{f}_{\text{Heat conduction window}}} \\ & + 58.6(\text{WWR})(\text{CF})(\text{SC}_{\text{f}})_{\text{Solar radiation and heat retention glass}}\end{aligned} \tag{3.3}$$

Table 3.3 Green mark awards

GM Score	Green mark awards
90 and above	Green mark platinum
85 to <90	Green mark gold plus
75 to <85	Green mark gold
50 to <75	Green mark certified

where

WWR is window-to-wall ratio (fenestration area/area of exterior wall)
U_w is total thermal transmittance of opaque wall (W/m^2 K)
U_f is total thermal transmittance of fenestration system (W/m^2 K)
CF is solar correction factor
SC_f is shading coefficient of fenestration system

According to Eq. (3.3), the $ETTV_{Res}$ is a function of the WWR, U_w, U_f, CF, and SC_f. The WWR represents the area of window over the total exterior area. The U_f and SC_f vary with types of windows, frames, and shading devices. The U_w and CF represent types of wall materials, and orientation and the pitch angle of fenestration components of a building, respectively (Singhaputtangkul et al. 2011a). If more than one type of material and/or fenestration is used, the respective term or terms shall be expanded into subelements as shown in Eq. (3.4).

$$\begin{aligned} ETTV_{Res} = {} & 3.4\left(\frac{A_{w1} \times U_{w1} + A_{w2} \times U_{w2} + \cdots + A_{wn} \times U_{wn}}{A_o}\right) \\ & + 1.3\left(\frac{A_{f1} \times U_{f1} + A_{f2} \times U_{f2} + \cdots + A_{fn} \times U_{fn}}{A_o}\right) \\ & + 58.6\left(\frac{(A_{f1} \times SC_{f1} + A_{f2} \times SC_{f2} + \cdots + A_{fn} \times SC_{fn})(CF)}{A_o}\right) \end{aligned} \tag{3.4}$$

where

A_{w1}, A_{w2}, A_{wn} are areas of different opaque walls (m^2)
A_{f1}, A_{f2}, A_{fn} are areas of different fenestration (m^2)
A_o is gross area of the external wall (m^2)
U_{w1}, U_{w2}, U_{wn} are thermal transmittance of opaque walls (W/m^2 K)
U_{f1}, U_{f2}, U_{fn} are thermal transmittance of fenestrations (W/m^2 K)
$SC_{f1}, SC_{f2}, SC_{fn}$ are shading coefficients of fenestrations

In the case where walls at different orientations receive different amounts of solar radiation, it is necessary to first compute the $ETTV_{Res}$ of individual walls. Subsequently, the $ETTV_{Res}$ of the whole building envelope is obtained by taking the weighted average of these values. To calculate the $ETTV_{Res}$ for the envelope of the whole building, the formula in Eq. (3.5) is suggested (BCA 2008).

$$ETTV_{Res} = \left(\frac{A_{o1} \times ETTV_{Res1} + A_{o2} \times ETTV_{Res2} + \cdots + A_{on} \times ETTV_{Res,n}}{A_{o1} + A_{o2} + \cdots + A_{on}}\right) \tag{3.5}$$

where A_{o1}, A_{o2}, A_{on} are gross areas of the external wall for each orientation (m^2).

SC of a fenestration system refers to the ability to control solar heat gain through the glazing. A high SC means high solar gain, while a low SC means low solar gain. The SC takes into account the effects of any integral part of the window system that reduces the flow of solar heat, such as multiple glazing layers, reflective

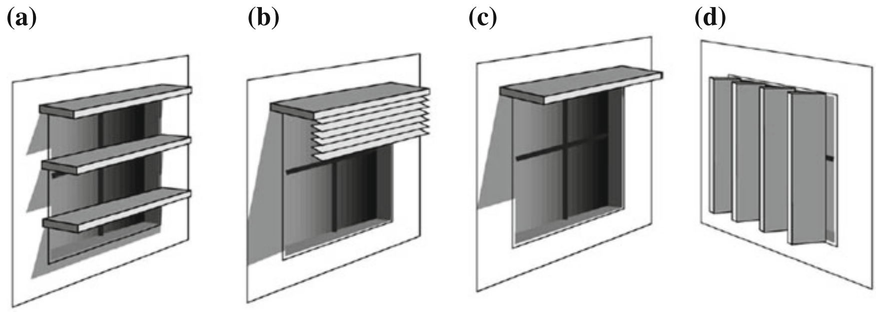

Fig. 3.2 Basic types of commonly found shading devices. **a** Horizontal shading device with horizontal projections. **b** Horizontal shading device with a blind. **c** Horizontal shading device. **d** Vertical shading device

coating, or blinds between layers of glass (Carmody et al. 2007). The SC_f of the fenestration system can also be affected if an external shading device is used as shown in Eq. (3.6) (BCA 2008; Chua and Chou 2010b).

$$SC_f = SC_{Glass} \times SC_{Shading} \tag{3.6}$$

where

SC_{Glass} is shading coefficient of glass

$SC_{Shading}$ is an effective shading coefficient of external shading devices

Notwithstanding the use of balconies, or inset windows to shade sun light, there are a number of basic types of commonly found shading devices as shown in Fig. 3.2a–d (TERI 2010). As the calculation of $SC_{Shading}$ for each type of the shading device is relatively different, to facilitate the calculation of the effective shading coefficient of external shading devices, only the horizontal type is considered in this book.

3.4 Buildability

Notwithstanding the concept of sustainability, buildability of a building also plays an important role in building design and construction. Buildability is defined as the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building (Low and Abeyegoonasekera 2001; Wong et al. 2006). Buildability relates to all aspects of a building project which enable the optimum utilization of construction resources. Benefits of buildability include lower costs of bidding, reduced site labor, increased cost effectiveness, and better resource utilization (Lam et al. 2007; Low and

Abeyegoonasekera 2001). Several factors have been proposed over the years for achieving good buildability such as simplicity of design details, ease in material handling, ease in construction, etc. (Wong et al. 2006). Importantly, to best achieve such benefits, these buildability considerations should be implemented in the early design stage (Fox et al. 2002; Nima et al. 2002).

In Singapore, buildability of a building is evaluated through buildable design appraisal system (BDAS) and constructability appraisal system (CAS) under the Building Control (Buildable Design) Regulations 2011 (BCA 2011a). The BDAS is applied to determine the buildability score of a building. Low (2001) studied the relationship between buildability and productivity based on actual data in Singapore. The positive relationship between productivity (m^2/man day) and overall buildability scores was observed with a correlation coefficient of 0.635. This suggested that building projects with higher buildable scores tend to achieve correspondingly higher productivity levels.

The BDAS requires all new building works, most of additions and alterations (A&A), and retrofit works with the GFA equal to or more than 2000 m^2 to meet a minimum buildability score for each category of building development. The total buildability score is 100 points for any category of building development. However, the minimum buildability scores for each category of the building development are different. Table 3.4 shows the example of the minimum buildability scores of new works in different building development types (BCA 2011a).

The buildability score is made up of three parts; namely buildability score of the structural system, buildability score of the wall system, and buildability score of other buildable design features. Equation (3.7) presents the formula for calculating the buildability score.

$$\text{The buildability score} = 50\left[\sum(A_s \times S_s)\right] + 40\left[\sum(L_w \times S_w)\right] + N + \text{Bonus points} \quad (3.7)$$

where

A_s is A_{sa}/A_{st}
L_w is L_{wa}/L_{wt}
A_s is percentage of total floor area using a particular structural system
A_{st} is total floor area which includes roof and basement area
A_{sa} is floor area using a particular structural system
L_w is percentage of total external and internal wall length using a particular wall system
L_{wt} is total wall length, excluding the length of external basement wall
L_{wa} is external and internal wall length using a particular wall system
S_s is labor saving index for structural system
S_w is labor saving index for external and internal wall system
N is buildability score for other buildable design features

Table 3.4 Minimum buildability scores of new works

Category of building work/development	Minimum buildability score		
	$2000\ m^2 \le GFA < 5000\ m^2$	$5000\ m^2 \le GFA < 25{,}000\ m^2$	$GFA \ge 25{,}000\ m^2$
Residential (landed)	60	65	68
Residential (nonlanded)	67	72	75
Commercial	69	74	77
Industrial	69	74	77
School	64	69	72
Institutional and others	60	66	69

The maximum buildability score is 100 points. The following explains the details of each component.

1. Buildability score of the structural system
   In this component, there are four different structural systems; namely precast concrete system, structural steel system, cast in situ system, and roof system. The buildability score for a particular structural system is the product of the percentage areas covered by the structural system and its corresponding labor saving indices. The maximum buildability score for this system is 50 points.

2. Buildability score of the wall system
   The wall system in the BDAS comprises different types of wall; namely curtain wall, precast concrete wall, precast concrete framework, precision blockwall, traditional brick/RC and plaster wall, cast in situ wall, cast in situ wall with prefabricated reinforcements, and brickwall. The buildability score for a particular wall system is a product of the percentage wall length covered by the wall system and its corresponding labor saving indices. The maximum buildability score for this system is 40 points. Table 3.5 shows the wall systems and their corresponding labor saving indices.

3. Buildability score of other buildable design features
   This section of the BDAS comprises three basic design characteristics including standardization of columns, beams, windows and doors, grids and usage of precast components. Points are awarded directly based on each type of design. The maximum buildability score for this system is 10 points. In addition, there is also another ten bonus points given to the use of single integrated components (BCA 2011a).

Low et al. (2008a) explored the relationships between BDAS requirements and TBP. It was found that achieving better TBP does not appear to show a significantly adverse effect on the buildability score. In practice, this allows building

Table 3.5 The wall system and its labor saving indices for calculating the buildability score

Wall system	Facing	Labor saving index
Curtain wall/full height glass partition	Full height glass partition	1.00
Precast concrete panel/wall	Skim coat	0.90
	Plastering	0.60
PC formwork	Skim coat	0.75
	Plastering	0.40
Cast in situ RC wall	Skim coat	0.70
	Plastering	0.40
Precision blockwall	Skim coat	0.40
	Plastering	0.10
Brickwall	With or without plastering	0.05

professionals to incorporate TBP guidelines without compromising on buildability. Singhaputtangkul et al. (2011a) further examined the relationships between the GM score and the buildability score by varying the WWR of a case study design from 0.151 to 0.510. Doing this influenced the GM score of the building envelope more strongly than the buildability score of the wall system.

Their study suggested that, as can be seen from Table 3.6, calculation of the buildability score is affected only when the wall types and their lengths are changed. In other words, calculation of the buildability score does take into consideration the change of the WWR when the wall types and their lengths remain the same. In response to this, as the WWR have a significant impact on buildability aspects of a building such as deliveries of materials or ease in construction, the building professionals in Singapore are recommended to consider several buildability aspects of the wall, window, and shading device additionally to achieve buildability in building envelope design and construction.

The CAS was launched by the Building and Construction Authority (BCA) of Singapore to measure the potential impact of downstream construction methods and technologies on the productivity at site under the Building Control (Buildability) Regulations (2011). The CAS results in a constructability score of the building works. While the BDAS focuses on the use of buildable designs during the upstream design process, the CAS aims to bring about the wider use of labor-saving construction methods and technologies that can help to reduce the demand for manpower on site. The CAS is a performance-based system with flexible characteristics that allow builders to adopt the most cost-effective solution to meet the constructability requirements (BCA 2011a). The minimum constructability score requirements apply to new building works with GFA equals to or greater than 5000 m^2. These also include building works consisting of repairs, alterations, and/or additions (A&A work) to an existing building if the building works involve the construction of new floor and/or reconstruction of existing floor for which their total GFA is 5000 m^2 or more. The minimum constructability score is shown in Table 3.6.

Constructability of building works is assessed in the areas of structural works, architectural, mechanical, electrical, and plumbing (AMEP) works as well as site practices. As structural works require the greatest manpower usage for building

Table 3.6 Minimum constructability scores of new works

Category of building work/development	Minimum constructability score	
	$5000\ m^2 \le GFA < 25{,}000\ m^2$	$25{,}000\ m^2 \le GFA$
Residential (landed)	40 (minimum 25 points from structural system)	50 (minimum 35 points from structural system)
Residential (nonlanded)		
Commercial		
Industrial		
School		
Institutional and others		

projects, and is usually along the critical path of construction, a switch to a more labor-efficient construction system for structural works is likely to bring about a direct improvement in site productivity. Besides structural works, manpower is also required for architectural works and M&E works. Hence, site productivity gains could be realized if builders were to embrace the greater use of efficient construction methods and technologies that reduce labor usage for these areas of works.

The computation of the constructability score for a project involves the summation of the constructability score attained for the structural component, AMEP component and the component on good industry practices. The total constructability score allocated under these three components is 120 points. The highest weightage is given to the structural component which is 50 % or 60 points of the total constructability score. The structural component of the constructability score focuses on the builder's choice of external access systems and formwork systems as these take up the bulk of the total manpower needed for structural works. The other 50 % of the constructability score is allocated to AMEP and Good Industry Practices, with 50 points given to the AMEP component and the remaining 10 points to the component on good practices. The CAS discourages the use of traditional external scaffold, but instead supports the use of self-climbing and crane-lift perimeter scaffold in building envelope construction. The CAS also promotes constructing the walls with paint or skim coat as external finish, and producing and distributing work manuals to show how wall installation, waterproofing, and window installation works should be done (BCA 2011a).

Based on the above literature review, the requirements governed by the GMS, BDAS, as well as CAS do not cover all important criteria expected by the stakeholders of a building. For example, the GM, buildability, and constructability scores are calculated without taking into account aesthetics, costs, or even durability of a design. As a result, compliance with these schemes may not guarantee satisfactions and success of a project. This seems to suggest that the building professionals cannot base selection of the building envelope materials and designs on meeting the minimum requirements of these schemes solely. This is because, as mentioned in Sect. 1.3, inadequate consideration of the key criteria may lead to several adverse impacts on a project such as delays, cost overrun, variations, and disputes. Singhaputtangkul et al. (2011a) therefore suggested that it would be better, if the designers could incorporate all key criteria at once in the early design stage to deliver more sustainable and buildable building envelope designs.

3.5 Identification of Criteria

As a comprehensive list of the criteria for the assessment of the building envelope materials and designs was not yet established, to compile a meaningful list of such criteria, extensive literature reviews and a pilot study were conducted. In this regard, the literature reviews suggested 30 related criteria. These criteria were then refined through the pilot study (see Appendix B) to 18 main criteria. Figure 3.3

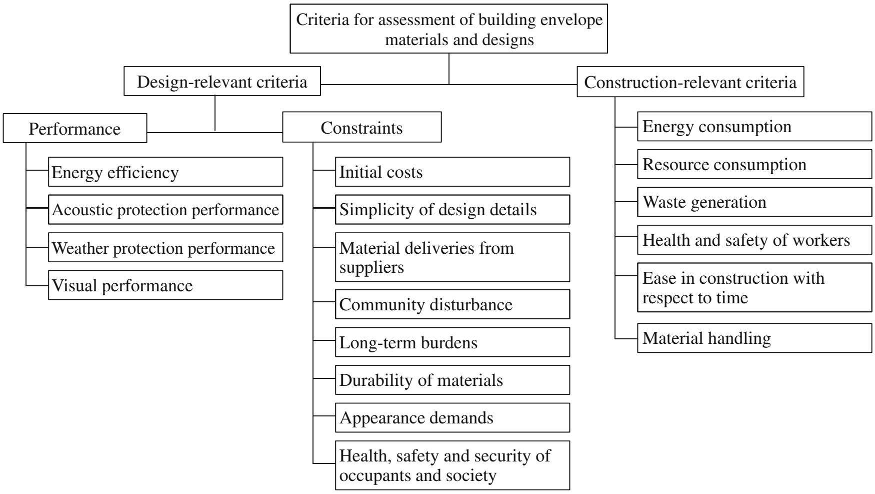

Fig. 3.3 Criteria for the assessment of the building envelope materials and designs

shows the design- and construction-relevant criteria structure suggested by Fischer and Tatum (1997) and Hanlon and Sanvido (1995), and the 18 criteria identified by this book which were arranged with respect to such structure.

Nevertheless, as can be seen, this structure does not seem to help the building professionals to realize the concepts of sustainability and buildability, so much; so these criteria should be regrouped to facilitate implementation of such sustainability and buildability concepts as suggested by the first objective of this book.

3.5.1 Energy Efficiency

Energy efficiency is an important feature in making a building design sustainable. This variable having an impact on the occupants of a building plays a vital role during the building occupation phase (Kibert 2008; Chua and Chou 2010a). Typical high-rise residential buildings consume most energy in their life cycles during this phase. The energy use of the buildings covers all living activities especially for both heating and cooling (Yu et al. 2008). This energy use is largely influenced by the capability of the building envelope to control heat gain and heat loss (Chua and Chou 2010b). In particular, it was reported that more than half of the total heat gain in buildings was typically contributed by their building envelope (Utama and Gheewala 2008). In this book, energy efficiency of the building envelope is represented by the GM score calculated by Eq. (3.5).

3.5.2 Acoustic Protection Performance

One of the most important performance mandates of a building relates to mitigation of unwanted noise by reducing unwanted sounds in the living and work environment to acceptable levels since high noise levels could create numerous adverse effects on the occupants (Bryan 2010). It was suggested the building envelope materials and designs account for a major portion to do so (Bryan 2010; Carmody et al. 2004). In this regard, the building professionals should evaluate for the acoustic insulating performance of the building envelope materials and designs and ensure that installation works are in accordance with relevant drawings, instruction manuals, and acoustic performance tests (Yang 2004; Low et al. 2008a).

3.5.3 Weather Protection Performance

The capability of the building envelope materials and designs to minimize weather impacts during the occupation phase of a building is one of the most important criteria expected by the occupants (Bryan 2010; Das 2008; Yang 2004). Supporting this, BCA (2004) reported that ingress of rainwater through the external wall systems and window systems is one of the most unacceptable problems for the occupants in Singapore. This suggests the building professionals that adopting appropriate joint designs and waterproof designs of the building envelopes plays a vital role in improving the weather protection performance of a building (Yang 2004).

3.5.4 Visual Performance

The visual performance of a building plays a vital role when the building professionals assess the building envelope materials and designs in the early design stage (BCA 2010a; Low et al. 2008c). In visual performance design, there are some general aspects that should be considered including: glare, visual transmission (VT), building envelope and building orientation, windows, and view and occupancy factors (Carmody et al. 2007; Nielsen 2002). Properties of the building envelope materials such as the length and shape of shading devices, and the visual transmission, diffusion and color of the window, and wall materials can affect this performance as a whole (WBDG 2012). It was noted that conscious assessment of the building envelope materials and designs may significantly enhance the visual performance of a building, providing better daylight management for the occupants (Low et al. 2008c).

3.5.5 Initial Costs

Initial costs of the building envelopes comprise their material costs and construction costs (Chen et al. 2010). The material costs seem to vary with project location, building design, construction method, availability of materials, as well as relationship with suppliers (Fryer 2004). In addition, these may sometimes relate to quantities of the materials purchased (Chua and Chou 2010a). The construction costs refer to labor costs, machine costs, expenses, and other relevant costs for completing the project (Fryer 2004). Collectively, the initial costs are one of the major considerations for the building professionals when assessing the building envelope materials and designs in the early design stage (Chen et al. 2010; Sadiq and Hewage 2011). The unit cost including the material and construction costs of the building envelope design is normally applied to represent the initial costs criterion (DLS 2010).

3.5.6 Simplicity of Design Details

Simplicity of design details in this book refers to repetition and standardization of the design (BCA 2011a). Adopting the building envelope materials and designs that show greater repetition and standardization of joint connections, waterproof designs, and overall designs benefits a project in several ways (Bryan 2010). For instance, doing this can reduce design time, improve the efficiency of materials handling in the fabrication shop, and accelerate site work, thus enhancing productivity of a project (Nethercot 1998). It was also found that simplified, flexible, and standardized design details can enhance communication with and between the manufacturer, design team, construction team, and service/inspection team (Tawresey 1991).

3.5.7 Material Deliveries from Suppliers

Maintaining the material delivery process to guarantee material availability for project tasks without the build-up of unnecessary inventory is a major challenge in managing a project (Gould 2005; Lapinski et al. 2006; Mantel et al. 2008). This is because material deliveries can greatly affect progresses of a project as some materials for construction are sometimes ordered either relatively late; leaving suppliers with uncertain ties, or too early; leading to buffering at site, thus affecting inventory and construction management. The main considerations of the material deliveries include relationship with suppliers, lead time in production and delivery, and quality of the materials delivered (Vrijhoef and Koskela 2000). These considerations should therefore be incorporated when the building professionals assess the building envelope materials and designs as early as possible.

3.5.8 Community Disturbance

Ofori (2000) found that construction site workers and residents of nearby homes experienced varying levels of annoyance with noise (from machinery such as piling machines, concrete pumps, and heavy vehicles), water (from discharge of silt, cement slurry, oil-based products and wastes) and air (from dust and smoke) pollution (from construction-related activities). Community disturbance during construction especially in the form of air pollution such as particulate matter and nitrous oxide from diesel exhaust can cause not only adverse health effects to people and but also adverse impacts on the surrounding environments (Chew 1999; Lim 1993). These problems appear to trigger the building professionals to focus on the minimization of environmental and community impacts of a project in the early design stage (Kibert 2008). The key considerations associated with this criterion are loading and unloading operations, lifting and installation techniques, as well as labor skill sets (Chew 2009).

3.5.9 Long-Term Burdens

Long-term burdens refer to two aspects: namely maintenance costs and ease in maintenance (BCA 2010b; WBDG 2012). Specifically, maintenance expenditure for high-rise buildings in Singapore has gone up significantly in the last 10 years (Das et al. 2010). The maintenance costs account for a major part of long-term burdens. These costs include cleaning, fixing, and replacement costs of building materials (Lacasse et al. 1997). Several studies suggested that the maintenance costs should be considered together with ease of maintenance to capture the actual burdens during the occupation phase faced by the occupants of a building (Das et al. 2010). Overall, the long-term burdens criterion seems to be a function of types of defects, their frequency of occurrence, seriousness of defects, and cleaning and repairing methods (Das 2008).

3.5.10 Durability

To a certain extent, durability of materials and their external finishes can be represented by service life in terms of functionality and appearance (Kneifel 2010). In general, materials that last longer, over a building's useful life, are more attractive than those that need to be replaced more often (Bryan 2010). There are various parameters that influence service life and appearance of building materials. Main parameters related to this criterion include joint designs, waterproof designs, types of defects, their frequency of occurrence, and seriousness of defects (BCA 2004, 2010b; Morrissey and Horne 2011). The durability criterion plays a vital role in the assessment of the building envelope materials and designs since it has a significant impact on satisfactions of the occupants (Kibert 2008).

3.5.11 Appearance Demands

Appearance demands, referring to the appearance demands of a developer as well as those reflected from the occupants and community on the building envelope of a building, seem to be influenced by several parameters, for instance location and orientation of a building, the design itself and, importantly, the building envelope materials (Brock 2005; Yang 2004). With this in mind, it is imperative for the building professionals to select the building envelope materials and designs that can represent the appearance demands of the developer, occupants, and community in a certain environment (Fazio 1989; Tzempelikos et al. 2007). To achieve this, the assessment has to incorporate the major appearance demands considerations especially style, image, and aesthetics (Bryan 2010).

3.5.12 Health, Safety, and Security of the Occupants and Society

It was found that type of the building envelope materials, design of the building envelopes, and quality of their construction works can heavily affect health, safety, and security of the occupants and society of a building; for example, window falling due to improper installation (BCA 2004; Brock 2005). Previous studies suggested that control of emissions from building materials and consumer products used in buildings is an important part of the policies and actions taken to protect both the occupants and public health from the adverse effects of indoor air pollution (Yu and Kim 2010). Apart from this, installation techniques of the building envelope materials, labor skill sets, fire resistance of the materials, types of defects, their frequency of occurrence, seriousness of defects, and cleaning and repairing methods of the materials and designs are among the most critical parameters affecting health, safety, and security of the occupants and society (Chew 2009; Das 2008).

3.5.13 Energy Consumption

Construction of a building requires intensive energy usage including electricity and diesel fuel used in construction-related activities (Kofoworola and Gheewala 2009). It was pointed out that energy usage during construction accounts for a significant amount of the life cycle energy consumption of a building (Adalberth 1997; Scheuer et al. 2003). In addition, energy consumption of residential buildings seems to vary with type of building materials (Monahan and Powell 2011; You et al. 2011). In the context of building envelope construction, overall energy consumption of a project during construction can be reduced by increasing repetition and standardization of the building envelope design, and selecting appropriate joint and waterproof designs as well as lifting and installation techniques of the materials (BCA 2011a; Bryan 2010).

3.5.14 Resource Consumption

Building envelope construction appears to consume several resources. These resources, besides the main building envelope materials, include water, chemicals, formwork materials, aggregates, sealants, plasters, and joints (Huberman and Pearlmutter 2008). The assessment and selection of the building envelope materials and designs have a great impact on resource consumption during construction of a project (Tsai et al. 2011). For example, it was found that a steel and glass building has its embodied water-footprint mainly on account of its materials, while onsite water use plays a major role in the case of a cast in situ reinforced concrete and brick building. This demonstrates that the resource consumption during construction affects overall project and construction management, and it is one of the factors that the building professionals should be aware of (Chen et al. 2010). The resource consumption criterion may be influenced by repetition and standardization of the building envelope design, joint and waterproof designs, and lifting and installation techniques of the materials (BCA 2011a; Bryan 2010; Chen et al. 2010).

3.5.15 Waste Generation

In recent years, organizations have paid higher attention to corporate environmental strategy, environmental impact assessments, ecological and land-management surveys and evaluations, and waste management (Tsai et al. 2011). Jaillon and Poon (2008) suggested that selecting appropriate building materials can significantly minimize waste generation during construction as well as promote the reuse and recycling of such materials. Main considerations regarding the waste generation criterion may include repetition and standardization of the building envelope design, joint and waterproof designs, and lifting and installation techniques of the materials and designs (BCA 2011a; Kibert 2008; Kofoworola and Gheewala 2009).

3.5.16 Health and Safety of Workers

The construction industry can be viewed as a hazardous industry in which fatal and nonfatal occupational injuries occur most frequently due to its unique nature (Tam et al. 2004). Hinze et al. (2006) observed that construction safety related to health and safety of workers has become more important because of the increasing workers' compensation insurance premiums that resulted from an increase in work injury-related medical costs and convalescent care. It was also found that applying suitable loading and unloading techniques, lifting and installation techniques, and labor skill sets can enhance the safety and health of workers during construction of the building envelopes (Chen et al. 2010; Sacks et al. 2009; Yang et al. 2003).

3.5.17 Ease in Construction with Respect to Time

Completing projects exactly on their assigned due-dates is considered a major objective for building professionals (Kanagasabapathi et al. 2010). Ease of materials, tools, and skills for construction plays an important role in doing this. It is associated with the buildability concept of using more labor-efficient designs and labor-saving construction methods to reduce the demand for manpower on site and construction time (BCA 2011a; Low et al. 2008a; Wong et al. 2006). Low and Abeyegoonasekera (2001) also suggested several benefits of applying this concept to enhance construction productivity. For example, while the construction process of cast in situ construction can be delayed by adverse weather or scheduling conflicts and is largely dependent on the skills of workers, the construction process of prefabrication can achieve up to 70 % time saving as compared to cast in situ construction (Chen et al. 2010).

3.5.18 Materials Handling

Materials handling is mainly associated with off-site access, onsite access, and storage of building materials (Chew 2009). Off-site access relates to routes from the source of the materials to the site, whereas onsite access implies internal access for deliveries of the materials within the site (Edward 1992). Storage of the materials refers to security and weather protection requirements in association of availability, type, and location of storage. Chew (2009) suggested that the building professionals should consider specific access and storage requirements for each type of building materials. This could be because each type of building materials appears to require relatively different types of loading and unloading techniques, storage areas, and weather protection methods. Importantly, taking the materials handling considerations into account in the early design stage would facilitate a smooth construction process (Fazio 1989).

3.6 Summary

This chapter reviewed the impacts that the building envelope materials and designs have on the TBP. The book found that the building envelope materials and designs largely affect the visual, thermal, building integrity, and acoustic performances of a building in the early design stage. These four performances thus are part of the criteria for the assessment of such materials and designs. After introducing the concepts of sustainability and buildability and main sustainability and buildability schemes implemented in Singapore, the book suggested that these regulations do not cover all key criteria expected by the stakeholders of a building. At the same time, meeting the minimum requirements of these schemes may not guarantee satisfactions of the stakeholders. In response to these, a more comprehensive set of the criteria for the assessment of the building envelope materials and designs should be considered by the building professionals.

Based on the literature review and pilot study, this chapter presented the 18 major criteria for the assessment of the building envelope materials and designs which were arranged into the design-relevant and construction-relevant criteria structure suggested by previous studies. However, this structure does not seem to support the building professionals to realize the concepts of sustainability and buildability. There seems to be a need to regroup the criteria as suggested by the first research objective of this book.

Chapter 4
Building Envelope Materials and Designs

4.1 Introduction

This chapter reviews the knowledge of the building envelope materials and designs to be stored in the KM-M and KM-R of the KMS. The chapter begins by introducing key elements of high-rise residential buildings (Sect. 4.2). Following this, important technical standards and good practices in Singapore with respect to design, delivery, handling and construction, and maintenance stages for development of the building envelope (Sect. 4.3) are highlighted. In particular, the book discusses these in regard to external walls (Sect. 4.3.1), windows (Sect. 4.3.2), and shading devices (Sect. 4.3.3). Subsequently, the chapter presents the building envelope design alternatives considered in this book (Sect. 4.4).

4.2 Key Elements of High-Rise Residential Buildings

Rapid economic growth over the past few decades has drawn an unprecedented explosion in residential building development (Goh 1996; Chew 2009). To meet an urgent need due to the increasing population and land scarcity, high-rise residential buildings have been constructed in central areas of large cities around the world (Chew 2009). Key components of high-rise residential buildings include foundation, structural floors and walls, roof, and envelope systems. The function of a foundation is to transfer the structural loads from a building safely into the ground. The building's stability depends on the behavior under load of the soil on which the building rests, and this is affected partly by the design of the foundation and partly by the characteristics of the soil. The design and construction of foundation systems can also influence the nature and strength of the materials to be used for the foundations (Bryan 2010; Chew 2009).

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The structure of high-rise residential buildings may be visualized as floor framing supported by columns, beams, and core walls. The floor systems can be in the form of cast in situ flat plate and precast slab. These floor systems allow the buildings to have a beamless structure with predominantly a flat ceiling. Core or shear walls, which are responsible for the overall stability of the building, such as staircase wall, lift core wall, and household shelters, are usually constructed using cast in situ reinforced concrete (RC). Prefabrication of these cores is possible and feasible in the form of three dimensioned elements, namely L shaped, U shaped, and Box shaped. In addition, proper connections need to be designed to achieve structural continuity required for lateral stability of the building structure (BCA 2006; Bryan 2010).

Next, the roof forms the top part of the building to protect the building interiors. Most high-rise residential building roofs are of the flat type suitably used for maintenance and service areas including water storage tanks, cooling towers, lift motor rooms, photovoltaic panels, etc. The last component is the envelope systems. This component serves the function of weather and pollution exclusion, and thermal, sound insulation, and so on. The envelope systems should be designed to provide adequate strength, stability, durability, fire resistance, aesthetics appeal, etc. (Chew 2009).

4.3 Building Envelope Materials

It has been found that the assessment and selection of the building envelope materials play a very important role in the design and construction of a building project (Bryan 2010; Chua and Chou 2010a; Singhaputtangkul et al. 2011b). This is because adopting different types and properties of the building envelope materials can affect not only the performance of a building but also planning and management of a project during different project phases (Carmody et al. 2007; Gould 2005; Wang et al. 2006). This book classifies the building envelope materials into three categories; namely external wall, window, and shading device.

4.3.1 External Wall

The external walls protect the interior spaces from the surrounding environment. Decisions concerning the exterior walls usually have an impact on aesthetics, total building performance, durability, and costs of a building project (Brock 2005). In general, the external walls serve two functions; namely nonload-bearing wall and load-bearing wall. The load-bearing walls function to resist and transfer loads from other elements. These walls cannot be removed without affecting the strength or stability of a building. On the other hand, simply used to enclose the space, the nonload-bearing walls are used only to support its own weight; however, if these form the external walls, the walls should be able to resist the wind force blowing against the building (Levy 2001).

The structural form of most high-rise residential buildings is normally built in the form of a center-cored building or skeletal frame building using a framework to support the building. The walls are attached to the frame, thus forming an external envelope. This encourages the use of nonload-bearing walls as the external walls or façade. With this consideration, the external building envelope walls in this book are restricted only to the nonload-bearing walls. This book concentrates on six basic external wall types; namely precast concrete cladding wall, infilled clay brickwall, precision concrete blockwall, cast in situ RC wall, fixed-glass wall, and full-glass curtain wall.

4.3.1.1 Precast Concrete Cladding Wall

Precast concrete cladding walls offer a wide range of shapes, colors, textures, and finishes in design. Precast concrete panels are typically used to enclose the space of high-rise residential buildings (Bryan 2010). The panels have many built-in advantages when it comes to saving energy and protecting the building from the outside environment (Chew 2009). With the advancements in precast technology, precast concrete elements can be manufactured with relatively straightforward repeated process, in different forms and finishes, to meet the rising expectation for faster construction and better quality buildings (BCA 2006). This section highlights the salient points that should be considered in the design, delivery, handling and construction, and maintenance phases of precast concrete walls.

Design

The design of precast concrete elements involves understanding the method of fabrication, implicit constraints, as well as various aspects that facilitate the erection and assembly of these elements on site. Important guidelines for the design of precast concrete elements can be found in Singapore Standard (SS) EN 1992-1-1: 2008 (Eurocode 2: Design of concrete structures part 1), SS EN 1992-1-2: 2008 (Eurocode 2: Design of concrete structures part 2), and CP 81: 1999 (Code of practice for precast concrete slab and wall panels). To achieve good quality precast concrete elements, it is imperative to consider the following aspects during the design stage: dimensions and shape of precast elements, concrete constituents, joints and connections, reinforcement, and lifting and handling devices (BCA 2010d).

It is noted that optimal dimensions of precast elements largely depend on the capacity of the lifting cranes at the fabrication yard and site as well as the transportation limitations. It is a good practice to design for the largest possible size to minimize jointing and handling. Considering the concrete constituents, depending on the design requirements, a variety of concrete strengths and characteristics can be used to achieve the optimum performance required of the precast concrete elements. Apart from the concrete constituents, precast concrete elements are often reinforced using welded wire meshes. Bars or prestressing tendons must be designed to achieve the required structural strength. These are required to be designed to meet the crack control criteria. Other relevant standards for precast panel design include SS 32: 1999 (Welded steel fabric for the reinforcement of concrete) for weld wire mesh, SS 2: 1999 (Steel for the reinforcement of concrete) for steel reinforcement, and SS 475: 2000 (Steel for the prestressing of concrete).

Delivery

Delivery of precast concrete elements should be planned according to the general erection sequence to minimize unnecessary site storage and handling. It is also desirable to transport the elements in a manner where these can be lifted directly for erection or storage without much change in orientation and sequence. Precast concrete elements should be loaded and delivered with proper supports, frames, cushioning, and tie-downs to prevent in-transit damage. Adequate packing or protection to the edges of precast elements should also be provided to minimize risk of damage during transit. The manner of delivery depends on the type, dimension, and weight of precast elements. Protective measures such as the use of cushion packing or polythene wrapping may be used to minimize damage to precast concrete elements (BCA 2010d).

Handling and construction

The handling process of precast concrete elements mainly involves loading and unloading operations, and erection of these elements at the job site. The storage area provided in the yard and job site should be adequate to permit easy access and handling of the precast elements. The area should be relatively level, firm, and well drained to avoid any differential ground settlements which may damage the stored elements. Precast concrete panels are usually stored in a vertical position supporting their own weight using racks with stabilizing wall. To minimize handling, the panels should also be stored based on the erection sequence (BCA 2010d). Different sets of lifting points and cast-in devices have to be used for various handling stages. It is therefore essential to ensure that precast concrete panels are handled in a way that is consistent with their shapes and sizes, to avoid excessive stresses or damages.

For construction, precast concrete panels can either hang from or sit on the frame. This choice is often based on the height of the panel. If the panel is of full-storey height spanning from beam to beam, it is more stable if it is hung from above with a bottom fixing to align and restrain the panel. If the panel is designed to cover the beam edge, perhaps from the window head below to the window sill above, it is desired to sit on the beam. The supports and restraints have to transfer not only the loads, but also allow adjustments to maintain its position, line, level, and plumb of each panel with the adjoining panel and across the whole façade (BCA 2004; Bryan 2010).

Joint details of precast walls are mainly required horizontally between the floor and the wall panels and vertically between the wall panels. In addition, waterproofing details of these joints must be adequately provided to pre-empt water ingress. For the vertical joints, these are mainly designed to be cast in situ with similar sealant and backer rod details for water-tightness. As for external surface finishes, there is a tendency to adopt simple, paint finish for high-rise residential buildings. If precast walls are constructed with good alignment and surface condition, their external surface finishes generally consist of a thin layer of skim coat to fill out minor voids/surface imperfections.

Maintenance

There are many types of defects associated with precast concrete walls. One of these is cracks. Cracks typically occur during the initial lifting due to friction between the elements and the casting mould forms, or during erection due to poor planning. Thus, there is a need to ensure proper curing method, proper handling techniques, and sufficient lifting points (BCA 2010d).

Chew and Silva (2004) reported that wall dampness, plaster crack, crazing, plaster delamination, biological growth, staining, paint peeling, paint crack, blistering, discoloration, and chalking can also be found on precast concrete walls. In Singapore, cleaning and surface repair of external walls including the precast walls should follow SS 509-1: 2005 (Code of practice for cleaning and surface repair of buildings: Cleaning of natural stones, brick, terracotta, concrete, and rendered finishes) and SS 509-2: 2005 (Code of practice for cleaning and surface repair of buildings: Surface repair of natural stones, brick, terracotta, and rendered finishes).

4.3.1.2 Brickwall

Another basic material type of the external walls is clay brickwall. Clay brickwall is normally used in brick masonry construction. Bricks may be made from burnt clay or concrete. These are intensively used in the local industry (WBDG 2012).

Design

Clay bricks used for the external walls should be solid, or with a frog. Their average dimensions are 65 ± 1.875 mm height, 102.5 ± 1.875 mm width, and 215 ± 3 mm length. These should possess a minimum compressive strength of 20 MN/m^2 for nonload-bearing walls. Moisture expansion in bricks may cause cracks to develop in the mortar joints or plaster. These cracks are potential paths for water seepage.

According to SS 103: 1974 (Specification for burnt clay and shale bricks), the average water absorption of common bricks should be laboratory tested to be not more than 2 % by mass after immersion in cold water for 24 h. It is also governed by CP 82: 1999 (Waterproofing of RC buildings) that sand used for external plastering should not contain silt content in excess of 5 % in mass in order to reduce shrinkage (BCA 2004).

Delivery

Clay bricks are usually delivered in packs or pallets. These should be transported with appropriate packing and protective measures (Chew 2009).

Handling and construction

Clay bricks can be offloaded by crane-mounted vehicles, forklift, dumper, crane hoist, or elevator. Clay bricks should be stored in selected stockpiles adjacent to their place of use (Chew 2009). Clay bricks should be placed on a prepared base of hardcore, and stacked above ground on pallets. It is also important to cover the stack from rain and rising damp and to avoid contact with soluble salts or sulfates (BCA 2004).

For constructing of clay brickwalls, main concentration should be given to the jointing processes. Cement mortar joints of clay brickwalls are relatively more porous and are, hence, more susceptible to water seepage than the bricks. The type of mortar bedding selected can have a considerable effect on its bonding strength and workability, which in turn affects the water-tightness of the joints. Rendered brickwalls give better rain resistance than fair-faced brickwalls. Consequently, it is imperative to select the appropriate mix ratio, thickness, and number of coats to minimize cracks in the rendering. Constructing concrete kerbs of at least 100 mm high for external brickwalls at every storey has shown enhancement in their water-tightness (BCA 2004; Chew 2009).

Where brickwalls abut a concrete member, bonding bars should be provided at the joints to minimize cracks at these locations. This can be achieved by securing bonding bars to the concrete member. Alternatively, these bars could be cast together with the concrete member. Some bonding bar systems come with a lipped frame that is fastened to the concrete member. The lipped frame allows greater flexibility in positioning the bonding bars to facilitate brick-laying. As a good practice, the bonding bars should be of a minimum length of 200 mm and installed at every fourth course of the brickwall. To distribute stress and prevent plaster cracks at the interfaces between dissimilar materials, for example, between brick and concrete member, a layer of mesh reinforcement should be applied (BCA 2004). Furthermore, external finishes of brickwalls usually consist of plaster and paint. The total thickness allowed for the plaster including all coats is limited to 25 mm (BCA 2004).

Defects and maintenance

The types of defects found in brickwalls are generally associated with external finishes. Chew and Silva (2004) suggested that the defects usually found in plaster and paint systems are peeling, staining, and paint cracks, while the defects in relation to exposed brickwalls include cracks, dampness, and efflorescence. Maintenance activities for brickwalls are primarily related to seriousness of each defect. Again, cleaning and surface repair of brickwalls should follow the SS 509-1: 2005 and SS 509-2: 2005.

4.3.1.3 Concrete Blockwall

Precision concrete blocks refer to hollow concrete blocks made from a mixture of Portland cement and aggregates under controlled conditions. In general, concrete masonry units are typically made in forms to the desired shape and then pressure-cured in the manufacturing plant. These units are based on weight categories; namely lightweight, normal weight, and heavyweight. This book emphasizes on the lightweight units. Since these units are larger than the clay brick units, the construction time required for laying the units tends to be less than that for bricks. Precision concrete block units can be solid or hollow with two or three cores, as well as solid or flanged ends (WBDG 2012).

Design

In Singapore, design and construction of concrete blockwalls should comply with SS 271: 1983 (Concrete masonry units for nonload-bearing applications). The concrete commonly used to make concrete blocks is a mixture of powdered Portland cement, water, sand, and gravel. This produces a light gray block with a fine surface texture and high compressive strength. Lightweight concrete blocks are made by replacing the sand and gravel with expanded clay, shale, or slate. Expanded clay, shale, and slate are produced by crushing the raw materials and heating them. The units can be moulded to various dimensions. In general, these have face dimensions of 390 × 190 × 90 mm (Das 2008).

Delivery

Delivery of precision concrete blocks is similar to that of the clay bricks. Fundamentally, concrete block materials should be protected to maintain quality and physical requirements during both transport and storage (Chew 2009; Das 2008).

Handling and construction

All masonry units should be stored on the jobsite and protected from rain by storing off ground and keeping them clean from contamination. This is to prevent the units from being soaked with water (Chew 2009; Das 2008). Construction of concrete blockwalls is relatively similar to that of clay brickwalls in that considerable attention is given to jointing processes. For jointing concrete blocks, mortar is applied to both the header face and the face edge. Unlike bricks, concrete blocks are hollow and mortar should be placed carefully on top of the block. Time can be saved by placing several blocks on the ends and applying mortar to the vertical faces in one operation. Each block is then placed over its final position and pushed downward into the mortar bed and against the previously laid block to obtain a well-filled vertical (Das 2008). In many events, where the concrete blocks need to be cut, the cut must be neat and performed with a power-driven saw (Das 2008). Furthermore, typical external finish of blockwalls is plaster and paint finish.

Defects and maintenance

The most frequent maintenance activity for concrete blockwalls is the regular replacement of sealant in expansion joints, perimeter of openings and at wall flashings. The time frame for sealant replacement depends on the sealant used and usually ranges from every 7 to 20 years. Defects of the precision concrete blockwalls with skim coat and paint finish usually include cracks, wall dampness, biological growth, staining, paint peeling, paint cracks, etc. The repair method for the walls is dependent on seriousness of each defect (WBDG 2012). In addition, cleaning and surface repair of blockwalls should follow the SS 509-1: 2005 and SS 509-2: 2005.

4.3.1.4 Cast in Situ Reinforced Concrete (RC) Wall

A cast in situ RC wall system is an exposed structural system that also serves as the façade.

Design

Constituent materials of cast in situ RC walls should satisfy the durability, structural performance, and safety requirements by taking into consideration the environment to which it will be subject to. Common types of cement used in concreting should comply with the SS EN 1992-1-1: 2008 and SS EN 1992-1-2: 2008. The exposure conditions of the concrete, whether there are other special requirements, should be considered in the selection of the cement type. For example, concrete made with Portland cement is not recommended for use in acidic conditions (BCA 2004).

Aggregates can be grouped into fine, coarse, and lightweight categories. For most common types of works, aggregates of 20 mm size are suitable. For thin concrete sections with closely spaced reinforcement or thin cover, aggregates of maximum 10 mm nominal size are used. Admixtures such as super-plasticizers, water-reducing agents, and accelerators may be added to serve its intended use. Admixtures selected should not impair the concrete durability or increase the corrosion of steel reinforcement consisting of steel bars, welded wire fabric, or wires. For normal RC, common types of reinforcement bars shall comply with SS 2: 1999 (Specification for steel for the reinforcement of concrete) with grades of the RC normally ranging from C30 to C50. This grade indicates the compressive strength of concrete after 28 days of curing (BCA 2004).

Delivery

The concrete can be prepared on site or delivered from suppliers. Due to quality concerns, ready mixed concrete is recommended. In the BDAS, higher labor saving indices are given for the use of prefabricated reinforcement cages in cast in situ components, and precast formwork panels with concrete infill (BCA 2004).

Handling and construction

Cast in situ RC walls are generally watertight, unless cracks are formed in the walls or at the joints between different elements. Cracks could be formed as a result of poor concrete quality, poor workmanship and/or unfavorable environmental factors. To ensure water-tightness at the joints between RC−RC members, several preparatory works should be carried out before subsequent pour of concrete. Some of these are to roughen the joint surface while the concrete is still green, and to remove laitance at the joint surface (BCA 2004).

Another main feature in casting the RC walls is to achieve alignment and verticality of the cast in situ RC walls. In doing so, it is essential to ensure that the formwork is in a good condition, and proper bracing and strutting coupled with thorough checks on plumb and alignment before casting are promoted. For the cast in situ RC walls that require plastering, proper bonding and keying are important in ensuring good adhesion of the plaster to the RC substrate. Importantly, a spatter-dash coat of 3–5 mm thick should be applied for better bonding with the plaster (BCA 2004).

Defect and maintenance

Durability of concrete and resistance to deterioration is dependent on proper design and good workmanship. A mix design for durable replacement concrete should utilize materials similar to those of the original concrete mix. Good workmanship leading to proper mix, placement, and curing procedures can enhance durability of the wall (WBDG 2012). Similar to the other types of external walls, the defects of a cast in situ RC wall with plaster and paint are typically associated with cracks, wall dampness, plaster cracks, plaster delamination, biological growth, staining, paint peeling, etc. However, repairs of a cast in situ RC wall require more preparation processes. The repair method of the walls depends on seriousness of their defects (Chew and Silva 2004). General guidelines for cleaning and surface repair of concrete walls in Singapore can be found in the SS 509-1: 2005 and SS 509-2: 2005.

4.3.1.5 Summary of External Finish Elements of Opaque Walls

Table 4.1 summarizes the external finishes, thickness of different opaque external walls, and their corresponding *U*-values.

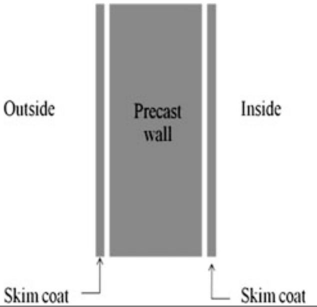
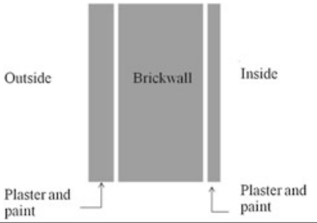
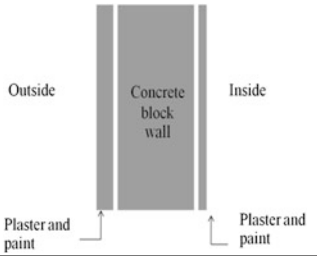
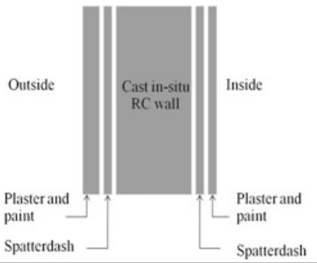
4.3.1.6 Glass Curtain Wall

Glass curtain wall is a lightweight external wall system hung on the building structure. It is a nonload-bearing external wall with its dead weight and wind loading transferred to the structural frame through anchorage points. Its flexibility allows designers to create striking designs for new buildings and refurbishment of old buildings. The reduction in weight leads to savings in structure and foundation costs. Coatings on glass panels can enhance the thermal insulation of curtain walls (BCA 2007; Bryan 2010; Chew 2009). Glass curtain walls can be used with aluminum and granite panels with backpans and insulation in spandrel areas. The panels can be preassembled under strict quality control and can incorporate architectural and solar control elements such as shading, lighting, light shelves, and blinds. The use of modular and standardized panel sizes appears to speed up the fabrication and keep the cost down (Bryan 2010; Chew 2009).

Design

Curtain wall is a system based on a structural framework, consisting of vertical mullions and horizontal transoms, connected to the building structure, spanning a storey height connected to the edge beam or the edge slab. Mullion sizes vary with different designs. Transom sections, based on the same profile as the mullion, but normally not so deep, are fixed to the mullions to form a series of glazable openings and stiffen the mullions against distortion under wind loading. The transoms and mullions are designed to receive glazing directly. This does not however have to be transparent glass but could be any panel, such as a granite panel, that mimics the edge of a glazing unit (Bryan 2010). Importantly, in Singapore, design and construction of curtain walls should follow CP 96: 2002 (Code of practice for curtain

Table 4.1 Summary of external finish elements

Wall	Cross-section	Thickness	U-value[a]
Precast cladding wall		5 mm skim coat + 100 mm precast panel + 5 mm skim coat	3.50
Clay brickwall		20 mm plaster and paint + 100 mm brick + 12 mm plaster and paint	2.87
Concrete blockwall		20 mm plaster and paint +100 mm concrete block + 12 mm plaster and paint	3.77
Cast in situ RC wall		20 mm plaster and paint and spatter dash + 100 mm concrete block +12 mm plaster and paint and spatter dash	3.66

[a]The calculation applied to determine U-value can be found in BCA (2008)

walls). This code specifies the criteria for performance and evaluation, and also gives guideline for good practices of a curtain wall system.

While it is possible to design curtain walls using many materials, the most commonly used material is aluminum. Another important system that should be incorporated into the curtain wall design is the pressure equalization system. The principle of the pressure equalization system is through eliminating the pressure difference at the level of the external joint (Chew 2009). The next principle is to design movement joints of curtain walls to have sufficient tolerance for thermal movement, live and dead load deflection, wind load, and possible ground movement (BCA-SIA 2005). In addition, curtain walls can be categorized into two groups by the way these are assembled; namely stick and unitized systems.

The stick system refers the system that its elements have to be installed on site. In contrast, the unitized system refers to the system that their panels including windows are factory assembled. As such, the unitized system requires less site work and ensures improved seal installation (Das 2008).

Delivery

Curtain wall elements of the stick system can be purchased from different suppliers, and these can be delivered in different packages. On the other hand, curtain wall elements of the unitized system are usually ordered from one supplier. The delivery processes of the curtain wall usually involve assembly, glazing, sealing, packing, loading, unloading, and dispatching (Choi 2006).

Handling and construction

Generally, installation method of curtain walls involves many factors, such as the type of system, module width and height, weight of material, site access, duration, height of building, etc. (Li 2003). One of the techniques of lifting a unitized curtain wall panel is to apply a mini crane for installing a prefabricated unitized curtain wall panel of about 1.8 m width by 4 m height (Smart-rig Cranes 2011).

Connections of curtain walls to the building frame coupled with allowance for movement and adjustment to achieve the required accuracy in alignment have to be considered. These connections are relatively straightforward with the use of either cast-in anchors or brackets secured to the floor to receive the mullion sections at each storey height (Bryan 2010; Chew 2009). Importantly, only the approved contractors registered with the BCA under the Regulation Workhead (CR16) can supply, install, and retrofit curtain wall systems in Singapore (BCA 2012).

Defect and maintenance

The types of defects usually found in curtain walls are cracks, sealant failure, sealant staining, dirt staining, as well as water seepage (Chew and Silva 2004). Curtain walls and perimeter sealants require maintenance to maximize the service life of the curtain walls. Perimeter sealants, properly designed and installed, have a typical service life of 10–15 years, although breaches related to perimeter sealants are likely to occur from day one. While removal and replacement of perimeter sealants may require meticulous surface preparation and proper detailing, painted or anodized aluminum frames seem to require only periodic cleaning. Meanwhile, as anodized aluminum frames cannot be reanodized in place, these can be cleaned and protected by proprietary clear coatings to improve appearance and durability. Furthermore, it is a good practice to regularly inspect and repair glazing seals and gaskets to minimize water penetration (WBDG 2012).

4.3.2 Window

Window in this book refers to the operable glazing window. However, this section also discusses the fixed-glass wall as the operable glazing window and fixed-glass wall share several common design, construction, and maintenance aspects. Overall, selecting and assessing windows require various considerations such as appearance, energy performance, human issues, technical performances, as well as costs. The appearance of the window glazing types and window frames are not as less important as their technical considerations. The way a window looks can sometimes override all other technical and cost considerations (Carmody et al. 2007; Yu et al. 2008). As mentioned in Chaps. 2 and 3, lack of consideration on a holistic set of important criteria may lead to numerous problems related to project performance and management. This section reviews four important aspects for assessing window materials with respect to the design, delivery, handling and construction, and maintenance phases of a project.

4.3.2.1 Design

On the technical side, the energy performance in terms of the capability to transfer heat is one of the most important selection criteria for the assessment of the building envelope materials. Heat flows through a window assembly in three ways: conduction, convection, and radiation. Conduction happens when heat travels through a solid material. Convection is the transfer of heat by the movement of gases or liquids. Radiation is the movement of heat energy through space without relying on conduction. When these mechanisms of heat transfer are applied to the performance of windows, they interact in complex ways. Thus conduction, convection, and radiation are not typically discussed and measured separately (Carmody et al. 2007; Muneer et al. 2000). The following subsections briefly present fundamentals of single-layered and double-layered window glazing types with low-Emissivity (E) coating.

Single layer window glazing

Relative to all other glazing options, clear single layer window glazing allows the highest transfer of energy. This property can be improved by tinting. Tint not only absorbs a portion of the light and solar heat, but also changes the color of the window and can increase visual privacy. The primary uses for tinting are to reduce glare from the bright outdoors, and to reduce the amount of solar energy transmitted through the glass. Tinted glazing is specially formulated to maximize its absorption across some or the entire solar spectrum. All of the absorbed solar energy is initially transformed into heat within the glass, raising the glass temperature. While the tint has no effect on the *U*-value, it often forces a tradeoff between visible light and solar gain. For instance, forming bronze- or gray-tinted glass may develop a greater reduction in visible transmittance than that in the SC (Carmody et al. 2007).

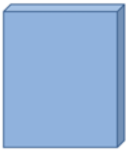
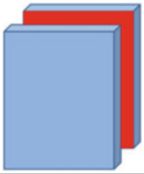
For windows where daylighting is desirable, it seems to be more satisfactory to use a spectrally selective tint or coating along with other means of controlling solar gain. In addressing the problem of reducing daylight, the manufactures have developed high-performance tinted glass that is sometimes referred to as spectrally selective. This glass preferentially transmits the daylight potion of the solar spectrum but absorbs the near-infrared part of sunlight. The glazing has a light blue or light green tint and visible transmittance values higher than conventional bronze- or gray-tinted glass, but lower SC. However, there are practical limits on how low SC can be made using tints. If larger reductions are desired, a reflective coating can be used to lower the SC by increasing the surface reflectivity of the material. These coatings usually consist of thin metallic layers and can be applied to either clear or tinted glazing (Carmody et al. 2007; Muneer et al. 2000).

Double -layered window glazing

Consisting of inner and outer layers of glass separated by an air gap, double-layered window glazing improves the insulating value of the glazing as compared to the single glazing. Double-pane units can be assembled by using different glass types for the inner and outer layers. Typically the inner layer is standard clear glass, while the outer layer is bronze- or gray-tinted glass. In this case, compared to a clear double glazing unit, the SC and visible light transmission are reduced due to the tinted layer. In contrast, double glazing with a high-performance tint can reduce SC to below that of bronze or gray tinted, but it has a visible transmittance closer to clear glass. The heat transfer could also be reduced by altering or replacing the air in the gap by other gases and by changing the types of coating, for example, to low-E coating (Carmody et al. 2007; Muneer et al. 2000).

Coating a glass surface with a low-E material and facing that coating into the gap between the glass layers block a significant amount of radiant heat transfer, thus lowering the total heat flow through the window while maintaining high levels of light transmission. Apart from the low-E coating, filling the space between the glass layers with a lees conductive, more viscous, or slow-moving gas can also minimize the convection currents within the space. Thermal resistance is increased with argon and krypton gases fills, reducing winter heat loss, and summer heat gain through conduction without influence on visible transmittance of the window unit (Carmody et al. 2007; Muneer et al. 2000).

Table 4.2 Specifications of different window glazing materials

Types of the window glazing	Single clear	Single clear Low-E	Double clear	Double clear low-E
				
Total thickness (mm)	6	6	18	18
U_w(W/m^{2}K)	5.678	4.053	3.577	2.668
SC	0.80	0.75	0.70	0.33
VT	0.70	0.6	0.63	0.55
STC	32	32	36	36

In considering a window frame, selecting window frame materials relies on the physical characteristics of windows such as operating types, thickness, weight, and durability. As a sash and window frame can represent 10–30 % of the total area of the window unit, the window frame can also have a major impact on the thermal performance of the window unit. Aluminum is one of the most common residential window frame materials used because it is light, strong, durable, easily extruded into complex shapes, and readily fitted with different types and materials for the window glazing, but it has high thermal conductance. The most common solution to this problem is to provide a "thermal break" by splitting the frame components into interior and exterior pieces and using less conductive materials to join these (BCA 2010b; Carmody et al. 2007). Table 4.2 shows specifications of different window glazing materials with aluminum thermal break frame.

In addition, operable windows can be classified into four main types based on how these are opened: namely side-hung, sliding, top hung, and louvers. The side-hung window has a fixed range of opening usually up to 90°. It can be fully opened of aperture unobstructed. The operable panel may be used as a wind scoop to direct wind through the window. However, the size and hardware used need to consider the distance needed to close the window. The sliding window has a limited range of opening usually up to 50 % of aperture size. Tracks at base and head are difficult to effectively seal while keeping the window operable with high air infiltration and poor acoustic performance. The top-hung has a fixed range of opening usually up to 90° but typically limited for safety reason to a 150 mm opening. Although, it is typically less effective for ventilation, its blades can provide partial protection from rain. The louvers window has a wide range of opening. It blades appear to direct air flow into the space. However, it tends to obstruct view, requires more complex mechanisms for installation and is prone to air leakage (BCA 2010b).

It is also worthwhile to mention that the Building Control Regulations (2007) stipulated that the design and installation of window glazing and frame shall at least meet SS 212: 2000 (Specifications for aluminum alloy windows) (BCA 2010c). In addition, types and quality of the window glazing should comply with Singapore and international standards, particularly, BS 952: 1995 (Glass for glazing: Classification and terminology for work on glass) and SS 341: 2001 (Safety glazing materials for use in buildings). Insulated glazed units shall comply with BS 5713: 1979 (Specifications for hermetically sealed flat double glazing units), whereas accessory stainless steel shall comply with BS EN 10088: 1995 (Stainless steels: List of stainless steels, and technical delivery conditions for sheet/plate and strip for general purposes) (BCA 2010c).

4.3.2.2 Delivery

Before delivery, windows and their components should be fully protected to ensure that these components remain in good condition until ready for installation. All required accessories, including friction stays, handles, locking devices, fixing, etc., should be delivered together with the main components. These could be packed in either steel pallets or skids.

4.3.2.3 Handling and Construction

After windows are delivered to site, proper site storage plays an important role to prevent damages to window components. A storage location should be sheltered from weathering and falling objects, and located for ease of material handling and distribution. Components should be placed on timber bases to avoid direct contact with the ground. Glass panels should be stored in pallets with individual glass panel separated from one another by protective sheets to avoid scratches and other damages. Significantly, large window units and components which cannot be delivered via staircases should be hoisted in pallets to each floor before distributing to the different areas for installation. In cases where window frames need to be hoisted without the pallet, the frames should be handled only at the designed strong points, and large pieces of glass panel should be handled with care using suction cups (BCA 2010c).

All operable and fixed-glass windows need to be installed as per the manufacturer's specifications. Furthermore, only the approved contractors registered with the BCA under the Regulation Workhead (CR17) can carry out the installation and retrofitting of the window systems (BCA 2012). Window installation involves the fixing of window frame at an earlier construction stage and subsequent installation of the window sashes (BCA 2010c). In general, installation of operable glazing windows and their frames covers processes; namely installation of window main frame, sealing of gap between wall and window frame, water proofing, installation of window glazing to inner frame, and installation of window inner frame (BCA 2004).

The main difference between operable windows and fixed-glass window/wall lies in their installation methods. Specifically, the installation process of fixed-glass walls involves slotting the glass panel into the glass pocket at the bottom frame and securing the panel in place using aluminum beadings. While it is a common design to install the glass panel from outside the building, a better design is to allow the installation of the glass panel from inside the building. Fixing of the aluminum beadings should start with the top beading followed by the side beadings. The beadings are knocked in place using a millet or the back of a rubberized screwdriver to give sufficient hold on the glass. The gap between the glass panel and beading could either be sealed by approved sealant or by insertion of gasket in compliance with the designer's specifications (BCA 2010c).

4.3.2.4 Defects and Maintenance

Defects such as sealant failure, sealant staining, dirt staining, and water seepage are usually found in association with the window systems. Their corresponding maintenance guidelines in relation to these defects are similar to those of curtain walls. However, as stated earlier, one of the main concerns related to the safety of the occupant and community is window falling. BCA (2004) reported that about 80 % of the fallen windows were casement windows. The majority of these had fallen due to corrosion of the aluminum rivets holding the friction stays, a result of wear and tear over time as well as poor design and workmanship (Chew and Silva 2004).

4.3.3 Shading Device

Since ordinary windows have been the primary source of heat gain in summer, any effort to shade them has had benefits in terms of comfort and energy performance. In this regard, external shading devices can be considered one of the most effective ways to reduce solar heat gain into a building. Installing shading devices is useful for achieving better thermal performance of a building, while maintaining the same daylight level used in a building (Kibert 2008). With the proper types of external shading devices being used, large reduction of cooling load may allow the capacity of the cooling equipment to be reduced (Chua and Chou 2010a). This section reviews important aspects related to assessment of the external shading devices with respect to their design, delivery, handling and construction, and maintenance phases.

4.3.3.1 Design

To design a shading device, a variety of aspects should be taken into consideration. These include climatic conditions, visual comfort, heat gain, aesthetic impact, maintenance, and so forth. Previous studies have demonstrated the performances of shading devices used extensively in residential buildings to control the amount of daylight into buildings (Kim and Kim 2009). By adopting a proper type of external shading devices, large reduction on the capacity of cooling equipment may be allowed. When the external shading devices are applied in combination with the appropriate glass type, the thermal performance of a building can be enhanced to a great extent (Gratia and Herde 2007; Tzempelikos et al. 2007). Considering the sun path of a building in Singapore facing north−south, to block direct sun light of the high-angle sun from late morning to late afternoon and the ETTV calculation, only the horizontal projection type is considered in this book.

4.3.3.2 Delivery, Handling, and Construction

Shading devices are subject to strong wind forces because of their large surface area. In new construction, it is recommended to construct the shading devices as an integral part of the structure due to structural concerns. This can be seen in the case where the horizontal shading device is built-in as an integrated precast component.

However, if shading devices have to be bolted to the wall, there is a need to ensure that the wall is strong enough to withstand the weight and wind loads (Wulfinghoff 1999). Generally, external walls may need to be reinforced at the attachment points before installing heavy shading devices. Concrete shading devices can either be prefabricated and then delivered to site together with other construction materials or cast in-place. Furthermore, the materials and construction methods for the horizontal shading devices for curtain walls should be those that are recommended by the manufacturer.

4.3.3.3 Maintenance

Durability and maintenance requirements of shading devices are an important consideration because shading devices are regularly exposed to sun and weather. In fact, these requirements of shading devices primarily depend on the types of shading devices, types of finishes, installation methods, as well as quality of workmanship. For example, although aluminum shading devices possess high durability, these seem to require high maintenance costs as compared to other materials, such as fibre cement (Phillips 1999).

4.4 Building Envelope Design Alternatives

Based on the literature review above, this section presents the building envelope design alternatives considered in this book as shown in Fig. 4.1. Each design alternative consists of principal components and additional components. The

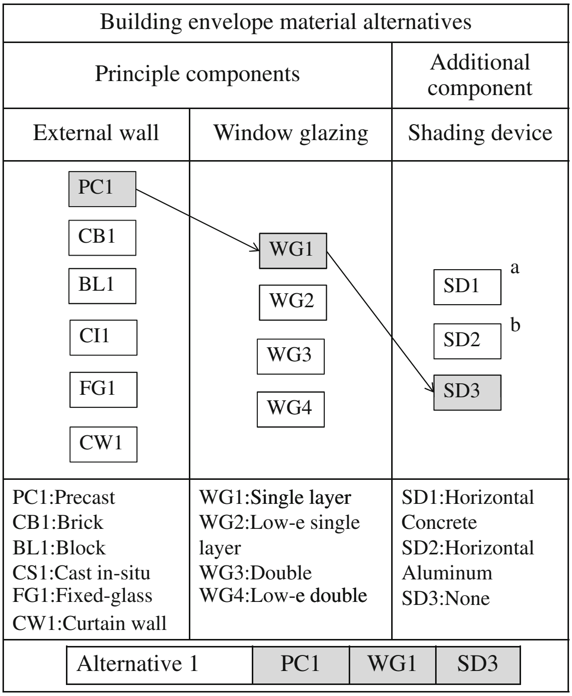


Fig. 4.1 Different design alternatives in this book. *a* For the precast concrete wall, only the concrete shading device prefabricated as part of the panel by the manufacturer is considered. For the brickwall, concrete blockwall, and cast in situ RC wall, only the concrete shading device installed on site is considered. *b* For the fixed-glass and glass curtain wall, only the aluminum shading device installed on site is considered

principal components are the components that the building envelope design must include as structural requirements. The additional components are the components that can either be included or not included as part of the building envelope design. In this book, the external wall and glazing window with the use of the aluminum window frame (Top-hung) are the basic components of each design alternative, with one additional component which is the shading device.

Figure 4.1 also illustrates combinations of different components for each design alternative. According to this figure, alternative “1” PC1WG1SD3 is made of “PC1” Precast wall, “WG1” Single layer window glazing and “SD3” None shading device, for example. To avoid potential conflicts between the materials, it is noted that, for the precast concrete wall, only the integrated (built-in) concrete shading device prefabricated as part of the precast panel by the manufacturer is considered, while, for the brickwall, and concrete blockwall, and cast in situ RC wall, only the concrete shading device installed on site is considered. Furthermore, only the aluminum shading device installed on site is applied for the fixed-glass wall and glass curtain wall.

Table 4.3 Building envelope design alternatives considered in this book

ID	External wall	Glazing window	Shading device	ID	External wall	Glazing window	Shading device
1	PC1	WG1	SD3	25	CI1	WG1	SD3
2	PC1	WG2	SD3	26	CI1	WG2	SD3
3	PC1	WG3	SD3	27	CI1	WG3	SD3
4	PC1	WG4	SD3	28	CI1	WG4	SD3
5	PC1	WG1	SD1	29	CI1	WG1	SD1
6	PC1	WG2	SD1	30	CI1	WG2	SD1
7	PC1	WG3	SD1	31	CI1	WG3	SD1
8	PC1	WG4	SD1	32	CI1	WG4	SD1
9	CB1	WG1	SD3	33	FG1	WG1	SD3
10	CB1	WG2	SD3	34	FG1	WG2	SD3
11	CB1	WG3	SD3	35	FG1	WG3	SD3
12	CB1	WG4	SD3	36	FG1	WG4	SD3
13	CB1	WG1	SD1	37	FG1	WG1	SD2
14	CB1	WG2	SD1	38	FG1	WG2	SD2
15	CB1	WG3	SD1	39	FG1	WG3	SD2
16	CB1	WG4	SD1	40	FG1	WG4	SD2
17	BL1	WG1	SD3	41	CW1	WG1	SD3
18	BL1	WG2	SD3	42	CW1	WG2	SD3
19	BL1	WG3	SD3	43	CW1	WG3	SD3
20	BL1	WG4	SD3	44	CW1	WG4	SD3
21	BL1	WG1	SD1	45	CW1	WG1	SD2
22	BL1	WG2	SD1	46	CW1	WG2	SD2
23	BL1	WG3	SD1	47	CW1	WG3	SD2
24	BL1	WG4	SD1	48	CW1	WG4	SD2

Based on the literature reviews, one unit of these building envelope design alternatives has the following design properties: Length = 4 m, Height = 3 m, Width = see Table 4.1, Floor-to-floor = 3 m, Window height = 1.5 m, WWR = 0.3, Plan configuration = Square, N–S shading horizontal length = 0.3 m, and E–W shading horizontal length = 1.2 m. Table 4.3 presents 48 possible design alternatives stored in the KM-M of the KMS in accordance with Fig. 4.1.

4.5 Summary

This chapter presented the building envelope materials and design alternatives which are parts of the engineering characteristics as prescribed in the HOQ. It introduced key elements of a building with a focus on the building envelope systems divided into three categories; namely external wall, glazing window, and shading device. The chapter also investigated the relevant technical standards and good local practices of the building envelope materials in association with the following project phases: design, delivery, handling and construction, and maintenance phases. According to the literature reviews, the basic design alternatives considered in this book were developed, and classified into four major groups; namely precast cladding wall, infilled clay brick, concrete block, cast in situ RC wall, fixed-glass wall, and stick curtain wall design-based alternatives. The technical standards and important local practices formed the knowledge for development of the KMS of the KBDSS-QFD tool.

Chapter 5
Conceptual Framework

5.1 Introduction

This chapter presents an overall conceptual framework of this book. This chapter first examines how sustainability and buildability play a role in the assessment of the building envelope materials and designs based on the Institutional Theory (Sect. 5.2). This includes reviewing pillars of the Institutional Theory. Next, the book applies these pillars to construct an Institutional Theory framework to suggest underlying factors governing the assessment of the building envelope materials and designed. This Institutional Theory framework is then integrated with the conceptual KBDSS-QFD tool explained in Chap. 2 to form the overall conceptual framework of this book (Sect. 5.3). Subsequently, based on this conceptual framework, two hypotheses of the book are formulated (Sect. 5.4).

5.2 Institutional Theory

Firms are operating in a complex environment today at various and varying development levels. This environment poses challenges to making appropriate responses to meet both current and future stakeholder expectations. Sustaining competitiveness, while maintaining several expectations in this environment, requires the firms or organizations to make the right decisions (Melville 2010; Murugesan 2007). In the context of this book, in order for building organizations to achieve sustainability and buildability, it is important to examine how the architects and engineers perceive requirements under complexity and dynamism in the assessment of the building envelope materials and designs. Scott's (2008) Institutional Theory has been found useful for this purpose (Low et al. 2010; Orlikowski and Barley 2001).

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In conception, institutions are multifaceted, durable social structures made up symbolic elements, social activities, and material resources functioning to provide stability and order. Institutions should be considered not only a property or state of an existing social order, but also process (Tolbert and Zucker 1996). Organizations, firms, or groups that comply with this definition can be considered institutions (Scott 2008). Institutions in general exhibit distinctive properties such as resistance to change (Jepperson 1991). These also tend to be transmitted across generations, and to be maintained and reproduced because of the processes set in motion by regulative, normative, and cognitive elements (Zucker 1977). These elements can be viewed as central building blocks of institutional structure, providing elastic fibers that guide behavior and resist change, thus affecting decision making in a number of actions (Hoffman 1997).

The Institutional Theory adopts an open system perspective asserting that firms are strongly influenced by their environments, not only by competitive forces and efficiency-based forces at work, but also by socially constructed belief and rule systems (Scott 2008). Scholars therefore increasingly promote the Institutional Theory as an important perspective for studies relating to decision making of firms. Supporting this, for example, Dao and Ofori (2010) suggested that the Institutional Theory provides a grounded approach in developing a firm compliance behavior framework and investigating-related attributes. Liu et al. (2010) pointed out that developing a framework based on the Institutional Theory could extend understanding from previous studies to explain things people do in a firm.

Similarly, Javernick-Will and Scott (2010) employed the Institutional Theory as a mainstream theory to formulate a framework to transfer knowledge for international project management. Importantly, they found that applying the Institutional Theory offered more practical categories in representing types of the knowledge as compared to other studies. With this in mind, the Institutional Theory seems to provide a good starting point for this book to develop a framework to address the rationale for architects and engineers' decisions in selecting building envelope materials and designs. As such, developing the framework based on the Institutional Theory would extend current understanding of firms and enhance effectiveness of the framework to explain results of this book in relation to assessment of the building envelope materials and designs.

The Institutional Theory focuses on deep and resilient aspects of the social structure of institutions. The theory considers the processes by which structures, schemas, rules, norms, and routines become established as authoritative guidelines for decision making of institutions (Scott 2008). There are three elements in the Institutional Theory; namely the regulative, normative, and cognitive pillars. These pillars have each been identified by one or another theorist as a vital ingredient of institutions (Hoffman 1997). Table 5.1 illustrates the different assumptions made between these three pillars.

Table 5.1 Assumptions of the pillars in the institutional theory

Elements	Regulative pillar	Normative pillar	Cognitive pillar
Compliance	Expedience	Social obligation	Taken for granted
Mechanisms	Coercive force	Normative force	Mimetic force
Indicators	Laws, sanctions	Certification	Isomorphism

5.2.1 Regulative Pillar

The regulative pillar suggests that regulatory processes are associated with the capacity of institutions to establish rules, inspect others' conformity to them, and manipulate sanctions in terms of rewards and punishments in an attempt to influence behaviors especially in decision making. These processes may operate through diffuse, informal mechanisms such as shaming or shunning activities, or may be highly formalized and assigned to specialized actors. In addition, it was noted that institutions or individuals construct rule systems or conform to rules in pursuit of their self-interests (DiMaggio and Powell 1983). As shown in Table 5.1, the basis of compliance in this pillar is expedience in regard to individual interests rationally driven by utilitarianism or cost-benefit logic (Scott 2008). This implies the idea that human reasoning and decision making could be roughly modeled by the expected utility function. In other words, a rational DM, when faced with a choice among a set of competing feasible alternatives, acts to select an alternative which maximizes his expected utility. For this reason, failure to comply with regulations, including laws and standards, would lead to additional costs and losses, thereby affecting the expected utility (Davis et al. 1998).

The main mechanism of this pillar is coercive pressure placed upon the organizations and individuals by outside institutions. Rules, laws, as well as sanctions are key indicators to instrumentally organize or form all of the organizations in a similar manner to receive legitimization or acceptance from external institutions (Helm 2004). This pillar seems to suggest that the coercive pressure applied by outside institutions forces the building organizations including the architectural firms and engineering consultancy firms toward compliance with relevant laws and regulations. This sets compliance with relevant laws, regulations, and standards as an important basis for the assessment of building envelope materials and design alternatives.

5.2.2 Normative Pillar

The normative pillar emphasizes on normative rules that introduce a prescriptive, evaluative, and obligatory dimensions into organizations. According to Table 5.1, the basis of compliance in this pillar is social obligation driven by normative force. In a broad sense, normative systems include both values and norms. Values are conceptions of the preferred or the desirable, together with the construction of standards to which existing structures or behaviors can be compared and assessed. Norms specify how things should be done, and these also define legitimate means to pursue value ends. Importantly, the two concepts can evoke strong feelings of individuals such as a sense of shame and disgrace or a feeling of pride and honor. Such emotions also appear to provide institutions powerful inducement to follow prevailing norms (March and Olsen 1989; Scott 2008).

Furthermore, normative systems typically impose constraints on social behavior, and, in parallel, the systems empower and enable social actions. The normative approach of institutions plays an important role in selecting choices evaluated by socially mediated values and normative frameworks. Consequently, the organizations morally focus on social responsibilities to obtain certification and accreditation (Scott 2008). In the domain of building design and construction, social responsibility can be referred to as the obligation of the building organizations to consider impacts of the design on themselves and the surrounding environments in terms of environmental, social, as well as economic impacts for achieving sustainability (Bansal 2005).

5.2.3 Cognitive Pillar

The cognitive pillar governs constitutive rules involving the creation and the construction of typifications. The cognitive dimensions of human existence refer to mediating between the external world of stimuli and the response of the individual organisms which is a collection of internalized symbolic representations of the world. In the cognitive paradigm, what a creature does is, in large part, a function of the creature's internal representation of its environment (D'Andrade 1984). Symbols, including words, signs, and gestures, shape the meaning of objects and activities. Meanings arise in interaction and are maintained and transformed as these are employed to make sense of the ongoing stream of happenings (Scott 2008). Cognitive frames help institutions to develop sedimentation of meaning or, to vary the image, a crystallization of meanings in objective form (Berger and Kellner 1981). It was also found that internal interpretive processes are shaped by external cultural frameworks providing pattern of thinking, feeling, and acting (Hofstede 1991).

Cognitive rules are widely applied to things, ideas, events, individuals, and organizations. In many circumstances, cultures and cognitive behaviors are inconceivable and routines are followed. Supporting this, Table 5.1 shows that the basis of compliance for organizations in this pillar is often taken for granted. This pillar further suggests that individual behaviors tend to be driven by the mimetic mechanism by which the organizations adopt systems and techniques perceived as successful, culturally supported, and conceptually correct by other organizations (DiMaggio and Powell 1983; Scott 1987). The key indicator in this pillar is isomorphism. This can be found when the firms search for "best practices" of actions in its operating environment (Helm 2004). Relating to the building industry, the best practices are represented by the concept of buildability aiming to promote the use of construction materials and construction techniques which are more labor-efficient and can enhance the ease and safety of construction (Dulaimi et al. 2004).

5.3 Conceptual Framework

The pressures faced by a given organization when implementing these three pillars depend on its operating environment and sources of such pressures. This is because organizations in different environments could encounter different pressures. For example, norms that are accepted in one particular area may be unacceptable in another (Helm 2004; Scott 2008). As a result, Roland (2004) suggested that organizations need to pay attention to combinations of the three pillars in the Institutional Theory because, although analytically distinct, these are nested and interdependent. When the pillars are aligned, the strength of their combined forces can be formidable (Scott 2008). As such, this book developed the Institutional Theory framework to simultaneously operate these three pillars to guide and to formulate some structures and behaviors, as well as to support each other. However, as the Institutional Theory framework was developed for the first time to formulate a specific hypothesis for this book, the degree of alignment and interdependence of the three pillars would not be examined in this book in the first instance.

Figure 5.1 illustrates the overall conceptual framework of this book which consists of two major portions. The first portion corresponds with the Institutional

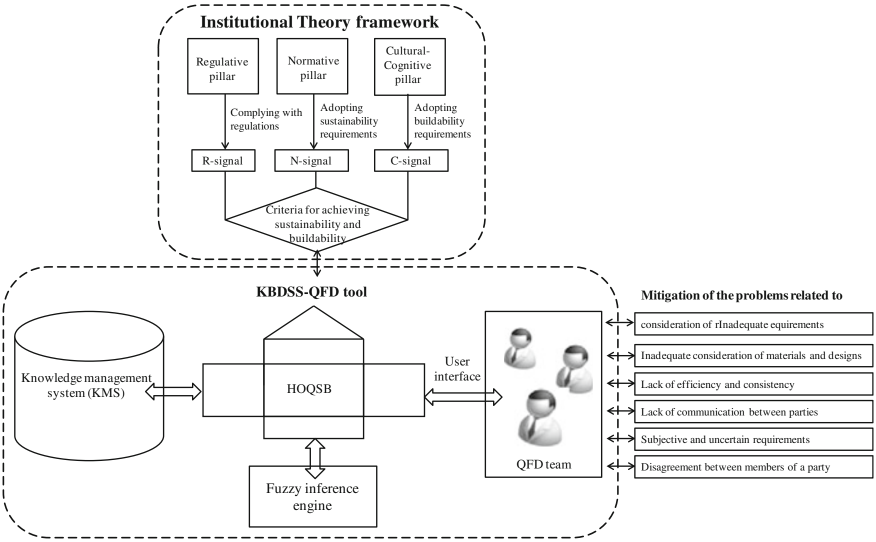

Fig. 5.1 Conceptual framework of this book

Theory framework that signifies how the regulative, normative and cognitive pillars have an impact on the assessment of the building envelope materials and designs for achieving sustainability and buildability. The second portion of this conceptual framework is associated with the KBDSS-QFD tool and its elements for mitigating the decision-making problems. In the first portion, the Institutional Theory framework posits that the institutional environment and organizational field provide regulative (R-signal), normative (N-signal), and cognitive (C-signal) information for the achievement of sustainability and buildability. The R-signal forms the basis for decision making that complies with rules and regulations. This signal simply builds the foundation in the minds of the architects and engineers that every decision must at least meet requirements of existing rules, law, and standards as a priority. The N-signal morally draws attention of the architects and engineers to concerns about the sustainability aspects of the building envelope materials and designs in terms of environmental, economic, as well as social impacts. Next, the C-signal requires the architects and engineers to consider the buildability aspects when making decisions (Butler 2011; Choo 2006). These signals collectively suggest the underlying factors for grouping the criteria for the assessment of the building envelope materials and designs to achieve sustainability and buildability.

In relation to the second portion of the conceptual framework, the R-signal, N-signal, and C-signal also govern how the architects and engineers perceive and select the criteria for the assessment of the building envelope materials and designs in the CR in the HOQSB of the KBDSS-QFD tool (see Sects. 2.13 and 2.14). The KBDSS-QFD tool proposed as the second portion of the overall conceptual framework plays a role to facilitate the design team to mitigate the decision-making problems when assessing the building envelope materials and designs for private high-rise residential buildings in the early design stage.

In brief, the KBDSS-QFD tool consists of four major elements which are the HOQSB, KMS, fuzzy inference engine, and user interface. The HOQSB integrated with the KMS was developed to mitigate the decision-making problem related to inadequate consideration of criteria by reminding the DMs of the key criteria and assisting the DMs to take these into account at once. This HOQSB would also be useful to mitigate the decision-making problem related to inadequate consideration of possible materials and designs by providing fundamental building envelope materials and design alternatives to facilitate the DMs to identify and compare possible materials and alternatives in a more comprehensive manner. To mitigate the decision-making problem related to lack of efficiency and consistency in making decisions, this book structured the relevant knowledge and stored this in the KMS to support the DMs. Applying this KMS may promote making decisions based on past similar experience and the same set of knowledge.

In addition to the KMS, the tool was also equipped with the fuzzy inference engine containing the fuzzy operation techniques to translate subjective and uncertain requirements, which is one of the decision-making problems, into quantifiable information. Furthermore, this engine was integrated with the fuzzy consensus scheme to mitigate the decision-making problem related to disagreement between members of the design team by helping the team to systematically seek consensus solutions that all the team members agree with. Apart from these elements, the book developed the user interface to promote spontaneity in making decisions through the use of a structured decision-making process. This would enhance team discussions as well as decision making, thereby helping to mitigate the decision-making problem related to lack of communication and integration among the DMs.

5.4 Hypotheses

The Institutional Theory framework developed as shown in Fig. 5.1 suggests that the regulative pillar forms a basis for decision making of the architects, C&S engineers, and M&E engineers by reminding them of the need to comply with relevant rules and regulations. This consideration simply builds the foundation in the mind of the architects and engineers that every decision must at least meet requirements of existing rules, law, and standards as a priority. The normative pillar draws the attention of the architects and engineers to take into account the criteria relating to sustainability, while the cognitive pillar requires the architects and engineers to adopt the criteria relating to buildability. Emphasizing on the sustainability and buildability parts of the Institutional Theory framework, the first hypothesis is formulated as follows:

H1 The criteria for the assessment of the building envelope materials and designs can be modeled by the four factors which are the environmental, economic, social, and buildability factors as shown in Fig. 5.2.

This hypothesis would serve to provide a better understanding of the concept to achieving sustainability and buildability by utilizing the Institutional Theory framework to further explain socially constructed belief and rule systems that influence and/or underpin decision making (Scott 2008). Testing this hypothesis would help to find a link between the Institutional Theory framework and the comprehensive list of the criteria, and thus providing a platform for the architects and engineers to achieve sustainability and buildability requirements in building envelope designs.

Apart from determination of the underlying factors, success of the assessment of the building envelope materials and designs for private high-rise residential buildings is also affected by several decision-making problems faced by the architects and engineers. These problems include inadequate consideration of requirements, inadequate consideration of possible materials and designs, lack of efficiency and consistency, lack of communication and integration between members of the team, subjective and uncertain requirements, and disagreement between members of the team. Based on the literature reviews, the book develops the KBDSS-QFD tool that consists of four main elements which are the HOQSB, KMS, fuzzy inference engine, and user interface to mitigate such problems as a

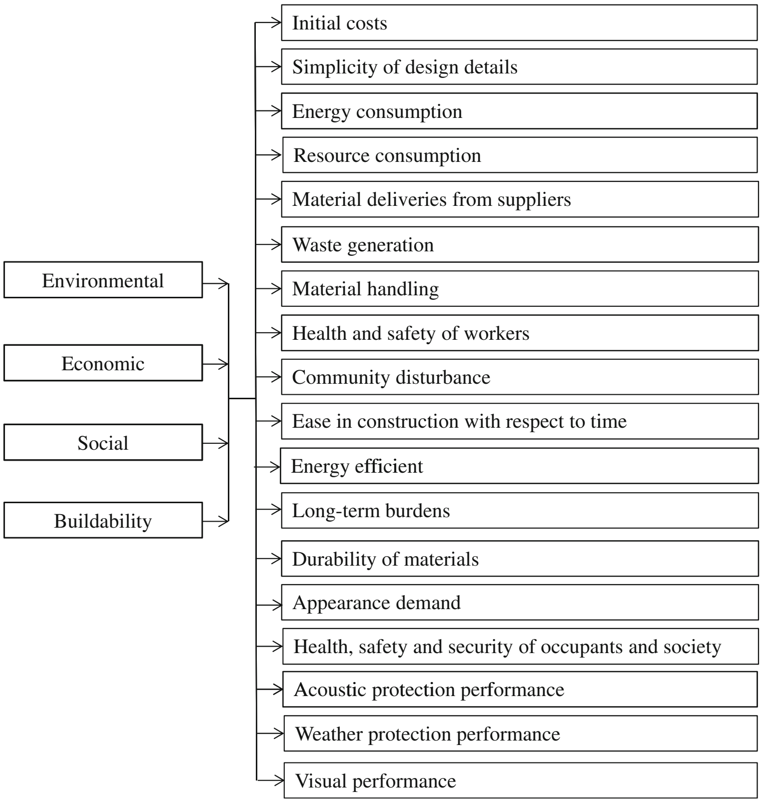

Fig. 5.2 The four-factor model for achieving sustainability and buildability

whole. As such, according to the second portion of the conceptual framework, the second hypothesis is formulated as follows:

H2 The KBDSS-QFD tool consisting of the HOQSB, KMS, fuzzy inference engine, and user interface can be applied to facilitate the design team to mitigate the decision-making problems as a whole.

Specifically, it is hypothesized that the KBDSS-QFD tool would remind the DMs about key criteria and possible building envelope materials and designs through the use of the HOQSB and KMS. The tool would also improve efficiency as well as consistency in making decisions for the assessment by facilitating the DMs to make a prompt decision and to learn from past experience stored in the KMS. In addition, through the structured decision process offered by the HOQSB and user interface, communication and integration among the DMs would be enhanced. In parallel, the fuzzy inference engine embedded with the fuzzy techniques and KMS would assist the design team in translating subjective and uncertain requirements into a more useful format, and the fuzzy consensus scheme would help the team to reduce disagreement between opinions of the team members.

5.5 Summary

This chapter presented the overall conceptual framework of this book consisting of two main portions. The first portion relates to development of the Institutional Theory framework governed by the regulative, normative, and cognitive pillars. In brief, the framework suggests that the regulative pillar forms a basis for decision making by the architects and engineers by reminding them of the need to comply with relevant rules and regulations. In the mean time, the normative and cognitive pillars draw attention of the designers to take into account the criteria related to sustainability and buildability, respectively. This led to the formulation of the first hypothesis suggesting that the criteria for the assessment of the building envelope materials and designs can be modeled by the four factors (environmental, economic, social, and buildability factors) to achieve sustainability and buildability.

The second portion of the conceptual framework corresponds with the use of the KBDSS-QFD tool to mitigate the decision-making problems. The tool also employs the four factors suggested by the first hypothesis to help the architects and engineers to identify the criteria for the assessment of the building envelope materials and designs. It is noted that this effort is governed by the CR in the HOQSB of the KBDSS-QFD tool. By incorporating the concepts proposed in Chap. 2 into the KBDSS-QFD tool, the book set up the second hypothesis which posits that the tool can be applied to facilitate the design team to collectively mitigate the decision-making problems.

Chapter 6
Research Methodology

6.1 Introduction

This chapter discusses the research methodology of this book. With respect to the two hypotheses set out in Chap. 5, this chapter introduces the overall research design and method of data collection (Sect. 6.2) for validating these hypotheses. Survey (Sect. 6.3) and case study (Sect. 6.4) were selected as the research design to test the first and second hypotheses, respectively.

6.2 Overall Research Design and Method of Data Collection

Figure 6.1 illustrates the overall research methodology of this book for the validation of the two hypotheses. The first hypothesis states that the criteria for the assessment of the building envelope materials and designs to achieve sustainability and buildability can be modeled by four factors which are the environmental, economic, social, and buildability factors. This hypothesis was tested using the survey as the research design, and survey questionnaire as the method of data collection. In an effort to develop a survey questionnaire, a pilot study (see Appendix B) and literature reviews were conducted to fine-tune the related criteria. A questionnaire pretest was also carried out to ensure that all questions in the questionnaire can be correctly interpreted and can be answered. After the completed questionnaires were returned, face-to-face interviews with five respondents were conducted to cross-check their responses. The book then applied factor analysis, ranking analysis, and Spearman rank correlation to analyze the data collected. The findings from the data analysis were validated through face-to-face interviews conducted with three selected respondents who had more than 10 years of

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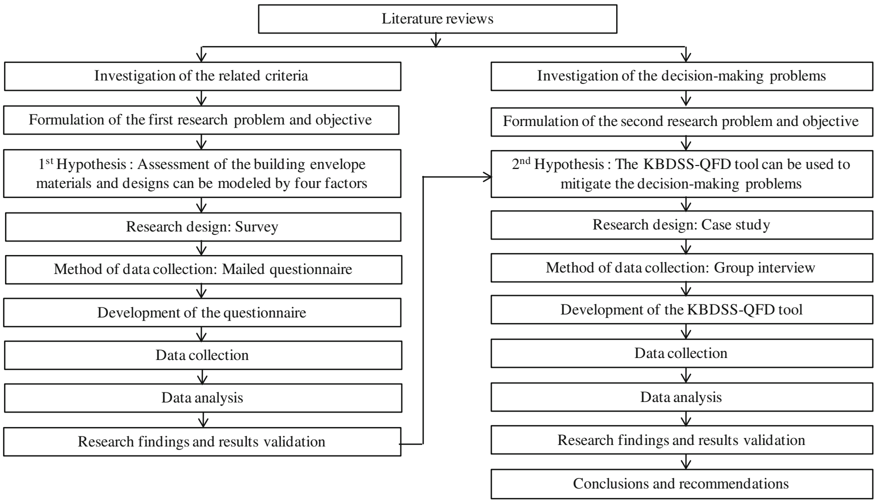

Fig. 6.1 The overall research methodology of this book

experience in the building envelope design and construction for private high-rise residential buildings in Singapore.

Next, the second hypothesis states that the KBDSS-QFD tool consisting of the HOQSB, KMS, fuzzy inference engine, and user interface can be applied to facilitate the design team to mitigate the decision-making problems as a whole. This hypothesis was tested by adopting the case study as the research design, and group interview as the method of data collection. The methodology started with conducting literature reviews and another pilot study (see Appendix A) to develop the conceptual KBDSS-QFD tool (see Sect. 2.14). This conceptual tool was further built in detail based on the feedbacks from semi-structured interviews conducted with 15 architects and engineers in total (see Appendix D). The tool's system analysis was carried out by the UML, and a prototype was subsequently modeled after this detailed tool. In particular, the prototype and its KMS were developed using Microsoft Visual Studio and Microsoft Access for Windows, respectively.

Importantly, another round of semi-structured interviews was also conducted with the same set of the architects and engineers to ensure usability of the prototype (see Appendix E). It is worth to note that the prototype adopted the four factors suggested by the first hypothesis to categorize the criteria stored in the KM-C of the KMS. Development of the detailed KBDSS-QFD tool and its first prototype is presented in Chap. 7. After that, three case studies of different design teams were engaged to use the prototype of the KBDSS-QFD tool by applying representative private high-rise residential building projects in Singapore. Each design team consists of an architect, a C&S engineer, and a M&E engineer who were active in the area of design development of the high-rise residential buildings in Singapore.

A qualitative data analysis approach was selected to assess the perspectives of the DMs with respect to the potential of applying the KBDSS-QFD tool to facilitate the design team to mitigate the decision-making problems identified through the group interview.

6.3 Survey

A survey was selected as the research design to test the first hypothesis of this book based on sampling. The basic sampling concept for a survey relies on the availability of the sampling frame which is the list of elements from which sampling takes place. A survey is a systematic method of collecting primary data based on a sample to gather information or make inferences about the population (Tan 2008). A survey was employed because it enables gathering of data from a large number of respondents within a limited time frame.

6.3.1 Questionnaire Design

Prior to conducting the survey, the pilot study (see Appendix B) was conducted with 12 architects and engineers in total to fine-tune the related criteria found from the literature reviews. In this regard, the literature reviews suggested 30 related criteria, and these criteria were subsequently refined through the pilot study to the 18 main criteria for the assessment of the building envelope materials and designs (see Sect. 3.5). The survey questionnaire (see Appendix C) was then developed in regard to these 18 criteria. Next, the questionnaire pretest was conducted with the same set of practitioners to formulate the questions in the questionnaire that respondents can answer and to test the appropriateness of the questionnaire as an instrument to achieve the first research objective. This questionnaire aimed at investigating the perspectives of the architects and engineers on importance weights of the criteria. The questionnaire consists of three main parts. Brief description for each section of the questionnaire is provided as follows:

- Section A was to collect general information of the respondents; including name, email address, contact numbers, professional discipline, years of experience, and willingness to participate in the face-to-face interview;
- Section B provided brief description and major considerations of the research and questionnaire; and
- Section C seeks to obtain the importance weights of the criteria. In this section, respondents were to rate the importance weights of the criteria based on a five-point scale of 1–5, where 1 is "Very unimportant,", 2 is "Unimportant," 3 is

"Medium," 4 is "Important," and 5 is "Very important." Clear definition of each criterion was also given in the survey questionnaire to ensure a better understanding of the criteria.

6.3.2 Questionnaire Survey

The sampling frame covered only the architectural, C&S engineering consultancy firms, and M&E engineering consultancy firms that had experience in design and construction of private high-rise residential buildings in Singapore. The firms were drawn from a list of the consultants registered with the BCA (2011b). This list divides the registered architectural and engineering consultancy firms into four panels based on project cost ranges. This is to facilitate the Singapore government in appointing consultants to undertake building development projects (BCA 2011b). As the private high-rise residential building is a capital-intensive project, only the panel-1 and panel-2 architectural and engineering consultancy firms who can participate in a large-scale project were selected. As a result, the sampling frame comprised 146 firms total, consisting of 59 architectural firms, 55 C&S engineering consultancy firms, and 32 M&E engineering consultancy firms.

6.3.3 Method of Data Collection for the Survey

The method of data collection for the survey was the questionnaire survey coupled with face-to-face interview. Mailing the questionnaire for the survey was selected since it can save the data collection cost, and can provide geographic flexibility without compromising on speed of communication. To receive a high-response rate, this book identified a name of the respondent for each firm and notified the respondent before mailing the questionnaire. The cover letter accompanying the questionnaire was then developed and addressed to the named respondent with an assurance to use the responses only for academic proposes. A questionnaire package consisting of the cover letter, one copy of the questionnaire and a prepaid envelope was sent to the 146 firms. This questionnaire survey was conducted in April 2012.

In parallel, the book also crosschecked the findings from the survey with five respondents by face-to-face interviews. Importantly, after all responses were received and analyzed, another set of face-to-face interviews was carried out to validate the findings from the data analysis. These interviews were conducted with three respondents of the survey who had more than 10 years of experience in the building envelope design and construction for private high-rise residential buildings in Singapore, and indicated the willingness to participate in the further in-depth discussion about the findings of the survey.

6.3.4 Data Analysis for the Survey

To ensure that the rating scale for measuring the criteria provides the same result over time, a reliability analysis using the internal consistency method to measure Cronbach's alpha of the data was examined (Tan 2008). Subsequently, factor analysis was applied to identify the underlying structure of the criteria or, in other words, to group the criteria into fewer factors. Factor analysis is typically used to condense a large set of variables into a few meaningful "factors." This analysis is a collection of models for explaining the correlations among variables in terms of more fundamental entities (Cudeck 2000). Its goal is to summarize complicated patterns of correlations between observed variables into a simpler explanatory framework. Factor analysis was originally developed as a procedure for disclosing unobserved or latent factors which presumably underlie subjects' performance on a given set of observed variables, and explained their interrelationships (Raykov and Marcoulides 2008; Tan 2008).

Conducting factor analysis for a given set of observed variables consists of two general steps. In the first step, the initial factors are extracted. This results in the so-called initial factor solution that, however, is often not easily interpretable. In this second step, in the search for a better and simpler means of interpretation, factor rotation is carried out. The factor extraction step is to disclose one or more hidden variables that are able to explain the interrelationships among a given set of observed variables. In particular, the factor rotation in the second step is to rotate the factor loadings for easier interpretation by adopting an orthogonal matrix technique. This is because the initial factor solution is generally not unique (Dugard et al. 2009). As such, the initial factor solution only determines the dimensional space containing the factors, but not the exact position of those factors in it. Most orthogonal rotation is carried out using the so-called Kaiser's varimax rotation to rotate the factors in order to facilitate interpretation without affecting the statistic analysis in the first step (Comrey and Lee 1992; Raykov and Marcoulides 2008). The result of this analysis, including factor loading and communality (sum of square of loadings), can be furnished using Statistical Packages for the Social Sciences (SPSS) (Bartholomev et al. 2008; Raykov and Marcoulides 2008).

To gain further understanding of the responses from the survey, ranking analysis was performed to calculate the relative importance of the criteria. It is also worth mentioning that the ratings in the ordinal scale indicate only a rank order of the importance of the criteria, rather than how much more important each rating is than the other. Applying parametric statistics such as means, standard deviations, etc., to rank such ordinal data may not produce meaningful results because parametric statistics do not reflect any relationship between the ratings. It was suggested that nonparametric procedures should be adopted. Importantly, using the nonparametric procedures enables a study to cross-compare relative importance of the criteria as perceived by respondents (Chen et al. 2010; Johnson and Bhattacharyya 1996).

Thus, this book selected severity index (SI) analysis to calculate SI values representing the relative importance of the criteria as expressed in Eq. (6.1) (Chen et al. 2010).

$$\text{Severity Index (SI)} = \left(\frac{\sum_{i=1}^{a} w_i \frac{f_i}{n}}{a} \right) \tag{6.1}$$

where i is the point given to each criterion by the respondent, ranging from 1 to 5; ω_i is the weight for each point; f_i is the frequency of the point i by all respondents; n is the total number of responses; and a is the highest weight (a = 5 in this book).

Based on SI values, Chen et al. (2010) suggested the following five importance levels: High (H) ($0.8 \le SI \le 1$), High-Medium (H-M) ($0.6 \le SI < 0.8$), Medium (M) ($0.4 \le SI < 0.6$), Medium-Low (M-L) ($0.2 \le SI < 0.4$) and Low (L) ($0 \le SI < 0.2$). To explore the findings further, the book also applied Spearman rank correlation to determine whether the architects, C&S engineers, and M&E engineers share the same perspectives with respect to the rankings of the criteria.

6.4 Case Study

A case study is appropriate for in-depth understanding or interpretation of particular instances. It tells a big story through the lens of a small case. In other words, this ensures that the instances are not explored through one lens, but rather a variety of lenses which allows for multiple facets of the phenomenon to be revealed and understood. The case study should be holistic and aim at thick description (Tan 2008). Although the case study is bounded by time and activity, this approach offers a close collaboration between the researchers and the participants, while enabling the participants to tell their stories (Crabtree and Miller 1999; Stake 1995). Through this approach, the participants are able to express their views of reality, so much, so that this allows the researcher to better understand the participants' actions and perspectives (Lather 1992; Robottom and Hart 1993).

6.4.1 Case Study Design

Flyvbjerg (2006) highlighted that there was a conventional view about the case study that the case study is claimed to be most useful for generating hypotheses in the first steps of a total research process, whereas hypothesis testing and theory building are best carried out by other methods later in the process. This conventional view was derived from a misunderstanding that one cannot generalize on the basis of individual cases. Flyvbjerg (2006) and Yin (2009), therefore, corrected this by suggesting that the case study is useful for both generating and testing of hypotheses. With this in mind, the case study was selected as the research design of this book to test the second hypothesis because of the following reasons:

1. The focus of the book is to answer "how" the KBDSS-QFD tool plays a role in mitigating the decision-making problems and "why" this tool is able to do so with respect to the perspectives of the DMs.
2. The behavior of the DMs involved in the case study cannot be easily manipulated.
3. There is a need to cover contextual conditions related to mitigation of the decision-making problems within the case study.
4. The boundaries between the capabilities of the KBDSS-QFD tool and effects of the tool on mitigation of the decision-making problems are not clearly evident.

Yin (2009) also suggested that there are three main types of case study design; namely exploratory, descriptive and explanatory design. Exploratory case studies are often used to define the framework of a future study. In this type of case study, fieldwork and data collection are undertaken prior to the final definition of study questions and hypotheses. Descriptive case studies are typically used to describe an intervention or phenomenon and the real-life context in which it occurred. Explanatory case studies, on the other hand, seek to define how and or why an experience took place. The explanatory approach was applied in this book since explanations from the case study would link implementation of the KBDSS-QFD tool with its effects (Yin 2009).

In addition, as mentioned earlier, the book conducted a series of the semi-structured interviews (see Appendix D and Appendix E) with 15 architects and engineers in parallel with the thorough literature reviews to build the automated KBDSS-QFD tool and to acquire the knowledge for the KMS database. Three representative design teams were approached to use this tool, and each design team consists of three different DMs which are the architect, C&S engineer, and M&E engineer. These nine DMs for the three case studies were drawn from the 15 architects and engineers who participated in the semi-structured interviews.

6.4.2 Method of Data Collection for the Case Study

The type of methodology adopted by any research depends on the central research objectives and questions (Crabtree and Miller 1999; Richards and Richards 1998). Case studies can include both qualitative and quantitative evidences (Yin 2009). The quantitative research methodology typically answers where, what, who, and when questions (Crabtree and Miller 1999; Silverman 2000). In contrast, qualitative research provides the necessary in-depth tools through an interview to achieve a clearer picture of a process, if the objective is to understand such process coupled with the how and why of a given phenomenon (Symon and Cassel 1998). Supporting this, Collis et al. (2003) pointed out that only qualitative research in the business environment can offer a strong basis for analysis and interpretation because it is grounded in the natural environment of the phenomenon. As such, qualitative data analysis was adopted to examine in-depth explanations of circumstances, interactions, observed behaviors, and perspectives of the DMs who used the KBDSS-QFD tool in the form of textual data obtained from the interview (Patton 2002).

In a broad sense, focus group interview and in-depth interview are among the most used interview methods to collect data when qualitative research approaches are applied. It was suggested that in-depth interviews are especially appropriate for addressing topics with the interest in individual information, not interaction between respondents (Linhorst 2002; Milena et al. 2008). On the other hand, the topics concerning new and complex issues, and requiring brainstorming opinions seem to be more appropriate to discuss in a group (Linhorst 2002; Milena et al. 2008). The focus group approach, according to Parahoo (1997), is an interaction between one or more researchers and more than one participant for the purpose of collecting data. In other words, a researcher interviews participants in a group. The group interview aims to reveal the underlying attitudes and beliefs held by the population being studied. The results obtained from the group interview application are particularly effective in supplying information about how people think, feel, or act regarding a specific topic (Creswell 2003). The group interview with semi-structured questions (see Appendix F) was selected in this book as the method of data collection for the case study due to the following reasons: (Creswell 2003; Holloway and Wheeler 2002):

1. The dynamic interaction among the participants may stimulate their thoughts and reminds them of their feelings right after using the KBDSS-QFD tool.
2. All the participants including the researcher have an opportunity to ask questions, and these may produce more useful information than individual interviews.
3. The researcher can refer to situations when the participants use the KBDSS-QFD tool, clarify misunderstanding issues (if any) between the participants, and ask about their different views.
4. As the research topic of this book seems to be quite new to the participants, applying the group interview may offer the participants an opportunity to reflect or react to the opinions of others with which they may disagree or, importantly, of which they are unaware.

6.4.3 Data Analysis for the Case Study

Qualitative research uses analytical categories to describe and explain social phenomena. It may be used in either an inductive or deductive way. The use of these approaches is determined by the purpose of the book. If there is not enough former knowledge about the phenomenon or if this knowledge is fragmented, the inductive approach is recommended (Lauri and Kyngas 2005). In opposite, deductive analysis should be applied when the structure of analysis is operated on the basis of previous knowledge and the purpose of the study is theory testing (Kyngas and Vanhanen 1999). Deductive qualitative analysis is also often applied in cases where the researcher wishes to retest existing data in a new context (Catanzaro 1988). This may also involve testing categories, concepts, and hypotheses (Marshall and Rossman 1995). Based on these suggestions, the deductive approach was adopted aiming to investigate whether the KBDSS-QFD tool can be used to mitigate the decision-making problems.

In addition, it was found that deductive analysis has increasingly been employed in qualitative data analysis particularly with use of the “framework approach” (Green and Thorogood 2006). Framework analysis was developed by Ritchie and Spencer (1994). This analysis can be said to be quite similar to grounded theory; however, framework analysis differs in that this technique is better adapted to research that has specific questions, a limited time frame, a predesigned sample and a priori issues. Framework analysis was therefore applied in this book to reveal the underlying attitudes and beliefs held by the DMs for supplying information about how the DMs think, feel, or act when applying the tool to mitigate each of the decision-making problems. Although framework analysis may generate theories, the prime concern is to explain and interpret what is happening in a particular setting (Creswell 2003; Green and Thorogood 2006; Ritchie and Spencer 1994).

In framework analysis, data is sifted, charted, and sorted in accordance with key issues and themes using five steps; namely familiarization, identifying a thematic framework, indexing, charting, and mapping and interpretation (Srivastava and Thomson 2009). Familiarization refers to immersion in the raw data or typically a pragmatic selection from the data by studying notes in order to list key ideas and recurrent themes. Identifying a thematic framework involves identifying the key issues, concepts, and themes by which the data can be examined and referenced. This is carried out by drawing on a priori issues and questions derived from the hypothesis of the book as well as issues raised by the respondents themselves and views or experiences that recur in the data (Green and Thorogood 2006; Ritchie and Spencer 1994; Srivastava and Thomson 2009). In the context of this book, the thematic framework was framed by the concepts applied to mitigate the decision-making problems as discussed in Chap. 2.

Indexing refers to applying the thematic framework systematically to all the data in textual form, usually supported by short text descriptors to elaborate the index heading. Charting is rearranging the data according to the appropriate part of the thematic framework to which they relate. In this book, charting was prepared with respect to each of the concepts to mitigate the decision-making problems (see Sect. 2.13) with entries for the three mentioned case studies. Nevertheless, unlike simple cut and paste methods that group verbatim text, the charts contain distilled summaries of views and experiences of each case. Thus, the charting process in this book involves a considerable amount of abstraction and synthesis. Lastly, mapping and interpretation can be carried out using the charts to define concepts, map the range and nature of phenomena, and, importantly, find associations between the concepts and how each concept plays a role in mitigating the decision-making problems with a view to providing explanations for the second hypothesis (Green and Thorogood 2006; Ritchie and Spencer 1994; Srivastava and Thomson 2009).

6.5 Summary

This chapter began by presenting the research design to test the first hypothesis through the use of the survey. Factor analysis was selected as the main data analysis technique to test whether the criteria identified can be grouped into four factors; namely the environmental, economic, social, and buildability factors as hypothesized. A brief process for development of the KBDSS-QFD and its prototype was also introduced. Explanatory case study was chosen to test the second hypothesis through three different design teams. Next, the deductive qualitative data approach was selected to examine in-depth explanations of circumstances, interactions, observed behaviors, and perspectives of the design team for each case study. The data were collected in the form of textual data obtained through the group interview conducted with each design team, and the framework analysis approach was used to analyze these textual data.

Chapter 7
Survey Results

7.1 Introduction

This chapter presents findings and discussion for the survey to validate the first hypothesis of this book. The chapter first summarizes general characteristics of the respondents from the survey (Sect. 7.2). This is followed by presenting findings and discussion from the survey (Sect. 7.3) divided into the findings from the reliability, factor analysis, ranking, and Spearman rank correlation tests.

7.2 Characteristics of the Respondents from the Survey

Table 7.1 shows the general characteristics of the respondents from the survey (see Sect. 6.3). Of the 146 firms which is the survey sampling frame, 54 firms responded to the survey by May 2012. 52 questionnaires were found to be suitable for the data analysis after checking through the completed questionnaires. This yielded a 35. 62 % total response rate. Among these 52 valid responses, 21 responses were from the architectural firms, 14 responses from the C&S engineering firms, and 17 responses from the M&E engineering firms, contributing to 35.59 %, 25.45 % and 53.13 % response rates for all the architectural, C&S engineering and M&E engineering firms, respectively. In addition, 5.77 % of all the respondents had between 0 and 5 years of experience in the area related to design and construction of private high-rise residential buildings, 17.31 % between 5 and 10 years, 44.23 % between 10 and 20 years, and 32.69 % with more than 20 years. As can be seen, the majority of the respondents, about 76.92 %, had more than 10 years of experience in this field. This suggests that, by virtue of the seniority of the respondents, the data obtained were representative of actual perspectives of the building professionals in the building envelope design and construction field.

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Table 7.1 Characteristics of the respondents of the questionnaire survey

Discipline	Number of the responses (firms)	Sampling size (firms)	Response rate (%)	Percentage of the responses (%)			
				0–5 (years)	5–10 (years)	10–20 (years)	>20 (years)
Architects	21	59	35.59	9.53	19.04	47.62	23.81
C&S engineers	14	55	25.45	7.14	14.29	35.71	42.86
M&E engineers	17	32	53.13	0.00	17.65	47.06	35.29
All respondents	52	146	35.62	5.77	17.31	44.23	32.69

7.3 Findings from the Survey and Discussion

The following sections present and discuss the findings from the survey with respect to reliability analysis, factor analysis, ranking analysis, and Spearman rank correlation analysis. This discussion also covers the findings from the validation interviews (see Sect. 6.3.3).

7.3.1 Reliability Analysis

Cronbach's alpha values of the data were calculated using SPSS. The alpha normally ranges between 0 and 1. The closer the Cronbach's alpha is to 1, the higher the internal consistency. Cronbach's alpha values for the responses of the architects, C&S engineers, M&E engineers, and all the respondents were 0.875, 0.732, 0.756, and 0.808, respectively. As all the alpha values were greater than 0.7, this indicated that the alpha values were acceptable, and the internal consistency of the criteria was good (Tan 2008).

7.3.2 Factor Analysis

Factor analysis was performed by using SPSS. Measurement of Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity were conducted to examine sampling adequacy of the responses, ensuring that factor analysis was appropriate for the book. To interpret the relationship between the observed variables and the latent factors more easily, the most commonly used rotation method, varimax rotation, was selected. The importance weights of the criteria received from the 52 valid survey questionnaires were entered into SPSS to conduct factor analysis. The results of this analysis showed that the KMO measure of sampling

Table 7.2 Eigenvalues of factors obtained from factor analysis

Factors	Eigenvalues		
	Total	% of variance	% cumulative
1	5.251	29.172	29.172
2	3.277	18.208	47.380
3	2.341	13.004	60.384
4	2.216	12.312	72.696
5	0.968	5.377	78.073

adequacy was 0.644, greater than 0.5, suggesting that the sample was acceptable for factor analysis.

The Bartlett Test of Sphericity was 671.5, and its significance level was 0.000, indicating that the population correlation matrix was suitable for performing factor analysis. These implied that the data obtained supported the use of factor analysis, and these criteria could be grouped into a smaller set of the underlying factors (Raykov and Marcoulides 2008). Table 7.2 illustrates eigenvalues and % of variance of factors obtained from factor analysis. This table shows the factors in order of decreasing eigenvalues which simply denote the importance of the factors. As only the factors with eigenvalues greater than 1.0 should be considered, the first four factors, explaining 72.696 % of the total cumulative variance, were extracted in this book.

Table 7.3 presents rotated factor loadings or eigenvectors of these four factors extracted. From this table, the first factor concerned six criteria which are the "Visual performance," "Weather protection performance," "Health, safety and security of occupants and society," "Appearance demands," "Energy efficiency," and "Acoustic protection performance." This factor was named a "social" factor since the criteria mentioned show a direct impact on the occupants and society of a project during the occupation phase. This suggested that the architects and engineers seem to put the social issues as a priority when assessing the building envelope materials and designs. According to the Institutional Theory framework (see Sect. 5.3), it can be implied that these social criteria account for a major portion of the normative systems of the organizations aiming to fulfill their social obligations. These findings were consistent with suggestions from several studies showing that there is an increasing social awareness among the building professionals (Chen et al. 2010; Kibert 2008). Furthermore, it was found from the validation interviews that viewing these six criteria as a group of the "social" factor can provide the building professionals with a better sense of how important these criteria are.

The second factor was composed of the following six criteria: the "Material deliveries from suppliers," "Material handling," "Simplicity of design details," "Health and safety of workers," "Ease in construction with respect to time," and "Community disturbance." This factor reflected "buildability" of the building envelope. The factor reinforced the importance for development of the building envelope designs that can facilitate deliveries of the building envelope materials, simplicity and flexibility of the designs, and handling of the materials. At the same

Table 7.3 Rotated factor loadings of the four factors extracted

Criteria	Factors			
	1. Social	2. Buildability	3. Environmental	4. Economic
Visual performance	0.893			
Weather protection performance	0.869			
Health, safety and security of occupants	0.805			
Appearance demands	0.786			
Energy efficiency	0.744			
Acoustic protection performance	0.734			
Material deliveries from suppliers		0.876		
Material handling		0.826		
Simplicity of design details		0.826		
Health and safety of workers		0.803		
Ease in construction with respect to time		0.799		
Community disturbance		0.764		
Resource consumption			0.919	
Waste generation			0.895	
Energy consumption			0.814	
Long-term burdens				0.899
Durability of materials				0.829
Initial costs				0.810

time, it promoted use of the materials and construction methods that not only can be labor-efficient but also can enhance safety performance of a project and can reduce community disturbance on site during construction (Lam et al. 2007; Wong et al. 2006). The results from the validation interviews were found in accordance with these findings as the respondents suggested that the building professionals seem to be aware of adopting these criteria for achieving buildability due to its various benefits. Furthermore, based on the Institutional Theory framework, the findings suggested that the building professionals perceive the buildability criteria as the successful practices in design and construction of the building envelopes in Singapore.

The third factor consisted of three criteria, namely the “Resource consumption,” “Waste generation,” and “Energy consumption.” This factor seemed to describe “environmental” impacts of the building envelope. This suggested that, when conducting the assessment in the early design stage, the architects and engineers appear to be relatively aware of the environmental issues arising from construction-related activities. In addition, from the validation interviews, the respondents agreed that these three criteria as a group well capture the environmental impacts of the building envelope.

Although managing these environmental issues seems to rely on the performance of the contractors, the architects, and engineers in Singapore nowadays tend to select the building envelope materials and designs that can facilitate the contractor in doing so, thereby leading to better overall project and construction management. Pasquire and Connolly (2002) and Chen et al. (2010) also found that reducing environmental impacts of a design benefits a project in several ways. The results showed the evidence pointing to the trend that the effect of environmental issues of a design has gained more recognition from the building professionals. In addition, with the Institutional Theory framework in mind, this factor appears to be an important part of the effort of the building professionals to obtain certification and accreditation from outside organizations.

The last factor was made of three criteria, including the "Long-term burdens," "Durability of materials," and "Initial costs." This factor represented "economic" impacts of the building envelope which refers to the influence of first costs and long-term costs of the building envelope materials and designs. This underscored that the "economic" factor is one of the factors governing the sustainability awareness of the building professionals as suggested by the Institutional Theory framework. Although this factor had the lowest variance among the underlying factors, from a traditional view, economic considerations are always a main project driver when building professionals assess building materials and designs (Bryan 2010; Chua and Chou 2010a). However, it was found that the first costs may no longer be the sole economic criterion considered by architects and engineers. One possible explanation is that there seems to be a growing realization of the advantages in using materials and designs with higher durability and lower long-term burdens (Chen et al. 2010).

Indeed, professionals believe that it is important to consider the first costs and long-term costs because, in many cases, the first costs of the materials and designs can be largely offset by potential reductions of their long-term costs (Jaillon and Poon 2008). From the validation interviews, the respondents were of the view that these three criteria as a group well represent the key economic considerations for the assessment of the building envelope materials and designs. Furthermore, this factor was found helpful for reminding the building professionals to find a balance between the first costs, durability, and long-term burdens of the building envelope materials and designs.

Importantly, the findings as described above supported the first hypothesis of this book that the perspectives of the building professionals on the criteria for the achievement of sustainability and buildability can be modeled by the four underlying factors. Importantly, the respondents from the validation interviews agreed that the new structure can better capture the essence of applying the criteria in the assessment of the building envelope materials and designs for achieving sustainability and buildability. As such, the assessment of the building envelope materials and designs based on the four factors extracted would provide the building professionals with the concise structure of sustainability and buildability in a more defined and tangible way, helping to deliver more sustainable and buildable building envelope design solutions.

7.3.3 Ranking Analysis

Equation (6.1) was applied to determine the SI value of the criteria based on their importance weights obtained from the survey of the architects, C&S engineers, M&E engineers, and all the respondents. Tables 7.4 and 7.5 show the SI values and

Table 7.4 SI values obtained from ranking analysis

Criteria	Severity index (SI)				Level
	Architects	C&S engineers	M&E engineers	All respondents	
Environmental criteria					
Waste generation	0.590	0.586	0.600	0.592	M
Resource consumption	0.514	0.543	0.624	0.558	M
Energy consumption	0.581	0.600	0.471	0.550	M
Economic criteria					
Initial costs	0.895	0.857	0.812	0.858	H
Long-term burdens	0.771	0.757	0.706	0.746	H-M
Durability	0.724	0.743	0.647	0.704	H-M
Social criteria					
Health, safety and security of occupants	0.886	0.829	0.776	0.835	H
Weather protection performance	0.867	0.814	0.729	0.808	H
Visual performance	0.838	0.729	0.765	0.804	H
Appearance demands	0.905	0.771	0.694	0.800	H
Energy efficiency	0.848	0.657	0.800	0.781	H-M
Acoustic protection performance	0.648	0.614	0.671	0.646	H-M
Buildability criteria					
Health and safety of workers	0.752	0.757	0.788	0.765	H-M
Simplicity of design details	0.638	0.686	0.612	0.642	H-M
Community disturbance	0.695	0.629	0.529	0.623	H-M
Ease in construction with respect to time	0.524	0.786	0.553	0.604	H-M
Material handling	0.629	0.671	0.494	0.596	M
Material deliveries from suppliers	0.533	0.500	0.482	0.508	M

Table 7.5 Rankings results obtained from ranking analysis

Criteria	Ranking				Level
	Architects	C&S engineers	M&E engineers	All respondents	
Environmental criteria					
Waste generation	14	16	13	15	M
Resource consumption	18	17	11	16	M
Energy consumption	15	15	18	17	M
Economic criteria					
Initial costs	2	1	1	1	H
Long-term burdens	7	6	7	8	H-M
Durability	9	8	10	9	H-M
Social criteria					
Health, safety and security of occupants	3	2	4	2	H
Weather protection performance	4	3	6	3	H
Visual performance	6	9	5	4	H
Appearance demands	1	5	8	5	H
Energy efficiency	5	12	2	6	H-M
Acoustic protection performance	11	14	9	10	H-M
Buildability criteria					
Health and safety of workers	8	7	3	7	H-M
Simplicity of design details	12	10	12	11	H-M
Community disturbance	10	13	15	12	H-M
Ease in construction with respect to time	17	4	14	13	H-M
Material handling	13	11	16	14	M
Material deliveries from suppliers	16	18	17	18	M

their corresponding ranking results, respectively, for the criteria in a descending order categorized by the four factors extracted.

According to these tables, five criteria obtained the “High” importance level with the SI values ranging between 0.800 and 0.858. The “Initial costs” was ranked as first in this level as well as among all the criteria. This suggested that initial costs, including material costs and construction costs, seemed to still be a primary concern of a project. In addition, while attempting to minimize the initial costs, the architects and engineers seek the materials and designs that can be applied to enhance satisfactions of the occupants (Kibert 2008). As “Health, safety and security of occupants (SC3),” “Weather protection performance (SC4),” “Visual performance (SC6),” and “Appearance demands (SC2)” also received the “High” importance level, this suggested that, from the perspectives of the architects and engineers, these four criteria are among the most importance performances of a building expected by the occupants.

Apart from the first five criteria discussed, eight criteria were recorded with the "High-Medium" importance level with the SI values ranging between 0.604 and 0.781. The "Energy efficiency" received the highest SI value among the criteria in this level. Energy efficiency is an important feature in making a building design sustainable. Some of the reasons supporting this could mainly be due to forces from the government to promote energy efficient buildings as well as efforts from the building professionals to reinforce their obligations to the occupants and environment (Scott 2008). The other criterion in this level that should be highlighted is the "Health and safety of workers." This criterion was rated as first in the buildability criteria category. This suggested that the architects and engineers tend to adopt the concept of buildability to promote use of the building envelope materials and designs that can enhance safety and health of the workers during construction. For example, it was found that nowadays prefabrication has been increasingly applied due to its manpower and safety benefits (Chen et al. 2010; Hinze et al. 2006).

Five criteria obtained the "Medium" importance level with the SI values ranging between 0.508 and 0.596. Interestingly, all the environmental criteria which are the "Waste generation," "Resource consumption," and "Energy consumption" fell within this level. Although these criteria received relatively low SI values, the results from the validation interviews suggested that, in practice, the architects and engineers in Singapore attempt to select the building envelope materials and designs that can facilitate a project in reducing waste generation, resources consumption, and energy consumption during construction. Corresponding to these observations, previous studies found that many organizations have incorporated the policies related to corporate environmental strategy, environmental impact assessments and waste management to ensure that all aspects of their business have the least harmful effect on the environment (Tsai et al. 2011).

It is also worth mentioning that the "Material deliveries from suppliers" received the lowest SI value in this level and among all the criteria. From the validation interviews, the respondents acknowledged that this value seemed to be just a representative of the relative importance of this criterion as compared to the other criteria. This could not simply be implied that the architects and engineers did not take into account this criterion when assessing the building envelope materials and designs. In accordance with this, Vrijhoef and Koskela (2000) highlighted that deliveries of building materials associated with availability, lead times, traveling distance and quality of the building envelope materials are an essential consideration to ensure the smooth construction process of a project.

Furthermore, as can be seen, considering the top five most important criteria rated by all the respondents, the second to fifth most important criteria lied in the social criteria category. This illustrated that the architects and engineers seem to put the social issues affecting satisfactions of the occupants as priority when assessing the building envelope materials and designs. These findings were in agreement with suggestions from several other studies demonstrating that there is an increasing social awareness among the building professionals (Chen et al. 2010; Kibert 2008). More specifically, the results from the validation interviews suggested that this could be because of the concern that meeting minimum requirements of relevant regulations and standards does not guarantee satisfactions of the occupants. Furthermore, Yang (2004) and Kibert (2008) pointed out these satisfactions are likely subject to uncertainty and intuitive judgments, so much so that achieving these satisfactions appears to be heavily reliant on capability in terms of knowledge and experience of the designers.

7.3.4 Spearman Rank Correlation

Spearman rank correlation was applied to investigate whether each party shares the same perspectives regarding its ranking of the criteria. As shown in Table 7.6, results from Spearman rank correlation indicated that all the correlations between the rankings by the three parties were significant at 0.01 (2-tailed).

These findings were in agreement with the concepts of the Institutional Theory framework suggesting that the organizations in the same arena tend to progress in the same direction, and, as a result, this creates similarities among the organizations (Scott 2008). Nevertheless, the correlation coefficient between the rankings by the architects and the C&S engineers (Coefficient = 0.707) and the correlation coefficient between the rankings by the architects and the M&E engineers (Coefficient = 0.796) were higher than the correlation coefficient between the rankings by the C&S engineers and M&E engineers (Coefficient = 0.616). This was not unexpected because, from the validation interviews, the respondents commented that as the architects typically play leading roles in the design development of the private high-rise residential buildings in the early design stage; this may allow the architects to be more familiar with the perspectives of both the C&S engineers and M&E engineers.

To gain further in-depth understanding of the findings, Table 7.7 shows the top five most important criteria with respect to each party (Hwang et al. 2009). Although the book demonstrated earlier that the correlations between the overall

Table 7.6 Spearman rank correlation coefficients

Party	Correlation coefficient	Architects	C&S engineers	M&E engineers
Architects	Correlation coefficient	1	0.707[a]	0.796[a]
	Sig. (2-tailed)		0.001	0.000
C&S engineers	Correlation coefficient	0.707[a]	1	0.616[a]
	Sig. (2-tailed)	0.001		0.006
M&E engineers	Correlation coefficient	0.796[a]	0.616[a]	1
	Sig. (2-tailed)	0.000	0.006	

[a]Correlation is significant at the 0.01 level (2-tailed)

Table 7.7 Top-five most important criteria of different parties

Ranking	Criteria			
	Architects	C&S engineers	M&E engineers	All respondents
1	Appearance demands	Initial costs[a]	Initial costs[a]	Initial costs[a]
2	Initial costs[a]	Health, safety and security of occupants[a]	Energy efficiency	Health, safety and security of occupants[a]
3	Health, safety and security of occupants[a]	Weather protection performance	Health and safety of workers	Weather protection performance
4	Weather protection performance	Ease in construction with respect to time	Health, safety and security of occupants[a]	Visual performance
5	Energy efficiency	Appearance demands	Visual performance	Appearance demands

[a]The criterion is found to be common among the parties

rankings of different parties were statistically significant, only two criteria, which are the "Initial costs" and "Health, safety and security of occupants," were found to be common between the top five most important criteria rankings by the architects, C&S engineers, M&E engineers, and all the respondents. In reality, this can pose major challenges, for example disagreement between the parties, to the building professionals during the assessment of the materials and designs (Behfar et al. 2008; Fryer 2004). Furthermore, the findings from the validation interviews supported the view that the architects and engineers often faced difficulties in managing the difference of the importance weights that each party gives to the criteria.

This observation is evident especially in the early design stage where the architects and engineers seem to consider only a first few most important criteria appearing in their mind to save time, and these professionals, in many events, seem to work towards multiple objectives because of their different responsibilities (El-Alfy 2010). This can also be seen in Table 7.7 where, for example, while the "Ease in construction with respect to time" was included in the top five most important criteria ranked by the C&S engineers, this criterion was not a part of the top five most important criteria ranked by the architects, M&E engineers, and all the respondents. This suggested that it would be useful to develop a DSS to assist the building professionals to discuss and find out the optimum point that can offer a good balance between their expectations as a team. In parallel, assessing the importance weights of the criteria as a team would also provide the building professionals a better opportunity to share, discuss and negotiate over multiple expectations to reach the consensual solution.

7.4 Summary

This chapter presented the findings and discussion from the survey to test the first hypothesis. The results from factor analysis applied to group the responses obtained from the survey supported the first hypothesis that the criteria for assessment of the building envelope materials and designs can be grouped into four underlying factors as suggested by the Institutional Theory framework. These four factors include the environmental, economic, social, and buildability factors. This four-factor structure was found useful in promoting the assessment of the building envelope materials and designs for achieving sustainability and buildability. In addition, the results from ranking test and Spearman correlation test suggested that this new structure should be used together with a DSS to help the building professionals find a good balance between the criteria.

Chapter 8
Prototype of the KBDSS-QFD and Case Studies Results

8.1 Introduction

This chapter is dedicated to the development of the detailed KBDSS-QFD tool and its prototype and testing the second hypothesis of this book through case studies. This chapter presents designing the architecture of the KBDSS-QFD tool (Sect. 8.2) and developing its elements including the HOQSB (Sect. 8.3), KMS (Sect. 8.4), fuzzy inference engine (Sect. 8.5), and user interface (Sect. 8.6). The chapter also presents a hypothetical example (Sect. 8.7) to explain steps to use the tool for assessing the building envelope materials and designs. After that, the prototype of the KBDSS-QFD tool is built (Sect. 8.8). Components of the prototype are presented in regard to the steps for assessing the building envelope materials and designs, and this is followed by verification and debugging of the prototype (Sect. 8.9). The Chapter then provides characteristics of the three case studies (Sect. 8.10) and subsequently discusses the in-depth findings from these case studies (Sect. 8.11) with respect to the framework analysis.

8.2 Architecture of the Detailed KBDSS-QFD Tool

The book incorporated feedbacks from the semi-structured interviews (see Appendix D) into the conceptual KBDSS-QFD tool as well as applied the UML to develop the detailed KBDSS-QFD tool. Figure 8.1 presents the architecture of the detailed KBDSS-QFD tool in the form of the UML-objected-based diagram. Based on the object-orientated technique, the diagram shows the structure of the KBDSS-QFD tool consisting of four major objects which are HOQSB, KMS, fuzzy inference engine, and user interface. In brief, the HOQSB has five major rooms

S. Natee et al., *Quality Function Deployment for Buildable and Sustainable Construction*, DOI 10.1007/978-981-287-849-6_8

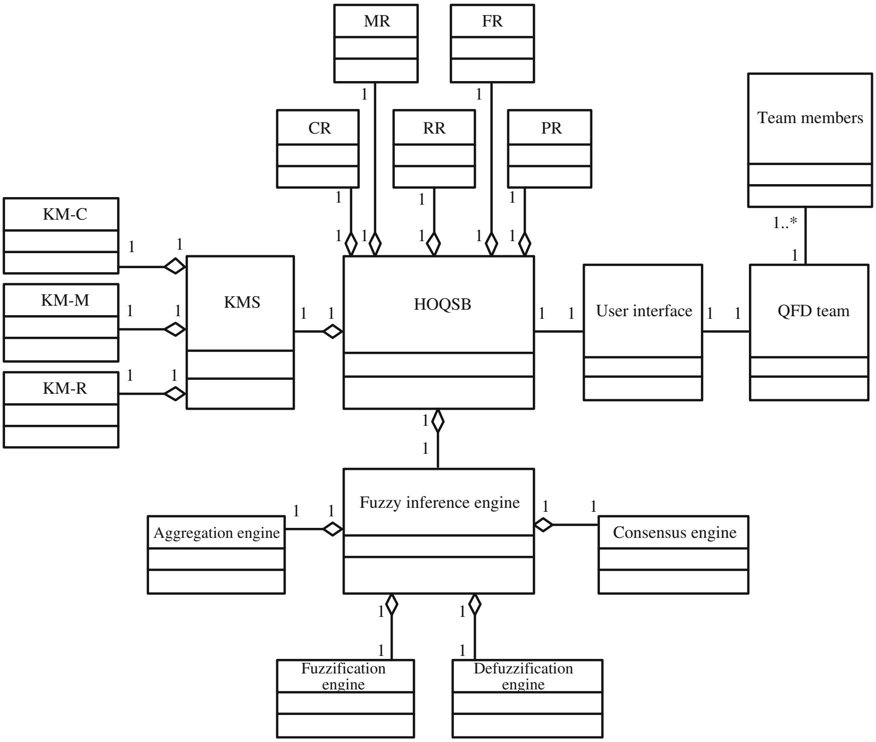


Fig. 8.1 Architecture of the detailed KBDSS-QFD tool

which are the criteria room (CR), materials and designs room (MR), relationships room (RR), fuzzy algorithms room (FR), and preference list room (PR). The KMS comprises three subsystems. These are the knowledge management for the criteria system (KM-C), knowledge management for the building envelope materials and designs system (KM-M), and knowledge management for the relationships between the criteria and materials system (KM-R). The user interface was developed with respect to the five rooms in the HOQSB. The fuzzy set theory and fuzzy consensus scheme were integrated into the fuzzy inference engine to facilitate the decision-making process.

8.3 House of Quality for Sustainability and Buildability (HOQSB)

The HOQSB is the central element serving as the blackboard of this tool (see Sect. 2.4). This element was developed to organize and structure the decision-making process for the assessment of the building envelope materials and designs based on the rooms in the HOQSB. The CR provides the sustainability and buildability criteria to assist the DMs in selecting key criteria for the assessment of the building envelope materials and design alternatives. The MR shows the building envelope materials and design alternatives to facilitate the DMs in selecting possible building envelope materials and design alternatives.

The RR structures the relationships between the criteria and the design alternatives and guides the DMs with the importance weights of the criteria and performance satisfactions of the materials and design alternatives. This room was also organized in the form of a matrix to show an impact of parameters on each criterion. The FR is equipped with the fuzzy operations which, in this tool, are based on the fuzzy set theory to prioritize the criteria and building envelope design alternatives. The PR then finalizes the results from the FR and reports these in the form of the preference list of the design alternatives ranked by a sustainability and buildability index (SBI).

Figure 8.2 shows the UML-based information class diagram for determining the SBI of the design alternative. As illustrated in this figure, the SBI is a sum of products of the importance weights of the criteria and performance satisfactions

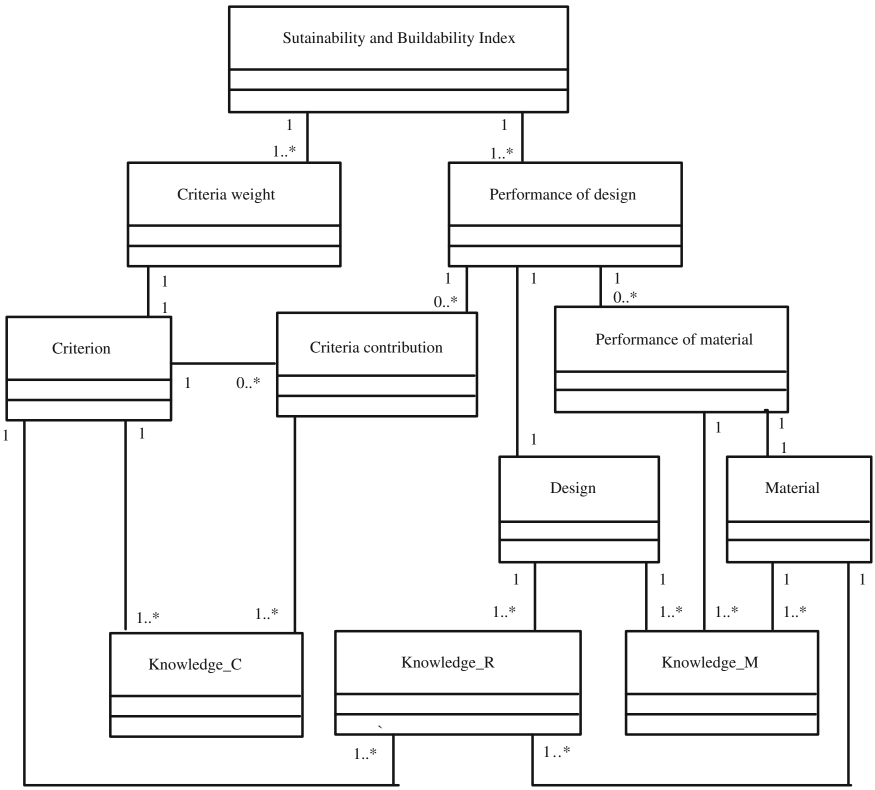


Fig. 8.2 UML-based information class diagram for determining the SBI

with respect to each criterion of the design alternative. The tool allows two types of the criteria for the assessment of the performance satisfaction of the design alternative; namely criteria for overall design assessment and criteria for individual material assessment. The performance satisfaction of the design alternative with respect to the criteria for overall design assessment is determined by the performance satisfaction of that alternative as a whole.

In contrast, the performance satisfaction of the design alternative with respect to the criteria for individual material assessment is modeled by a sum of products of the performance satisfactions of the materials that assemble such alternative and contribution weights of the these materials. This structure is provided as an option for the users if there is a need to breakdown the performance satisfaction of the design alternative into the performance satisfactions of the materials individually for achieving a better estimation. Overall, each criterion is associated with one importance weight. It may also involve one or many sets of the knowledge in the KM-C and KM-R. The contribution weight of the material is associated with one or many sets of the knowledge in the KM-C. Furthermore, each material and design alternative can relate to one or many sets of the knowledge in the KM-M and KM-R.

Hence, the book offers two approaches for the determination of the overall performance of the design alternatives. The first approach applies a divide and conquer approach to calculate the overall performance of the alternative where different components of a design alternative are evaluated separately and then aggregated using fuzzy logic. However, it was found that, in theory, a set of satisfactory components when combined could produce an unsatisfactory performance. For example, it was suggested that the individual performance of fixed glass wall and concrete shading device was satisfied, if these were evaluated separately. Nevertheless, if the concrete shading device was installed on the fixed glass wall, an overall performance of this specific design could be unsatisfactory. This could be due to potential design and installation conflicts, and, the first approach may not be able to take into account these conflicts.

In response to this, the second approach is employed. Through this second approach, the DMs directly assess the overall performance of the design alternatives by considering aspects including potential conflicts between individual materials as a whole. Overall the first approach should be applied when considering the criteria that do not introduce significant conflicts between the building envelope materials such as cost, energy consumption, and waste generation criteria. These criteria correspond with the criteria for individual material assessment. At the same time, the second approach should be considered when dealing with the criteria that may introduce possible conflicts between the individual materials such as appearance demands criterion. These criteria are the basis for overall design assessment discussed above.

The DMs may refer to the KMS to find knowledge regarding selection of the appropriate approach for determination of the overall performance of the alternatives with respect to each criterion. Applying the concept of the interrelationship matrix discussed in Sect. 2.14, the KMS through its KM-M stores the knowledge of building envelope materials including potential conflicts between individual materials with respect to each criterion.

8.4 Knowledge Management System (KMS)

The KMS comprising the KM-C, KM-M, and KM-R was developed in the Microsoft Access environment. The KM-C, KM-M, and KM-R are employed to store the knowledge for helping the DMs in making the decisions in the CR, MR, and RR in the HOQSB, respectively. The knowledge in the KM-C, KM-M, and KM-R of KMS was acquired through the literature reviews and semi-structure interviews (see Appendix E) and represented as decision rules in the IF/THEN format as well as textual data (Yang 2004). These decision rules were validated by asking the experts to review and correct them (Fischer and Tatum, 1997).

Figure 8.3 shows the relational diagram of the KMS presenting all the parameters and their knowledge in the KM-C, KM-M, and KM-R considered in this book. The KM-C covers the "Criteria for sustainability and buildability" and "Criteria with contribution weight" tables. The KM-M governs the "Project summary," "Wall material for design," "Wall material for handling," "Wall material for construction," "Wall material for maintenance," "Window material for design," "Window material for handling," "Window material for construction," "Window material for maintenance," "Shading material for design," "Shading material for handling," "Shading material for construction," and "Shading material for maintenance" tables. The KM-R covers the "Performance of individual material," "Performance of alternative," and "Matrix for assessment" tables.

8.4.1 Knowledge Management of the Criteria System (KM-C)

The literature reviews and pilot study suggested 18 major criteria applied by the architects and engineers for the assessment of the building envelope materials and designs (see Sect. 3.5). These criteria were grouped into the environmental, economic, social, and buildability criteria categories as suggested by the institutional theory framework developed (see Sect. 5.3). The knowledge related to these criteria including descriptions, relevant laws and regulations, and types of the criteria and importance weights were acquired and refined based on the literature reviews and semi-structured interviews. This set of the knowledge was stored in the KM-C as shown in the screenshot in Fig. 8.4 to allow the DMs to manage, maintain current, and add new knowledge.

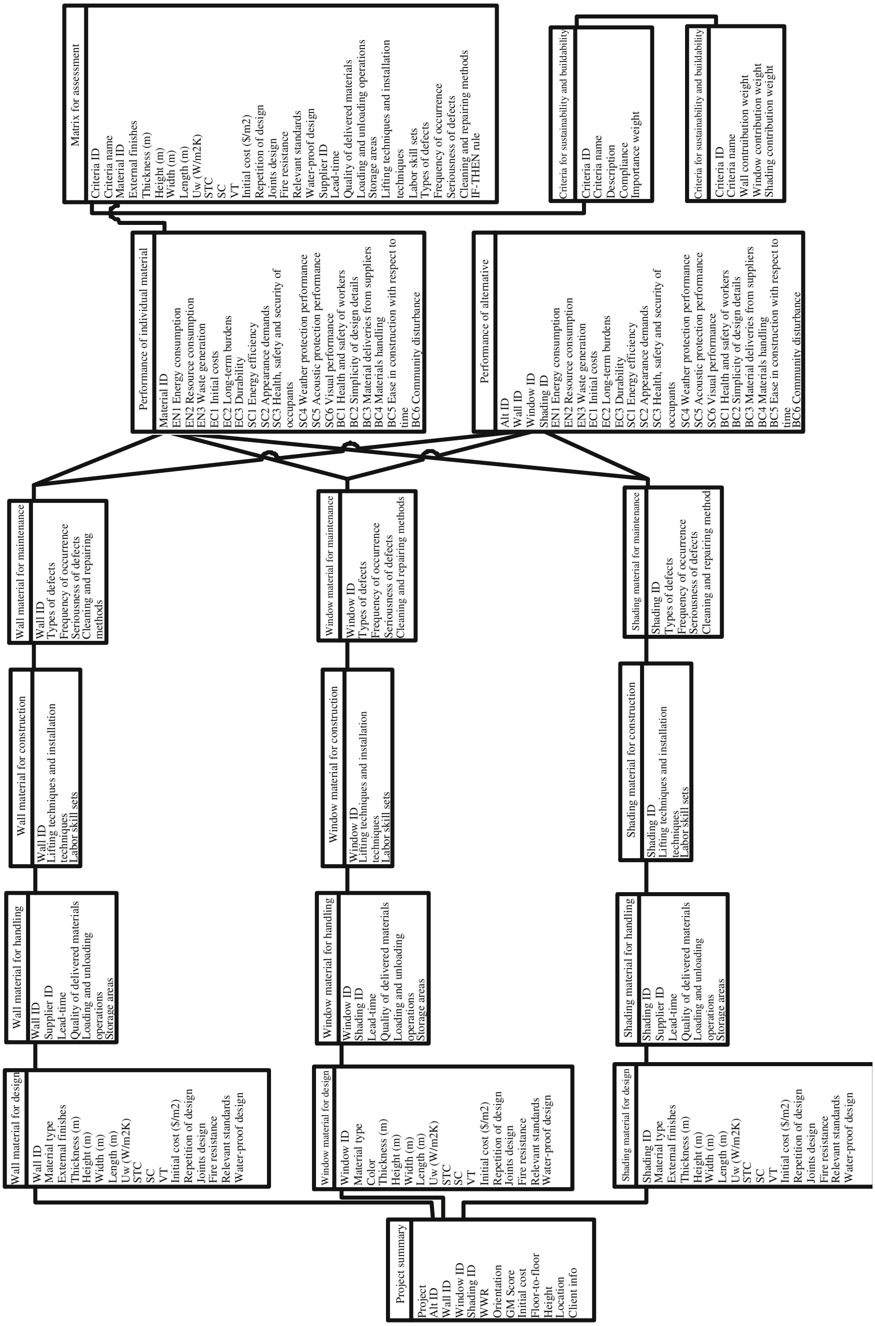
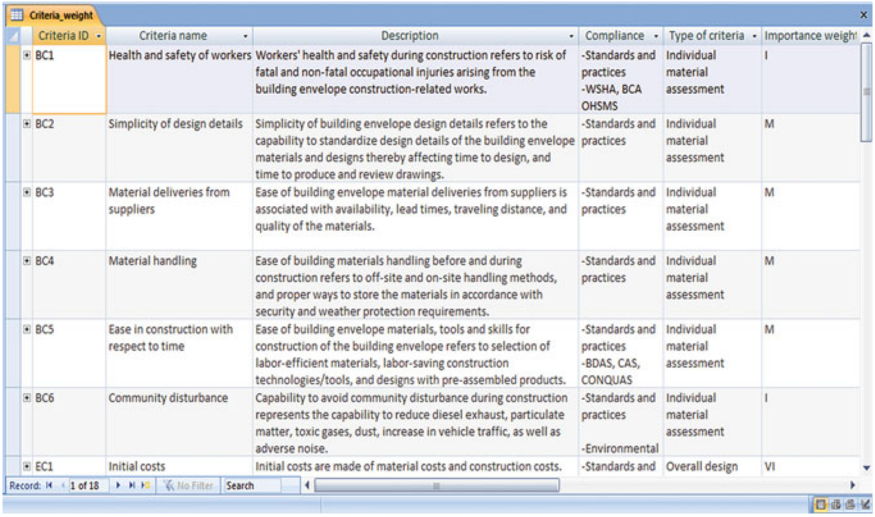


Fig. 8.3 Relational diagram of the KMS



Criteria ID	Criteria name	Description	Compliance	Type of criteria	Importance weight
BC1	Health and safety of workers	Workers' health and safety during construction refers to risk of fatal and non-fatal occupational injuries arising from the building envelope construction-related works.	-Standards and practices -WSHA, BCA OHSMS	Individual material assessment	I
BC2	Simplicity of design details	Simplicity of building envelope design details refers to the capability to standardize design details of the building envelope materials and designs thereby affecting time to design, and time to produce and review drawings.	-Standards and practices	Individual material assessment	M
BC3	Material deliveries from suppliers	Ease of building envelope material deliveries from suppliers is associated with availability, lead times, traveling distance, and quality of the materials.	-Standards and practices	Individual material assessment	M
BC4	Material handling	Ease of building materials handling before and during construction refers to off-site and on-site handling methods, and proper ways to store the materials in accordance with security and weather protection requirements.	-Standards and practices	Individual material assessment	M
BC5	Ease in construction with respect to time	Ease of building envelope materials, tools and skills for construction of the building envelope refers to selection of labor-efficient materials, labor-saving construction technologies/tools, and designs with pre-assembled products.	-Standards and practices -BDAS, CAS, CONQUAS	Individual material assessment	M
BC6	Community disturbance	Capability to avoid community disturbance during construction represents the capability to reduce diesel exhaust, particulate matter, toxic gases, dust, increase in vehicle traffic, as well as adverse noise.	-Standards and practices -Environmental	Individual material assessment	I
EC1	Initial costs	Initial costs are made of material costs and construction costs.	-Standards and	Overall design	VI

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Fig. 8.4 Knowledge of the criteria in the KM-C

Importantly, this tool also allows the DMs to breakdown each criterion into several subcriterion based on its description. For example, the "BC3" material deliveries from suppliers may be divided into "Relationship with suppliers," "Lead-time," and "Quality of delivered material" subcriteria. Likewise, the "SC2" appearance demands may be divided into "style," "image," and "aesthetics" subcriteria.

8.4.2 *Knowledge Management of the Materials and Designs System (KM-M)*

The building envelope systems in this book consist of three main categories of the building envelope materials which are the external wall, window, and shading device. As there could be many possible materials and designs, the KMS of this book was developed in the first instance based on only the basic building envelope materials as shown in Fig. 8.5 (see Sect. 4.4).

In brief, the external wall category covers the following six material types; namely precast concrete cladding, in-filled clay brick, concrete block, cast in-situ reinforced concrete (RC), full fixed glass, and full glass curtain walls. In the window category, the glazing materials include only the following four glazing materials types, namely clear single glazing, low-E clear single glazing, double clear glazing, and low-E double clear glazing. In the shading device category, the book includes concrete and aluminum as material options of a horizontal shading device. Based on these considerations, the 48 possible design alternatives were formulated as shown in the screenshot in Fig. 8.6.

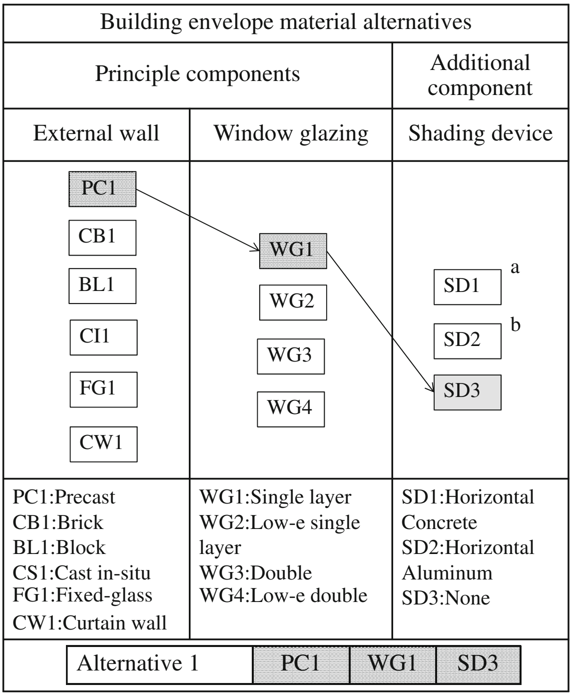
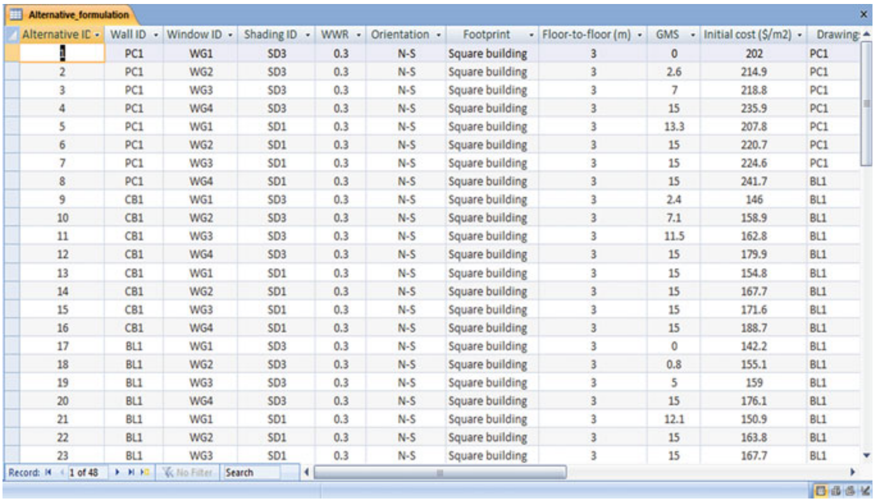


Fig. 8.5 Building envelope materials and designs in the KM-M, **a** for the precast concrete wall, only the concrete shading device prefabricated as part of the panel by the manufacturer is considered. For the brickwall, concrete blockwall, and cast in-situ RC wall, only the concrete shading device installed on site is considered, **b** for the fixed glass and glass curtain wall, only the aluminum shading device installed on site is considered



Alternative_formulation

Alternative ID	Wall ID	Window ID	Shading ID	WWR	Orientation	Footprint	Floor-to-floor (m)	GMS	Initial cost ($/m2)	Drawing
1	PC1	WG1	SD3	0.3	N-S	Square building	3	0	202	PC1
2	PC1	WG2	SD3	0.3	N-S	Square building	3	2.6	214.9	PC1
3	PC1	WG3	SD3	0.3	N-S	Square building	3	7	218.8	PC1
4	PC1	WG4	SD3	0.3	N-S	Square building	3	15	235.9	PC1
5	PC1	WG1	SD1	0.3	N-S	Square building	3	13.3	207.8	PC1
6	PC1	WG2	SD1	0.3	N-S	Square building	3	15	220.7	PC1
7	PC1	WG3	SD1	0.3	N-S	Square building	3	15	224.6	PC1
8	PC1	WG4	SD1	0.3	N-S	Square building	3	15	241.7	BL1
9	CB1	WG1	SD3	0.3	N-S	Square building	3	2.4	146	BL1
10	CB1	WG2	SD3	0.3	N-S	Square building	3	7.1	158.9	BL1
11	CB1	WG3	SD3	0.3	N-S	Square building	3	11.5	162.8	BL1
12	CB1	WG4	SD3	0.3	N-S	Square building	3	15	179.9	BL1
13	CB1	WG1	SD1	0.3	N-S	Square building	3	15	154.8	BL1
14	CB1	WG2	SD1	0.3	N-S	Square building	3	15	167.7	BL1
15	CB1	WG3	SD1	0.3	N-S	Square building	3	15	171.6	BL1
16	CB1	WG4	SD1	0.3	N-S	Square building	3	15	188.7	BL1
17	BL1	WG1	SD3	0.3	N-S	Square building	3	0	142.2	BL1
18	BL1	WG2	SD3	0.3	N-S	Square building	3	0.8	155.1	BL1
19	BL1	WG3	SD3	0.3	N-S	Square building	3	5	159	BL1
20	BL1	WG4	SD3	0.3	N-S	Square building	3	15	176.1	BL1
21	BL1	WG1	SD1	0.3	N-S	Square building	3	12.1	150.9	BL1
22	BL1	WG2	SD1	0.3	N-S	Square building	3	15	163.8	BL1
23	BL1	WG3	SD1	0.3	N-S	Square building	3	15	167.7	BL1

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Fig. 8.6 Knowledge of the design alternatives in the KM-M

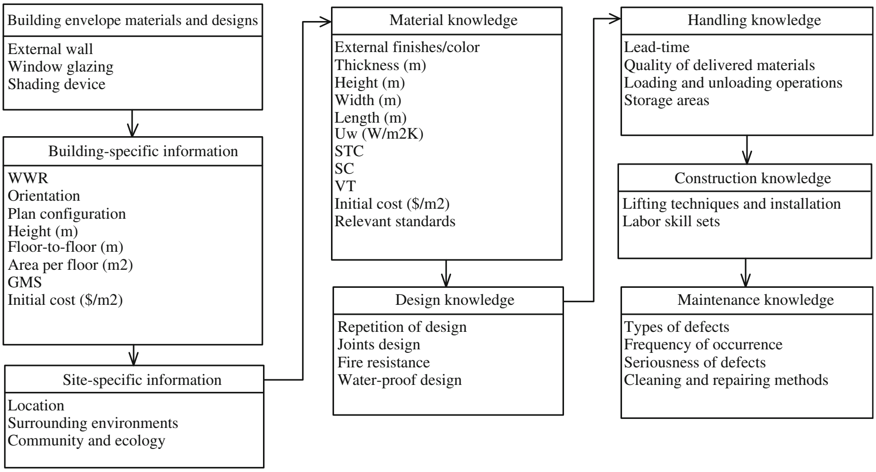


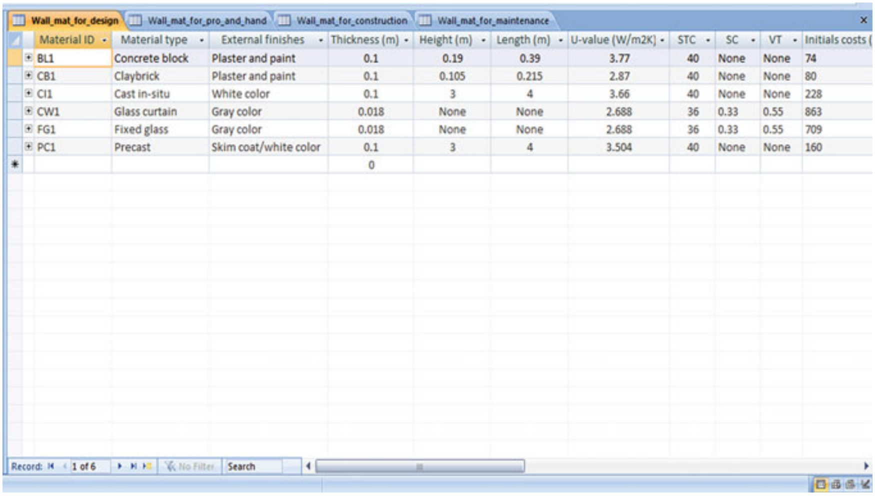
Fig. 8.7 Parameters in relation to the materials and designs used in the KM-M

The parameters related to the building envelope materials and design alternatives as shown in Fig. 8.7 were acquired, refined, and stored in the KM-M with respect to the design, handling, construction, and maintenance phases. Figure 8.8 illustrates an example of the KM-M screenshot developed to store the knowledge of the external wall materials with respect to the design, handling, construction, and maintenance phases.

8.4.3 Knowledge Management of Relationships Between the Criteria and Design Alternatives System (KM-R)

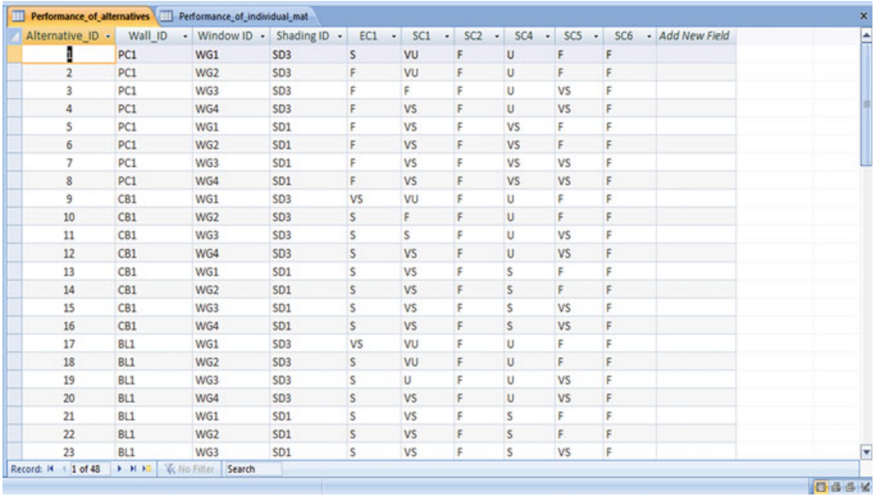
The KM-R was built to manage the relationships between the criteria and the building envelope materials and designs. This system as shown in the screenshot in Fig. 8.9 stores the performance satisfactions of the individual materials and designs alternatives with respect to the criteria for individual material assessment and criteria for overall design assessment, respectively. For instance, Fig. 8.9 suggests that the performance satisfaction of the design alternative “1” PC1WG1SD3 with respect to the “EC1” Initial costs is “S” Satisfied.

In addition, the KM-R also guides the DMs in making the decisions by showing the relationship matrix consisting of the IF-THEN rules and key parameters affecting the assessment of the performance satisfactions as shown in the screenshot in Fig. 8.10. “*Yes*” indicates that the parameter in the column has an impact on the assessment of the performance satisfaction with respect to the criterion in the row. This figure purposely presents only a few parameters, and the remaining parameters



Material ID	Material type	External finishes	Thickness (m)	Height (m)	Length (m)	U-value (W/m2K)	STC	SC	VT	Initials costs (
BL1	Concrete block	Plaster and paint	0.1	0.19	0.39	3.77	40	None	None	74
CB1	Claybrick	Plaster and paint	0.1	0.105	0.215	2.87	40	None	None	80
CI1	Cast in-situ	White color	0.1	3	4	3.66	40	None	None	228
CW1	Glass curtain	Gray color	0.018	None	None	2.688	36	0.33	0.55	863
FG1	Fixed glass	Gray color	0.018	None	None	2.688	36	0.33	0.55	709
PC1	Precast	Skim coat/white color	0.1	3	4	3.504	40	None	None	160
			0							

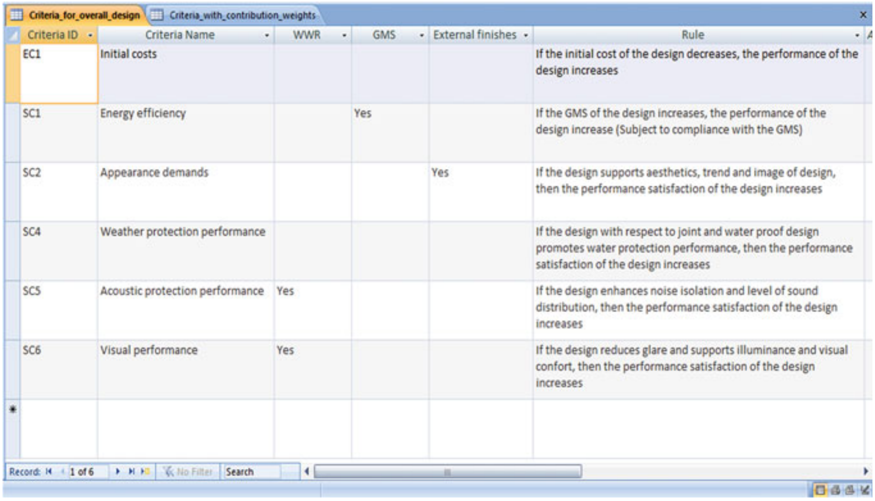
Fig. 8.8 Knowledge of the external wall in the KM-M



Alternative_ID	Wall_ID	Window ID	Shading ID	EC1	SC1	SC2	SC4	SC5	SC6	Add New Field
1	PC1	WG1	SD3	S	VU	F	U	F	F	
2	PC1	WG2	SD3	F	VU	F	U	F	F	
3	PC1	WG3	SD3	F	F	F	U	VS	F	
4	PC1	WG4	SD3	F	VS	F	U	VS	F	
5	PC1	WG1	SD1	F	VS	F	VS	F	F	
6	PC1	WG2	SD1	F	VS	F	VS	F	F	
7	PC1	WG3	SD1	F	VS	F	VS	VS	F	
8	PC1	WG4	SD1	F	VS	F	VS	VS	F	
9	CB1	WG1	SD3	VS	VU	F	U	F	F	
10	CB1	WG2	SD3	S	F	F	U	F	F	
11	CB1	WG3	SD3	S	S	F	U	VS	F	
12	CB1	WG4	SD3	S	VS	F	U	VS	F	
13	CB1	WG1	SD1	S	VS	F	S	F	F	
14	CB1	WG2	SD1	S	VS	F	S	F	F	
15	CB1	WG3	SD1	S	VS	F	S	VS	F	
16	CB1	WG4	SD1	S	VS	F	S	VS	F	
17	BL1	WG1	SD3	VS	VU	F	U	F	F	
18	BL1	WG2	SD3	S	VU	F	U	F	F	
19	BL1	WG3	SD3	S	U	F	U	VS	F	
20	BL1	WG4	SD3	S	VS	F	U	VS	F	
21	BL1	WG1	SD1	S	VS	F	S	F	F	
22	BL1	WG2	SD1	S	VS	F	S	F	F	
23	BL1	WG3	SD1	S	VS	F	S	VS	F	

Fig. 8.9 Performance satisfactions of the design alternatives in the KM-R

can be found in Fig. 8.7. Figure 8.10 also shows the IF-THEN rules with respect to the criteria for overall design assessment. For example, the IF-THEN rule with respect to the "SC2" appearance demands is "If the design supports aesthetics, trend and image of design, then the performance satisfaction of the design increases." Importantly, to keep the knowledge in the KM-R alive, these relationships can be edited and updated, and new parameters are allowed to be inserted as necessary.



Criteria ID	Criteria Name	WWR	GMS	External finishes	Rule
EC1	Initial costs				If the initial cost of the design decreases, the performance of the design increases
SC1	Energy efficiency		Yes		If the GMS of the design increases, the performance of the design increase (Subject to compliance with the GMS)
SC2	Appearance demands			Yes	If the design supports aesthetics, trend and image of design, then the performance satisfaction of the design increases
SC4	Weather protection performance				If the design with respect to joint and water proof design promotes water protection performance, then the performance satisfaction of the design increases
SC5	Acoustic protection performance	Yes			If the design enhances noise isolation and level of sound distribution, then the performance satisfaction of the design increases
SC6	Visual performance	Yes			If the design reduces glare and supports illuminance and visual confort, then the performance satisfaction of the design increases

Fig. 8.10 IF-THEN rules and important parameters in the KM-R

8.5 Fuzzy Inference Engine

The fuzzy inference engine was developed based on the fuzzy set theory as explained in Chap. 2. This engine plays an important role to compute the SBI of each design alternative. There are four major parts working together in the fuzzy inference engine including fuzzy aggregation, fuzzification, defuzzification, and consensus scheme engines. Through the use of these four parts, the fuzzy inference engine processes the fuzzy linguistic terms received from the DMs and translates these into the SBI of the design alternative and consensus level of each decision.

8.5.1 Fuzzy Linguistic Terms

This book adopted the triangular fuzzy numbers to define the fuzzy linguistic terms for assessing the importance weights of the criteria, contribution weights of the materials, and the performance satisfactions of the building envelope materials and designs as shown in Fig. 8.11. Their corresponding fuzzy numbers are presented in Table 8.1.

It is assumed that there are n DMs in the design team who assess the importance weights of k criteria and performance satisfactions of g materials and f design alternatives. A linguistic set of both the importance and contribution weights is; W = (very unimportant (VU), unimportant (U), medium (M), important (I), very Important (VI)). The fuzzy numbers of the importance and contribution weights are $\tilde{W}_{\mathrm{tj}} = \left(p_{tj}, q_{tj}, r_{tj}\right)$ and $\tilde{W}_{atj} = (d_{atj}, e_{atj}, f_{atj})$, respectively, where t = (1, 2, . . ., k), a = (external wall, window glazing, shading device, …, g) and j = (1, 2, …, n).

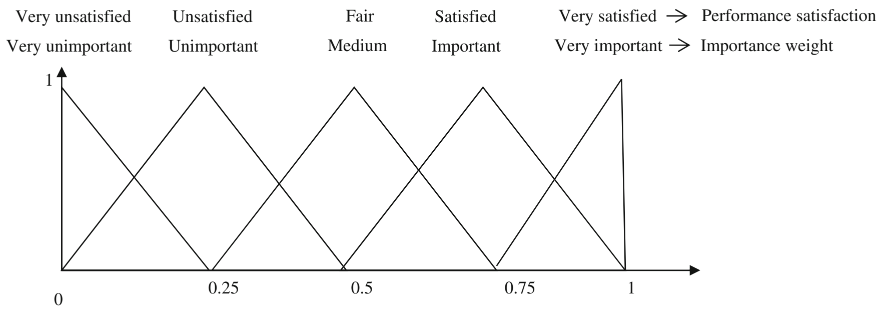


Fig. 8.11 Triangular fuzzy linguistic terms applied in this book

Table 8.1 Fuzzy numbers of weights and performance satisfactions

Importance/contribution weight	Performance satisfaction	Fuzzy number (a,b,c)
Very unimportant (VU)	Very unsatisfied (VU)	(0, 0, 0.25)
Unimportant (U)	Unsatisfied (U)	(0, 0.25, 0.5)
Medium (M)	Fair (F)	(0.25, 0.50, 0.75)
Important (I)	Satisfied (S)	(0.50, 0.75, 1.0)
Very important (VI)	Very satisfied (VS)	(0.75, 1.0, 1.0)

A linguistic set for the performance satisfactions of both the materials and design alternatives is: A = (very unsatisfied (VU), unsatisfied (U), fair (F), satisfied (S), very satisfied (VS)). Assigned by the j DM to the g material and f design alternative with respect to the k criteria, the fuzzy numbers of the performance satisfactions of the materials and design alternatives are $\tilde{A}_{ait} = \left(g_{aijt}, h_{aijt}, l_{aijt}\right)$ and $\tilde{A}_{it} = \left(a_{ijt}, b_{ijt}, c_{ijt}\right)$, respectively, where i = (1, 2,…, f).

8.5.2 *Fuzzy Operations*

Based on the extension principle, the fuzzy operations for calculating the SBI consist of the following six major steps:

Step 1: To assess the importance weights of the criteria, W_t^C, and contribution weights of the materials, W_{at}^C, through the fuzzy aggregation engine based on Eqs. (8.1) and (8.2), respectively.

$$W_t^C = \left(\sum_{j=1}^{n} \frac{p_{tj}}{n}, \sum_{j=1}^{n} \frac{q_{tj}}{n}, \sum_{j=1}^{n} \frac{r_{\mathrm{tj}}}{n}\right) \tag{8.1}$$

$$W_{at}^{C} = \left(\sum_{j=1}^{n} \frac{d_{\mathrm{tj}}}{n}, \sum_{j=1}^{n} \frac{e_{\mathrm{tj}}}{n}, \sum_{j=1}^{n} \frac{f_{\mathrm{tj}}}{n} \right) \tag{8.2}$$

where

j (DMs) = (1, 2, 3, …, n)
t (Criteria) = (1, 2, 3, . . . , k)

Step 2: To determine the performance satisfactions of the design alternatives with respect to the criteria for overall design assessment, A_{it}^{C}, and performance satisfactions of the materials with respect to the criteria for individual material assessment, A_{ait}^{C}, through the fuzzy aggregation engine based on Eqs. (8.3) and (8.4), respectively.

$$A_{it}^{C} = \left(\sum_{j=1}^{n} \frac{a_{itj}}{n}, \sum_{j=1}^{n} \frac{b_{itj}}{n}, \sum_{j=1}^{n} \frac{c_{itj}}{n} \right) \tag{8.3}$$

$$A_{ait}^{C} = \left(\sum_{j=1}^{n} \frac{g_{aitj}}{n}, \sum_{j=1}^{n} \frac{h_{aitj}}{n}, \sum_{j=1}^{n} \frac{l_{aitj}}{n} \right), \tag{8.4}$$

where

i (Alternatives) = (1, 2, 3, …, m)
a (Contribution) = (external wall, window glazing, shading device,…, g)
j (DMs) = (1, 2, 3, …, n)
t (Criteria)= (1, 2, 3, …, k)

Step 3: To determine the performance satisfaction of the design alternative based on the performance satisfactions of the individual materials with respect to the criteria for individual material assessment, A_{it}^{C}, through the fuzzification engine based on Eqs. (8.5) and (8.6).

$$A_{it}^{C} = \left(\sum_{a} W_{at}^{C} \times A_{ait}^{C} \right) \Big/ \sum_{a} W_{at}^{C} \tag{8.5}$$

$$A_{it}^{C} = \left(\frac{\sum_a (g \times d)}{\sum_a d}, \frac{\sum_a (h \times e)}{\sum_a e}, \frac{\sum_a (l \times f)}{\sum_a f} \right) \tag{8.6}$$

where

i (Alternatives) = (1, 2, 3, …, m)
a (Contribution) = (external wall, window glazing, shading device,…, g)
t (Criteria) = (1, 2, 3, . . . , k)

Step 4: To determine fuzzy preference index of the design alternative, F_i, through the fuzzification engine based on Eqs. (8.7) and (8.8).

$$F_i = \sum_{1}^{t} \left(W_t^C \times A_{it}^C \right) \Big/ \sum_{1}^{t} W_t^C \tag{8.7}$$

$$F_i = \left(\frac{\sum_t (a \times p)}{\sum_t p}, \frac{\sum_t (b \times q)}{\sum_t q}, \frac{\sum_t (c \times r)}{\sum_t r} \right), \tag{8.8}$$

where

i (Alternatives) = (1, 2, 3, …, m)
t (Criteria) = (1, 2, 3, . . . , k)

Step 5: To convert the fuzzy preference index, F_i, into a crisp number. It is assumed that fuzzy number, $D = (d_1, d_2, d_3)$, could be converted into the crisp number through the defuzzification engine based on Eq. (8.9).

$$S_i = (d_1 + d_2 + d_3)/3, \tag{8.9}$$

where S_i is the SBI
Step 6: To translate the fuzzy number into the fuzzy linguistic term based on the assumption that the fuzzy number D is "approximately the linguistic term A," when it has the membership function based on Eq. (8.10). However, for this book, ($b - a$) and ($c - b$) for each of the linguistic terms are equal to 1. As a result, Eq. (8.11) shows the $\mu_A(x)$ representing the possibility that the fuzzy number D is "approximately the linguistic term A."

$$\mu_A(x) = \begin{cases} 0, & x < a, \text{ or } x > c \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b < x \le c \end{cases} \tag{8.10}$$

$$\mu_A(x) = \begin{cases} 0, & x < a, \text{ or } x > c \\ x - a, & a \le x \le b \\ c - x, & b < x \le c \end{cases}, \tag{8.11}$$

where

$u_A(x)$ is membership function that describes the degree of membership of x in A
x is the crisp number transformed by Eq. (8.9)

Furthermore, if it is assumed that the fuzzy set; $A = \left(\sum_{u=1}^{y} \frac{\mu_{A_u}(x)}{A_u} \right)$ could represent the possibility that the fuzzy number, D, which is "approximately the linguistic terms A_1, A_2, …, A_y," the triangular fuzzy number D can be converted into the linguistic terms, A_z, where $1 < z < y$, based on Eq. (8.12).

$$\frac{\mu_{A_z}(x)}{A_z} = \left(\sum_{u=1}^{y} \frac{\mu_{A_u}(x)}{A_u} \right) \quad (8.12)$$

8.5.3 Fuzzy Consensus Scheme

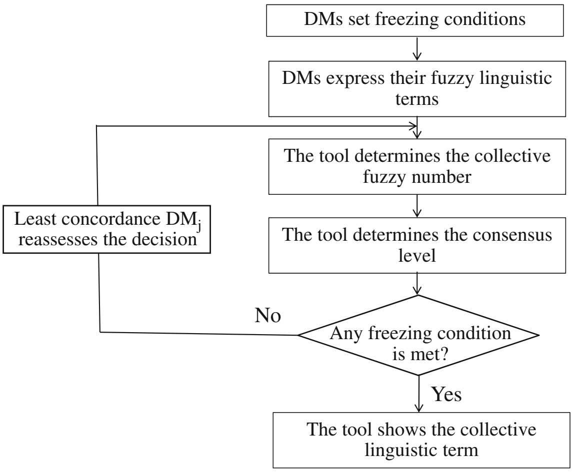
The last component in the fuzzy inference engine is the fuzzy consensus scheme engine. As mentioned in Sect. 2.7, the consensus level is the function of the intersection areas and distances between individual fuzzy linguistic terms and collective fuzzy linguistic term. The consensus level ranges from 0 to 1. However, to keep the scope for coding the tool manageable, the consensus level for making the decisions by three DMs including the architect, C&S engineer, and M&E engineer were divided into only three levels which are "High," "Medium," and "Low" consensus levels in the first instance. The decision receives the "High" consensus level if all the three DMs give the same linguistic term, or if any pairs of the DMs share the same linguistic term, while the other DM gives the linguistic term next to it. The decision obtains the "Medium" consensus level if all the three linguistic terms assigned by each DM can be arranged in relative order and right next to each other, regardless of which DM is responsible for each linguistic term. The rest of the combinations receive the "Low" consensus level. Table 8.2 presents decision examples showing their corresponding consensus levels for assessment of the importance weights.

Figure 8.12 illustrates how the fuzzy consensus scheme is operated. After setting the fuzzy linguistic terms and numbers, the DMs establish freezing conditions for the assessment. These conditions include a minimum consensus level, maximum assessment cycle of the individual DM, and maximum assessment cycle of the team. In the first assessment cycle of the team on any decision, if the consensus level of the team for that decision meets the minimum consensus level agreed, the team moves on to make the next decision. However, if the consensus level of that decision is lower than the minimum consensus level, a team facilitator invites the least concordant DM to explain his/her reason for group discussion and to reassess that particular decision.

Table 8.2 Example of the consensus levels with respect to different decisions

Decision result	Importance weight			Consensus level	Least concordance DM
	DM1	DM2	DM3		
1	VU	VU	VU	High	None
2	M	U	M	High	DM2
3	VU	M	U	Medium	DM1 or DM2
4	I	VI	M	Medium	DM2 or DM3
5	U	I	I	Low	DM1
6	VI	VI	M	Low	DM3

Fig. 8.12 Fuzzy consensus scheme in the tool



It is noted that if there is more than one least concordance DM, the reassessment may take place on a voluntary basis. This least concordant DM may or may not change his/her decision depending on the discussion, but this increases both the number of the assessment cycle of that DM and the team by one. This loop goes on until one of the freezing conditions is met. In addition, to maintain a conductive atmosphere for the team, in the event where the least concordant DM does not change the decision, the second least concordance DM is invited to reassess his/her decision and so on. Doing this also increases both the number of the assessment cycle of that DM and the team by one (Pedrycz *et al.*, 2011).

8.6 User Interface

Figure 8.13 presents the UML-based case view of the tool. This figure shows how the DMs make decisions through the user interface of the prototype based on the five rooms in the HOQSB. First, the design team starts with updating the knowledge stored in the KM-C, KM-M, and KM-R to ensure that the assessment is based on updated-to-date data, information, and relationships. The FR then directs the team to provide membership numbers of the triangular fuzzy linguistic terms and to set up the consensus levels. Next, the team selects the criteria for the assessment in the CR. In parallel, the criteria knowledge in the KM-C is presented to support the DMs in making the selection.

Following this, the design team has to choose which of the criteria are selected for overall design assessment and for individual material assessment. Subsequently, the DMs assess the importance weights of all the criteria and contribution weights of the materials with respect to the criteria chosen for individual material assessment based on the knowledge provided by the KM-C. In this regard, the fuzzy aggregation engine calculates the importance weights of the criteria, while the

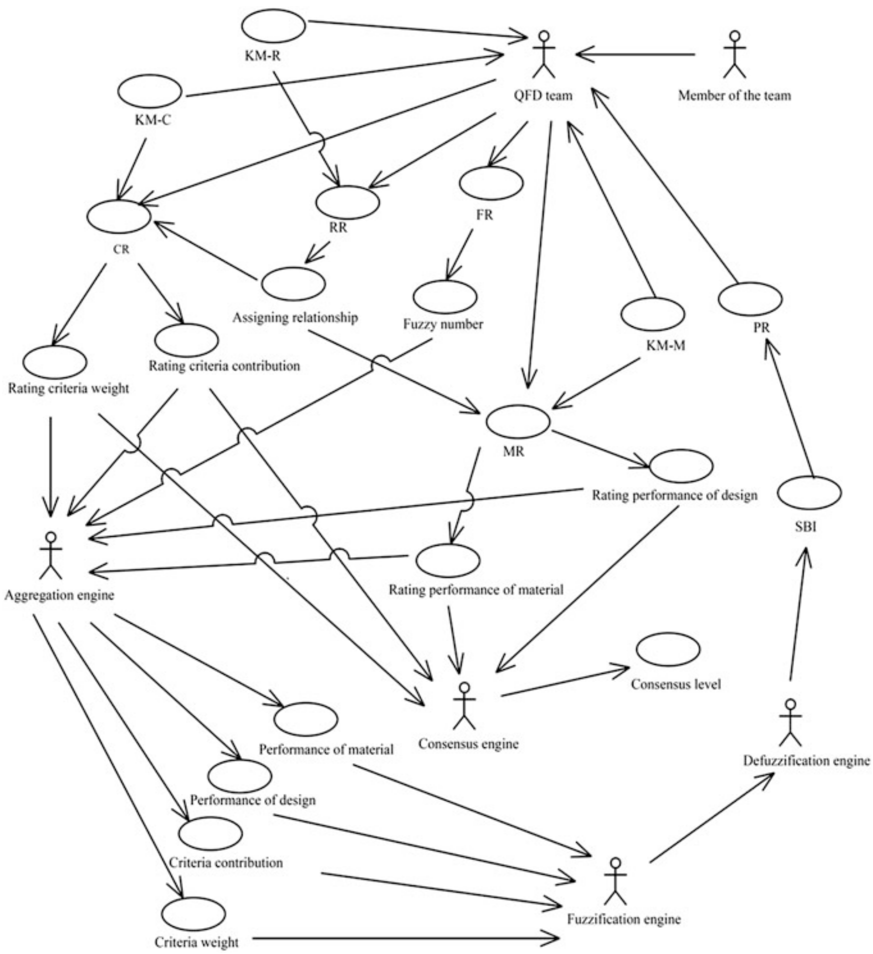


Fig. 8.13 UML-based case view of the KBDSS-QFD tool

consensus engine determines the consensus levels of the decisions. According to the fuzzy consensus procedure, some DMs may be asked to reassess the importance weights if their corresponding consensus levels need to be increased. In addition, to reduce the time in making the decision, assessing the contribution weights of the materials is made as a team.

Next, in the MR, the design team selects the materials for the assessment by considering the knowledge stored in the KM-M. After that, the DMs rate the performance satisfactions of the individual materials and performance satisfactions of the overall design alternatives as part of the RR. In this step, the DMs should take into consideration the key parameters of the materials and design alternatives, IF-THEN rules and performance satisfactions stored in the KM-R prior to making the decisions. The fuzzy aggregation engine then determines the performance satisfactions of the materials and the performance satisfactions of the design alternatives, and the consensus scheme engine computes the consensus levels of the decisions. The performance satisfactions can be reassessed in regard to the fuzzy consensus scheme. Lastly, the fuzzification and defuzzification engines governed by the PR calculate the SBI of the design alternative and report these together with the linguistic importance weights and performance satisfactions through the user interface. The team may also apply these results to update the KMS accordingly.

For simplicity, the mentioned decision-making steps were categorized into seven major steps for the DMs to provide their inputs through the user interface as follow:

Step 1: Input the membership numbers of the triangular fuzzy linguistic terms and set up the freezing conditions of the fuzzy consensus scheme.
Step 2: Select the criteria for the assessment and decide which of the criteria are for overall design assessment and individual material assessment.
Step 3: Assess the importance weights of all the criteria.
Step 4: Assess the contribution weights of the building envelope materials with respect to the criteria selected for individual material assessment.
Step 5: Select the materials for the assessment.
Step 6: Assess the performance satisfactions of the design alternatives with respect to the criteria for overall design assessment.
Step 7: Assess the performance satisfactions of the materials with respect to the criteria for individual material assessment.

8.7 Hypothetical Example

This section shows a hypothetical example to illustrate how the SBI is manually calculated and how the design team of three DMs, including the DM1, DM2, and DM3, assesses the building envelope materials and designs by following through the seven steps to provide the inputs.

Step 1: The team adopted the fuzzy linguistic terms and their corresponding membership numbers as shown in Table 8.3.
Step 2: The team selected the "EN1" energy consumption and "SC2" appearance demands for this assessment. The team agreed that the "EN1" energy consumption

Table 8.3 Fuzzy numbers of the weight and satisfaction applied in this example

Weight	Performance satisfaction	Fuzzy number (*a*,*b*,*c*)
Very unimportant (VU)	Very unsatisfied (VU)	(0, 0, 0.25)
Unimportant (U)	Unsatisfied (U)	(0, 0.25, 0.5)
Medium (M)	Fair (F)	(0.25, 0.50, 0.75)
Important (I)	Satisfied (S)	(0.50, 0.75, 1.0)
Very important (VI)	Very satisfied (VS)	(0.75, 1.0, 1.0)

is for individual material assessment, while the “SC2” appearance demands is for overall design assessment.
Step 3: The DM1, DM2, and DM3 assigned the “M,” “M,” and “I” linguistic terms, respectively, as the importance weight of the “EN1” Energy consumption. After that, the DM1, DM2, and DM3 assigned the “VI”, “VI,” and “VI” linguistic terms, respectively, as the importance weight of the “SC2” Appearance demands.
Step 4: The team gave the “VI”, “M,” and “M” linguistic terms to allocate the contribution weights with respect to the “EN1” energy consumption of the external wall, window glazing, and shading device, respectively.
Step 5: The team selected the “PC1” precast wall, “WG4” double layer low-E window glazing, and “SD1” Horizontal shading device. According to Fig. 8.5, this combination corresponds to the design alternative “8” PC1WG4SD1.
Step 6: The DM1, DM2, and DM3 assigned the “F,” “F,” and “F” linguistic terms, respectively, as the performance satisfaction of the alternative “8” PC1WG4SD1 with respect to the “SC2” Appearance demands.
Step 7 The DM1, DM2, and DM3 gave the “VS,” “VS,” and “VS” linguistic terms, respectively, as the performance satisfaction of the “PC1” Precast wall with respect to the “EN1” Energy consumption. The DM1, DM2, and DM3 assigned the “S,” “S,” and “S” linguistic terms, respectively, as the performance satisfaction of the “WG4” double layer low-E window glazing with respect to the “EN1” energy consumption. The DM1, DM2, and DM3 gave the “S,” “S,” and “S” linguistic terms, respectively, as the performance satisfaction of the “SD1” horizontal concrete shading device with respect to the “EN1” energy consumption

The fuzzy inference engine then processes these inputs by following the six fuzzy operation steps to calculate the SBI (see Sect. 8.5.2) as shown below:

Step 1: The fuzzy inference engine computed the fuzzy collective numbers of the importance weights and contribution weights. Table 8.4 shows an example for calculation of the importance weights of the “EN1” energy consumption and its corresponding consensus level.
Steps 2 and 3: The fuzzy inference engine calculated the performance satisfactions of the design alternative with respect to the “EN1” energy consumption and “SC2” appearance demands. Table 8.5 provides an example for determining the performance

Table 8.4 Example for calculation of the importance weight

	Importance weight		
Criteria selected	EN1: Energy consumption		
Inputs	DM1	DM2	DM3
Linguistic terms	M	M	I
Fuzzy number	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1.0)
Collective fuzzy numbers (see Eq. 7.1)	((0.25 + 0.25 + 0.5)/3, (0.5 + 0.5 + 0.75)/3, (0.75 + 0.75 + 1)/3) = (0.333, 0.583, 0.833)		
Consensus level (see the consensus scheme)	“High”		

Table 8.5 Example for calculating the performance satisfaction

	External wall	Window glazing	Shading device
Contribution weight	VI	M	M
Fuzzy numbers	(0.75, 1, 1)	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)
Performance of material	VS	S	S
Fuzzy number	(0.75, 1, 1)	(0.50, 0.75, 1.0)	(0.50, 0.75, 1.0)
Performance of design (see Eq. (8.5))	= ((0.75 * 0.75, 1 * 1, 1 * 1) + (0.5 * 0.25, 0.75 * 0.5, 1 * 0.75) + (0.5 * 0.25, 0.75 * 0.5, 1 * 0.75))/((0.75, 1, 1) + (0.25, 0.5, 0.75) + (0.25, 0.5, 0.75)) = ((0.5625, 1, 1) + (0.125, 0.375, 0.75) + (0.125, 0.375, 0.75))/(1.25, 2, 2.5) = ((0.5625 + 0.125 + 0.125), (1 + 0.375 + 0.375), (1 + 0.75 + 0.75)/(1.25, 2, 2.5) = (0.8125, 1.75, 2.5)/(1.25, 2, 2.5) = (0.8125/1.25, 1.75/2, 2.5/2, 5) = (0.65, 0.875, 1.0)		

Table 8.6 Calculation of the fuzzy preference index

Criteria	Importance weight	Performance satisfaction	Fuzzy preference index (See Eq. (8.7))
EN1	(0.333, 0.583, 0.833)	(0.65, 0.875, 1.0)	= ((0.65 * 0.33, 0.875 * 0.583, 1 * 0.833) + (0.25 * 0.75, 0.5 * 1, 0.75 * 1))/(0.333 + 0.75, 0.583 + 1, 0.833 + 1) = ((0.216, 0.51, 0.833) + (0.187, 0. 5, 0.75))/(1.083, 1.583, 1.833) = (0.216 + 0.187, 0.51 + 0.5, 0.833 + 0.75)/(1.083, 1.583, 1.833) = (0.403, 1.01, 1.583)/(1.083, 1.583, 1.833) = (0.372, 0.638, 0.863)
SC2	(0.75, 1.0, 1.0)	(0.25, 0.5, 0.75)	

satisfaction of the design alternative "8" PC1WG4SD1 with respect to the "EN1" energy consumption after the individual decisions of the DMs were aggregated.

Step 4: The engine computed the fuzzy preference index of the design alternative "8" PC1WG4SD1 as shown in Table 8.6.

Step 5: The fuzzy inference engine translated the preference index into the SBI based on Eq. (8.9) which equals (0.372 + 0.638 + 0.863)/3 = 0.624.

Step 6: According to Eq. (8.11), the possibility of the SBI that was approximately two linguistic terms, which are the "Fair" and "Satisfied" linguistic terms, was computed, respectively as:

For the "Fair" linguistic term, $\mu_{\text{Fair}}(x_{\text{SBI}}) = (0.75 - 0.624) = 0.126$
For the "Satisfied" linguistic term, $\mu_{\text{Satisfied}}(x_{\text{SBI}}) = (0.624 - 0.5) = 0.124$.

In addition, according to the same equation, the possibilities that the SBI was approximately the other linguistic terms as shown in Fig. 8.11 were zero. Finally, based on Eq. (8.12), the max $\left(\sum_{u=1}^{y} \frac{\mu_{A_u}(x)}{A_u}\right)$ is $\mu_{\text{Fair}}(x_{\text{SBI}})/(\text{Fair})$. Thus, the SBI of the design alternative "8" PC1WG4SD1 for this example was classified as the "Fair" or "F" performance satisfaction.

8.8 Prototype of the KBDSS-QFD Tool

The prototype of the KBDSS-QFD tool was developed as a desktop application for the Windows operating system using Microsoft Visual Studio. The screenshots as given in Figs. 8.14 and 8.15 show the introduction page and main menus of the tool, respectively. The prototype was modeled after the detailed KBDSS-QFD tool (see Sects. 8.2–8.6), and its usability was improved by taking into account the feedbacks obtained from the semi-structured interviews (see Appendix E). The menu bar of the tool includes five main menus. The first main menu of this prototype is the **File** menu. This menu allows the design team to create a new file, open the KMS database, save the file, print a current page, and exit the program.

The second main menu is the **Edit** menu. This menu enables the team to undo the work, copy, and cut as well as paste words. The third menu is entitled the **KMS** menu. The **KMS** menu involves the three subsystems of the KMS which are the **KM-C**, **KM-M,** and **KM-R** submenus. The fourth menu entitles the **HOQSB** menu governing the decision-making process divided into the seven steps as mentioned earlier. The last menu is the **Help** menu. The **Help** menu assists the design team to use the tool by, for example, explaining what the QFD is, what the fuzzy theory is, what the fuzzy consensus level is and, importantly, the steps for using the tool.

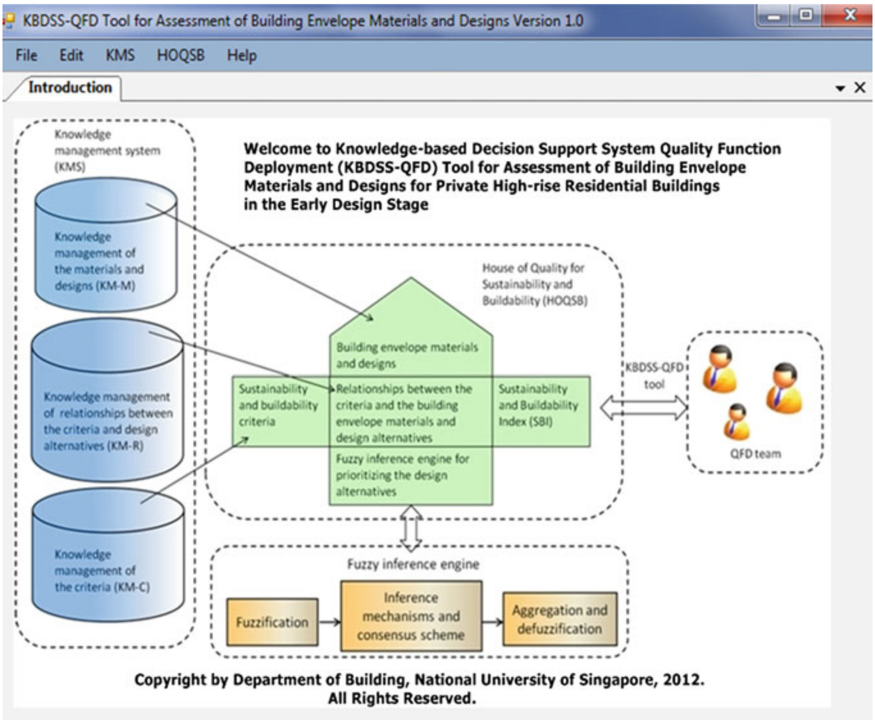


Fig. 8.14 Introduction page of the tool

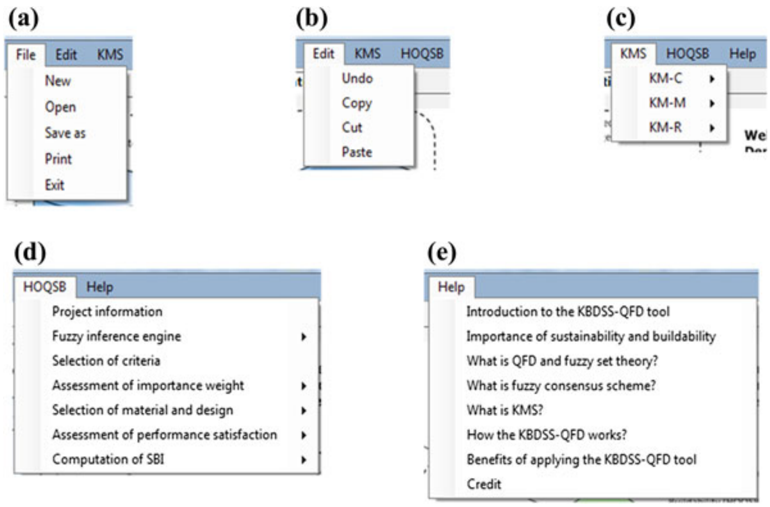


Fig. 8.15 Menus and submenus of the tool. **a** File menu and submenus. **b** Edit menu and submenus. **c** KMS menu and submenus. **d** HOQSB menu and submenus. **e** Help menu and submenus

8.8.1 KMS

The prototype makes use of a wealth of the knowledge stored in the KM-C, KM-M, and KM-R by allowing the DMs to study the knowledge stored in these systems and update this knowledge before entering into the assessment. By clicking on the **KMS** menu and then pointing the **KM-C** submenu, the tool presents the **Environmental criteria**, **Economic criteria**, **Social criteria,** and **Buildability criteria** items as shown in Fig. 8.16. Subsequently, by pointing any of these items, the tool shows the **Importance weight** and **Contribution weight** sub-items.

Figure 8.17 presents the screenshot obtained from clicking on the **Importance weight** sub-item of the **Environmental criteria** item. As can be seen, the **Importance weight** sub-item provides the same knowledge as opened from the KM-C database; however, the important difference is that this prototype makes it easier for the DMs to apply such knowledge during the assessment. The **KM-M** submenu includes four items which are the **Design alternative**, **External wall**, **Window glazing,** and **Shading device** as shown in Fig. 8.18. The **Design alternative** item contains available design alternatives and their corresponding parameters as shown in Fig. 8.19.

The rest of the items under the **KM-M** submenu store the knowledge pertaining to the design-, handling-, construction-, and maintenance-related parameters of the external wall, window glazing, and shading device materials. Figure 8.20 presents the screenshot, under the **KM-M** submenu, when the team clicks on the **External wall** item and its **Design related properties** sub-item.

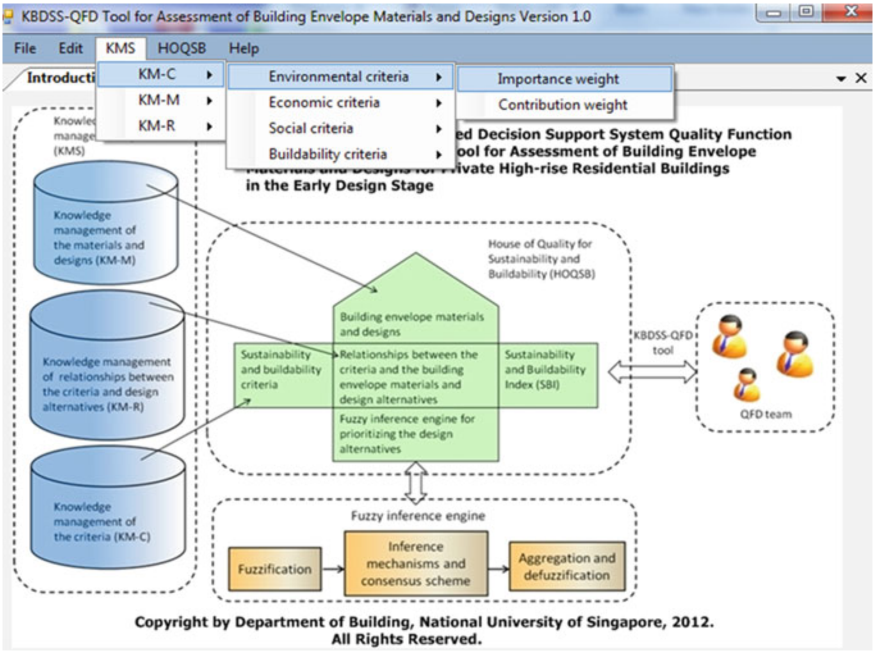


Fig. 8.16 Items and sub-items under the KM-C submenu

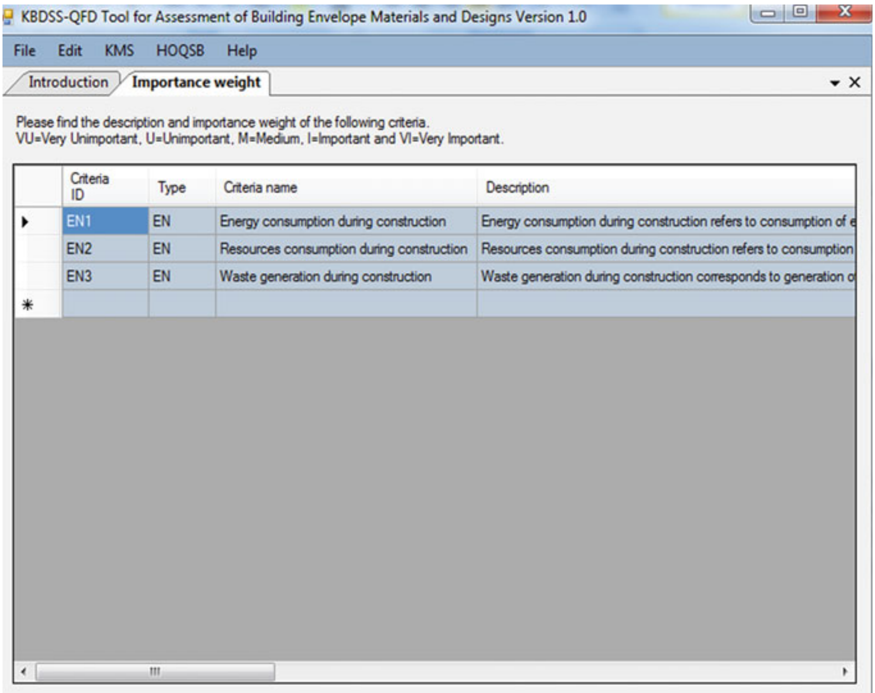


Fig. 8.17 Importance weight sub-item under the KM-C submenu

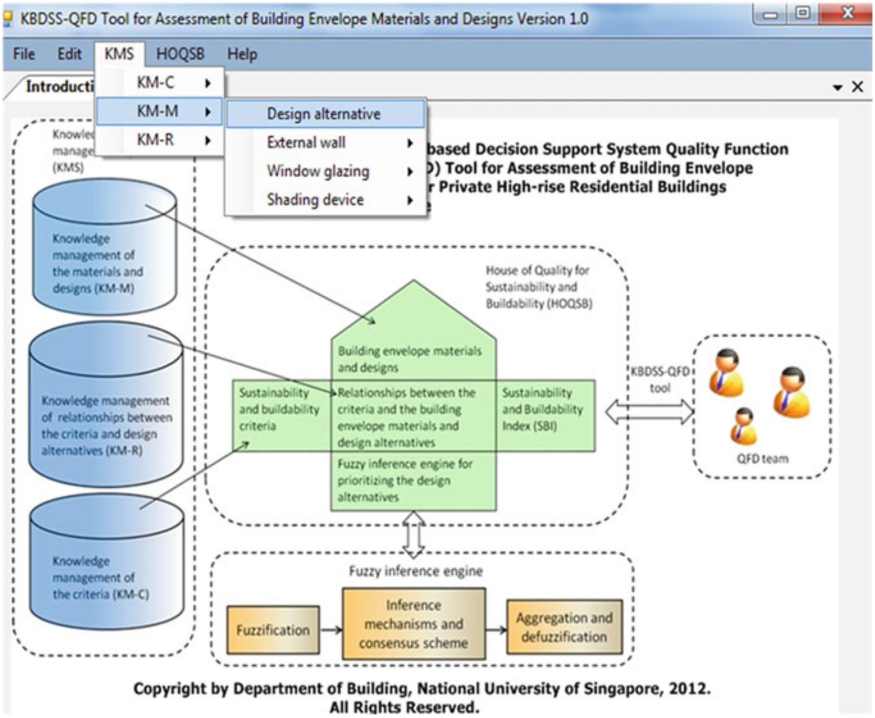
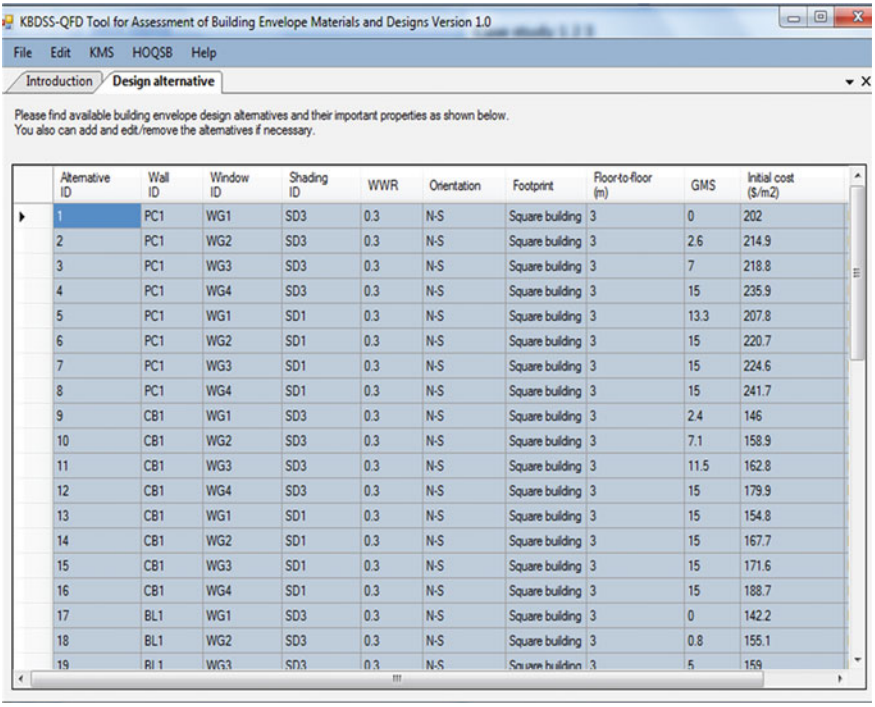


Fig. 8.18 Items under the KM-M submenu

The **KM-R** submenu comprises three items; namely the **Relationship matrix**, **Performance of overall design,** and **Performance of individual material** as shown in Fig. 8.21. The **Relationship matrix** item contains two sub-items including the **Criteria for overall design assessment** and **Criteria for individual material assessment**. These two sub-items provide the parameters affecting the criteria for both overall design and individual material assessment. Figure 8.22 shows the screenshot of the tool when the **Criteria for overall design assessment** sub-item is accessed. Next, the **Performance satisfaction of overall design** sub-item as shown in Fig. 8.23 and **Performance satisfaction of individual material** sub-item as shown in Fig. 8.24 present the performance satisfactions of the design alternatives and individual materials, respectively.

8.8.2 HOQSB and Fuzzy Inference Engine

As the HOQSB governs the seven decision-making steps for the design team to assess the building envelope material, this section presents submenus, items, and sub-items under the **HOQSB** menu based on these seven steps.



Alternative ID	Wall ID	Window ID	Shading ID	WWR	Orientation	Footprint	Floor-to-floor (m)	GMS	Initial cost ($/m2)
1	PC1	WG1	SD3	0.3	N-S	Square building	3	0	202
2	PC1	WG2	SD3	0.3	N-S	Square building	3	2.6	214.9
3	PC1	WG3	SD3	0.3	N-S	Square building	3	7	218.8
4	PC1	WG4	SD3	0.3	N-S	Square building	3	15	235.9
5	PC1	WG1	SD1	0.3	N-S	Square building	3	13.3	207.8
6	PC1	WG2	SD1	0.3	N-S	Square building	3	15	220.7
7	PC1	WG3	SD1	0.3	N-S	Square building	3	15	224.6
8	PC1	WG4	SD1	0.3	N-S	Square building	3	15	241.7
9	CB1	WG1	SD3	0.3	N-S	Square building	3	2.4	146
10	CB1	WG2	SD3	0.3	N-S	Square building	3	7.1	158.9
11	CB1	WG3	SD3	0.3	N-S	Square building	3	11.5	162.8
12	CB1	WG4	SD3	0.3	N-S	Square building	3	15	179.9
13	CB1	WG1	SD1	0.3	N-S	Square building	3	15	154.8
14	CB1	WG2	SD1	0.3	N-S	Square building	3	15	167.7
15	CB1	WG3	SD1	0.3	N-S	Square building	3	15	171.6
16	CB1	WG4	SD1	0.3	N-S	Square building	3	15	188.7
17	BL1	WG1	SD3	0.3	N-S	Square building	3	0	142.2
18	BL1	WG2	SD3	0.3	N-S	Square building	3	0.8	155.1
19	BL1	WG3	SD3	0.3	N-S	Square building	3	5	159

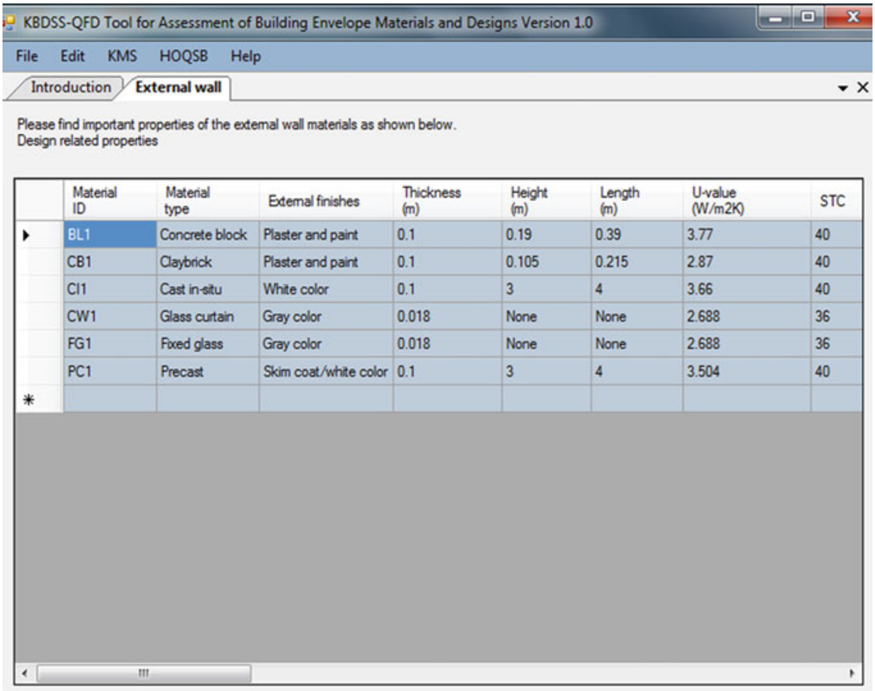
Fig. 8.19 Design alternative item under the KM-M submenu

Step 1: Input membership numbers of the triangular fuzzy linguistic terms and set up the freezing conditions of the fuzzy consensus scheme.

The team starts the assessment by clicking on the **Project information** submenu under the **HOQSB** menu. Doing this allows the team to add the project, client, and users information into the tool as shown in Fig. 8.25. The team can click on the **Save** button to record the information or the **Edit** button to edit the information. Subsequently, the team moves on to inputting the fuzzy membership numbers of the triangular linguistic terms under the **Fuzzy inference engine** submenu by clicking on the **Fuzzy linguistic terms** item as shown in Fig. 8.26.

Next, the team updates the consensus levels by clicking on the **Fuzzy consensus scheme** item and followed by the **Consensus level of importance weight** and **Consensus level of performance satisfaction** sub-items as shown in Fig. 8.27. At this stage, the team has to identify the freezing conditions of the consensus scheme, which include the minimum consensus level, maximum assessment cycle of the individual DM and maximum assessment cycle of the team. However, to keep the scope for programming the tool manageable, recording these numbers is done manually.

Step 2: Select the criteria for the assessment and decide whether the criteria selected are for overall design assessment.



Material ID	Material type	External finishes	Thickness (m)	Height (m)	Length (m)	U-value (W/m2K)	STC
BL1	Concrete block	Plaster and paint	0.1	0.19	0.39	3.77	40
CB1	Claybrick	Plaster and paint	0.1	0.105	0.215	2.87	40
CI1	Cast in-situ	White color	0.1	3	4	3.66	40
CW1	Glass curtain	Gray color	0.018	None	None	2.688	36
FG1	Fixed glass	Gray color	0.018	None	None	2.688	36
PC1	Precast	Skim coat/white color	0.1	3	4	3.504	40

Fig. 8.20 External wall item and its design-related properties sub-item under the KM-M submenu

By the clicking on the **Selection of material** submenu, the team can find the criteria, their description and compliance with respect to the environmental, economic, social, and buildability criteria as shown in Fig. 8.28.

In this step, the team has to decide whether the criteria selected are for overall design assessment by ticking the **Overall design assessment** checkbox. The suggestions for making such decisions are provided in the KM-C database. The tool records the criterion for the assessment if the **Add** button is clicked and the team confirms this by clicking on the **OK** button when the pop-up box appears. By default, if the criteria are added into the assessment with their **Overall design assessment** checkboxes unchecked, these criteria are considered the criteria for individual material assessment automatically. In addition, if the team needs to add more criteria, edit criteria, or breakdown some criteria, these have to be done in the KMS before opening the tool. Figures 8.29 and 8.30 show the screenshots when the team selects the "EN1" energy consumption for individual material assessment and "SC2" appearance demands for overall design assessment, respectively.

Step 3: Assess the importance weights of all the criteria chosen.

The assessment of the importance weights of all the criteria is carried out through the **Assessment of importance weight** submenu. This submenu consists of two

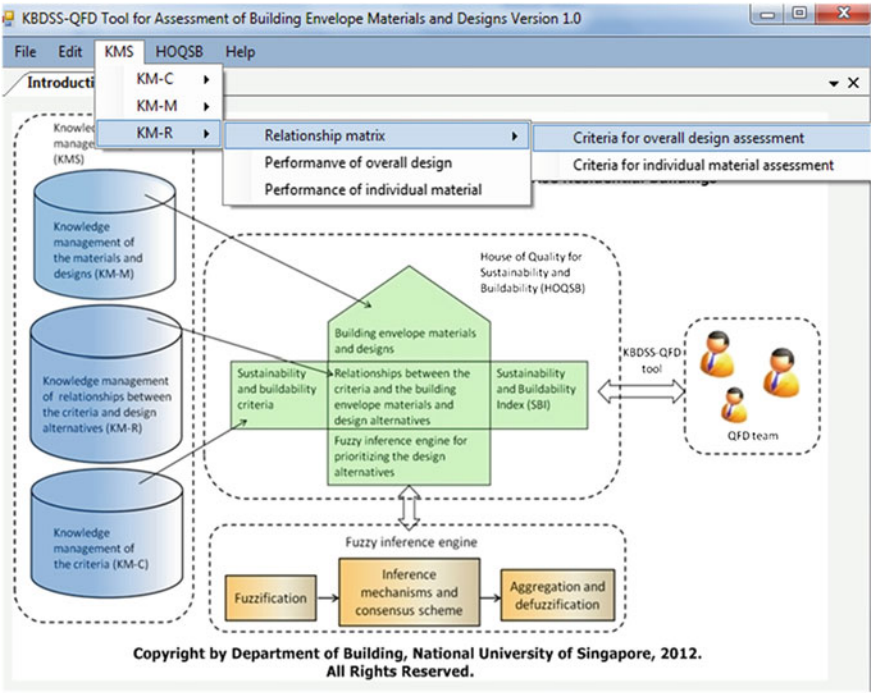


Fig. 8.21 Items and sub-items under the KM-R submenu

items which are the **Assessment of importance weight** and **Assessment of contribution weight**. In this step, the DMs start rating the importance weights of the criteria selected in Step 2 by clicking on the **Assessment of importance weight** item. To support making such decisions, the tool provides the relevant knowledge in the KM-C and the guided importance weights in the “KM guide” column. The individual DMs then input their perspectives on the importance weights of the criteria in the form of the fuzzy linguistic terms by selecting the linguistic terms set up in Step 1 from the drop-down list. After that, the team clicks on the **Calculate** button to calculate the consensus levels and collective importance weights of the criteria. Figure 8.31 presents the screenshot for rating the importance weight of the “EN1” energy consumption.

After the tool calculates whether the decision result of the team receive the “High,” “Medium,” or “Low” consensus level, the fuzzy aggregation engine computes the collective importance weights of the criteria in the form of the fuzzy linguistic terms. Subsequently, based on the fuzzy consensus scheme (see Sect. 8.5.3), if the consensus level of any decision falls under the minimum consensus level that the team agrees on, the team facilitator notifies the least concordant DM for the reassessment of that decision until one of the freezing conditions is met.

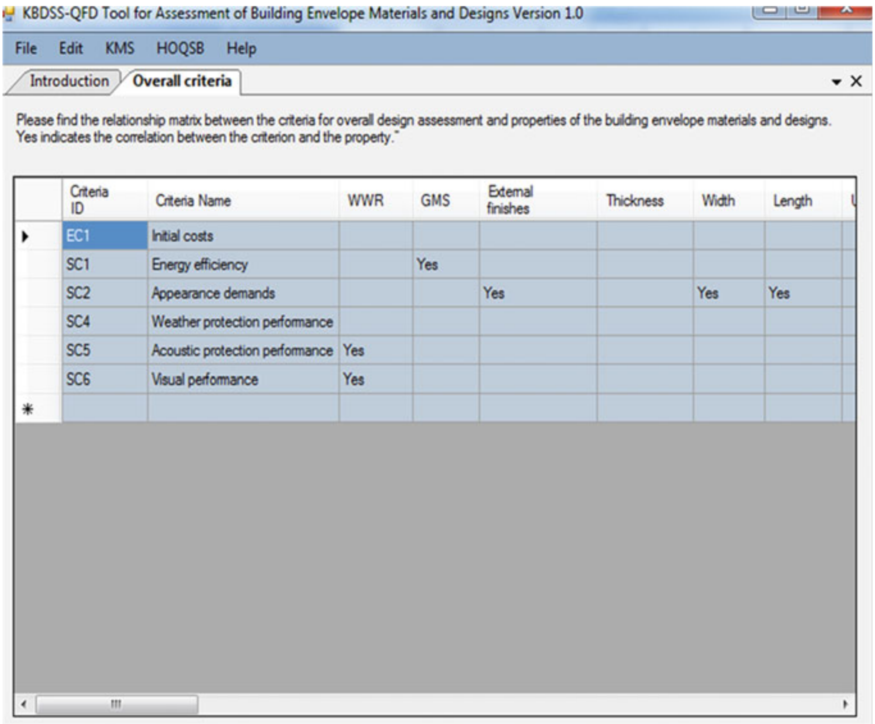


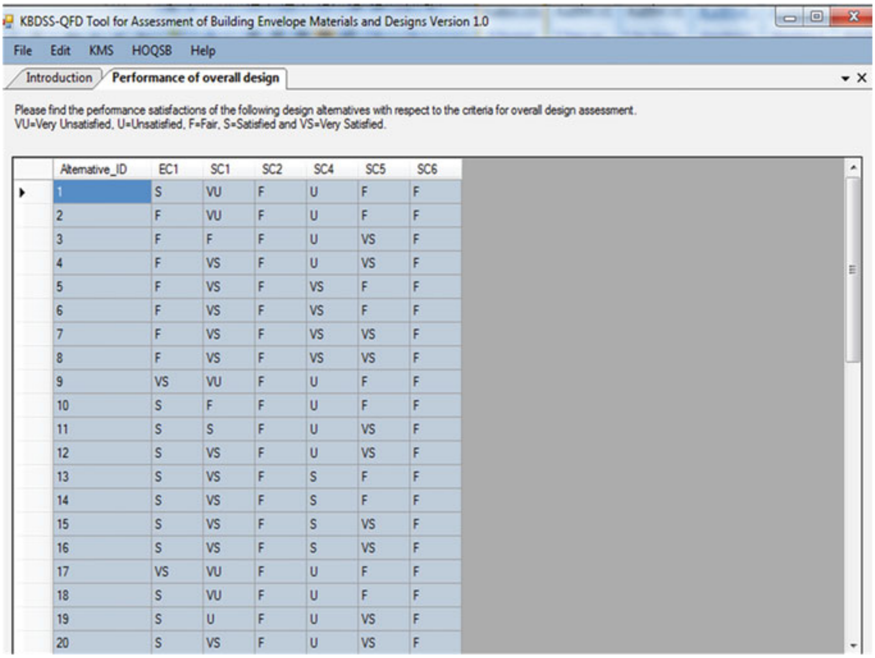
Fig. 8.22 Criteria for overall design assessment sub-item under the KM-R submenu

Step 4: Assess the contribution weights of the materials with respect to the criteria selected for individual material assessment.

In this step, the team clicks on the **Assessment of contribution weight** item under the **Assessment of importance weight** submenu to allocate the contribution weights of the external wall, window glazing, and shading device with respect to the criteria for individual material assessment. The tool assists the team to do so by showing the guided contribution weights as default. By considering this, the team assigns the contribution weights of the materials from the drop-down list and clicks on the **Save** button to record them. The screenshot as given in Fig. 8.32 shows the example for rating the contribution weights of the external wall, window glazing, and shading device with respect to the "EN1" energy consumption.

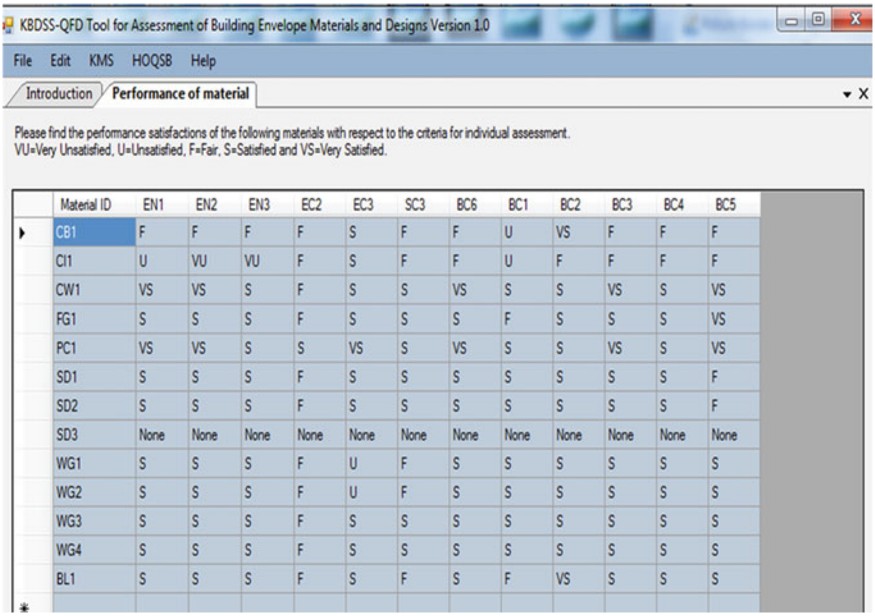
Step 5: Select the building envelope materials and design alternatives for the assessment.

Selection of the building envelope materials and design alternatives for the assessment is accomplished through the **Selection of material and design** submenu. This submenu includes two items which are the **Selection of material** and **Corresponding design**. By clicking on the **Selection of material** item, the team is



Alternative_ID	EC1	SC1	SC2	SC4	SC5	SC6
1	S	VU	F	U	F	F
2	F	VU	F	U	F	F
3	F	F	F	U	VS	F
4	F	VS	F	U	VS	F
5	F	VS	F	VS	F	F
6	F	VS	F	VS	F	F
7	F	VS	F	VS	VS	F
8	F	VS	F	VS	VS	F
9	VS	VU	F	U	F	F
10	S	F	F	U	F	F
11	S	S	F	U	VS	F
12	S	VS	F	U	VS	F
13	S	VS	F	S	F	F
14	S	VS	F	S	F	F
15	S	VS	F	S	VS	F
16	S	VS	F	S	VS	F
17	VS	VU	F	U	F	F
18	S	VU	F	U	F	F
19	S	U	F	U	VS	F
20	S	VS	F	U	VS	F

Fig. 8.23 Performance satisfactions of the building envelope designs sub-item under the KM-R submenu



Material ID	EN1	EN2	EN3	EC2	EC3	SC3	BC6	BC1	BC2	BC3	BC4	BC5
CB1	F	F	F	F	S	F	F	U	VS	F	F	F
CI1	U	VU	VU	F	S	F	F	U	F	F	F	F
CW1	VS	VS	S	F	S	S	VS	S	S	VS	S	VS
FG1	S	S	S	F	S	S	S	F	S	S	S	VS
PC1	VS	VS	S	S	VS	S	VS	S	S	VS	S	VS
SD1	S	S	S	F	S	S	S	S	S	S	S	F
SD2	S	S	S	F	S	S	S	S	S	S	S	F
SD3	None	None	None	None	None	None	None	None	None	None	None	None
WG1	S	S	S	F	U	F	S	S	S	S	S	S
WG2	S	S	S	F	U	F	S	S	S	S	S	S
WG3	S	S	S	F	S	S	S	S	S	S	S	S
WG4	S	S	S	F	S	S	S	S	S	S	S	S
BL1	S	S	S	F	S	F	S	F	VS	S	S	S

Fig. 8.24 Performance satisfactions of the building envelope materials sub-item under the KM-R submenu

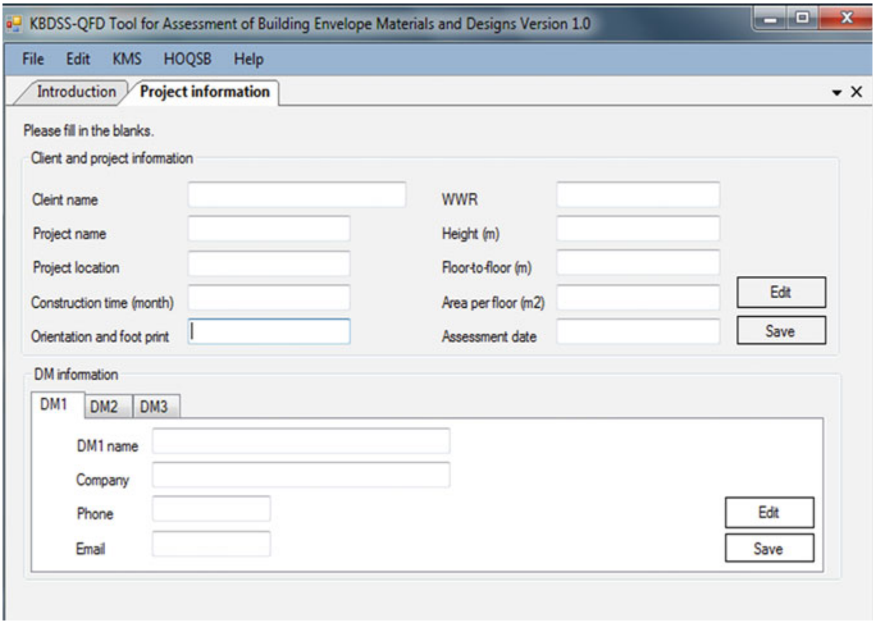


Fig. 8.25 Project information submenu under the HOQSB menu

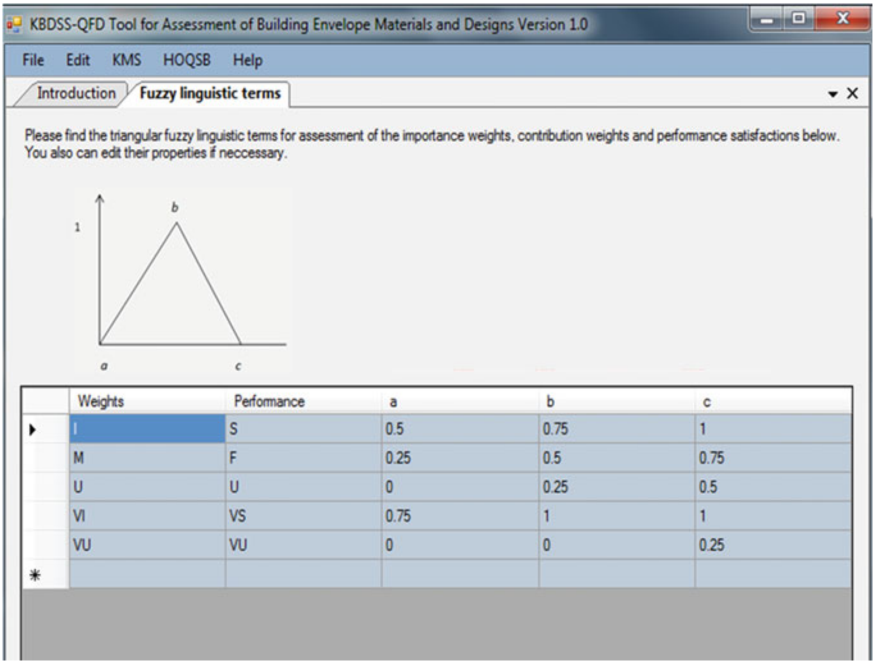


Fig. 8.26 Fuzzy linguistic terms item under the Fuzzy inference engine submenu

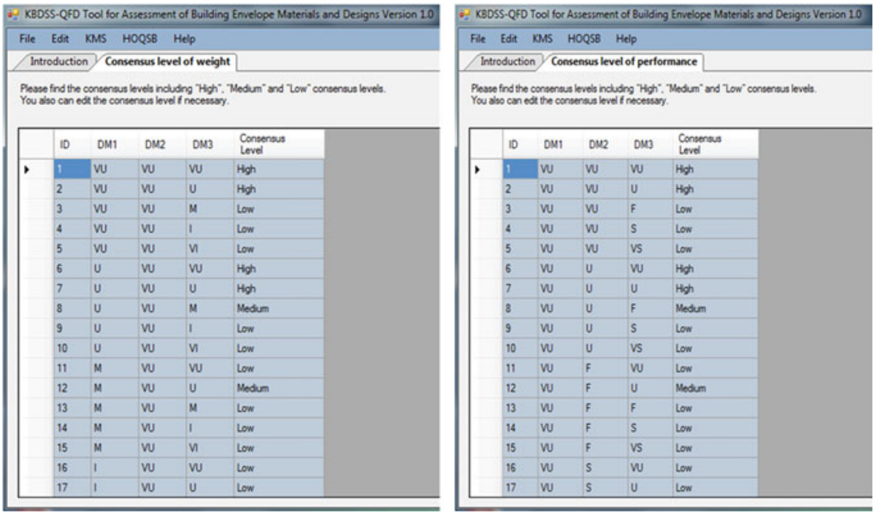


Fig. 8.27 Consensus level of importance weight and consensus level of performance satisfaction sub-items under the fuzzy inference engine submenu

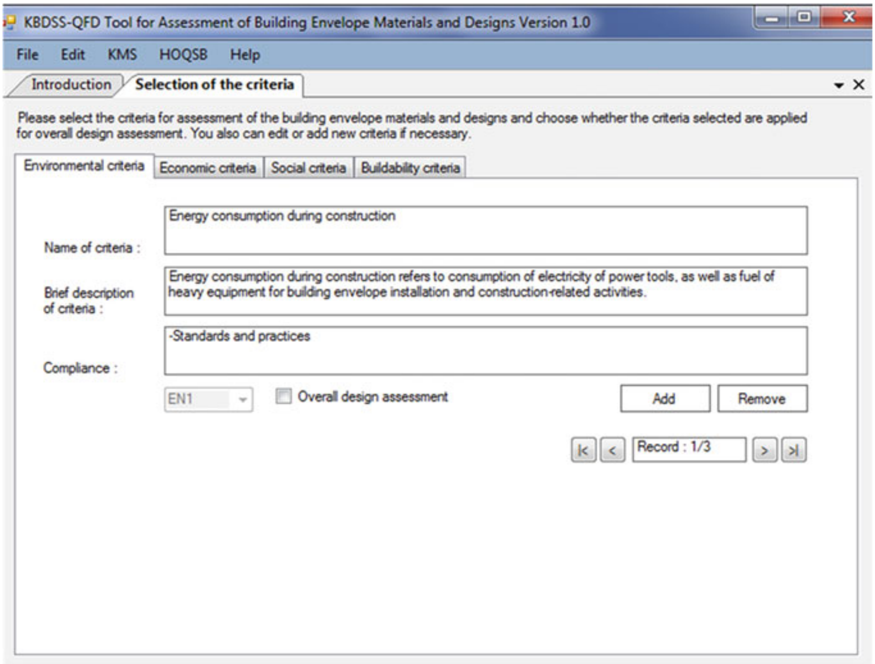


Fig. 8.28 Selection of criteria submenu under the HOQSB menu

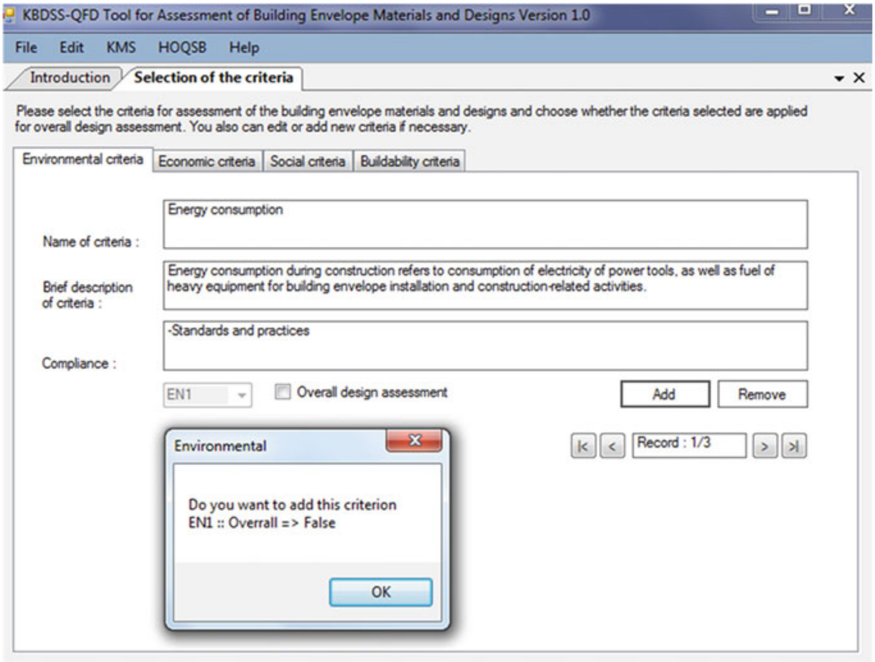


Fig. 8.29 Selection of the "EN1" energy consumption for individual material assessment

presented with all the available building envelope materials stored in the KM-M divided into the external wall, window glazing, and shading device material categories. The team ticks the box located in front of each material and then clicks on the **Save** button to take such materials into consideration as shown in Fig. 8.33.

It is noted that at least one material in each of the external wall, window glazing, and shading device material categories have to be saved in order to allow the tool to match these with the design alternatives stored in the database. For example, if the "PC1" Precast wall, "WG4" Double layer low-E window glazing, and "SD1" Horizontal concrete shading device materials are selected, after the team clicks on the **Corresponding design** item, the design alternative "8" PC1WG4SD1 is extracted from the KM-M and reported as shown in Fig. 8.34. Importantly, similar to adding more criteria, if the team needs to add more materials or consider more hybrid design, the team has to carry out these in the KMS before opening the tool.

Step 6: Assess the performance satisfactions of the design alternatives with respect to the criteria selected for overall design assessment.

By pointing to the **Assessment of performance satisfaction** submenu, the team can gain access to two items which are the **Performance satisfaction of overall**

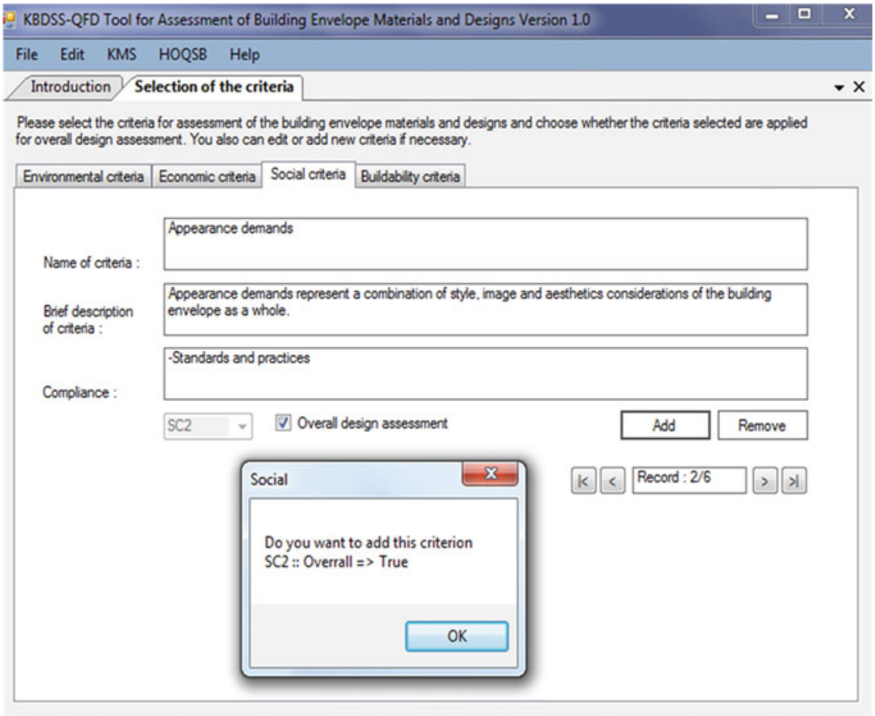


Fig. 8.30 Selection of the "SC2" appearance demands for overall design assessment

design and **Performance satisfaction of individual material**. To complete Step 6, the team begins by clicking on the **Performance satisfaction of overall design** item. After considering the guided performance satisfaction, relationship matrix and IF-THEN rule, the individual DMs rate the performance satisfactions of the design alternative formulated in Step 5 with respect to the criteria for overall design assessment by selecting the linguistic terms from the drop-down list. The team then clicks on the **Calculate** button to determine the consensus levels and performance satisfactions of the design alternatives. Figure 8.35 shows the screenshot for rating the performance satisfaction of the design alternative "8" PC1WG4SD1 with respect to the "SC2" Appearance demands. The fuzzy consensus scheme as explained in Step 2 is also applied in this step.

Step 7: Assess the performance satisfactions of the individual materials with respect to the criteria selected for individual material assessment.

In this step, after the team clicks on the **Performance satisfaction of individual material** item under the **Assessment of performance satisfaction** submenu, the individual DMs rate the performance satisfactions of the building envelope materials selected in Step 5 with respect to the criteria for individual material assessment by selecting the linguistic terms from the drop-down list. Figure 8.36 presents the

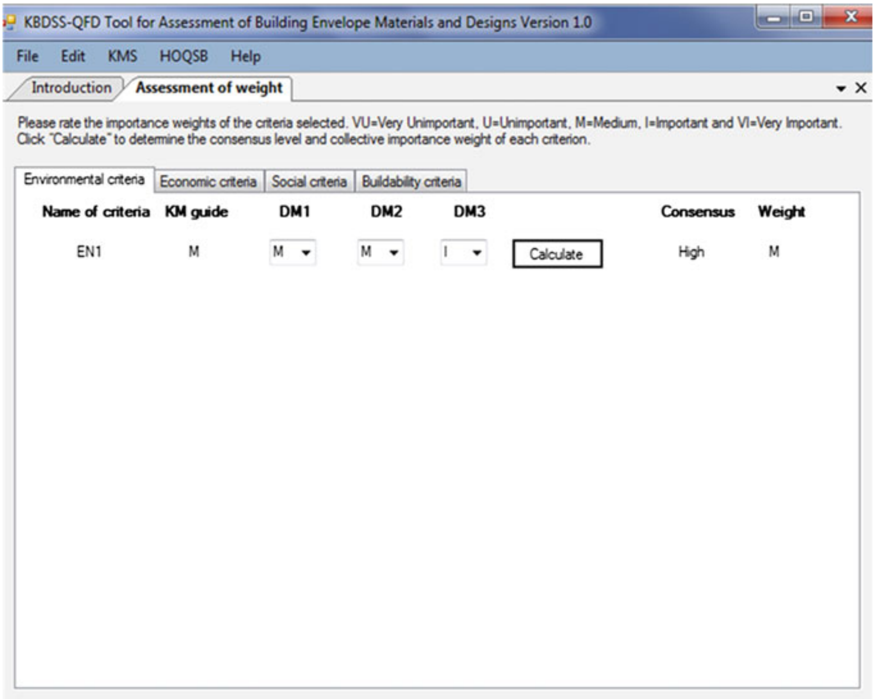


Fig. 8.31 Assessment of the importance weight with respect to the “EN1” energy consumption

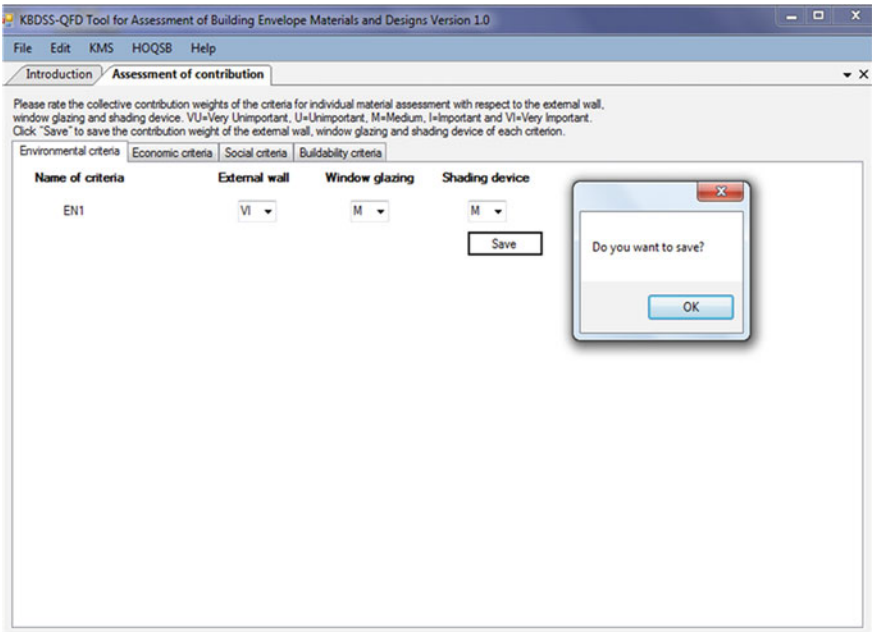


Fig. 8.32 Assessment of the contribution weights with respect to the “EN1” energy consumption

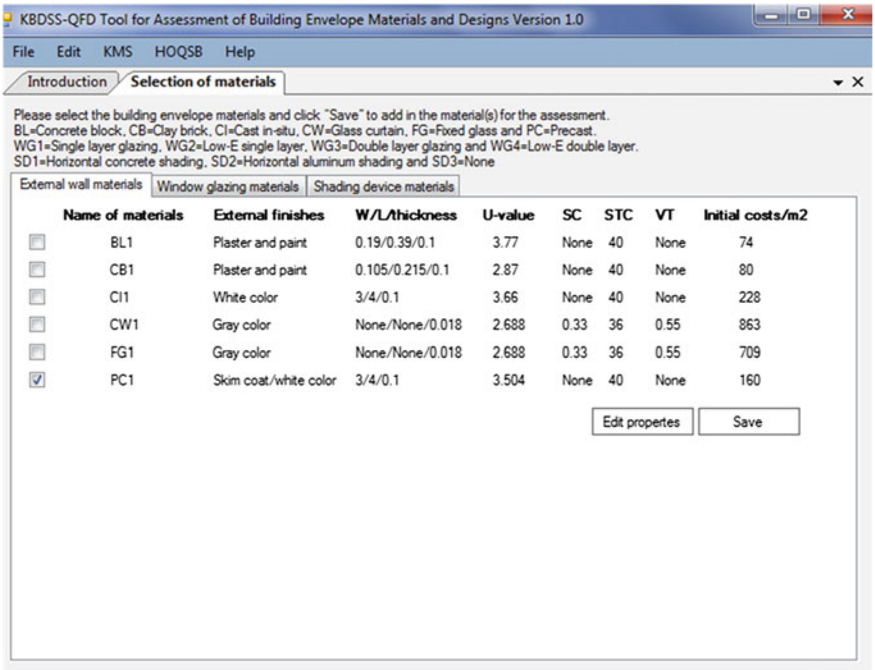


Fig. 8.33 Selection of the materials item under the selection of material and design submenu

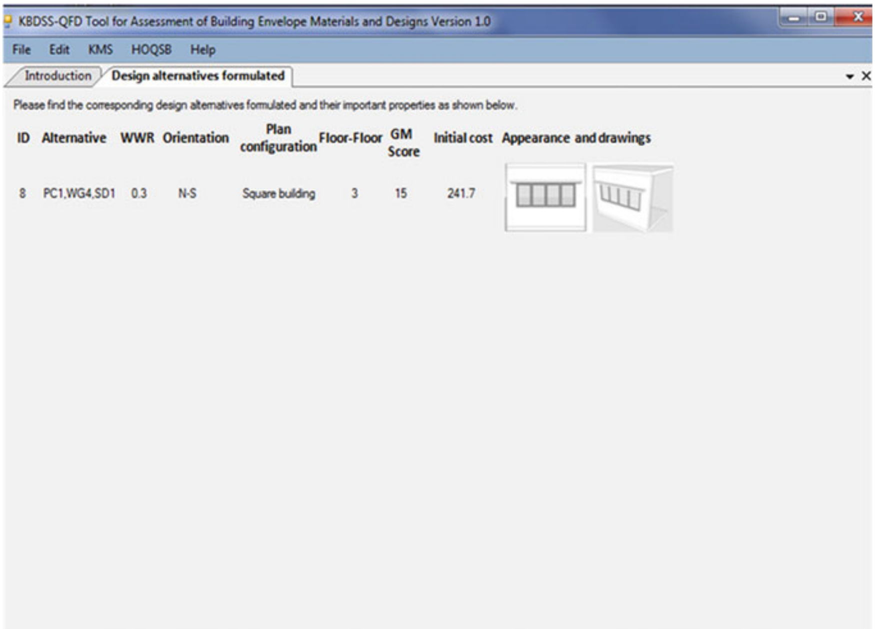


Fig. 8.34 Corresponding design item under the Selection of material and design submenu

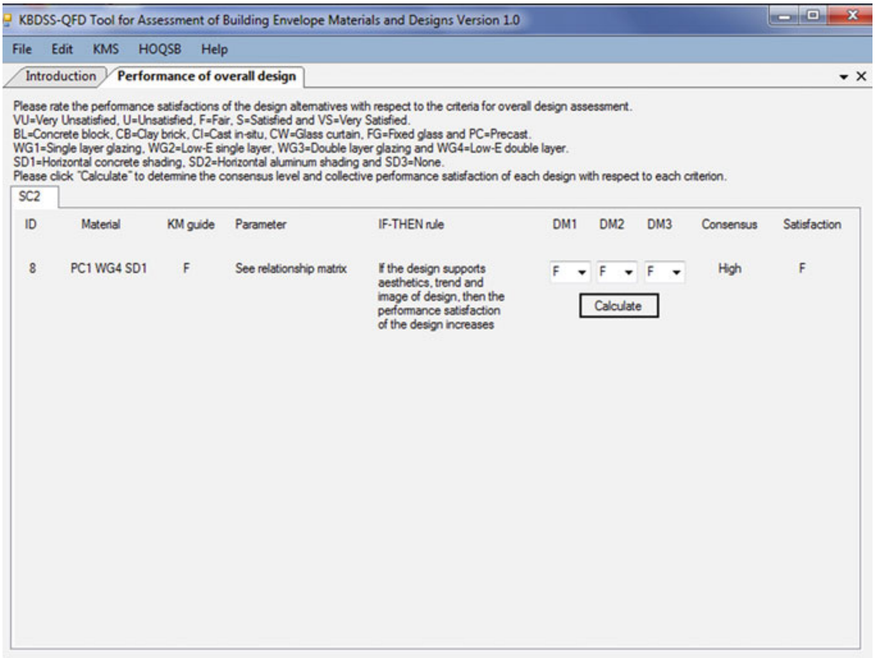


Fig. 8.35 Performance satisfaction of overall design item under the assessment of performance satisfaction submenu

screenshot for rating the performance satisfactions of the building envelope materials with respect to the "EN1" energy consumption which is the criterion for individual material assessment. Similar to Step 6, clicking on the **Calculate** button delivers the corresponding consensus levels and performance satisfactions of the decisions, and the assessment process in this step follows the fuzzy consensus scheme as well.

After completing Step 1 to Step 7, the team has to access the **Computation of SBI** submenu to view the SBI of each design alternative. This submenu serves two items which are the **Summary table** and **Preference list**. The **Summary table** item presents a summary table showing the importance weights with respect to all the criteria, performance satisfactions of the design alternatives, and their corresponding SBI. The screenshot as given in Fig. 8.37 is shown when the team clicks on this **Summary table** item.

In the mean time, the team can find the design alternatives in the form of the preference list as shown in Fig. 8.38 by clicking on the **Preference list** item. This item also shows the information inputted in Step 1 as well as the ranking of the design alternatives based on their SBI in a descending order. In addition, to ensure a smooth assessment process, the tool is equipped with the **Help** menu consisting of submenus to present background of the tool as well as instructions to use the tool. For instance, Figs. 8.39 and 8.40 show the screenshot when the **What are QFD**

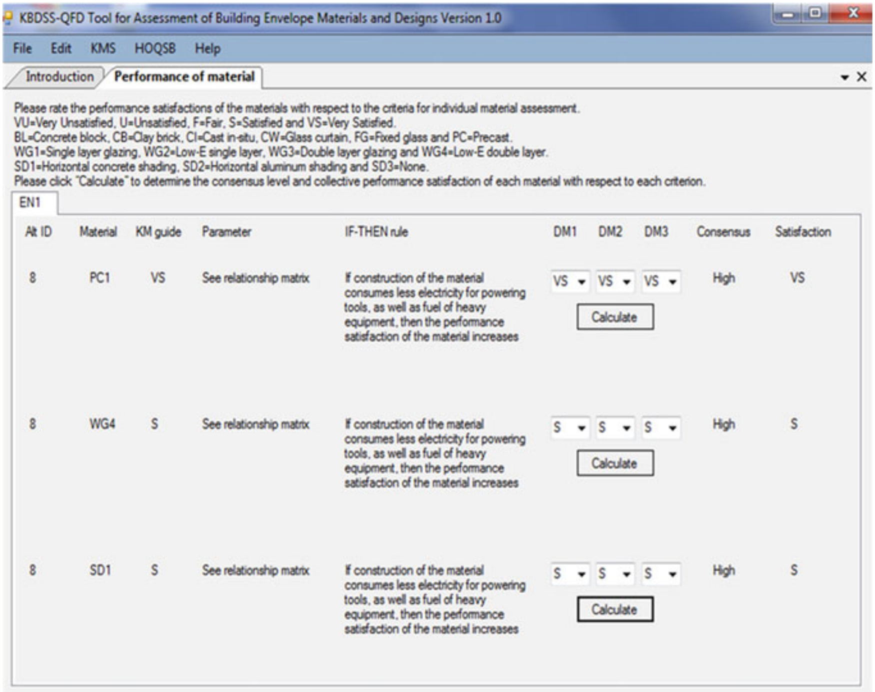


Fig. 8.36 Performance satisfaction of individual material item under the assessment of performance satisfaction submenu

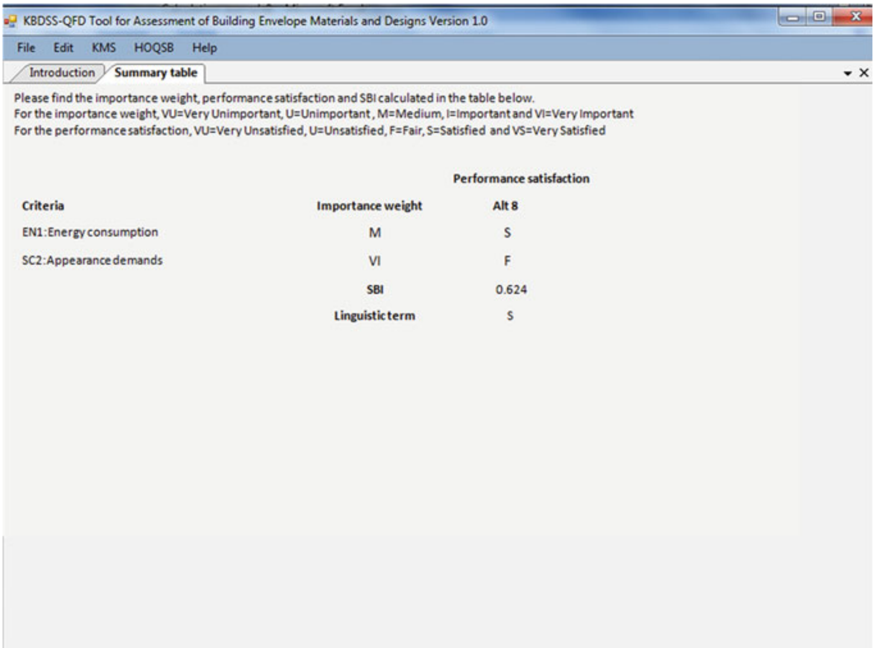


Fig. 8.37 Summary table item under the computation of SBI submenu

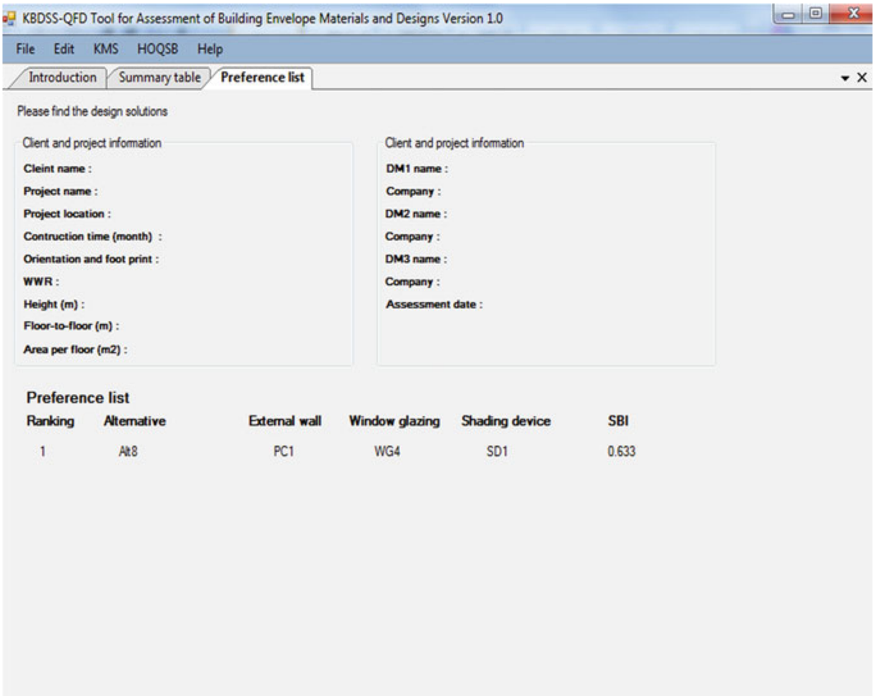


Fig. 8.38 Preference list item under the computation of SBI submenu

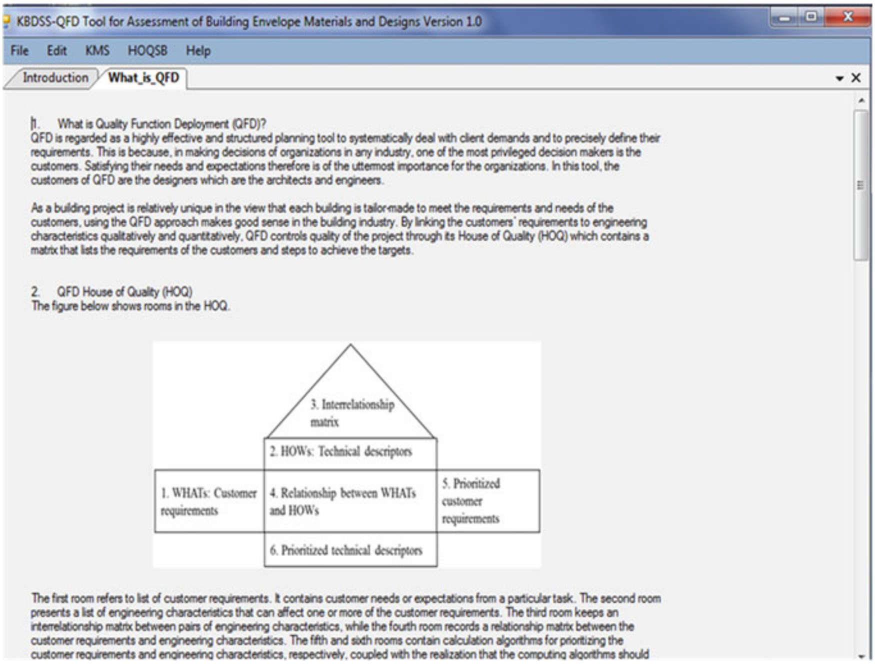


Fig. 8.39 What is QFD submenu under the Help menu

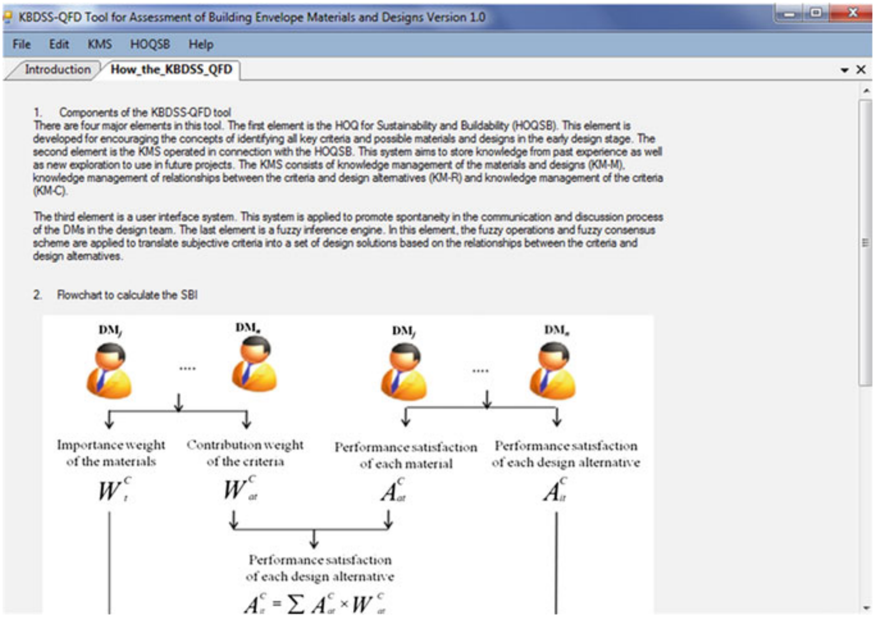


Fig. 8.40 How the KBDSS-QFD tool works submenu under the Help menu

and fuzzy set theory? and **How the KBDSS-QFD tool works?** submenus are accessed, respectively.

8.9 Verification and Debugging of the Tool

In the final phase to develop the prototype, verification and debugging of the prototype were carried out to uncover errors that have not been discovered when the KBDSS-QFD tool is running perfectly. These include the following steps:

1. The data and information of hypothetical cases were inputted into the prototype of the KBDSS-QFD tool to determine whether the tool was going to function as intended.
2. The outputs of the KBDSS-QFD tool were verified by comparing with the results from the tedious manual computations.
3. The debugging applications of Microsoft Visual Studio were used to uncover and correct the errors in the code of the KBDSS-QFD tool when errors were identified.

Verification and debugging were carried out successfully for the three steps mentioned above.

8.10 Case Studies

The objective of this section is to present the characteristics of the three case studies (see Sect. 6.4). It emphasizes on describing the outcomes of the KBDSS-QFD tool for all the design teams. Their official group meetings were held during August and September 2012; however, preparation activities for the meetings such as individual discussions between the researcher and individual DMs or preparation of project information started since June 2012 to allow the participants to be familiar with the tool and project information.

8.10.1 Case Study One

A "design team A" was engaged in the first case study to develop a conceptual design of the building envelopes for a representative "private high-rise residential building A" for a developer in Singapore. This design team consists of three DMs including an architect ("AR1"), C&S engineer ("CS1"), and M&E engineer ("ME1") as shown in Table 8.7.

The project general information and criteria preliminarily identified by the architect were shown in Tables 8.8 and 8.9, respectively. The design team aimed to deliver the conceptual design alternatives to the developer for making further acceptance decisions. To do so, the team used the prototype of the KBDSS-QFD tool to suggest the building envelope materials and designs. In this case study, the researcher acted as a team facilitator to operate the tool by presenting the project information, components of the tool, and then following through the seven steps for determining the SBI of each design alternative.

Step 1: Considering the information given in Table 8.8, the team entered relevant information of the project as shown in the actual screenshot in Fig. 8.41 and set up the fuzzy linguistic terms. The team adopted the minimum consensus level of "Medium," maximum assessment cycle of an individual DM of two cycles, and maximum assessment cycle of the group of three cycles as the freezing conditions of the consensus scheme. It is noted that the number of these cycles were manually recorded by the facilitator.

Table 8.7 Characteristics of the DMs in the case study one

DM name	DM assigned	Professional discipline	Years of experience	Organization
AR1	DM1	Architect	>10	Architectural firm 1
CS1	DM2	C&S engineer	>10	C&S engineering firm 1
ME1	DM3	M&E engineer	>10	M&E engineering firm 1

Table 8.8 General project information for the case study one

Developer	Condominium developer
Project title	High-rise residential building
Contract type	Design-bid-build
Project location	Central area of the city
Preferred external wall material	Curtain wall or fixed glass
Orientation/plan configuration	North–south/Square
WWR	0.3
Height	75 m
Floor-to-floor	3 m
Area per floor	400 m^2
Design and construction period	33 months

Table 8.9 Project key criteria for the case study one

Criteria category	Criteria name	Brief description
Environmental	EN3: Waste generation	Waste generation should be minimized to reduce the impacts on the surrounding environments
Economic	EC1: Initial costs	The project budget must be minimized
	EC2: Long-term burdens	The design must minimize long-term burdens particularly repairing and replacing costs.
Social	SC1: Energy efficiency	Energy efficiency of the design must be maximized to achieve high GM score and occupant comfort
	SC2: Appearance demands	Appearance demands must be maximized and modern and represent positive image
	SC3: Health, safety and security of occupants	Health, safety, and security of the occupants and society must be maximized
	SC4: Weather protection performance	The design should minimize negative influence from adverse weather during occupation phase
	SC5: Acoustic protection performance	The design should minimize adverse acoustical impacts from both indoor and outdoor activities
	SC6: Visual performance	Visual performance of the design should be maximized to achieve high occupant comfort
Buildability	BC5: Ease in construction with respect to time	The material, design, and construction techniques should be labor efficient while promoting high buildability

Step 2: The team selected the criteria as given in Table 8.9. Apart from these criteria, since the project would be located in a central area of the city, after having gone through the comprehensive list of the criteria provided by the KM-C, the team agreed that access to site, transportation of materials and community disturbance were major concerns of this project and should be taken into account. As a result, the "BC3" material deliveries from suppliers and "BC6" community disturbance were added into the assessment, contributing to a total of twelve criteria selected for

the assessment. The "EC1" initial costs, "SC1" energy efficiency, "SC2" appearance demands, "SC4" weather protection performance, "SC5" acoustic protection performance, and "SC6" visual performance were selected as the criteria for overall design assessment. By default, the rest of the criteria were automatically recorded as the criteria for individual material assessment to provide a systematic evaluation.

Step 3: The DMs rated the importance weights of the criteria selected in consideration of the guided importance weights and relevant knowledge stored in the KM-C. Figure 8.42 shows the screenshot for rating the importance weights of the "BC3" material deliveries from suppliers, "BC5" ease in construction with respect to time, and "BC6" community disturbance. The tool employs Eq. (8.1) and the fuzzy consensus scheme to calculate the collective importance weights and consensus levels, respectively. The weights were then converted back to the linguistic terms by Eq. (8.12). In this step, out of the twelve selected criteria, nine criteria received the same weights as suggested by the KM-C, while the other three criteria which are the "EN3" waste generation, "BC3" material deliveries from suppliers, and "BC6" community disturbance received a higher weight due to increasing concerns over the impacts of the project on the surrounding environments during the construction period. Considering the consensus level, a majority of the decisions received the "High" consensus level.

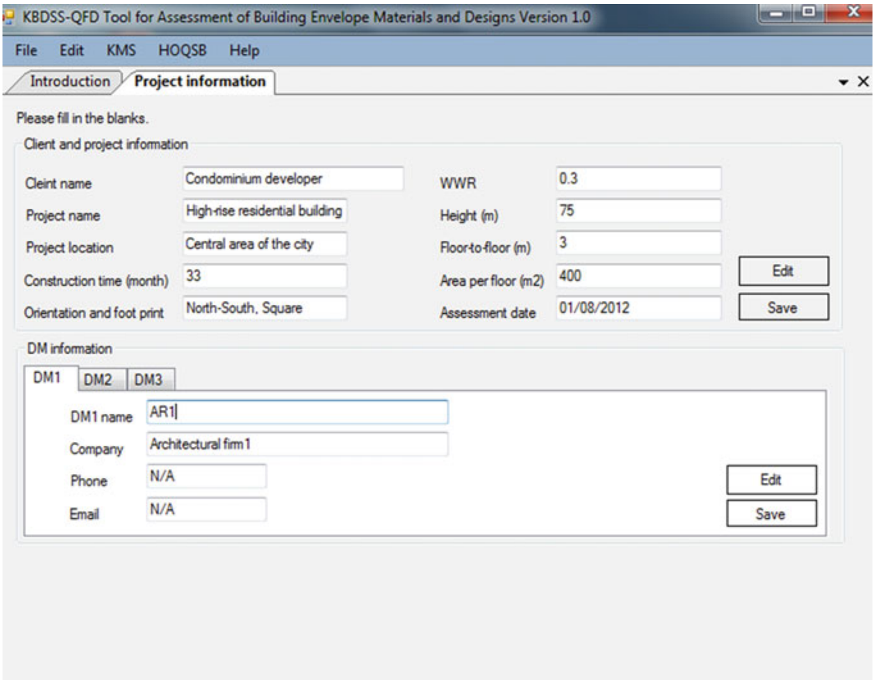


Fig. 8.41 Project information and fuzzy linguistic terms for the case study one

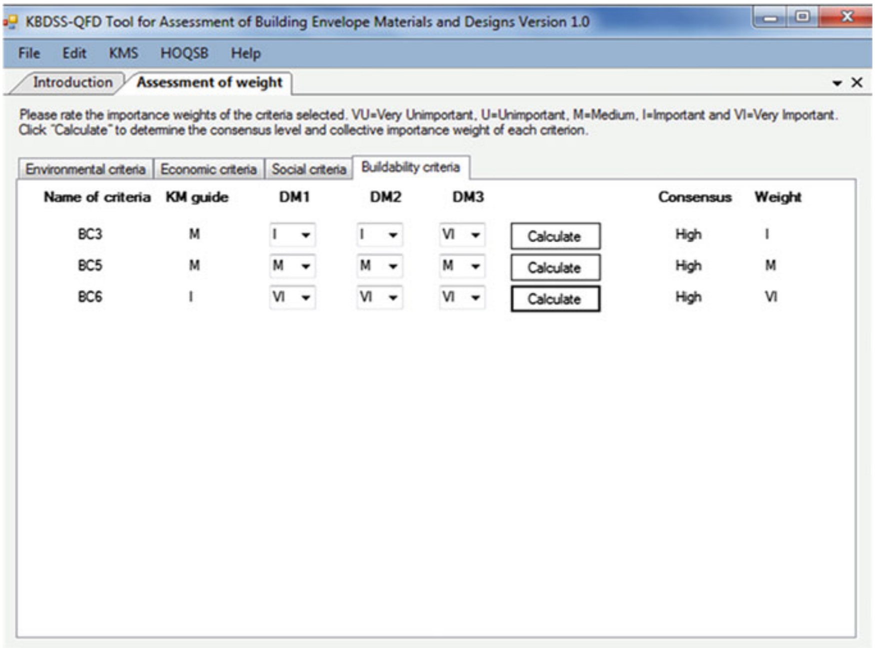


Fig. 8.42 Assessment of the importance weights for all the criteria for the case study one

In addition, there were two decisions for rating the importance weights of the "EC2" long-term burdens and "SC1" energy efficient that obtained the "Medium" consensus level in the second assessment cycle, and one decision for rating the importance weight of the "EN3" waste generation that received the "Medium" consensus level in the third assessment cycle of the team. This seemed to suggest that the perspectives among the DMs on the importance weights of these three criteria appeared to be more divergent than the others.

Step 4: The design team rated the contribution weights of the external wall, window glazing, and shading device with respect to the criteria for individual material assessment. Figure 8.43 presents the screenshot for rating such contribution weights regarding the "BC3" material deliveries from suppliers, "BC5" ease in construction with respect to time and "BC6" community disturbance.

Step 5: As Table 8.8 suggested that the preferred external wall materials include curtain wall and fixed glass wall, the team selected the "CW1" glass curtain, and "FG1" fixed glass as the external wall material options, the "WG3" double layer glazing and "WG4" Low-E double layer glazing as the window glazing material options, and the "SD2" horizontal aluminum shading as the shading device material option. According to this selection, four design alternatives corresponding to the design alternative "47" CW1WG3SD2, "48" CW1WG4SD2, "39" FG1WG3SD2, and "40" FG1WG4SD2 were extracted from the KM-M as shown in the screenshot given in Fig. 8.44.

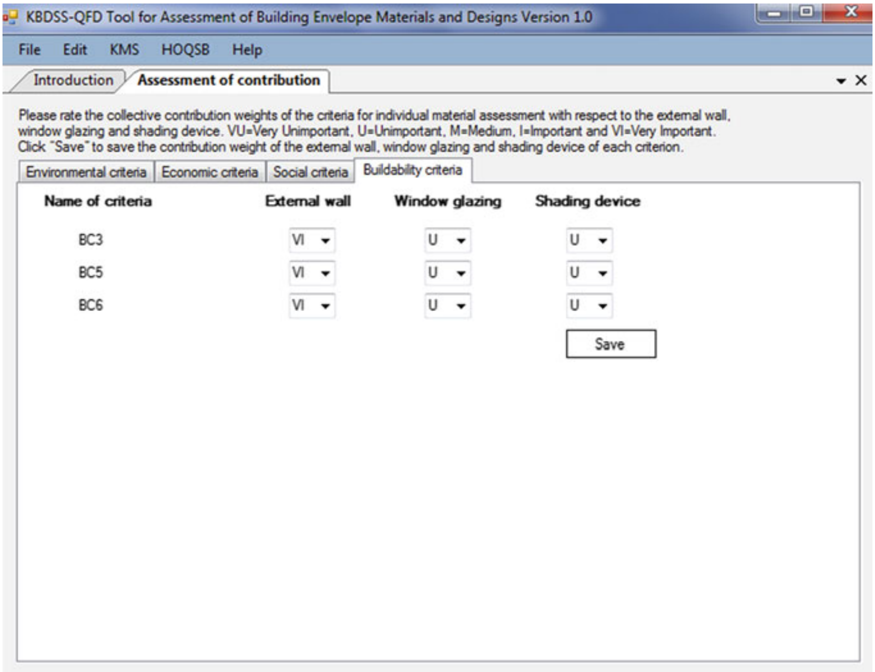


Fig. 8.43 Assessment of the contribution weights for the case study one

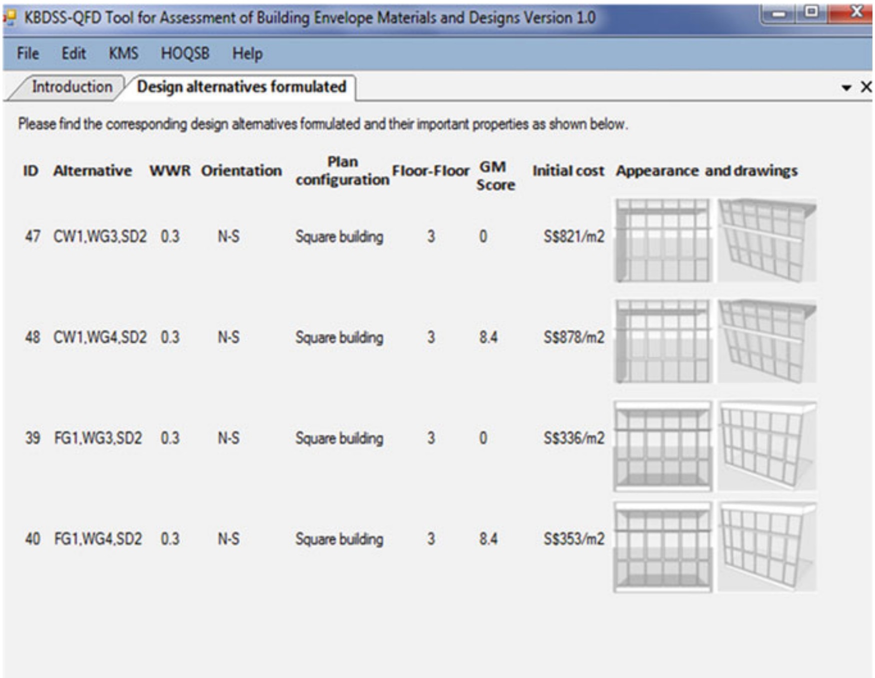


Fig. 8.44 Building envelope design alternatives for the case study one

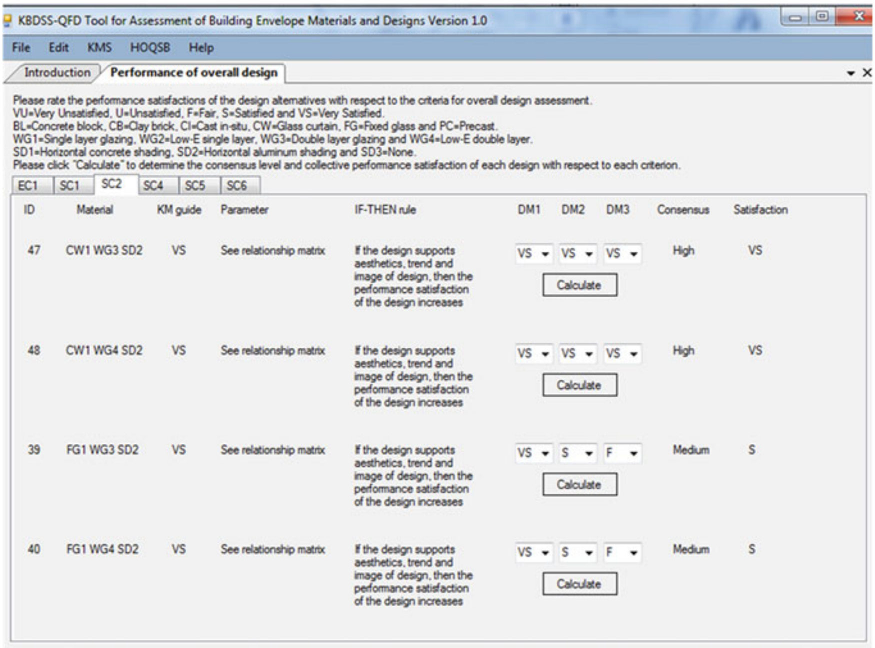


Fig. 8.45 Assessment of the performance satisfactions of the design alternatives for the case study one

Step 6: The DMs rated the performance satisfactions of these four design alternatives with respect to the criteria for overall design assessment. The screenshot in Fig. 8.45 reflects rating the performance satisfactions of the design alternatives with respect to the "SC2" appearance demands in consideration of the guided performance satisfactions, relationship matrix, and the IF-THEN rule. Equations (8.3) and (8.12) were applied to determine the collective performance satisfactions of the design alternatives in the form of the fuzzy numbers and linguistic terms, respectively

Although a majority of the decisions received the same performance satisfactions as suggested by the KM-R, as can be seen in Fig. 8.45, the collective performance satisfactions of the alternative "39" FG1WG3SD2 and "40" FG1WG4SD2 with respect to the "SC2" appearance demands appeared to be lower than the guided performance satisfaction as the "DM1" and "DM2" viewed that the fixed glass wall design-based alternatives do not reflect the appearance demands of the project well. In addition, all the decisions in this step received either the "High" or "Medium" consensus levels within the second assessment cycle of the team.

Step 7: The DMs assessed the performance satisfactions of the materials with respect to the criteria for individual material assessment. Figure 8.46 presents the screenshot for rating the performance satisfactions of the individual materials of

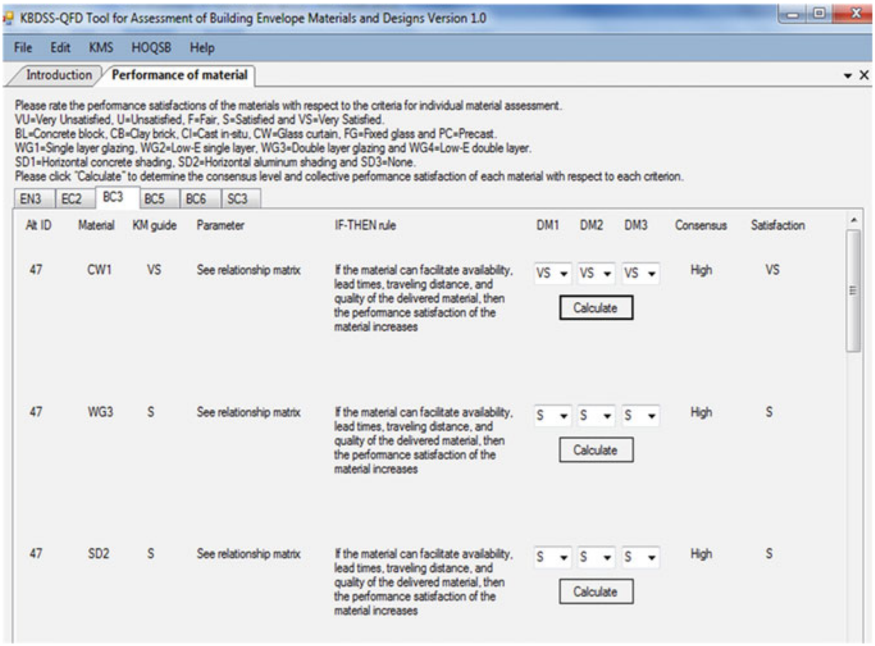
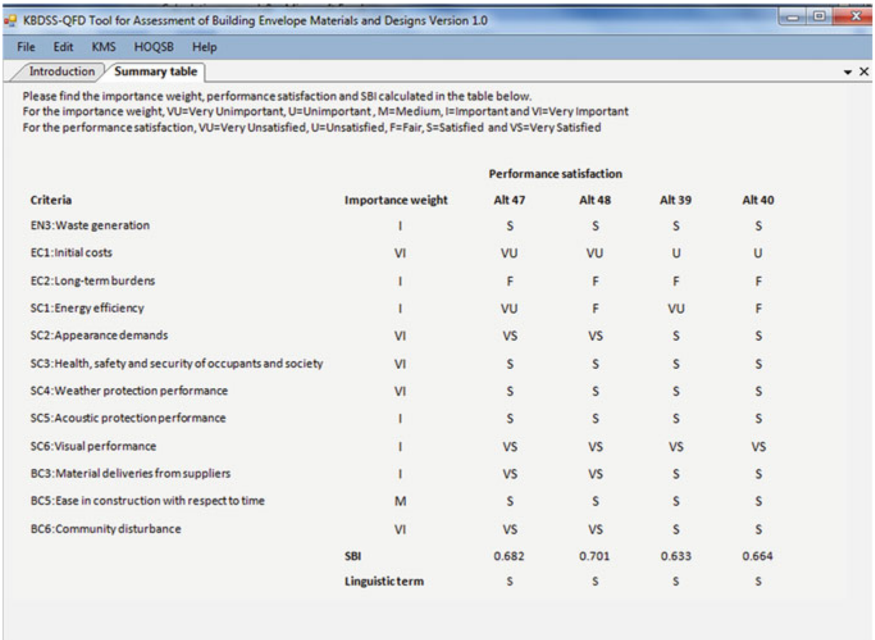


Fig. 8.46 Assessment of the performance satisfactions of the individual materials for the case study one

each alternative with respect to the "BC3" Material deliveries. Equations (8.5) and (8.12) were applied to determine the collective performance satisfactions in the form of the fuzzy numbers and linguistic terms, respectively.

According to this figure, the decisions received the same performance satisfactions as suggested by the KM-R with the "High" consensus level. It is noted that, in this step, a majority of the decisions obtained the "High" consensus level in the first assessment cycle. Figure 8.47 presents the screenshot of the tool showing a summary of the importance weights of the criteria, performance satisfactions of the design alternatives, and their corresponding SBI calculated by Eqs. (8.7) and (8.9).

As can be seen, although the alternative "39" FG1WG3SD2 and "40" FG1WG4SD2 received a higher performance satisfaction with respect to the "EC1" initial costs as compared to that of the alternative "47" CW1WG3SD2 and "48" CW1WG4SD2, the latter pair obtained higher performance satisfactions with respect to the "SC2" appearance demands, "BC3" material deliveries from suppliers, and "BC6" community disturbance. This contributed to their higher SBI overall. Furthermore, comparing between the alternative "47" CW1WG3SD2 and "48" CW1WG4SD2, the latter posed a higher performance satisfaction with respect to the "SC1" energy efficiency due to energy-saving applications of the low-E window glazing. For this reason, its SBI appeared to be slightly higher. In



Criteria	Importance weight	Performance satisfaction Alt 47	Alt 48	Alt 39	Alt 40
EN3:Waste generation	I	S	S	S	S
EC1:Initial costs	VI	VU	VU	U	U
EC2:Long-term burdens	I	F	F	F	F
SC1:Energy efficiency	I	VU	F	VU	F
SC2:Appearance demands	VI	VS	VS	S	S
SC3:Health, safety and security of occupants and society	VI	S	S	S	S
SC4:Weather protection performance	VI	S	S	S	S
SC5:Acoustic protection performance	I	S	S	S	S
SC6:Visual performance	I	VS	VS	VS	VS
BC3:Material deliveries from suppliers	I	VS	VS	S	S
BC5:Ease in construction with respect to time	M	S	S	S	S
BC6:Community disturbance	VI	VS	VS	S	S
	SBI	0.682	0.701	0.633	0.664
	Linguistic term	S	S	S	S

Fig. 8.47 Summary of the design solutions for the case study one

conclusion, the DMs mutually agreed to adopt the alternative “48” CW1WG4SD2 as a base case for the conceptual design of the project. The team took approximately three hours in this case study to reach a consensus through clear, step-by-step deliberations.

8.10.2 Case Study Two

A “design team B” was engaged in the second case study to develop a conceptual design for the building envelopes of a “private high-rise residential building B.” The “design team B” consists of three DMs; namely architect (“AR2”), C&S engineer (“CS2”), and M&E engineer (“ME2”) as shown in Table 8.10.

The project general information and criteria preliminarily identified by the architect are given in Tables 8.11 and 8.12, respectively. The “design team B” also aimed to deliver conceptual design alternatives to the developer using the prototype of the KBDSS-QFD tool to suggest the building envelope materials and designs as part of the preliminary conceptual design solutions.

Step 1: Considering the information given in Table 8.11, the team entered relevant information of the project as shown in the screenshot in Fig. 8.48 and set up the fuzzy linguistic terms. The team adopted the minimum consensus level of

Table 8.10 Characteristics of the DMs in the case study two

DM name	DM assigned	Professional discipline	Years of experience	Organization
AR2	DM1	Architect	>5	Architectural firm 2
CS2	DM2	C&S engineer	>5	C&S engineering firm 2
ME2	DM3	M&E engineer	>10	M&E engineering firm 2

Table 8.11 General project information for the case study

Developer	Condominium developer
Project title	High-rise residential building B
Contract type	Design-bid-build
Project location	Jurong East
Preferred external wall material	Precast/concrete block/claybrick
Orientation/Plan configuration	North–south/Square
WWR	0.3
Height	90 m
Floor-to-floor	3 m
Area per floor	400 m^2
Design and construction period	28 months

"Medium," maximum assessment cycle of an individual DM of two cycles, and maximum assessment cycle of the group of three cycles as the freezing conditions. Step 2: The design team inputted the criteria as given in Table 8.12 as the basic requirements of the project. The team also agreed to add the "BC5" ease in construction with respect to time for consideration. This aimed to take into account different construction periods of different building envelope materials and designs since the construction period given in this project is relatively short. This addition increased the total number of the criteria to 13 criteria. The "EC1" initial costs, "SC1" energy efficiency, "SC2" appearance demands, "SC4" weather protection performance, and "SC6" visual performance were chosen as the criteria for overall design assessment as suggested by the KM-C. By default, the rest of the criteria were automatically assigned for individual material assessment.
Step 3: The DMs assigned the importance weights of all the criteria selected. Figure 8.49 shows the screenshot for rating the importance weights of the "EN1" energy consumption, "EN2" waste consumption, and "EN3" resource consumption.

The tool then determined the collective importance weights and consensus levels accordingly. In this step, out of the 13 criteria, 10 criteria received the same importance weights as suggested by the KM-C, while the other two criteria which are the "BC1" health and safety of workers and "BC5" ease in construction with respect to time received a higher importance weight. This seemed to highlight the

Table 8.12 Project key criteria for the case study two

Criteria category	Criteria name	Brief description
Environmental	EN1: Energy consumption	The building envelope material and design must minimize consumption of electricity and fuel during construction
	EN2: Resource consumption	The building envelope material and design must minimize resources used during construction such as water, chemicals, sealants, etc.
	EN3: Waste generation	Waste generation especially air pollution and wastewater should be minimized to reduce the impacts on the surrounding environments
Economic	EC1: Initial costs	The project budget must be minimized.
	EC2: Long-term burdens	The design must minimize long-term burdens particularly repairing and replacing costs
Social	SC1: Energy efficiency	Energy efficiency of the design must be maximized to achieve high GM score and occupant comfort
	SC2: Appearance demands	Appearance demands of the design must be maximized and the design must be modern and represent positive image
	SC3: Health, safety and security of occupants	Health, safety, and security of the occupants and society must be maximized
	SC4: Weather protection performance	The design should minimize negative influence from adverse weather during occupation phase
	SC6: Visual performance	Visual performance of the design should be maximized to achieve high occupant comfort
Buildability	BC1: Health and safety of workers	The building envelope material and design must maximize workers' health and safety during construction
	BC4 : Material handling	The building envelope material and design must maximize ease in off-site and on-site handling methods

importance of the issues-related safety and construction time for this project which the client wished to complete quickly. Additionally, a majority of the decisions received the "High" consensus level. There were in fact only two decisions that received the "Medium" consensus level in the second assessment cycle of the team. These include the decisions for rating the importance weights of the "EC2" long-term burdens and "SC1" energy efficient.

Step 4: The team rated the contribution weights of the external wall, window glazing, and shading device for the criteria for individual material assessment. Figure 8.50 presents the screenshot for rating such contribution weights with respect to the "EN1" energy consumption, "EN2" waste consumption, and "EN3" resource consumption.

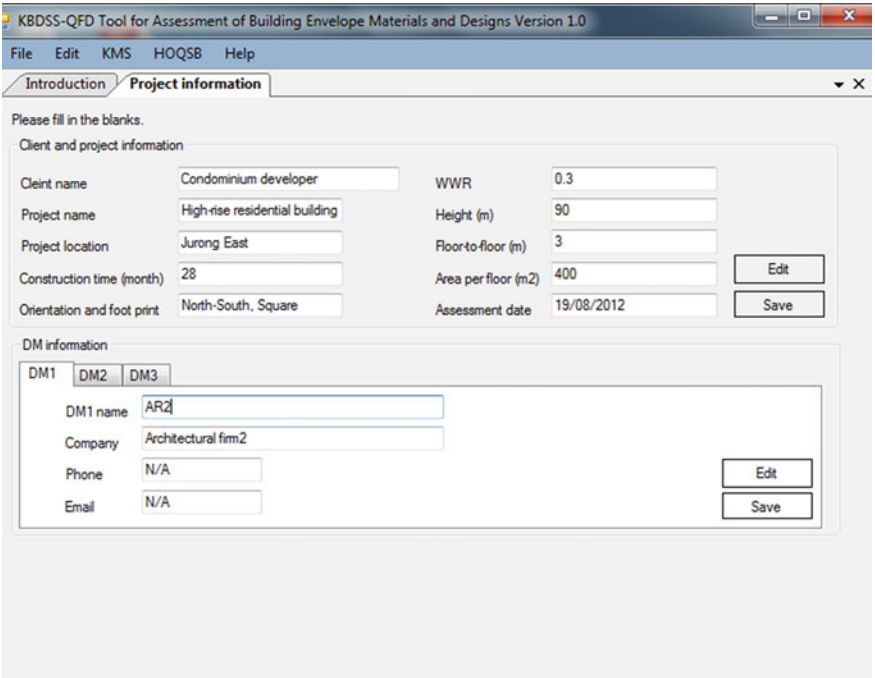


Fig. 8.48 Project information and fuzzy linguistic terms for the case study two

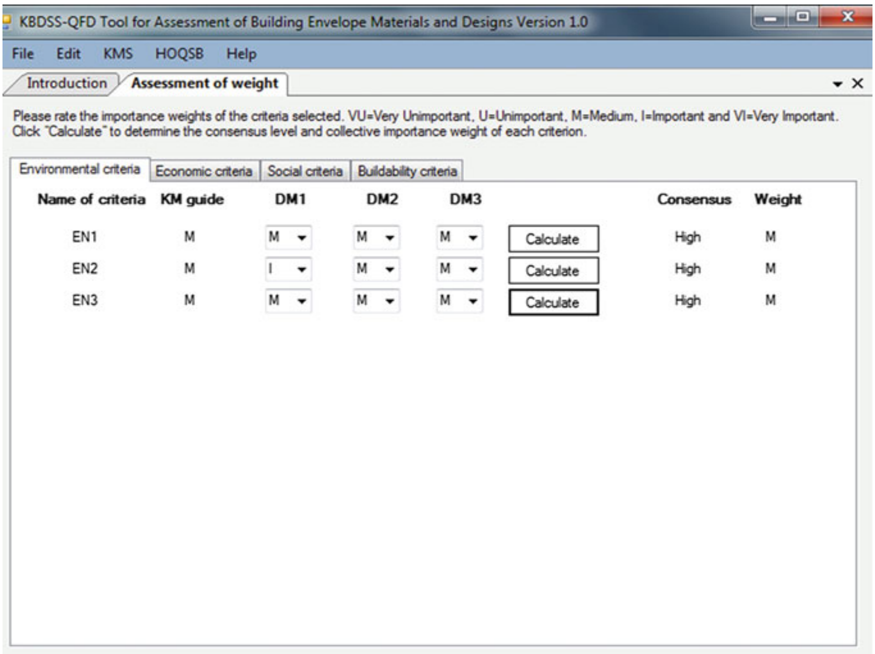


Fig. 8.49 Assessment of the importance weights for all the criteria for the case study two

Step 5: Based on the preferred external wall materials given in Table 8.11, the team selected the "PC1" precast, "CB" claybrick, and "BL1" concrete block as the external wall material options, the "WG4" double layer low-E glazing as the window glazing material option, and the "SD1" horizontal concrete shading as the shading device material option. According to this selection, three design alternatives corresponding to the alternative "8" PC1WG4SD1, "16" CB1WG4SD1, and "24" BL1WG43SD1 were extracted from the KM-M as shown in the screenshot given in Fig. 8.51.

Step 6: The DMs rated the performance satisfactions of these three design alternatives with respect to the criteria for overall design assessment. The screenshot given in Fig. 8.52 reflects rating of the performance satisfactions of the design alternatives with respect to the "SC4" weather protection performance in consideration of the guided performance satisfactions, relationship matrix and the IF-THEN rule. In this step, a majority of the decisions received the same performance satisfactions as suggested by the KM-R, and all the decisions received either the "High" or "Medium" consensus levels within the second assessment cycle of the team.

Step 7: The DMs assessed the performance satisfactions of the materials with respect to the criteria for individual material assessment. Figure 8.53 presents the

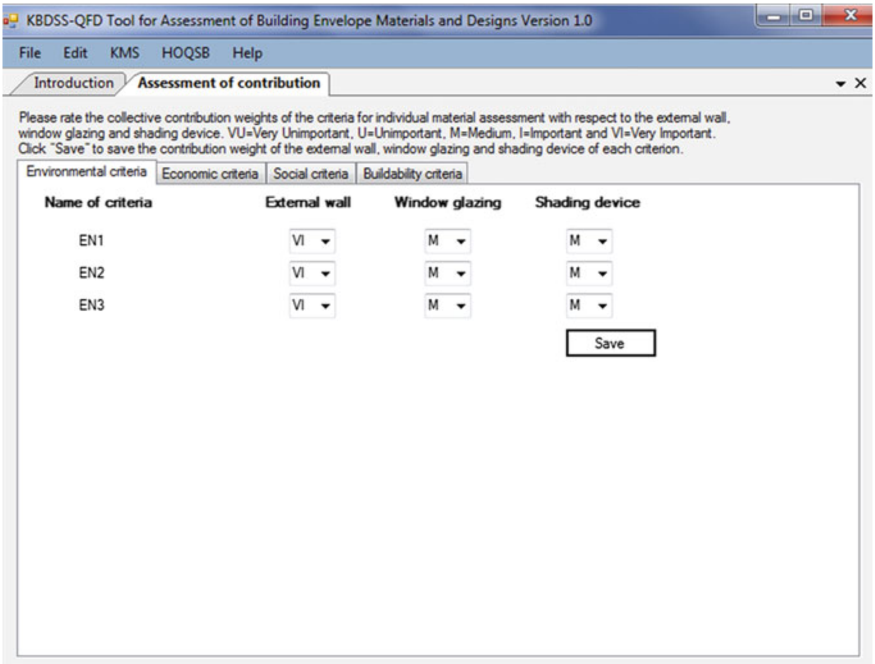


Fig. 8.50 Assessment of the contribution weights for the case study two

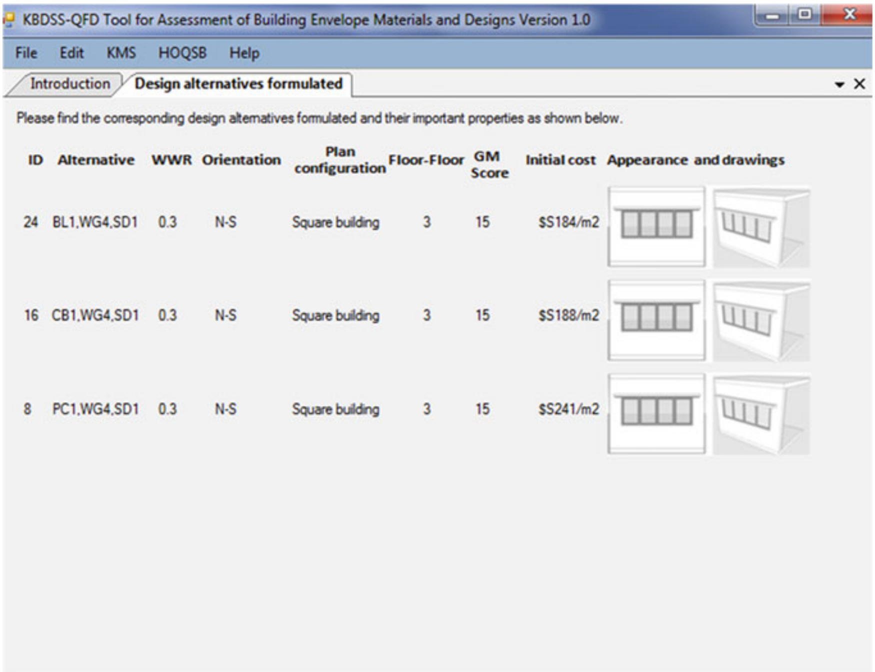


Fig. 8.51 Building envelope design alternatives for the case study two

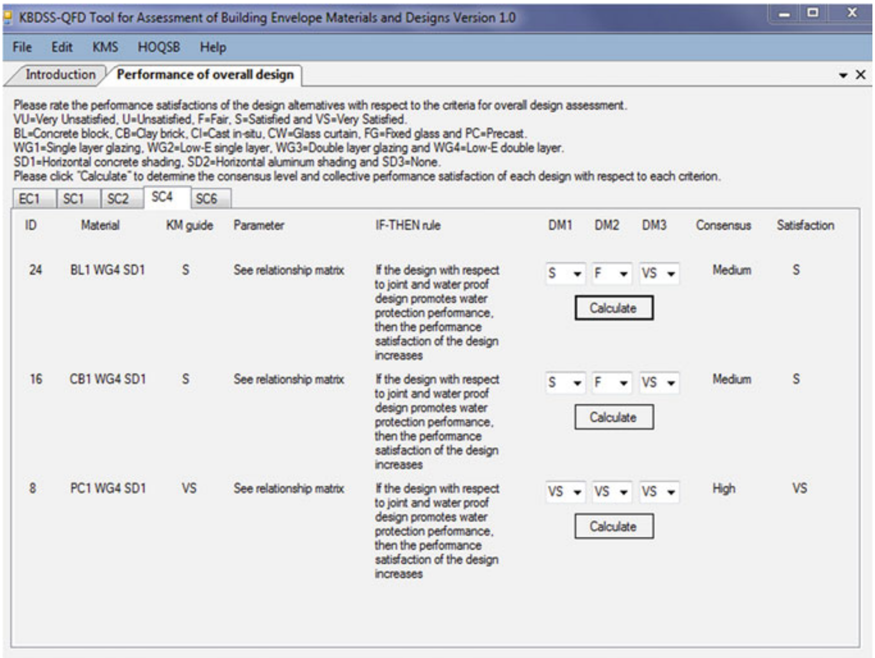


Fig. 8.52 Assessment of the performance satisfactions of the design alternatives for the case study two

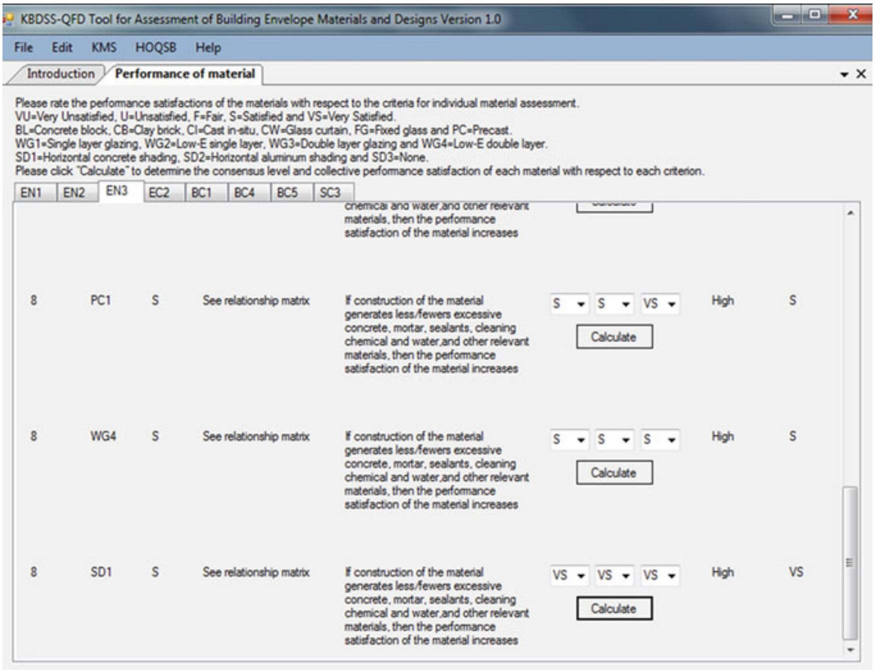
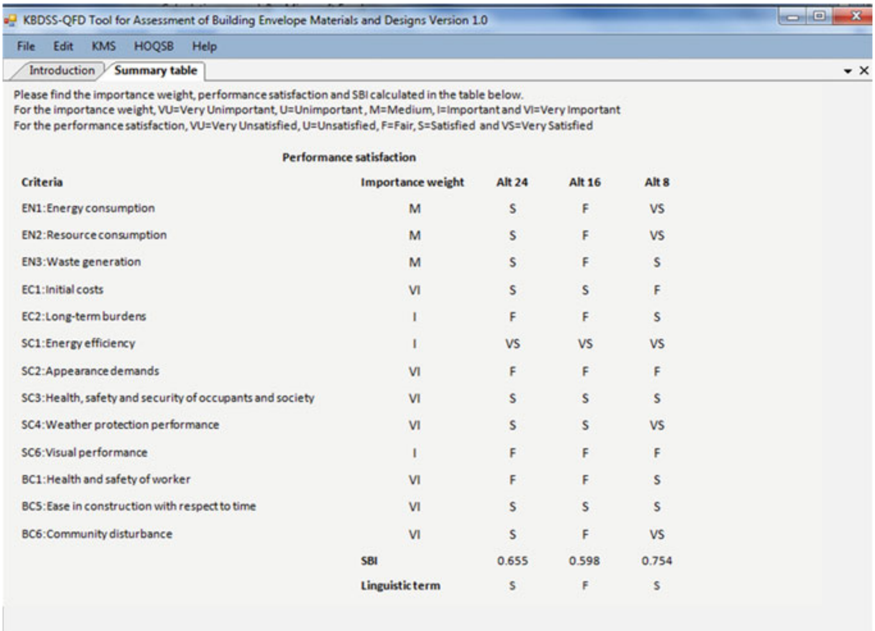


Fig. 8.53 Assessment of the performance satisfactions of the individual materials for the case study two

screenshot for rating the performance satisfactions of the individual materials with respect to the "EN3" waste generation. According to this figure, the performance satisfaction of the "SD1" horizontal shading device of the alternative "8" PC1WG4SD1 was rated higher than the performance satisfaction guided by the KM-R. All the DMs held the consensus opinion that because the shading device of this alternative would be integrated with the precast panel during the prefabrication process, its performance satisfaction with respect to the "EN3" waste generation during construction was therefore raised as compared to that of the "SD1" horizontal shading device of the alternative "16" CB1WG4SD1 and "24" BL1WG43SD1 installed on site.

The screenshot of the tool given in Fig. 8.54 provides a summary of the importance weights of the criteria, performance satisfactions of the design alternatives, and their corresponding SBI. As can be seen in this figure, the ranking from the highest to lowest SBI of the design alternatives is the alternative "8" PC1WG4SD1, "24" BL1WG4SD1, and "16" CB1WG4SD1. Comparing between the alternative "16" CB1WG4SD1 and "24" BL1WG4SD1, the type of the external wall is the only difference between these two alternatives. However, the alternative



Please find the importance weight, performance satisfaction and SBI calculated in the table below.
For the importance weight, VU=Very Unimportant, U=Unimportant, M=Medium, I=Important and VI=Very Important
For the performance satisfaction, VU=Very Unsatisfied, U=Unsatisfied, F=Fair, S=Satisfied and VS=Very Satisfied

		Performance satisfaction		
Criteria	Importance weight	Alt 24	Alt 16	Alt 8
EN1:Energy consumption	M	S	F	VS
EN2:Resource consumption	M	S	F	VS
EN3:Waste generation	M	S	F	S
EC1:Initial costs	VI	S	S	F
EC2:Long-term burdens	I	F	F	S
SC1:Energy efficiency	I	VS	VS	VS
SC2:Appearance demands	VI	F	F	F
SC3:Health, safety and security of occupants and society	VI	S	S	S
SC4:Weather protection performance	VI	S	S	VS
SC6:Visual performance	I	F	F	F
BC1:Health and safety of worker	VI	F	F	S
BC5:Ease in construction with respect to time	VI	S	S	S
BC6:Community disturbance	VI	S	F	VS
	SBI	0.655	0.598	0.754
	Linguistic term	S	F	S

Fig. 8.54 Summary of the design solutions for the case study two

"16" CB1WG4SD1 received higher performance satisfactions with respect to a number of criteria particularly the "EN1" energy consumption and "EN2" resource consumption. This could be because the DMs viewed that the concrete blockwall requires less energy and resource consumption during construction as compared to the clay brickwall.

Furthermore, when it comes to comparison between the alternative "8" PC1WG4SD1 and "24" BL1WG4SD1, there are two main differences which are the type of the external wall and type of the shading device. In brief, the "PC1" precast wall received higher performance satisfactions than the "BL1" blockwall with respect to the "EN1" energy consumption, "EN2" resource consumption, "SC4" weather protection, and "BC6" community disturbance. Similarly, the shading device of the precast wall also obtained higher performance satisfactions than that of the blockwall with respect to various criteria such as the "EN1" energy consumption, "EN2" resource consumption, and "EN3" waste generation. This was because the first would be integrated with the precast panel by the manufacturer, while the latter would be installed on site. These collectively contributed to a higher SBI of the design alternative "8" PC1WG4SD1. As such, the design team adopted this design alternative as a base case for further development of the conceptual designs of this project. The design team took approximately two hours and a half to complete the exercise in this case study.

8.10.3 Case Study Three

Case study three was represented by a "design team C" aiming to develop a conceptual design of a "private high-rise residential building C." The "design team C" consists of three DMs; namely architect ("AR3"), C&S engineer ("CS3"), and M&E engineer ("ME3") as shown in Table 8.13.

The project general information and criteria preliminarily identified by the architect are given in Tables 8.14 and 8.15, respectively. Similar to the previous case studies, the "design team C" attempted to deliver conceptual design alternatives to the developer using the prototype of the KBDSS-QFD tool to suggest the building envelope materials and designs as part of the preliminary conceptual design solutions.

Step 1: Considering the information given in Table 8.14, the team entered relevant information of the project as shown in the screenshot in Fig. 8.55 and set up the fuzzy linguistic terms. The team adopted the minimum consensus level of

Table 8.13 Characteristics of the DMs in the case study three

DM name	DM assigned	Professional discipline	Years of experience	Organization
AR3	DM1	Architect	>15	Architectural firm 3
CS3	DM2	C&S engineer	>10	C&S engineering firm 3
ME3	DM3	M&E engineer	>10	M&E engineering firm 3

Table 8.14 General project information for the case study three

Developer	Condominium developer
Project title	High-rise residential building C
Contract type	Design-Bid-Build
Project location	Novena
Preferred external wall material	Precast/Fixed glass/Curtain wall
Concept	Long-term occupant satisfaction
Orientation/Plan configuration	North–south/Square
WWR	0.3
Height	90 m
Floor-to-floor	3 m
Area per floor	625 m^2
Design and construction period	30 months

Table 8.15 Project key criteria for the case study three

Criteria category	Criteria name	Brief description
Environmental	EN3: Waste generation	Waste generation especially air pollution and wastewater should be minimized to reduce the impacts on the surrounding environments
Economic	EC1: Initial costs	The project budget must be minimized
	EC2: Long-term burdens	The building envelope design must minimize long-term burdens particularly repairing and replacing costs
	EC3: Durability	Durability of the building envelope materials and designs must be maximized over their life span
Social	SC1: Energy efficiency	Energy efficiency of the design must be maximized to achieve high GM score and occupant comfort
	SC2: Appearance demands	Appearance demands of the design must be maximized and the design must be modern and represent positive image
	SC3: Health, safety and security of occupants	Health, safety, and security of the occupants and society must be maximized
	SC4: Weather protection performance	The design should minimize negative influence from adverse weather during occupation phase
	SC5:Acoustic protection performance	The design should minimize adverse acoustical impacts from both indoor and outdoor activities
	SC6: Visual performance	Visual performance of the design should be maximized to achieve high occupant comfort
Buildability	BC1: Health and safety of workers	The building envelope material and design must maximize workers' health and safety during construction
	BC5:Ease in construction with respect to time	The building envelope material and design must maximize ease in construction within a time given

"Medium," maximum assessment cycle of an individual DM of two cycles, and maximum assessment cycle of the group of three cycles as the freezing conditions.

Step 2: The team selected the 12 criteria as given in Table 8.15 as the requirements of this project. The "EC1" initial costs, "SC1" energy efficiency, "SC2" appearance demands, "SC4" weather protection performance, "SC5" acoustic protection performance, and "SC6" visual performance were chosen as the criteria for overall design assessment as suggested by the KM-C. By default, the rest of the criteria were automatically assigned for individual material assessment.

Step 3: The DMs assigned the importance weights of all the criteria selected. Figure 8.56 shows the screenshot for rating the importance weights of the "EC1" initial costs, "EC2" long-term burdens, and "EC3" durability.

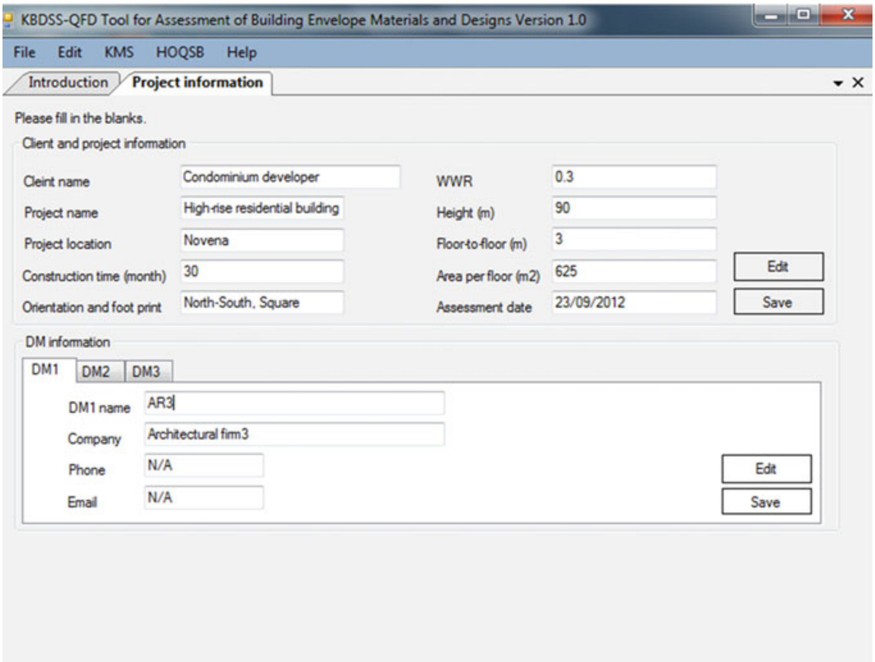


Fig. 8.55 Project information and fuzzy linguistic terms for the case study three

Based on the inputs given by the DMs, the KBDSS-QFD tool determined the collective importance weights of the criteria and consensus levels of the decisions accordingly. In this step, out of the 12 criteria, only the "SC1" energy efficient received a higher importance weight than the one guided by the KM-C. As the main concept of this project is to enhance long-term satisfaction of the occupants, the DMs agreed with the "High" consensus level in the first assessment cycle of the team that the "SC1" energy efficient of the designs should play a larger part in this assessment to increase thermal comfort of the occupants. Aside from this decision, the rest of the decisions received either the "High" or "Medium" consensus levels within the third assessment cycle of the team.

Step 4: The design team rated the contribution weights of the external wall, window glazing, and shading device for the criteria for individual material assessment. Figure 8.57 presents the screenshot for rating such contribution weights with respect to the "BC1" energy consumption and "BC5" ease in construction with respect to time.

Step 5: Based on the information given in Table 8.14, the DMs selected the "PC1" precast, "FG1" fixed glass and "CW1" curtain wall as the external wall material options, the "WG4" double layer low-E glazing as the window glazing material

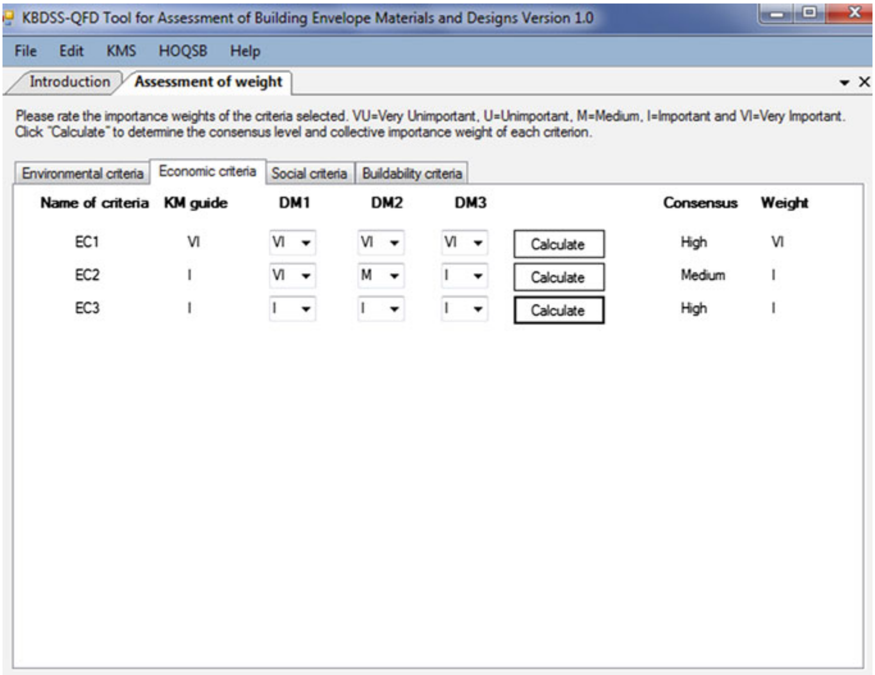


Fig. 8.56 Assessment of the importance weights for the case study three

option, the "SD1" horizontal concrete shading, and "SD2" Horizontal aluminum shading as the shading device material options. According to this selection, three design alternatives corresponding to the alternative "8" PC1WG4SD1, "40" FG1WG4SD2, and "48" CW1WG4SD2 were extracted from the KM-M as shown in the screenshot given in Fig. 8.58.

Step 6: The DMs rated the performance satisfactions of these three design alternatives with respect to the criteria for overall design assessment. The screenshot as shown in Fig. 8.59 reflects rating the performance satisfactions of the design alternatives with respect to the "SC2" appearance demands in consideration of the guided performance satisfactions, relationship matrix, and the IF-THEN rule. From this figure, interestingly, the decision for rating the performance satisfaction of the alternative "8" PC1WG4SD1 with respect to the "SC2" appearance demands still received the "Low" consensus level after the third assessment cycle. This suggested that the DMs' perspectives on this criterion are quite diverse; however, more importantly, the consensus scheme managed to reduce this diversity to the level that everyone in the team agreed with.

Step 7: The DMs rated the performance satisfactions of the individual materials with respect to the criteria for individual material assessment. Figure 8.60 presents

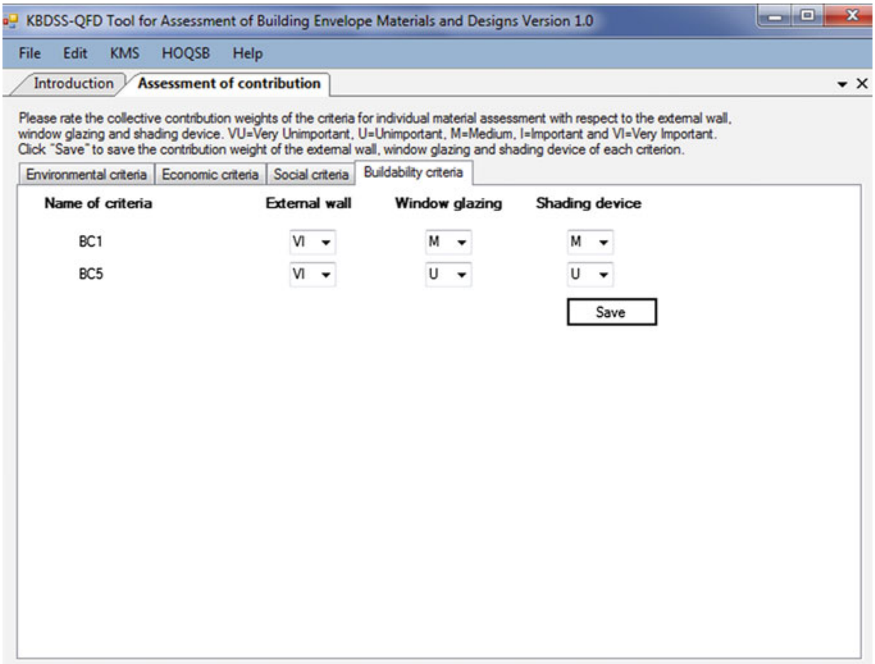


Fig. 8.57 Assessment of the contribution weights for the criteria for individual material assessment for the case study three

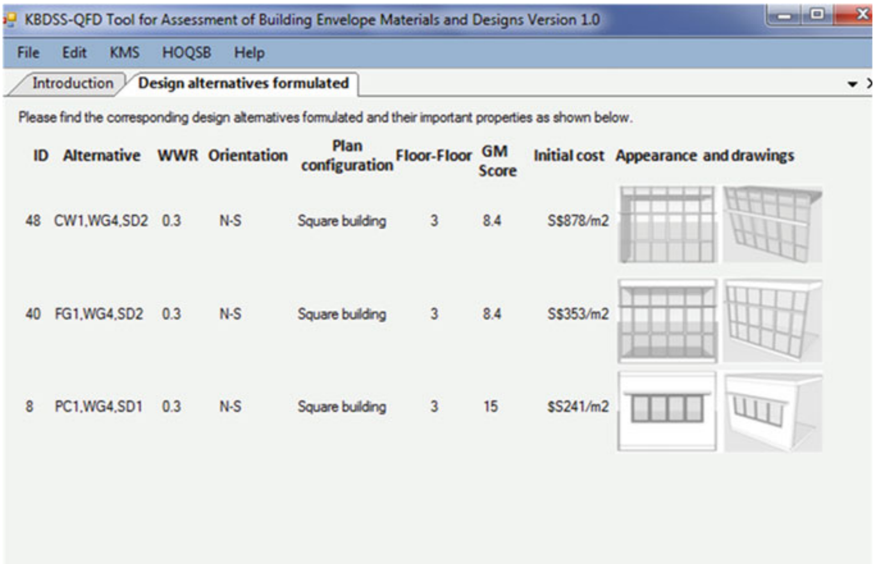


Fig. 8.58 Building envelope design alternatives for the case study three

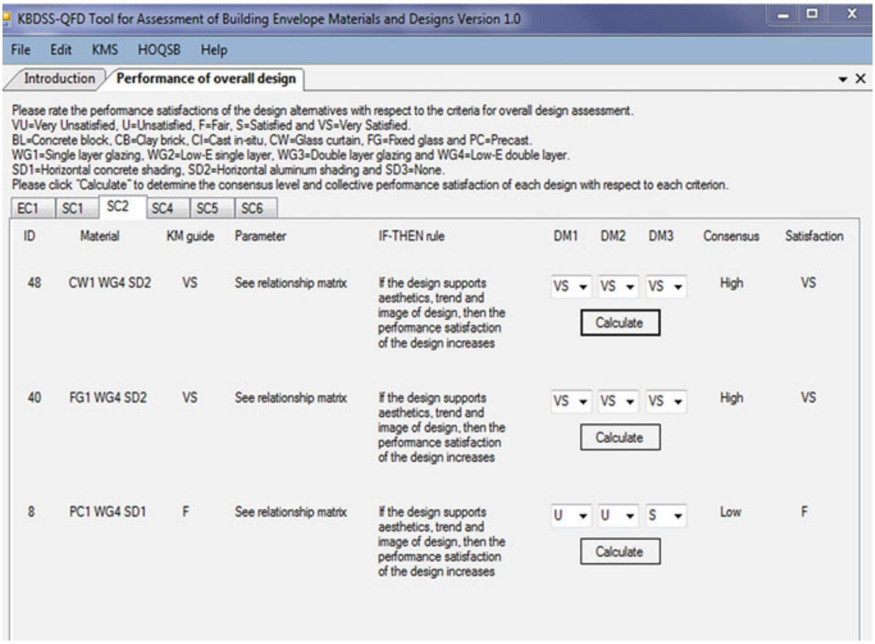


Fig. 8.59 Assessment of the performance satisfactions of the design alternatives for the case study three

the screenshot for rating the performance satisfactions of the individual materials of each alternative with respect to the "EC3" durability of materials. Figure 8.61 shows the screenshot of the tool presenting a summary of the importance weights of the criteria, performance satisfactions of the design alternatives, and their corresponding SBI. From this figure, the overall ranking of the design alternatives from the highest to lowest SBI is the alternative "8" PC1WG4SD1, "48" CW1WG4SD2, and "40" FG1WG4SD2. As can be seen, the SBIs of the alternative "40" FG1WG4SD2 and "48" CW1WG4SD2 are quite close to each other. The main difference between these two alternatives is that the latter received a higher performance satisfaction with respect to the "BC1" health and safety of workers due to the better health and safety performance of the curtain wall.

Furthermore, comparing between all the three alternatives, the SBI of the alternative "8" PC1WG4SD1 is relatively higher than that of the alternative "48" CW1WG4SD2 and "40" FG1WG4SD2. This is because of its higher performance satisfactions with respect to the "EC1" initial costs, "EC2" long-term burdens, "SC1" energy efficiency, "SC4" weather protection performance, and "SC5" acoustic protection performance. For this reason, the DMs as a team decided to

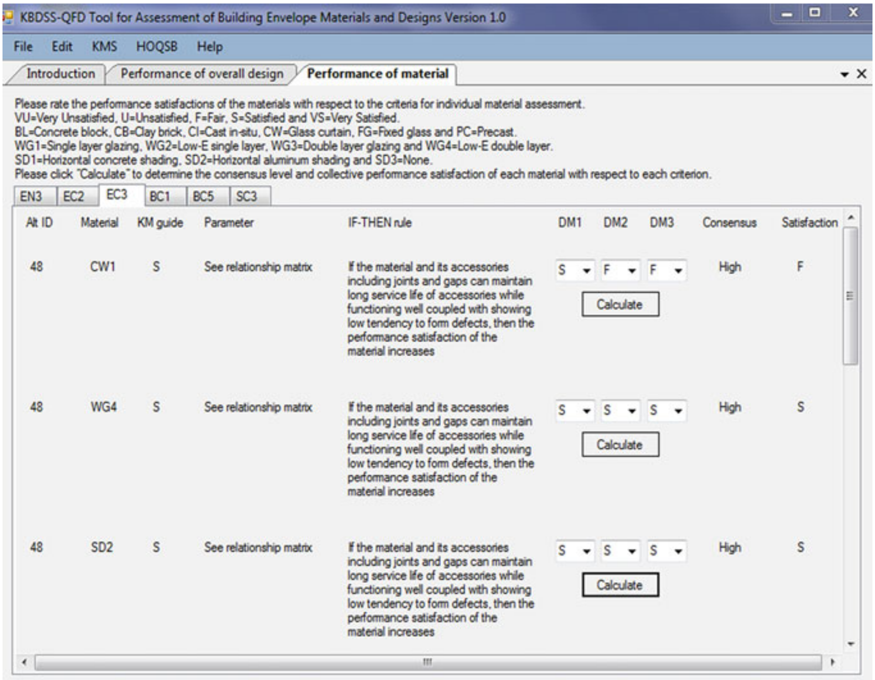
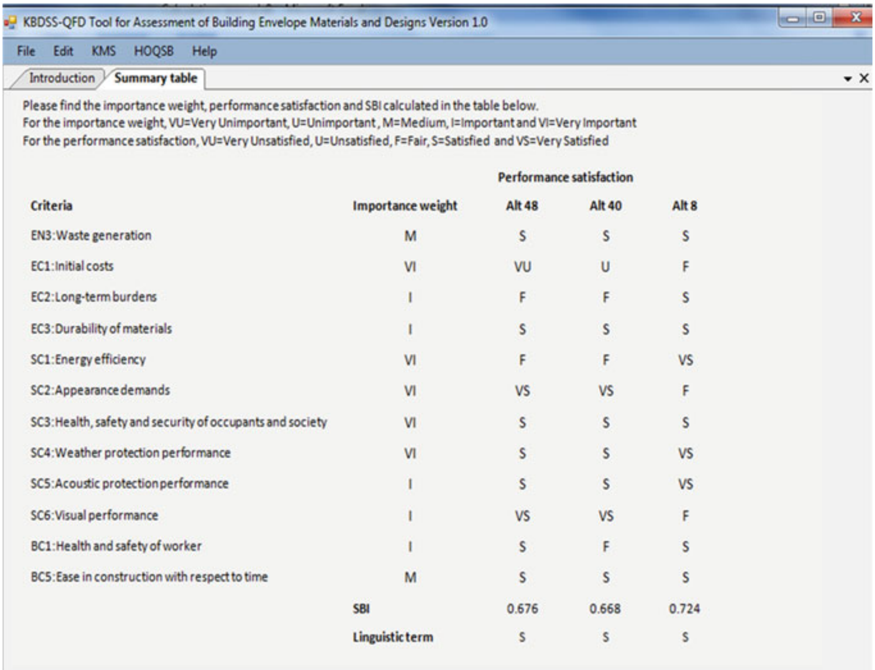


Fig. 8.60 Assessment of the performance satisfactions of the individual materials for the case study three

adopt the alternative "8" PC1WG4SD1" for further development of the conceptual design of the project. The team took approximately three hours to complete the exercise in this case study.

8.11 Findings from the Case Studies and Discussion

The book applied the framework analysis (see Sect. 6.5.2) to analyze the qualitative data collected through the group interviews with the design team in each case study. The findings were arranged in the form of the thematic chart as shown in Table 8.16. This chart contains the six main concepts to mitigate the decision-making problems and their corresponding subconcepts extracted from the conceptual framework and data collected. It is important to note that, unlike simple cut and paste methods that are presented in verbatim text, the chart contains distilled summaries of views and experiences. Thus, the charting process involves a considerable amount of abstraction and synthesis.


KBDSS-QFD Tool for Assessment of Building Envelope Materials and Designs Version 1.0

File Edit KMS HOQSB Help

Introduction Summary table

Please find the importance weight, performance satisfaction and SBI calculated in the table below.
For the importance weight, VU=Very Unimportant, U=Unimportant, M=Medium, I=Important and VI=Very Important
For the performance satisfaction, VU=Very Unsatisfied, U=Unsatisfied, F=Fair, S=Satisfied and VS=Very Satisfied

		Performance satisfaction		
Criteria	Importance weight	Alt 48	Alt 40	Alt 8
EN3:Waste generation	M	S	S	S
EC1:Initial costs	VI	VU	U	F
EC2:Long-term burdens	I	F	F	S
EC3:Durability of materials	I	S	S	S
SC1:Energy efficiency	VI	F	F	VS
SC2:Appearance demands	VI	VS	VS	F
SC3:Health, safety and security of occupants and society	VI	S	S	S
SC4:Weather protection performance	VI	S	S	VS
SC5:Acoustic protection performance	I	S	S	VS
SC6:Visual performance	I	VS	VS	F
BC1:Health and safety of worker	I	S	F	S
BC5:Ease in construction with respect to time	M	S	S	S
	SBI	0.676	0.668	0.724
	Linguistic term	S	S	S

Fig. 8.61 Summary of the design solutions for the case study three

Figure 8.62 illustrates the mapping diagram developed in relation to the thematic chart to present the associations between the decision-making problems and concepts/main themes of the tool with a view to providing explanations for the findings of the case studies. The book applied this diagram coupled with the thematic chart to explain how the tool played a role in mitigating the six decision-making problems and why the tool could do so. Overall, it was found that mitigation of one decision-making problem may be associated with at least one concept. Considering mitigation of the decision-making problem related to inadequate consideration of criteria, the results from the analysis suggested that applying the criteria knowledge stored in the KMS through the HOQSB helped the design teams in the early design stage to thoroughly consider key criteria required for the assessment. This reminded the teams of relevant regulations, reasons for compliance, description, and importance of each criterion.

Additionally, the tool facilitated the teams to collectively consider the criteria altogether at once based on a systematic approach. This subsequently improved comprehensiveness of the assessment and made the decision-making process become more effective and consistent. The literature reviews support that, instead of redesigning a product, when design parameters are changed, or when new assessment criteria have to be additionally considered, the design would be more

Table 8.16 Thematic chart of the framework analysis

Main concept: 1. Identifying a full set of criteria		
Subconcept: 1.1 Reminder of key criteria		
Case study one	Case study two	Case study three
• The list of the criteria improved awareness on key sustainability and buildability criteria of the team	• Considering the criteria as a whole assisted the team to conduct the thorough assessment	• The knowledge provided good understanding of each criterion
• It was helpful to be reminded of impacts on design, construction, and maintenance phases	• The tool fine-tuned perspectives of the DMs based on importance of each criterion	• Providing a full list of the criteria can make the design more comprehensive
• The tool allowed better and clearer understanding of the requirements of the project	• The set of the criteria and their compliance suggested how important the criteria are	• The criteria and their knowledge helped the team to pinpoint main considerations
	• The team benefited from the set of criteria in terms of time saving	• The tool offered both awareness of the criteria and time saving for the early stage design
Subconcept: 1.2 Taking all criteria into consideration at once		
Case study one	Case study two	Case study three
• Considering all the criteria at the same time facilitated better project and construction management	• Incorporation of all the related criteria at once supported comprehensive assessment	• The tool raised awareness of determining a balance view regarding several criteria
• The process can reduce design and review cycle	• The list of the criteria supported comprehensive assessment benefiting the stakeholders of a project	• The set of the criteria helped balancing conflicting criteria at once and reducing the assessment time
• Considering all requirements at once delivered a more consistent and holistic assessment	• Evaluating design alternatives regarding these criteria ensured that the team diligently offered the best value design to the client	• Comparing all the criteria selected was useful for achieving better design and project management
Main concept: 2. Identifying possible materials and designs		
Subconcept: 2.1 Reminder of basic materials and designs		
Case study one	Case study two	Case study three
• Providing key parameters of the materials and designs improved efficiency and consistency in making decisions	• The data stored were useful to find the materials and designs that meet requirements	• The wall, window and shading device materials given cover basic materials used in real life
• The materials and their corresponding designs offered a good start for the assessment and a clearer picture of what would be evaluated	• Using this tool saved time in acquisition of the knowledge	• The materials database and its knowledge broadened a scope of the assessment applied in practice

(continued)

Table 8.16 (continued)

Case study one	Case study two	Case study three
Main concept: 2. Identifying possible materials and designs		
Subconcept: 2.1 Reminder of basic materials and designs		
Case study one	Case study two	Case study three
• The tool reminded the fundamental designs	• The key parameters identified were useful for the assessment of the materials and designs	• If more materials and designs were included the assessment would be more holistic
Subconcept: 2.2 Comparing materials and designs at once		
Case study one	Case study two	Case study three
• Evaluating the glass and curtain wall alternatives selected at the same time ensured a more comprehensive assessment	• Although the process took quite a long time, evaluating the materials and alternatives at once seemed to yield more acceptable and consistent solutions	• Finding an appropriate conceptual design required a comprehensive assessment by considering several alternatives
• Several materials and their corresponding designs allowed the team to compare similarities and differences among them	• Comparing possible materials and designs may reduce repetitive works which could occur during the detailed design stage	• The tool allowed the team to compare the envelope materials and designs in a more efficient and consistent basis
Main concept: 3. Developing a KMS		
Subconcept: 3.1 Making decisions based on past similar experience		
Case study one	Case study two	Case study three
• The database helped to overcome limitations for the assessment of both the criteria and materials	• The tool makes use of the large knowledge efficiently	• Making intuitive judgments was well supported by the knowledge given
• The parameters provided guided the team to focus on appropriate issues	• The structured knowledge promoted quick and more effective communication among the DMs	• The knowledge of the tool formed a basis in communication and integration for the DMs
• Making the decisions based on knowledge given increased consensus, communication and integration among the members	• The team spent less time to find necessary information for conducting the assessment	• Using the IF/THEN rules eliminated nonrelevant considerations to a great extent
Subconcept: 3.2 Making decisions based on the same set of knowledge		
Case study one	Case study two	Case study three
• The DMs accessed the same set of knowledge and guidelines	• The knowledge and decision-making process offered by the tool assisted the DMs in making prompt and consistent decisions	• The knowledge assisted the DMs to interact based on the same guidelines
• The system especially the IF/THEN rules and guidelines played an important role to guide communication and integration of the DM in a systematic way	• The KMS guided the DMs to focus on salient points for making complex decisions	• The knowledge, rules and weights, and performance satisfactions reduced subjectivity in the assessment

(continued)

Table 8.16 (continued)

Case study one	Case study two	Case study three
Subconcept: 3.2 Making decisions based on the same set of knowledge		
• The decision making was not much biased since the DMs considered the same set of knowledge	• The knowledge in the database facilitated translation of subjective and uncertain issues	• Assessing the criteria and materials based on the guided information can reduce potential conflicts to a certain extent
Main concept: 4. Spontaneity in making decisions		
Subconcept: 4.1 Making decisions as a team		
• The structured decision-making process greatly supported participation and making decisions as a team	• The structure of the assessment reduced the time consumed when the DMs came together to use the tool	• The tool supported making decisions as a team and making prompt responses
• The computerized calculation ensured a smooth decision-making process and saved significant time	• The tool systematically incorporated opinions of all the DMs at the same time	• Making decisions together with other DMs ensured that expectations are listened to and acknowledged
• Making the decisions through the tool as a team promoted prompt or quick responses of each DM	• The structured decision-making process brought more efficient and consistent opinions of DMs	
Subconcept: 4.2 Promoting discussion		
• The structured discussion with respect to the database was promoted through the use of the interface	• The interface enabled fast and effective discussion, providing a more co-operative environment	• Meeting key DMs promoted prompt response and better clarification from the DMs
• The tool encouraged participation and integration among the DMs	• The discussion process governed by the tool enhanced collaboration among the DMs	• Making decisions together with the other DMs allowed better communication, integration
• A better discussion atmosphere was promoted when everyone was allowed to share the ideas	• Voices of each DM were integrated at the same time	• The decision-making process and consensus scheme encouraged discussion on strategic issues
Main concept: 5. Applying fuzzy set theory		
Subconcept: 5.1 Translating subjective and uncertain data into quantifiable data		
• The fuzzy linguistic terms helped communicating and integrating DMs' opinions quickly	• Demands and judgments of the DMs were translated into useful values efficiently	• The DMs could analyze subjective and uncertain requirements in a more defined and efficient structure

(continued)

Table 8.16 (continued)

Main concept: 5. Applying fuzzy set theory		
Subconcept: 5.1 Translating subjective and uncertain data into quantifiable data		
Case study one	Case study two	Case study three
• The linguistic terms and calculation helped to overcome intuitive assessment	• The fuzzy linguistic terms made it easier for the DMs to discuss and negotiate	• The fuzzy linguistic terms enhanced participation from the DMs
Subconcept: 5.2 Delivering optimized design solutions		
Case study one	Case study two	Case study three
• The SBI took into account subjective requirements well	• The assessment shows clear difference between the design alternatives in a holistic way	• The design solutions based on this analysis increased efficiency and consistency of the assessment
• The design outcome yielded more consistency assessment	• The assessment took into consideration subjective aspects and this was reflected in the index as well as ranking	• The SBI optimized several subjective requirements together
• The preference list was useful for interpretation of the assessment		
Main concept: 6. Applying consensus scheme		
Subconcept: 6.1 Reviewing and updating opinions		
Case study one	Case study two	Case study three
• The consensus scheme helped the DMs to clarify issues and concerns prior to making the decisions	• Making the decisions under the consensus scheme ensured that every DMs understood the issues and had equal chance to influence the decisions in an efficient manner	• Applying the freezing conditions increased the attention of the DMs during the assessment and reducing likelihood of changing their opinions after completion of the assessment
• The DMs had a chance to reconsider their own opinions and listen to others, so much so that the assessment delivered more effective and consistent solutions	• The freezing conditions encouraged effective discussion and communication, thereby reducing potential disagreement	• Adjusting opinions under the consensus procedure allowed the team to share opinions effectively
Subconcept: 6.2 Achieving optimized consensus solutions		
Case study one	Case study two	Case study three
• The freezing conditions ensured that the assessment meets the mutually agreed conditions by listening to discordant opinions	• The consensus level and the other freezing conditions represented how much the DMs' opinions were in agreement and encouraged the DMs to voice their concerns	• The DMs can apply the consensus level to improve a level of agreement among their decisions
• The optimized decisions reduce potential disagreement among the DMs to an optimal level	• The discordant opinions were not neglected but instead listened to	• Conflicting opinions were disclosed more openly and all the DMs attempted to mitigate these as a team

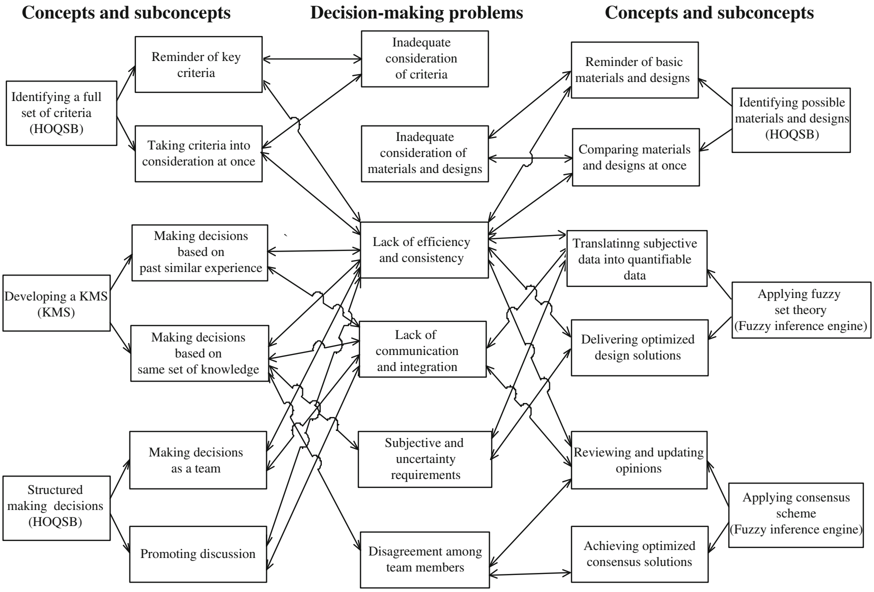


Fig. 8.62 Mapping diagram from the qualitative data analysis

comprehensive if an exhaustive set of the criteria can be identified before conducting such design deliberations (Singhaputtangkul et al. 2011a). Furthermore, the design teams also found that dividing the criteria into four groups as suggested by factor analysis (see Sect. 7.3) reminded the teams of the awareness of environmental, economic, social and buildability impacts of the building envelope design.

Regarding mitigation of the decision-making problem related to inadequate consideration of possible building envelope materials and designs, the design teams agreed that the KBDSS-QFD tool and its building envelope materials and designs knowledge reminded them to consider various basic building envelope materials and designs. In particular, this provided the DMs with the basic building envelope materials and designs for consideration coupled with their relevant design-, construction-, and procurement-related knowledge in regard to all the criteria. This not only gave the design teams an instant access to information related to important properties of such building envelope materials and alternatives, but also enabled the teams to evaluate and compare a wider range of possible design alternatives in a more efficient and consistent manner. In accordance with these findings, Sener and Karsak (2011) found the QFD approach useful in determining optimized engineering characteristics. Similarly, Kim *et al.* (1998) suggested that the knowledge-based QFD approach can help experts to extend a range of possible engineering characteristics.

Next, it can be seen from the thematic chart and mapping diagram that the decision-making problem related to lack of efficiency and consistency in making decisions could be mitigated by a number of the concepts. One of these is establishment of the KMS. From the data analysis, the KMS containing a wealth of the useful knowledge supported the design teams in making a prompt response, and in producing more accurate and consistent solutions by promoting making the decisions based on past similar experience and same set of the knowledge. As such, the KMS has played an important role in mitigating the decision-making problem related to lack of efficiency and consistency in making the decisions. Supporting this, Kirton (1976) proposed the adaption-innovation theory (AIT) to define and measure two styles of decision making: adaption and innovation. The theory suggests that professionals who seek guidance from past decisions by learning from past knowledge experiences are more likely to make precise, timely, reliable, and sound decisions. Kirton (1984) further explained that adaptors characteristically produced a sufficiency of ideas based on existing agreed definitions of the problems and solutions.

In addition, Vat (2006) and Wegner (2002) suggested various benefits of applying a well-established KMS such as improvement of organizational learning, business resilient, human resource management, effectiveness for group decision making, etc. Furthermore, Arain and Low (2006) pointed out that an established KMS storing relevant knowledge and creating several situational decisions can assist the building professionals in learning from similar situational decisions. It is noted that, although every construction project seems to have its own specific conditions, the design teams can still obtain certain useful knowledge from the KMS as it reminds them of important considerations with respect to each project development phase. Apart from the KMS, as can be seen in the mapping diagram, the HOQSB, user interface and fuzzy inference engine of the tool as a whole also contributed to mitigation of the decision-making problem related to lack of efficiency and consistency.

The user interface of the tool showed the capability to mitigate the decision-making problem related to lack of communication and integration among the DMs. In this regard, the results from the analysis suggested that the structured decision-making process offered by the HOQSB through the user interface enhanced spontaneity in making decisions of the design teams. Particularly, the teams agreed that the user interface supported making decisions as a team and promoted effective discussions among the team members as compared to a traditional way to assessing the building envelope materials and designs. Furthermore, the DMs mentioned that, with the structured decision-making process in mind, they had more confidence to communicate and share ideas. Supporting this, Holsapple and Whinstone (1996) found that a computerized tool provides a smoother decision-making process and promotes cohesive environment. Fryer (2004) highlighted that a cohesive group tends to make better decisions while maintaining high level of group satisfaction. Apart from the structured decision-making process, the KMS and fuzzy inference engine embedded with the fuzzy set theory and fuzzy consensus scheme also played a role to improve communication and integration between the designers to a certain level.

Considering mitigation of the decision-making problem related to subjective and uncertain requirements, the results from the analysis showed that the fuzzy inference engine through the use of the fuzzy linguistic terms and fuzzy operations assisted the design teams to deal with the subjective and uncertain requirements, and to determine the optimized design solutions. Previous studies have noted that applying the fuzzy set theory helped professionals to determine a meaningful set of solutions (Chou and Chang 2008; Juan et al. 2009; Yang 2004). The findings suggested that the tool equipped with the fuzzy techniques captured complex and imprecise perspectives of the designers well, and it could present these in a more tangible form, the SBI. Additionally, the subjective and uncertain requirements faced by the design teams were made more interpretable by taking into account the knowledge stored in the KMS.

In addition, from the analysis, it was found that the fuzzy consensus scheme was helpful in mitigating the decision-making problem related to disagreement between opinions of the DMs. To be specific, the consensus level reminded the DMs to discuss and clarify potentially conflicting issues before making the decisions. The fuzzy consensus procedure allowed the DMs to systematically review and update their opinions to minimize any discordance among the DMs' opinions. As a result, it was observed that the DMs tried together as a team to meet the minimum consensus level of their decisions by allocating more time to discuss and share relevant opinions before arriving at their own answers. With this in mind, the scheme showed the potential to offer a balance between encouraging the DMs to express their disagreement to avoid "groupthink" (the event where experts are not in agreement but do not express this) and reducing discordant opinions of the DMs through the structured procedure (Cline 1994).

Furthermore, the tool equipped with the fuzzy consensus scheme seemed to facilitate the DMs to not be afraid of facing potential disagreement. Possible reasons are that the DMs were aware that the tool could provide the structured procedure to overcome disagreement and, importantly, the DMs were not forced to accept only the decisions with the "High" consensus level. In accordance with these findings, Ekel (2009) agreed that the consensus scheme can enhance discussion and communication between members of a team. Likewise, Parreiras et al., (2012a) underlined effectiveness of exploiting the capabilities of each member of the group in a co-operative work through the use of the fuzzy consensus scheme.

Apart from these benefits, when assessing the building envelope materials and designs, the DMs felt that they had an equal opportunity to influence the decision and would continue to support the group. This may be due to the concept of the scheme that depends on continuous discussion and negotiation in the group until everyone affected through understanding, agree with what will be done (Pedrycz et al. 2011). In parallel, the consensus level received in each decision would be useful for future assessment as these could allow the DMs to manage their efforts in discussing key issues prior to making decisions. Making decisions based on the same set of the knowledge stored in the KMS provided the DMs with better guidelines during the assessment, thereby reducing potential biases and disagreement between the DMs to a certain extent.

The validation exercise was also carried out through the individual interviews with another set of a senior architect, C&S engineer, and M&E engineer to validate the results from the qualitative data analysis. Overall, the respondents from the validation interviews agreed with these results. There was an agreement among the respondents that one decision-making problem can be mitigated by at least one concept. The results from the validation interviews seemed to suggest that the book has delivered successful integration of the concepts into the KBDSS-QFD tool for mitigation of the decision-making problems.

Based on all of the above discussion, the hypothesis that the tool can be applied to facilitate the design team to mitigate the decision-making problems as a whole was supported. Nevertheless, a few comments for future improvement of the tool were obtained from the design teams as presented below:

1. The KBDSS-QFD tool was perceived to be a bit complicated due to its many functions. This seemed to make the assessment in the case studies quite dependent on the team facilitator and preliminary discussion between may be affected by familiarity of the DMs with the project requirements and functions of the tool.
2. As the tool is embedded with complex calculation algorithms and stores a wealth of the useful knowledge from different designers, modifying the tool as well as updating its KMS could be a time-consuming and complex process. Doing these may require a knowledge engineer who well understands how the tool communicates with the KMS.
3. It was found from the analysis that, although the tool could provide the knowledge to support selection of the criteria and materials for the assessment, this was still relatively dependant on the experience of the design team to a great extent. For example, if the team members were new or short of experience and knowledge, the use of the KBDSS-QFD tool might not produce the best results.
4. It was suggested that, in many practical cases, selection of the criteria and building envelope materials for the assessment seems to be contingent on how well the architect communicates with a client to identify the project requirements and preferred materials and designs. As the architect also typically leads the design team for the assessment of the building envelope materials and designs under the design-bid-build procurement method, the architect seems to be more suitable than the other parties to maintain the tool and to play a team facilitator role.
5. Regarding the fuzzy consensus scheme, it was observed from the assessment in the case studies that, for some decisions where the opinions of the DMs were quite divergent, different minimum consensus levels, and minimum numbers of the assessment cycle for both the individual DMs and design team should be adopted to save time and maintain a conducive environment. This comment seems to suggest that the scheme should be made more flexible when dealing with different decisions.

8.12 Summary

The chapter presented development of the detailed KBDSS-QFD tool and its automated prototype. Its focus was on integration of the components of the tool. These components include the HOQSB, KMS, fuzzy inference engine, and user interface. The function of each component was thoroughly explained with respect to how the components were integrated. The UML analysis was carried out to evaluate the architecture, information class, and case view of the detailed KBDSS-QFD tool. The book also suggested the seven steps to the DMs for the assessment of the building envelope materials and designs to calculate the SBI. This was followed by showing how the DMs can use these seven steps to determine the SBI of the design alternative through the hypothetical example. The book subsequently developed a prototype of the KBDSS-QFD tool by modeling this after the detailed KBDSS-QFD tool. Screenshots of the prototype were also given with respect to the seven steps to show the prototype's main menus, submenus, items, and sub-items in details.

This chapter then presented the findings and discussion from the case studies to test the second hypothesis of the book. Three case studies of the design teams were selected as the research design to test the second hypothesis that the tool can facilitate the design team to mitigate all the decision-making problems as a whole. The results from the qualitative data analysis suggested that this second hypothesis was supported. In brief, the results showed that the tool can be used to remind the DMs of key criteria and building envelope materials and designs for the assessment of the building envelope materials and designs. It also improved efficiency as well as consistency of the assessment by facilitating the DMs to make a prompt decision and to learn from past experience. In addition, through the structured decision process offered by the tool, communication and integration among the DMs were enhanced. It was observed that, with the use of the fuzzy set theory, the subjective and uncertain requirements were translated into the more useful format. The consensus scheme helped the team to reduce disagreement among the team members. Overall, the results suggested that the tool showed immense potential to mitigate the decision-making problems as a whole.

Chapter 9
Conclusions

9.1 Summary

Success of a private high-rise residential building project is associated with the assessment and selection of building envelope materials and designs that can satisfy requirements of the stakeholders of the project. These requirements typically refer to the criteria for achieving sustainability and buildability in building envelope design, as it has been found that sustainability and buildability in the building industry have gained more importance in recent years. Despite this, the designers, particularly the architects and engineers, seem to be unable to grasp the concept of sustainability and buildability collectively when assessing the building envelope materials and designs in the early design stage. This led to the formation of the first objective to identify a new structure that can assist the building professionals to address the concepts of sustainability and buildability in the assessment of the building envelopes.

The knowledge gap is such that none of the previous studies established an exhaustive set of criteria for achieving sustainability and buildability in building envelope design. The issue is significant since inadequate consideration of the key criteria when conducting the assessment and selection of building envelope materials and designs may lead to undesirable additional cost and time as well as adverse quality, thereby obstructing the achievement of sustainability and buildability. This increases a need to establish the comprehensive set of the criteria and group these into a more defined and tangible structure for achieving sustainability and buildability. To do so, the book develops the Institutional Theory framework to frame this structure and adopts factor analysis to reveal the underlying factors of the criteria (see Sect. 5.3).

Apart from this problem, as the assessment of building envelope materials and designs requires large amount of information and inputs from several building professionals, this assessment appears to be affected by a number of decision-making problems. The literature reviews and pilot study suggest that there

S. Natee et al., *Quality Function Deployment for Buildable and Sustainable Construction*, DOI 10.1007/978-981-287-849-6_9

are six major decision-making problems faced by the architects and engineers as a team when assessing the building envelope materials and designs in the early design stage. These problems include inadequate consideration of requirements, inadequate consideration of possible materials and designs, lack of efficiency and consistency, lack of communication and integration between members of the team, subjective and uncertain requirements, and disagreement between members of the team. These decision-making problems can cause significant adverse impacts to a project such as delays, increase in expenses, increase in manpower of a building project, poor professional relationship, and poor client satisfactions. As such, it is imperative for the design team to mitigate such decision-making problems.

Previous studies suggest that the use of the QFD approach not only can facilitate decision-making processes of a design team, but also improve the quality of design solutions. In particular, QFD is a widely accepted method to implement and augment concurrent engineering principles. Although it was primarily used in the manufacturing industry, QFD is a viable and productive tool that can also benefit the construction industry. It has the potential to be used to aid in the development of a comprehensive design approach to support the process of the assessment of building envelope materials and designs with proper adoption and extension.

The knowledge gap is that no study has yet developed a comprehensive QFD tool with the focus to holistically deal with the decision-making problems faced by the design team when assessing the building envelope materials and designs as a whole. Based on the literature reviews and pilot study, the book identifies the concepts to mitigate the decision-making problems and applies these to build a QFD-based DSS as part of the conceptual framework of this book. This conceptual framework shows how the book improves the conventional QFD tool by modifying its HOQ and then integrating this with the KMS, fuzzy inference engine, and user interface. This system is named as the KBDSS-QFD tool. This led to the formation of the second objective which is to develop the KBDSS-QFD tool to facilitate the design team to simultaneously mitigate the decision-making problems.

The conceptual KBDSS-QFD tool is modeled by comprehensively combining the four elements together which are the HOQSB, KMS, fuzzy inference engine, and user interface. The book then conducts semi-structured interviews with the architects and engineers to develop the detailed KBDSS-QFD tool. This tool is subsequently applied to build its first prototype. Another set of the semi-structured interviews is also carried out to ensure that the prototype can represent the actual expectations of the designers, and to acquire and verify the knowledge required by the KMS database. Specifically, the prototype itself is developed using Microsoft Visual Studio, while the KMS is built using Microsoft Access. The book adopts three case studies of different design teams to test the tool. Each team consists of the architect, the C&S engineer, and the M&E engineer who are active in the area of design development of high-rise residential buildings in Singapore. The qualitative data analysis approach is then applied to analyze the findings from the case studies.

9.2 Conclusions of the Research Problems

This section provides a summary of the findings with reference to the research problems.

Research problem 1 *What are the abstract concepts governing the assessment of the building envelope materials and designs?*

The results from factor analysis suggest that there are four major factors forming the abstract concept to achieve sustainability and buildability in assessment of the building envelope materials and designs. These factors include the environmental, economic, social, and buildability factors (see Sect. 7.3.2).

Research problem 2 *How are the decision-making problems faced by the design team in the early design stage mitigated through the use of KBDSS-QFD tool?*

The results from the qualitative data analysis suggest that the design team can adopt the KBDSS-QFD tool to mitigate all the decision-making problems at once. In brief, the tool can be used to remind the DMs of key criteria and building envelope materials and designs for the assessment of the building envelope materials and designs. It also improved efficiency as well as consistency of the assessment by facilitating the DMs to make a prompt decision and to learn from past experience. In parallel, through the structured decision-making process offered by the tool, communication and integration among the DMs are enhanced. With the use of the fuzzy set theory and KMS, subjective and uncertain requirements can be translated into a more useful format. In the mean time, the fuzzy consensus scheme facilitates the design team to reduce disagreement among its members (see Sect. 8.11).

9.3 Conclusions of the Research Hypotheses

This section provides a summary of the findings with reference to the research hypotheses.

Research hypothesis 1 *The criteria for the assessment of the building envelope materials and designs can be modeled by the four factors which are the environmental, economic, social, and buildability factors.*

The Institutional Theory framework developed (see Sect. 5.3) posits that every decision of the architects and engineers must comply with rules, law, and standards as governed by the regulative signal. The normative signal morally draws attention of the architects and engineers to concerns about the sustainability aspects of the building envelope materials and designs in terms of the environmental, economic, as well as social factors. The cognitive signal reminds the architects and engineers to consider the buildability factor while making decisions. This Institutional Theory framework forms the first hypothesis of this book. The results from factor analysis in regard to the perspectives of the architects and engineers on the importance weights of the criteria for the assessment of the building envelope materials and designs, reveal that this hypothesis is supported.

Overall, the social factor is found to be the most important underlying factor in the assessment of the building envelope materials and designs because it heavily affects the end users of a project which includes the occupants and society. The results also show that the buildability factor plays an important role in the assessment. This factor promotes the use of the materials and designs that can facilitate the design development as well as construction process. The environmental factor supports the trend indicating that the issues affecting the environment have gained more importance among the building professionals. The economic factor suggests that although the initial costs remain a major consideration in the assessment of the building envelope materials and designs, there is an attempt from the building professionals to integrate the economic considerations at once while assessing the building envelope materials and designs.

Research hypothesis 2 *The KBDSS-QFD tool consisting of the HOQ, KMS, fuzzy inference engine, and user interface can facilitate the design team to mitigate the decision-making problems as a whole.*

This book improves on the use of the conventional QFD tool for simultaneous mitigation of the decision-making problems by incorporating the concepts which include identifying key criteria, identifying possible materials and designs, establishing the KMS, promoting spontaneity in the communication and integration process, applying the fuzzy set theory to translate subjective criteria, and applying the consensus scheme to reach optimized consensus solutions (see Sects. 2.13 and 2.14). As a result, the prototype of the KBDSS-QFD tool is developed, and it consists of the HOQSB, KMS, fuzzy inference engine, and user interface (see Sect. 8.8). The book applies the qualitative data analysis to analyze the data collected from the group interviews of the three design teams in the form of the thematic chart and mapping diagram (see Sect. 8.11).

From this analysis, using the tool coupled with the knowledge suggested by its KMS facilitates the design teams at the early design stage to consider key criteria required for the assessment. This also reminds the DMs of relevant regulations, reasons for compliance, description, and importance of each criterion. Additionally, the four factors structure adopted from the first hypothesis assists the team to consider the criteria together to find a good balance between sustainability and buildability considerations. For mitigation of the decision-making problem related to inadequate consideration of possible building envelope materials and designs, the results show that the tool can help the DMs to consider various basic building envelope materials and designs. Prior to making decisions, the KBDSS-QFD tool provides the design team with useful knowledge in relation to the criteria and the building envelope materials and designs considered. This seems to offer the DMs an instant access to important considerations enabling the DMs to evaluate a wider range of criteria and possible alternatives.

The results of this book also suggest that the tool plays a vital role in mitigating the decision-making problem related to lack of efficiency and consistency in making the decisions. In particular, the KMS helps the designers to overcome limitation of knowledge, to increase consensus and confidence of the team, to reduce bias when dealing with similar decisions, and to make a prompt response. The user interface of the tool greatly promotes participation and decision-making of the team members through the structured decision-making process. These become part of an important effort to reduce the decision-making problem related to lack of communication and integrations among members of the design team.

Regarding mitigation of the decision-making problem related to subjective and uncertain requirements, the KBDSS-QFD tool offers a systematic and structured approach that can support the design team to analyze design information, to generate the design alternatives, and to deliver the optimal design solution through the use of the fuzzy inference engine. It is suggested that the fuzzy consensus scheme is a main instrument to mitigate disagreement between opinions of the DMs. This allows the team members to share knowledge and to find optimized consensus solutions that everyone agrees. As such, the likelihood that the DMs continue to support the team increases. In fact, the freezing conditions of the scheme facilitate the team to discuss and fine-tune opinions of the DMs. This not only avoids "groupthink," but also gives an equal opportunity to the team members to influence the decisions. Hence, it is concluded that the findings of this book lend support to the second hypothesis and serve as a basis for accepting the hypothesis.

Most importantly, as the KBDSS-QFD tool aims to provide structure and guidance for systematic thinking in dealing with the decision-making problems, it does not claim to recommend the design alternatives that must be absolutely accepted. Instead of providing the solutions, the KBDSS-QFD tool is perhaps best thought of simply as a knowledge source, providing insights about the situation, uncertainty, objectives and tradeoffs, and possibly yielding a recommended course of action.

9.4 Academic Contributions

The main academic contributions of this book are presented with respect to the (1) Institutional Theory framework, (2) concepts to mitigate the decision-making problems, and (3) conceptual framework for integration of the QFD approach with the KMS, fuzzy set theory and fuzzy consensus scheme as presented in the following:

1. Scott's (2008) Institutional Theory has been widely applied in various academic areas. This theory is also found useful to investigate the theoretical roles of sustainability and buildability in the assessment of building envelope materials and designs. This book applies the three elements in the Institutional Theory; namely the regulative, normative, and cognitive pillars to develop the Institutional Theory framework for the first time. This framework advances the

body of theoretical knowledge related to the three elements of the Institutional Theory since these had not been framed in regard to making the decisions for achieving sustainability and buildability in the assessment of building envelope materials and designs. In brief, the Institutional Theory framework contributes to the body of academic knowledge by suggesting that making decisions for achieving sustainability and buildability are governed by the regulative, normative, and cultural-cognitive signals. These findings can be applied to guide future studies in analyzing the perspectives of professionals in other industrial contexts.

2. This book presents the successful concepts to mitigate the decision-making problems. This contributes to the body of academic knowledge related to development of a tool to improve project management. Overall, the book shows that these concepts can be applied to develop the KBDSS-QFD tool to mitigate the decision-making problems. Notwithstanding that the tool is found useful for mitigation of the decision-making problems as a whole, the results of this book suggest that some of the concepts can play a role to mitigate more than one decision-making problem. For example, establishing an organized KMS is a main contributor to deal with lack of efficiency and consistency in making decisions. The knowledge provided by this KMS also enhances communication and integration of the design team, helps the design team to understand subjective and uncertain requirements, and mitigate disagreement among the team members to a certain level. Overall, the concepts to mitigate the decision-making problems form an important basis to build the KBDSS-QFD tool for better project management in the early design stage.
3. The book develops the conceptual framework by integrating the QFD approach with the KMS, fuzzy inference engine, and user interface to capture the concepts to mitigate the decision-making problems for the first time. The integration of these elements for building the KBDSS-QFD tool advances the body of academic knowledge related to both QFD and DSS studies. According to this conceptual framework, the conventional QFD tool is improved by the development of the HOQSB, which is operated in collaboration with the KMS, fuzzy inference engine, and user interface.

In this regard, the HOQSB plays a central role in combining the other elements together as part of the KBDSS-QFD tool. The rooms in the HOQSB govern the decision-making steps of the tool. These steps are presented through the user interface for the designers to operate the tool. The KMS provides important knowledge in several forms to suggest to the DMs in every decision-making step, while the fuzzy set theory serves as a basis of the fuzzy inference engine to translate the inputs received from the decision-making steps into the design outcomes. Furthermore, the inputs are monitored whether the optimized consensus decisions are achieved by using the fuzzy consensus scheme.

9.5 Practical Contributions

Main practical contributions of this book with respect to the (1) four-factor model for achieving sustainability and buildability and (2) automated KBDSS-QFD tool are presented below

1. The four-factor structure which consists of the environmental, economic, social, and buildability factors allows the building professionals to determine an optimal balance between the factors. This structure takes into consideration not only main sustainability and buildability schemes implemented in Singapore, but also key requirements of the stakeholders of a project which are not included in these schemes. Significantly, the factors are found useful as these provide the building professionals with the concise structure of sustainability and buildability in a more defined and tangible way, helping to deliver more sustainable and buildable building envelope design solutions.
2. The main aim of this book is to develop the automated KBDSS-QFD tool to mitigate the decision-making problems faced by the design team. As such, its main practical contributions relate to benefits arising from mitigation of the decision-making problems. Apart from these benefits, fundamentally, the design team can easily find the design solutions that meet the minimum needs of the sustainability and buildability regulations, if the team does not consider other key sustainability and buildability factors that could affect the designs such as durability of materials, aesthetics, performances, costs, etc. In practice, however, it is almost impossible to develop an optimal sustainable and buildable design because, this requires making tradeoffs between various conflicting criteria. This research contributes toward the development of the prototype of KBDSS-QFD tool that can also be applied to facilitate the design team to compare different building envelope design alternatives based on their SBI.

   Furthermore, the KBDSS-QFD tool does not attempt to take over the role of human experts or force them to accept the assessment outputs. Instead, the tool brings more relevant evidence and facts to facilitate human experts in making well-informed design decisions. From a design point of view, this tool facilitates the design team to classify and define the various factors that affect the sustainable and buildable designs, to evaluate building envelope systems and design features, and to select and determine the most appropriate building envelope design alternative. From a project management point of view, the tool enables the design team to facilitate mitigation of the decision-making problems and to achieve more effective project planning and management. Overall, applying the KBDSS-QFD tool to assess the building envelope materials and designs in the early design stage increases the effectiveness of the building project and enhances the likelihood of project success.

9.6 Limitations of the Research

The research is subject to limitations related to the research methodology and data analysis as presented below. Nevertheless, the researcher was fully aware of these limitations, so much so that every effort has been made to minimize errors that may occur.

1. The survey data of this book is collected in the form of perceptions of the architects and engineers based on limited information provided by the questionnaire. Although there is the attempt, for example, to pretest the questionnaire and cross-check the responses through the face-to-face interviews, their perceptions might still be undermined by subjective views. This seems to be the limitation of such a survey exercise. Nevertheless, in the absence of a better method, the survey can provide sufficient understanding of how the architects and engineers perceive importance of each criterion on a large scale, and this allows the book to fulfill its objective.
2. The second limitation of this book is associated with development of the case studies. Ideally, the case studies should have been conducted under the actual environment where the design team is engaged by the project owner and communicates with the owner to identify the project requirements. However, due to legal and contractual concerns, time constraints, and other practical limitations, this book engaged the design teams to test the tool by applying it to representative projects. It should be noted that as, in practice, accuracy and availability of the project information and requirements could be one of the most critical problems for the design team, and these seem to be heavily dependent on the project owner to furnish such information. With the awareness of these issues in mind, the book attempts to provide the project information as given in the case studies that can represent the actual projects in detail as much as possible.
   Furthermore, as the data collected through the group interviews from the case studies are based on the perceptions of the DMs, and these perceptions might be correlated with several aspects such as power of project leaders, professional relationships between the members of the design team, or influences from a project client and authority. In relation to the limitation related to the development of case studies as mentioned earlier, the level of existence of these aspects may not be fully captured in the case studies. As such, the findings from the case studies are only discussed within the context of this book, and, importantly, are not made generalizable to other populations, universes, or scopes.
3. The last limitation is that as the results from the case studies are collected and analyzed by one researcher, one may view that there could be a tendency that such results may confirm the researcher's preconceived notions. To minimize this limitation, in brief, the book first applies the appropriate research design, method of data collection, and data analysis to increase reliability of the results of the case studies. Subsequently, the book supports such results from two other sources which are the literature reviews and validation exercise. These external

evidences improve rigor in terms of validity of the results of this book which, in other words, implies that the results fairly and accurately represent the data collected.

9.7 Recommendations for Future Studies

The recommendations for future studies are discussed below

1. The four-factor structure developed in accordance with the Institutional Theory framework demonstrates how the architects and engineers perceive sustainability and buildability in the assessment of building envelope materials and designs for high-rise residential buildings in Singapore. Future studies may adopt this framework to investigate underlying factors in making decisions in other academic areas such as risk management and crisis management.
2. The KBDSS-QFD tool developed shows the potential to overcome the decision-making problems faced by the design team when assessing the building envelope materials and designs in the early design stage. As such, future research can extend the conceptual framework of KBDSS-QFD tool by embedding a shared KMS server, web-based system, or a hybrid decision-making technique such as the combination of RBR and CBR. Future research can also apply this tool to study more complex types of building envelope design or other systems of a building.
3. The SBI calculated in this book is a sum of the performance satisfactions of the design alternatives and important weights of the criteria. If the DMs select more criteria for the assessment and some of these criteria appear to be strongly correlated, tradeoffs and repetitive errors affecting the final SBI could possibly be generated. With this in mind, future studies are recommended to develop a technique, for example, based on principal component analysis (PCA), to add onto the KBDSS-QFD tool to deal with possible intercorrelations between the criteria which can cause a problem of multicollinearity.
4. As the freezing conditions of the fuzzy consensus scheme are recorded manually in this book, future studies may further develop the KBDSS-QFD tool by computerizing its fuzzy consensus scheme. Furthermore, it would also be useful if the tool could allow users to set up different values of the freezing conditions for different decisions to enhance flexibility of the scheme.
5. The KBDSS-QFD tool is designed for the assessment of the building envelope materials and designs in the early design stage. It would be useful, if this tool could be integrated with other tailor-made DSSs for making more comprehensive and holistic decisions for the other project development stages, such as detailed design and construction stages. In addition, this recommendation may include an attempt to develop the KBDSS-QFD tool further by making it a central platform connecting with commercial software to facilitate other complex group decision-making processes.

Appendix A
Pilot Study to Investigate Decision-Making Problems and Concepts to Mitigate such Decision-Making Problems

Objectives

1. To articulate decision-making problems and challenges in assessment and selection of the building envelope materials and designs in the early design stage (Part A)
2. To preliminarily find out if the concepts proposed can be applied to mitigate such problems (Part B)

Research design Interview two architectural firms and two engineering firms offering private high-rise residential building design in Singapore.

Method of data collection Face-to-face interview.

Part A: Interview questions

1.1 How do the developer, QS, AR, CS, PM, and Contractor play a role in the building envelope materials and designs assessment and selection for high-rise residential buildings in the traditional design, bid, build (DBB) route during the pre-construction phase including conceptual design, schematic design, design development, and contract documents processes?

1.2 Is there a problem in the industry for building professionals to discuss, deliberate, and come to a decision on façade selection in the early design stage? For example:

- Do you usually receive insufficient information from the parties for completing your responsibilities in the early design stage?
- Are building professionals fully aware of the procurement-, construction-, and maintenance-related design inputs when assessing and selecting façade materials and designs?
- Do you usually receive subjective and complex requirements from the other parties?

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- Do you usually consider several alternatives when selecting the materials and designs?
- Are façade materials normally assessed and selected based on only the materials that a design team has in its own collection?
- Is there some lack of communication between the parties impeding making decisions on façade selection?
- Are there any challenges in reaching consensus solutions in façade selection during each review cycle?
- Are there any problems related to knowledge loss as, for example, when one project is completed, members of the parties move on to different projects?

1.3 How does the early façade design stage affect detailed design, procurement, construction, and maintenance phases in your opinion? Can some problems related to facade development arising during detailed design, procurement, construction, and maintenance phases be improved or mitigated if these are considered at the early design stage?
1.4 How does the firm communicate with the other parties involved in the early design stage?

- How do you typically proceed to incorporate changed requirements (including additions or deletions)?
- Depending on cases (change of façade material specifications, construction methods, cost and time constraints, GM Score, etc.), how long does it normally take to incorporate all considerations, including each of the major changes?

1.5 What are the main causes of changes?

Part B: Interview questions (After introducing what QFD is and benefits and applications of a knowledge-based decision-support system QFD tool, and showing what the KBDSS QFD tool may look like)

2.1 What are your opinions regarding applying the tool to identify all important criteria in façade selection in the early design stage?
2.2 What are your opinions regarding applying the tool to identify possible façade materials and designs and find relationships between the materials and the criteria in the early design stage?
2.3 What are your opinions regarding applying the tool to systematically store knowledge relating to façade selection for use in future projects?
2.4 What are your opinions regarding applying the tool and forming a QFD team to spontaneously assess the materials and designs?
2.5 What are your opinions regarding applying the tool to articulate/translate requirements into design solutions, to integrate opinions of members of the team, and to reach consensus solutions in making decisions?

2.6 What are your opinions regarding applying the tool to prioritize design alternatives with respect to different combinations of the client's requirements?
2.7 What are your opinions regarding the use of the fuzzy consensus scheme?
2.8 Do you have any further comments or suggestions?

Summary of Findings

In summary, this pilot study articulated the decision-making problems relating to the assessment of building envelope materials and designs for private high-rise residential buildings in Singapore, through conducting face-to-face interviews with two senior architects and two engineers who had rich experience in the façade industry. Their profiles are shown in Table A.1.

In brief, it was found that most high-rise residential buildings in Singapore adopt a design-bid-build procurement method where a developer engages designers to design and prepare contract documents before selection of a contractor. In this method, architects from an architectural firm lead a design team in design development including building envelope design development with the help of civil and structural (C&S) engineers, and mechanical and electrical (M&E) engineers from engineering consultancy firms to satisfy requirements of the developer by providing a set of design alternatives.

From the literature review, six major decision-making problems affecting the assessment of the building envelope materials and designs are identified, and existence of these problems in the real-world was investigated through interviews. Table A.2 shows that all the interviewees confirmed that a building envelope design team comprising architects and engineers had indeed faced decision-making problems when assessing the building envelope materials and designs during the conceptual design stage. The interviewees also shared the same views that the problems can cause several adverse impacts on a project during different project phases, and, more importantly, there is a need to mitigate these problems in the early design stage.

By virtue of their seniority, the views of the four interviewees are representative of real-life practices in the façade industry, which underpins the rationale of this research study. With the aim to mitigate these decision-making problems, the research problems and objectives are set out accordingly. Based on the QFD

Table A.1 Profiles of the interviewees

Interviewee	Discipline	Position	Years of experience
AR1	Architect	Managing Director	>30
AR2	Architect	Associate Designer	>10
EN1	Engineer	Regional Leader	>20
EN2	Engineer	Managing Director	>20

Table A.2 Decision-making problems faced by the design team in the early design stage

Decision-making problems affecting assessment of the building envelope materials and designs	Interviewees			
	AR1	AR2	EN1	EN2
Inadequate consideration of requirements	✓	✓	✓	✓
Inadequate consideration of possible materials and designs	✓	✓	✓	✓
Lack of efficiency and consistency in making decisions	✓	✓	✓	✓
Disagreement between members of a design team	✓	✓	✓	✓
Lack of communication between members of a design team	✓	✓	✓	✓
Subjective and uncertain requirements	✓	✓	✓	✓

✓ = Interviewee confirmed existence of the decision-making problem in the real-world

Table A.3 Research concepts to mitigate the decision-making problems

The decision-making problems	Research concepts to mitigate each problem	Interviewees			
		AR1	AR2	EN1	EN2
Inadequate consideration of requirements	Identifying key criteria and taking these into account at once	✓	✓	✓	✓
Inadequate consideration of possible materials and designs	Identifying a wide range of possible materials and designs	✓	✓	✓	✓
Lack of efficiency and consistency in making decisions	Storing and structuring existing and new knowledge for future use	✓	✓	✓	✓
Disagreement between members of a design team	Applying a fuzzy consensus scheme to reach consensus solutions	✓	✓	✓	✓
Lack of communication between members of a design team	Promoting spontaneity in the communication and discussion process	✓	✓	✓	✓
Subjective and uncertain requirements	Translating subjective requirements into quantitative data	✓	✓	✓	✓

✓ = Interviewee supported for applying the research concepts and the proposed tool to mitigate the decision-making problem

approach, the research concepts to do so were then proposed. The research concepts coupled with the proposed KBDSS-QFD tool and how this tool incorporates the research concepts were thoroughly presented to the interviewees. It is found that the interviewees supported that the research concepts and the proposed tool can potentially be applied to mitigate the decision-making problems as shown in Table A.3.

Appendix B
Pilot Study to Investigate Criteria for the Assessment of the Building Envelope Materials and Designs

Research design Survey of 15 building professionals including architects and engineers

Method of data collection Face-to-face questionnaire survey

Please indicate the importance weights of the criteria below for assessing and selecting the building envelope materials and design alternatives based on the following scale;

1 = Very unimportant, **2** = Unimportant, **3** = Medium, **4** = Important, **5** = Very Important

(Please mark the appropriate box with a tick or a cross)

Criteria for assessing building envelope materials and designs	Importance weight				
1. Energy efficiency of building envelope	1	2	3	4	5
2. Weather protection performance of building envelope	1	2	3	4	5
3. Acoustic protection performance of building envelope	1	2	3	4	5
4. Visual performance of building envelope	1	2	3	4	5
5. Ease in maintenance of building envelope	1	2	3	4	5
6. Strength of material	1	2	3	4	5
7. Quality of delivered materials	1	2	3	4	5
8. Material costs of building envelope	1	2	3	4	5
9. Construction costs of building envelope	1	2	3	4	5
10. Long-term costs of building envelope	1	2	3	4	5
11. Service life of building envelope	1	2	3	4	5
12. Aesthetics of material and design	1	2	3	4	5
13. Tendency to form defects	1	2	3	4	5
14. Style of material and design	1	2	3	4	5
15. Image of material and design	1	2	3	4	5
16. Health, safety occupant and society during occupation	1	2	3	4	5
17. Security of occupant and society during occupation	1	2	3	4	5
18. Capability to avoid community disturbance during construction	1	2	3	4	5
19. Simplicity of building envelope design details	1	2	3	4	5

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20. Availability of building envelope materials	1	2	3	4	5
21. Traveling distance of building envelope materials	1	2	3	4	5
22. Energy consumption for building envelope during construction	1	2	3	4	5
23. Resources consumption during building envelope during construction	1	2	3	4	5
24. Waste generation during building envelope during construction	1	2	3	4	5
25. Health and safety of workers during building envelope construction	1	2	3	4	5
26. Ease for construction with respect to materials	1	2	3	4	5
27. Ease for construction with respect to tools	1	2	3	4	5
28. Ease for construction with respect to labor skills	1	2	3	4	5
29. Ease in storing building envelope materials	1	2	3	4	5
30. Off-site and on-site handling	1	2	3	4	5

31. Please include the criteria that in your opinion should be added into consideration for assessment of building envelope materials and designs in the early design stage

    ……………………………………………………………………………………
32. Have you faced any situation whereby the designers encounter a difficulty in identifying key criteria in the early design stage? Please explain.
33. Have you faced any situation whereby the designers encounter a difficulty in relating key criteria to sustainability and buildability regulations such as GMS and BDAS? Please explain.

Appendix C
Questionnaire Survey

Survey questionnaire to identify important criteria used in assessment of building envelope materials and designs for private high-rise residential buildings in the early design stage

Dear

Respondent name
Respondent address

I am a Ph.D. student from the Department of Building, National University of Singapore. I am conducting a survey as part of my Ph.D. research to identify important criteria used by engineers in assessing building envelope materials and designs in the early design stage for new private high-rise residential buildings in Singapore. Your participation is highly beneficial to this research.

Brief scope of this research is provided in the questionnaire attached. This survey questionnaire has three pages in total and will take about 10 minutes to fill in. Your reply will be treated as confidential and will only be used for research purpose. We would also be pleased to share our findings with you, if you kindly indicate your request and provide us with your email address.

Please also kindly return the completed questionnaire in the prepaid return envelope. Nevertheless, if you are not convenient to fill in this questionnaire, please kindly forward the questionnaire to your colleague who you think may be appropriate. If you have any queries, please do not hesitate to contact me either at 9398-6772 or A0066412@nus.edu.sg. Thank you very much for your valued inputs and consideration.

Yours faithfully,
Natee Singhaputtangkul

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Survey questionnaire To identify important criteria used in assessment of private high-rise residential building envelope materials and designs in the early design stage

This survey questionnaire contains Sections A to C (3 pages total). To complete the questionnaire, please mark the appropriate box with a tick or a cross.

Section A Respondent's details

A1: Name (Optional): ....
A2: Company name (Optional): ....
A3: E-mail (Optional): ....
A4: Phone number (Optional): ....
A5: Discipline: ☐ Architect. ☐ Civil and structural engineer. ☐ Mechanical and electrical engineer.
A6: Years of experience in this discipline: ☐ <5 years ☐ >5–10 years ☐ >10–20 years ☐ >20 years
A7: Years of experience in private high-rise residential building envelope development: ☐ <5 years ☐ >5–10 years ☐ >10–20 years ☐ >20 years
A8: Would you like to receive a summary of the report of this research by email?: ☐ Yes. ☐ No.

Section B Research scope

The purpose of this research is to propose a set of criteria used in assessment of building envelope materials and designs of new private high-rise residential buildings in Singapore by a design team including architects and engineers in the early design stage. As sustainability and buildability in building envelope design have become more important in recent years, to promote the use of building envelope materials and designs which are more sustainable and buildable, it is important to understand the holistic set of criteria. 18 main criteria were proposed in this regard.

Section C Determining the importance weights of the criteria

Please indicate the importance weights of the proposed criteria that you apply when assessing the building envelope materials and design alternatives in the early design stage based on the following five-point scale:

1 = Very unimportant, **2** = Unimportant, **3** = Medium, **4** = Important, **5** = Very important

(Descriptions of each criterion are also given below, and please mark the appropriate box with a tick or a cross)

Criteria used in the assessment of building envelope materials and designs	Importance weight				
1. Energy consumption during construction of the building envelope Description: Energy consumption during construction refers to consumption of electricity of power tools, as well as fuel of heavy equipment for building envelope installation and construction-related activities	1	2	3	4	5
2. Resource consumption during construction of the building envelope Description: Resource consumption during construction refers to consumption of construction resources including water, chemicals, formwork materials, aggregates, sealants, plasters, and joints in installation and construction of the building envelope	1	2	3	4	5
3. Waste generation during construction of the building envelope Description: Waste generation during construction corresponds to generation of wastes in the form of excessive concrete, mortar, sealants, cleaning chemical and water, aluminum or vinyl window frame, concrete blocks, bricks, as well as glazing materials	1	2	3	4	5
4. Energy efficiency of the building envelope Description: Energy efficiency of the building envelope represents the capability of the building envelope to reduce the average heat gain into the envelope, thereby affecting the cooling energy load of a building	1	2	3	4	5
5. Initial costs of the building envelope Description: Initial costs are made of material costs and construction costs. The material costs include costs of materials and transportation, while the construction costs cover labor and machine costs, and other relevant expenses	1	2	3	4	5
6. Long-term burdens of the building envelope Description: Long-term burdens of the building envelope refer to ease in maintenance and long-term expenses pertaining to cleaning, fixing, and replacement expenses of the building envelope during the occupation phase	1	2	3	4	5
7. Durability of the building envelope Description: Durability of the building envelope implies the service life of accessories, materials, joints, and gaps in consideration of functionality, tendency to form defects, and aesthetics	1	2	3	4	5
8. Appearance demands of the building envelope Description: Appearance demands represent a combination of style, image, and aesthetics considerations of the building envelope as a whole	1	2	3	4	5
9. Health, safety, and security of occupant and society during the occupation phase Description: Health, safety, and security of occupants and society during the occupation phase are associated with selection of materials that contain no hazardous substances, can resist fire, and can provide security to the occupants and society	1	2	3	4	5

(continued)

(continued)

10. Weather protection performance of the building envelope Description: Weather protection performance of the building envelope refers to the capability of the building envelope to protect against weather impacts during the occupation phase of a building	1	2	3	4	5
11. Acoustic protection performance of the building envelope Description: Acoustic protection performance refers to the capability of the building envelope to protect against acoustic impacts during the occupation phase of a building	1	2	3	4	5
12. Visual performance of the building envelope Description: Visual performance refers to the capability of the building envelope to optimize visual comfort for the occupants. This is associated with transmission properties of windows and external walls, length and shape of shading devices, color of the window and wall materials, and amount of light penetrated	1	2	3	4	5
13. Capability to avoid community disturbance during construction of the building envelope Description: Capability to avoid community disturbance during construction represents the capability to reduce diesel exhaust, particulate matter, toxic gases, dust, increase in vehicle traffic, as well as adverse noise arising from any building envelope construction-related activities	1	2	3	4	5
14. Simplicity of building envelope design details Description: Simplicity of building envelope design details refers to the capability to standardize design details of the building envelope materials and designs thereby affecting time to design, and time to produce and review drawings	1	2	3	4	5
15. Ease of building envelope material deliveries from suppliers Description: Ease of building envelope material deliveries from suppliers is associated with availability, lead times, traveling distance, and quality of the materials	1	2	3	4	5
16. Ease of building materials handling before and during construction Description: Ease of building materials handling before and during construction refers to off-site and on-site handling methods, and proper ways to store the materials in accordance with security and weather protection requirements	1	2	3	4	5
17. Ease of building envelope materials, tools, and skills for construction of the building envelope Description: Ease of building envelope materials, tools, and skills for construction of the building envelope refers to selection of labor-efficient materials, labor-saving construction technologies/tools, and designs with pre-assembled products based on availability and skill levels of workers, and good local practices	1	2	3	4	5

Appendix D
Semi-structured Interviews to Develop the Detailed KBDSS-QFD Tool

Interview questions (15 designers)

The interviewee was briefed about the purposes and aims of this book, overall concepts of building design, decision-making problems, concepts to mitigate such problems, as well as preliminary user interface of the KBDSS-QFD tool in PowerPoint slides and then asked the following questions:

1. What are your opinions regarding usefulness and completeness of the knowledge management system?
2. What are your opinions regarding the linguistic terms and usefulness of the importance weights, performance satisfactions, and SBI?
3. What are your opinions regarding the collaboration between the user interface and knowledge management system?
4. What are your opinions regarding the level of completeness from the tool's results or outputs?
5. What are your opinions regarding the fuzzy consensus procedure and its freezing conditions?
6. What are your opinions regarding the decision-making steps?
7. What are your opinions regarding the tool's user-friendliness, usability, and layout?
8. What are your opinions regarding the tool's applicability in practice?
9. Do you have any other comments or suggestions for improvement of this tool?

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Appendix E
Semi-structured Interviews to Improve the Prototype of the Tool and Acquire/Verify the Knowledge Stored in the KMS

Part E1 Interview questions (15 designers)

The interviewee was shown how the prototype of the KBDSS-QFD tool works on a laptop and then asked the following questions:

1. What are your opinions regarding the usefulness and completeness of the knowledge management system?
2. What are your opinions regarding the linguistic terms and usefulness of the importance weights, performance satisfactions, and SBI?
3. What are your opinions regarding the collaboration between the user interface and the knowledge management system?
4. What are your opinions regarding the level of completeness from the tool's results or outputs?
5. What are your opinions regarding the fuzzy consensus procedure and its freezing conditions?
6. What are your opinions regarding the decision-making steps?
7. What are your opinions regarding the tool's user-friendliness, usability, and layout?
8. What are your opinions regarding the tool's applicability in practice?
9. Do you have any other comments or suggestions for improvement of the prototype?

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Part E2 Acquisition of Knowledge for the KMS

The interviewee was asked to verify and add/update the knowledge required by the KM-C, KM-M, and KM-R. Some screenshots of the knowledge required are given as follows:

Criteria_weight

Criteria ID	Criteria name	Description	Compliance	Type of criteria	Importance weight
BC1	Health and safety of workers	Workers' health and safety during construction refers to risk of fatal and non-fatal occupational injuries arising from the building envelope construction-related works.	-Standards and practices -WSHA, BCA OHSMS	Individual material assessment	I
BC2	Simplicity of design details	Simplicity of building envelope design details refers to the capability to standardize design details of the building envelope materials and designs thereby affecting time to design, and time to produce and review drawings.	-Standards and practices	Individual material assessment	M
BC3	Material deliveries from suppliers	Ease of building envelope material deliveries from suppliers is associated with availability, lead times, traveling distance, and quality of the materials.	-Standards and practices	Individual material assessment	M
BC4	Material handling	Ease of building materials handling before and during construction refers to off-site and on-site handling methods, and proper ways to store the materials in accordance with security and weather protection requirements.	-Standards and practices	Individual material assessment	M
BC5	Ease in construction with respect to time	Ease of building envelope materials, tools and skills for construction of the building envelope refers to selection of labor-efficient materials, labor-saving construction technologies/tools, and designs with pre-assembled products.	-Standards and practices -BDAS, CAS, CONQUAS	Individual material assessment	M
BC6	Community disturbance	Capability to avoid community disturbance during construction represents the capability to reduce diesel exhaust, particulate matter, toxic gases, dust, increase in vehicle traffic, as well as adverse noise.	-Standards and practices -Environmental	Individual material assessment	I
EC1	Initial costs	Initial costs are made of material costs and construction costs.	-Standards and	Overall design	VI

Record: 1 of 18 No Filter Search

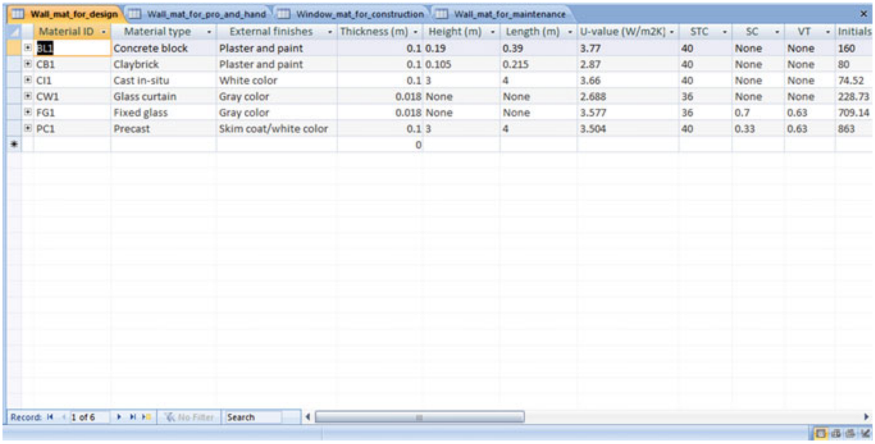
Knowledge of the criteria in the KM-C

Alternative_formulation

Alternative ID	Wall ID	Window ID	Shading ID	WWR	Orientation	Footprint	Floor-to-floor (m)	GMS	Initial cost ($/m2)	Drawing
1	PC1	WG1	SD3	0.3	N-S	Square building	3	0	202	PC1
2	PC1	WG2	SD3	0.3	N-S	Square building	3	2.6	214.9	PC1
3	PC1	WG3	SD3	0.3	N-S	Square building	3	7	218.8	PC1
4	PC1	WG4	SD3	0.3	N-S	Square building	3	15	235.9	PC1
5	PC1	WG1	SD1	0.3	N-S	Square building	3	13.3	207.8	PC1
6	PC1	WG2	SD1	0.3	N-S	Square building	3	15	220.7	PC1
7	PC1	WG3	SD1	0.3	N-S	Square building	3	15	224.6	PC1
8	PC1	WG4	SD1	0.3	N-S	Square building	3	15	241.7	BL1
9	CB1	WG1	SD3	0.3	N-S	Square building	3	2.4	146	BL1
10	CB1	WG2	SD3	0.3	N-S	Square building	3	7.1	158.9	BL1
11	CB1	WG3	SD3	0.3	N-S	Square building	3	11.5	162.8	BL1
12	CB1	WG4	SD3	0.3	N-S	Square building	3	15	179.9	BL1
13	CB1	WG1	SD1	0.3	N-S	Square building	3	15	154.8	BL1
14	CB1	WG2	SD1	0.3	N-S	Square building	3	15	167.7	BL1
15	CB1	WG3	SD1	0.3	N-S	Square building	3	15	171.6	BL1
16	CB1	WG4	SD1	0.3	N-S	Square building	3	15	188.7	BL1
17	BL1	WG1	SD3	0.3	N-S	Square building	3	0	142.2	BL1
18	BL1	WG2	SD3	0.3	N-S	Square building	3	0.8	155.1	BL1
19	BL1	WG3	SD3	0.3	N-S	Square building	3	5	159	BL1
20	BL1	WG4	SD3	0.3	N-S	Square building	3	15	176.1	BL1
21	BL1	WG1	SD1	0.3	N-S	Square building	3	12.1	150.9	BL1
22	BL1	WG2	SD1	0.3	N-S	Square building	3	15	163.8	BL1
23	BL1	WG3	SD1	0.3	N-S	Square building	3	15	167.7	BL1

Record: 1 of 48 No Filter Search

Knowledge of the design alternatives in the KM-M

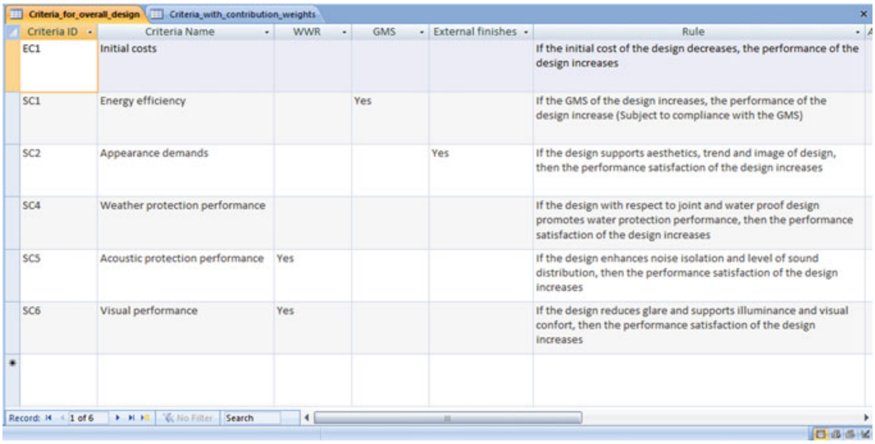


Wall_mat_for_design | Wall_mat_for_pro_and_hand | Window_mat_for_construction | Wall_mat_for_maintenance

Material ID	Material type	External finishes	Thickness (m)	Height (m)	Length (m)	U-value (W/m2K)	STC	SC	VT	Initials
BL1	Concrete block	Plaster and paint	0.1	0.19	0.39	3.77	40	None	None	160
CB1	Claybrick	Plaster and paint	0.1	0.105	0.215	2.87	40	None	None	80
CI1	Cast in-situ	White color	0.1	3	4	3.66	40	None	None	74.52
CW1	Glass curtain	Gray color	0.018	None	None	2.688	36	None	None	228.73
FG1	Fixed glass	Gray color	0.018	None	None	3.577	36	0.7	0.63	709.14
PC1	Precast	Skim coat/white color	0.1	3	4	3.504	40	0.33	0.63	863
			0							

Record: 1 of 6 No Filter Search

Knowledge of the building envelope materials including external wall, window glazing, and shading device in the KM-M



Criteria_for_overall_design | Criteria_with_contribution_weights

Criteria ID	Criteria Name	WWR	GMS	External finishes	Rule
EC1	Initial costs				If the initial cost of the design decreases, the performance of the design increases
SC1	Energy efficiency		Yes		If the GMS of the design increases, the performance of the design increase (Subject to compliance with the GMS)
SC2	Appearance demands			Yes	If the design supports aesthetics, trend and image of design, then the performance satisfaction of the design increases
SC4	Weather protection performance				If the design with respect to joint and water proof design promotes water protection performance, then the performance satisfaction of the design increases
SC5	Acoustic protection performance	Yes			If the design enhances noise isolation and level of sound distribution, then the performance satisfaction of the design increases
SC6	Visual performance	Yes			If the design reduces glare and supports illuminance and visual confort, then the performance satisfaction of the design increases

Record: 1 of 6 No Filter Search

IF-THEN rules and parameters in the KM-R

Performance_of_alternatives | Performance_of_individual_mat

Alternative_ID	Wall_ID	Window ID	Shading ID	EC1	SC1	SC2	SC4	SC5	SC6	Add New Field
1	PC1	WG1	SD3	S	VU	F	U	F	F	
2	PC1	WG2	SD3	F	VU	F	U	F	F	
3	PC1	WG3	SD3	F	F	F	U	VS	F	
4	PC1	WG4	SD3	F	VS	F	U	VS	F	
5	PC1	WG1	SD1	F	VS	F	VS	F	F	
6	PC1	WG2	SD1	F	VS	F	VS	F	F	
7	PC1	WG3	SD1	F	VS	F	VS	VS	F	
8	PC1	WG4	SD1	F	VS	F	VS	VS	F	
9	CB1	WG1	SD3	VS	VU	F	U	F	F	
10	CB1	WG2	SD3	S	F	F	U	F	F	
11	CB1	WG3	SD3	S	S	F	U	VS	F	
12	CB1	WG4	SD3	S	VS	F	U	VS	F	
13	CB1	WG1	SD1	S	VS	F	S	F	F	
14	CB1	WG2	SD1	S	VS	F	S	F	F	
15	CB1	WG3	SD1	S	VS	F	S	VS	F	
16	CB1	WG4	SD1	S	VS	F	S	VS	F	
17	BL1	WG1	SD3	VS	VU	F	U	F	F	
18	BL1	WG2	SD3	S	VU	F	U	F	F	
19	BL1	WG3	SD3	S	U	F	U	VS	F	
20	BL1	WG4	SD3	S	VS	F	U	VS	F	
21	BL1	WG1	SD1	S	VS	F	S	F	F	
22	BL1	WG2	SD1	S	VS	F	S	F	F	
23	BL1	WG3	SD1	S	VS	F	S	VS	F	

Record: 1 of 48 No Filter Search

Knowledge related to performance satisfactions of the design alternatives and individual materials in the KM-R.

Appendix F
Group Interview for the Case Studies

Objectives

To reveal the underlying attitudes and beliefs held by the DMs for supplying information about how the DMs think, feel, or act when applying the tool to mitigate each of the decision-making problems.

Research design Semi-structured interview conducted with the DMs of the three representative teams.

Method of data collection Group interview.

Interview questions (based on the framework analysis)

1. What are your opinions when applying the tool to facilitate the team to mitigate the problem related to inadequate consideration of criteria? Was the full set of criteria given helpful to remind the team to consider these criteria holistically? Was considering all criteria at once helpful as a reminder to the team?
2. What are your opinions for applying the tool to facilitate the team to mitigate inadequate consideration of possible building envelope materials and designs? Were the materials and designs provided by the tool helpful as a reminder to the team? Was comparing these alternatives at once helpful as a reminder to the team?
3. What are your opinions for applying the tool to facilitate the team to mitigate lack of efficiency and consistency in making decisions? Was making decisions based on the knowledge stored in the tool helpful to facilitate the team to do so? Was making decisions based on the same set of the knowledge offered by the tool helpful to facilitate the team to do so?
4. What are your opinions for applying the tool to facilitate the team to mitigate the lack of communication and integration among members of the team? Was making decisions as a team through the user interface helpful to facilitate the team to do so? Was discussion arising from using the tool helpful to facilitate the team to do so?

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5. What are your opinions for applying the tool to facilitate the team to mitigate the problem related to subjective and uncertain requirements? Was translating subjective and uncertain data into quantifiable data by the tool helpful to facilitate the team to deal with subjective requirements and perspectives? Were the results calculated by the tool helpful to facilitate the team to interpret the design solutions?
6. What are your opinions for applying the tool to facilitate the team to mitigate disagreement between opinions of the DMs? Was reviewing and updating opinions of the DMs governed by the tool helpful to facilitate the team to do so? Was applying the tool helpful for the team to achieve optimized consensus solutions?

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