ADAPTATIONS OF QFD FOR CONSTRUCTABLE DESIGNS WITHIN A CONCURRENT CONSTRUCTION ENVIRONMENT: AN INFORMATION MODELING APPROACH

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SUMMARY

Constructable designs have been regarded as an important strategy to enhance overall performance in the construction industry. To achieve constructable designs, the design teams need to respond swiftly and efficiently to client requirements, but also to quickly and effectively exchange design and construction information. However, this process is not always easy due to the entrenched horizontal and vertical fragmentation in the industry. Concurrent engineering principles provide a general framework to realize the integration and improvement of the industry through the use of appropriate models, methods and tools to facilitate their implementation. This paper addresses the challenge of developing an intelligent decision support system (DSS) for constructable designs within a concurrent engineering environment. Quality function deployment (QFD), which is an established method to implement and augment concurrent engineering principles, is adopted to communicate, analyze and satisfy the integrated requirements of design teams' upstream customers, the clients, and their downstream customers, the construction professionals. Intelligent decision support tools are integrated with QFD to facilitate the knowledge transfer and information processing between members of extended design teams. The information model approach is adopted to allow valuable client information and constructability knowledge to be captured within an Industry Foundation Classes (IFC)-based concurrent engineering environment. The resulting model provides an information environment to adapt QFD to support constructable designs.

INTRODUCTION

Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support (Winner, et al, 1988). The concept emphasizes integration of complementary engineering expertise, cooperation of multiple competing perspectives, communication upstream and downstream product life-cycle concerns, and coordination of group problem-solving activities (Krause, et al 1993). It is termed as 'concurrent construction' (CC) in the construction industry, which is defined as 'an integrated approach to the planning and execution of all project activities, from the conceptualization state through to the handover of the facility' (Jaafari, 1997). The need for adopting concurrent engineering in construction is discussed by several publications (e.g. De la Garza, et al, 1994; Eldin, 1997; Love and Gunasekaran, 1997; AbulHassan, 2001) and is summarized as follows:

- It is a philosophy that can overcome the disadvantages of existing fragmentation and specialization in the construction industry if applied properly (De la Garza, et al, 1994).
- It is a schedule reduction tool that could reduce project delivery duration by 20-25% without an associated increase in project cost (Eldin, 1997).
- It is an approach imported from the manufacturing industry to assist in overcoming the construction industry's poor productivity and performance (Love and Gunasekaran, 1997).
- Its application in a construction project tended to increase project delivery speed and project quality but do not have a significant impact on project unit cost (AbulHassan, 2001).

Compared with the concept of manufacturable design in the manufacturing industry, constructable design is already adopted as an element of concurrent engineering philosophy in construction (De la Garza, et al, 1994). Quality function deployment (QFD) is a widely accepted method to implement and augment concurrent engineering principles. Although it is primarily used in the manufacturing industry, QFD is a viable and productive tool to benefit the construction industry (Oswald and Burati, 1993) and has the great potential to be used to aid the development of a concurrent design approach to support the process of constructable design decision-making with proper adoption and extension to facilitate its implementation.

This paper addresses the challenge of extending the conventional QFD method for constructable designs and bringing QFD and a concurrent construction environment together to provide the design team with valuable, integrated design-construction information to support its implementations. It proposes to fulfill two research aims, firstly, to adapt the conventional House of Quality (HOQ) matrices of QFD and combine the adapted HOQ with intelligent support tools for constructable designs; and secondly, to create a supportive environment to acquire and process the valuable, integrated design-relevant QFD information to facilitate the implementation of the adapted QFD.

ADAPTING QFD FOR CONCURRENT CONSTRUCTABLE DESIGNS

Quality function deployment

QFD is a method for structured product planning and development that enables a development team to specify clearly the customer's needs, and then to evaluate each proposed product or service capability systematically in terms of its impact on meeting those needs (Cohen, 1995). The approach, originated in Japan during the 1960s, was developed to respond to two issues: how to develop a new product that meets customer needs, and how to provide quality control process charts to manufacturing before production (Cristiano, et al, 2000). The method provides a structured concurrent framework to translate the customer requirements into corresponding technical requirements of a product or service, and subsequently, into component characteristics, process steps, and operational steps. Each translation uses a very complex matrix called a HOQ, as shown in Figure 1 (Cohen, 1995). The typical HOQ process is summarized into the following nine steps:
(1) Obtaining customer attributes (CAs);
(2) Assigning weightings to CAs;
(3) Conducting customer competitive survey;
(4) Generating engineering characteristics (ECs) responsive to CAs;
(5) Building technical correlations between ECs;
(6) Determining relationships between ECs and CAs
(7) Calculating importance weightings of ECs;
(8) Setting target values of ECs;
(9) Evaluating technical competitiveness of ECs.

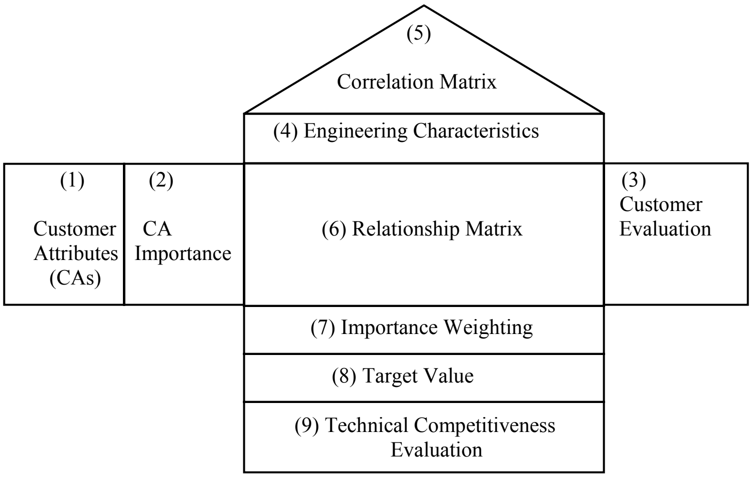

Figure 1 House of Quality (Adapted from Cohen, 1995)

The practical applications of QFD have reported a variety of benefits to organizations. For instance, Sullivan (1986) reported that:
"The QFD system has been used by Toyota since 1977. … Between January 1977 and April 1984, Toyota introduced four new van-type vehicles. Using 1977 as a base, Toyota reported a 20% reduction in start-up costs on the launch of a new van in October 1979; a 38% reduction in November 1982; and a cumulative 61% reduction in April 1984. During this period, the product development

cycle was reduced by one third with a corresponding increase in quality because of a reduction of the number of engineering changes."

However, the practical implementations of QFD in the construction industry have encountered difficulties. For instance, although design-relevant constructability knowledge and information are usually fuzzy, incomplete, and even conflicting in nature (Gray and Hughes, 2001), the conventional QFD applications always assume that the input data are precise and therefore force the QFD team to form consensus views. It is also difficult for QFD to support the process of constructable designs in which design teams need firstly to satisfy client requirements and then optimally use the construction knowledge and expertise to achieve an improved constructable design with a suitable or increased client satisfaction, but also they need to assess the degree of satisfaction of client needs and constructability needs respectively. In particular, there is lack of a supportive environment in the construction industry to successfully apply QFD in constructable designs due to the traditional separation of design and construction. Thus, new theories and approaches that support the applications of QFD in constructable designs need to be developed.

The HOQ for constructable designs (HOQCD)

A new proposed HOQ model, called the HOQCD, is developed to support constructable designs based on the conventional QFD rationale, as shown in Fig. 2. The HOQCD is organized into three parts, client requirement analysis, constructability analysis, and design feature analysis. The client requirement analysis processes design-relevant client information and evaluates design features' contributions on client satisfaction. The constructability analysis processes the design-relevant constructability inputs and evaluates design features' contributions on ease of construction. The design feature analysis computes importance weightings of design features on client satisfaction and on ease of construction, respectively, and then analyzes and evaluates alternative design features based on the computed weightings. The HOQCD includes the following twelve components:

1. Matrix of Client attributes (CliAs), which contains a list of client attributes.
2. Matrix of importance ratings of CliAs, each of which is associated with one client attribute and represents the importance of the attribute.
3. Matrix of constructability attributes (ConAs), which contains a list of constructability attributes.
4. Matrix of importance ratings of ConAs, each of which is associated with one constructability attribute and represents the importance of the attribute.
5. Matrix of design features (DFs), which are the geometric forms or properties of design components in CAD drawings or specifications that are used in satisfying their corresponding client attributes or constructability attributes.
6. Matrix of correlations between DFs, which shows the interrelationships and interdependencies between design features, e.g., the supporting or conflicting relationships between a pair of design features (Cohen, 1995).
7. Matrix of relationships between CliAs and DFs, which indicates how much each design feature impacts on each of its corresponding client attributes.
8. Matrix of client satisfaction evaluation, which represents the strength of overall design feature's contribution to each client attribute satisfaction. The overall client attribute satisfaction results in a client satisfaction index, which shows the extent of a building design to overall client satisfaction.
9. Matrix of weightings of DFs for client satisfaction, which represents the strength of each design feature's contribution to overall client satisfaction.
10. Matrix of relationships between ConAs and DFs, which indicates how much each design feature impacts on each of its corresponding constructability attributes.
11. Matrix of constructability satisfaction evaluation, which represents the strength of overall design features' contribution to each constructability attribute satisfaction. The overall constructability attribute satisfaction results in a constructability satisfaction index, which shows the extent of a building design to ease of construction.
12. Matrix of weightings of DFs for constructability satisfaction, which represents the strength of each design feature' contribution to overall constructability satisfaction.

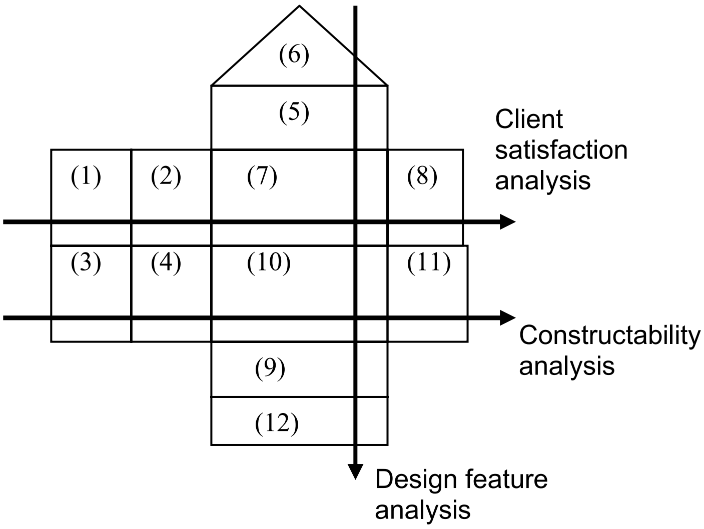

Figure 2 The HOQCD

An information model of the HOQCD

The information included in the HOQCD is modeled using the object-oriented technique, which has produced the class hierarchy shown in Figure 3 using the unified modeling language (UML). The concept behind the information model is based on the twelve matrices that form the HOQCD. Each building design is an instance of a building design class and may be associated with one or more client attributes and constructability attributes. Client attributes and constructability attributes are grouped into related attributes and represented as a two-level hierarchy structure in the information model. Each client attribute (primary/detailed) or constructability attribute (primary/detailed) is held as an instance of attribute class. Each primary client attribute or primary constructability attribute may be aggregated by one or several more detailed client attributes or constructability attributes. Each detailed client attribute or detailed constructability attribute is associated with one detailed client attribute satisfaction or detailed constructability attribute satisfaction. The design components and their relevant features that are used to achieve or satisfy client attributes and constructability attributes are captured in the design component package. The correlation information of design component package is stored in the component correlation class and each correlation between design components and their features is an instance of the component correlation class. The two relationships, 'CliA_DF_relationship' and 'ConA_DF_relationship', provide main links to communicate the design-relevant client information and design-relevant constructability information with the design component package. If a particular feature of a design component contributes to a particular client attribute or a particular constructability attribute to some extent, the relationship is built between them. The remaining information classes in Figure 3 relate to the final information that is derived from the relationships built. Each detailed client attribute satisfaction or detailed constructability attribute satisfaction is associated with zero or several 'CliA_DF_relationship' classes or 'ConA_DF_relationship' classes. Each 'client_satisfaction_index' or 'constructability_satisfaction_index' is associated with one or several 'detailed_CliA_satisfaction' classes or 'detailed_ConA_satisfaction' classes. And each building design has one 'client_satisfaction_index' and one 'constructability_satisfaction_index'.

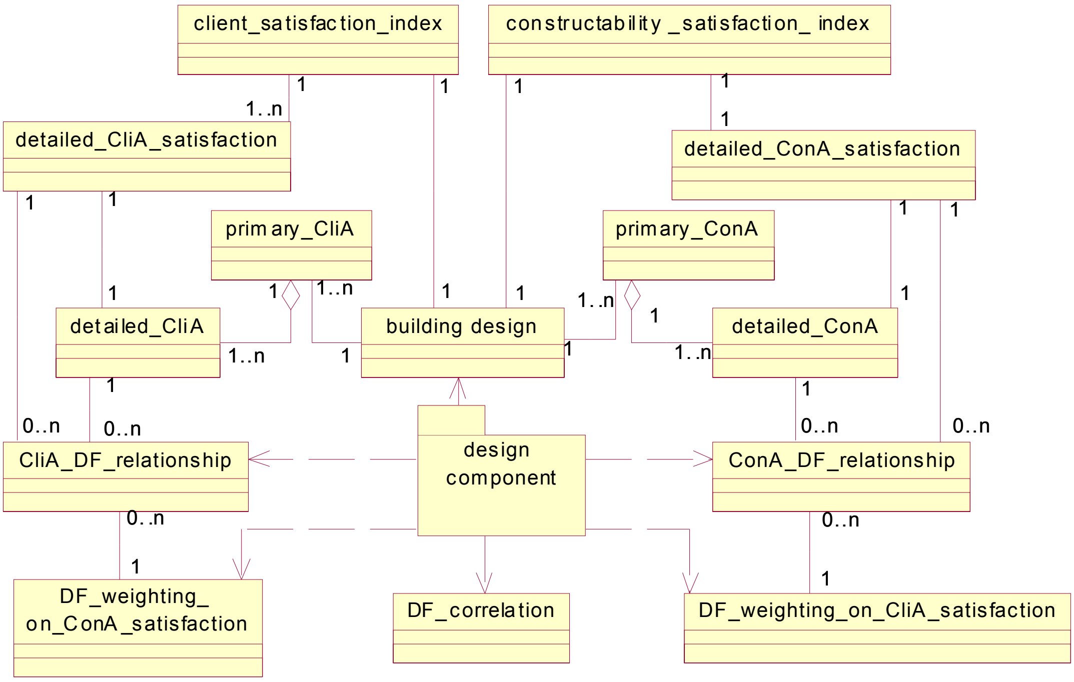

Figure 3 UML-based information class hierarchy of the HOQCD

Building intelligent design experts to support constructable designs

An intelligent design expert that makes use of artificial intelligence paradigms is built to further extend the HOQCD for constructable designs. The expert module has two fundamental functions, firstly to transfer the QFD-relevant constructability knowledge and information to the design team, and secondly to help the design team to process QFD-relevant constructability information and client information. The object model of the intelligent expert, as shown in Figure 4, includes three objects, a user interface, a knowledge base and an inference engine.

User interface

The user interface is used for exchanging the inputted data and relevant constructable design information between the system's internal environments (e.g., knowledge base, inference engine) and external environment (e.g., QFD facilitator; members of the design team). A QFD facilitator is the entity (e.g., a member of the design team) that inputs the QFD-relevant constructability information into the system's internal environments through the user interface and is responsible for supporting and coordinating the design team that uses the HOQCD to make an improved constructable design decisions. A member of design team is a participant of the constructable design decision-making (e.g., an architect, a structural engineer). The QFD facilitator and members of design team are responsible for dealing with the following information through the user interface (Figure 5):

- CliAs and weightings of CliAs;
- ConAs, which are identified with the help of the intelligent Knowledge Management expert for Constructable Attributes (KM-ConA), and weightings of ConAs;
- DFs, which are generated with the help of the intelligent Knowledge Management expert for Design Features (KM-DF), and correlation of DFs;
- Strengths of DFs' contributions on satisfaction of CliAs;
- Strengths of parameters of rules between DFs and ConAs.

Knowledge engine

The knowledge engine, called intelligent Knowledge Management expert for Constructable Designs with QFD (KM-CD-QFD), is constructed to automate the transfer of QFD-relevant constructability knowledge and information. The KM-CD-QFD (Figure 4) is aggregated by three objects, intelligent Knowledge Management expert for Constructability Attributes (KM-ConA, e.g., the detailed ConAs class in Figure 3), intelligent Knowledge Management expert for Design Features (KM-DF, e.g., the package of design component in Figure 3), intelligent Knowledge Management expert for relationships between Constructability Attributes and Design Features (KM-ConA-DF, e.g., the class of ConA_DF_relationship). The KM-CD-QFD provides the following information to support the application of QFD for constructable designs (Figure 5):

- ConAs, which is contained in the KM-ConA;
- DFs, which is contained in the KM-DF;
- Relationships between ConAs and DFs, which is contained in the KM-ConA-DF.

Inference engine

The inference engine is designed to automate the processing of QFD-relevant client information and constructability information. The inference engine (Figure 4) is aggregated by four objects, namely fuzzy number engine, rule inference engine, satisfaction inference engine and Fuzzy Weight Average (FWA) engine. The components of inference engine and their functions are introduced below (Figure 5):

- Fuzzy linguistic terms are used to communicate information between the system's internal environment and external environment through the user interface. The fuzzy number engine is built to satisfy this requirements, which has two basic functions, namely fuzzification to translate the linguistic teams into fuzzy numbers (e.g., Bonissone and Decker, 1986; George and Bo, 1995) so that the numeric information can be processed by the system's internal environment, and defuzzification to retranslate the fuzzy numbers into linguistic terms so that the linguistic information can be easily utilized by the system's external environment (e.g., members of the design team).
- A rule inference engine is developed based on the linguistic order weighted average (LOWA) operator (Yager, 1988; Bordogna, et al 1997), which is established to reason the relationships between constructability attributes and constructable design features based on the fuzzy rules contained in KM-ConA-DF.
- A satisfaction inference engine is developed based on Cross and Sudkamp's (1994) rationale, which is used to reason the strength of overall design features' contribution to each constructability attribute satisfaction and the strength of overall design features' contribution to each client attribute satisfaction.
- A FWA engine employs fuzzy weighted average (e.g., George and Bo, 1995) to compute constructability satisfaction index, client satisfaction index, design features' weightings for constructability attributes and design features' weightings for client attributes.

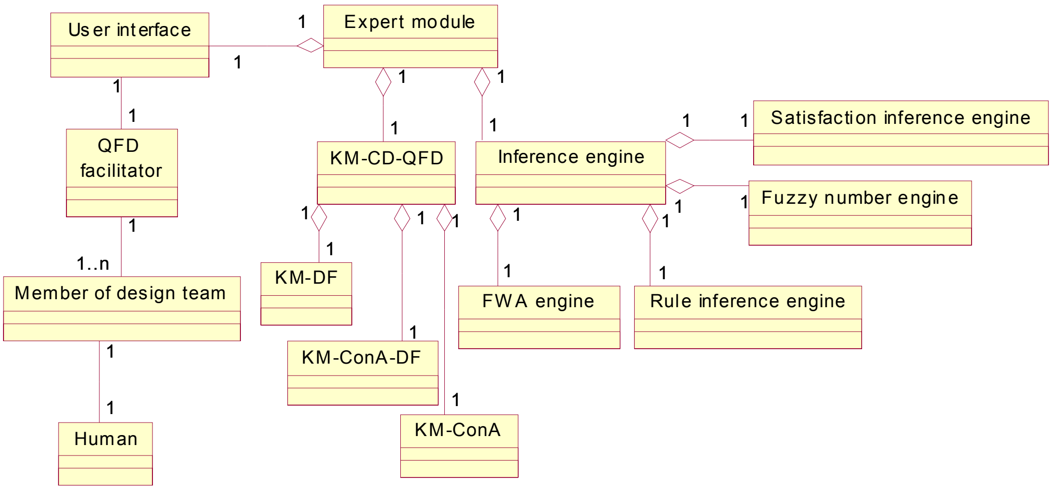

Figure 4 UML-based object model of intelligent experts

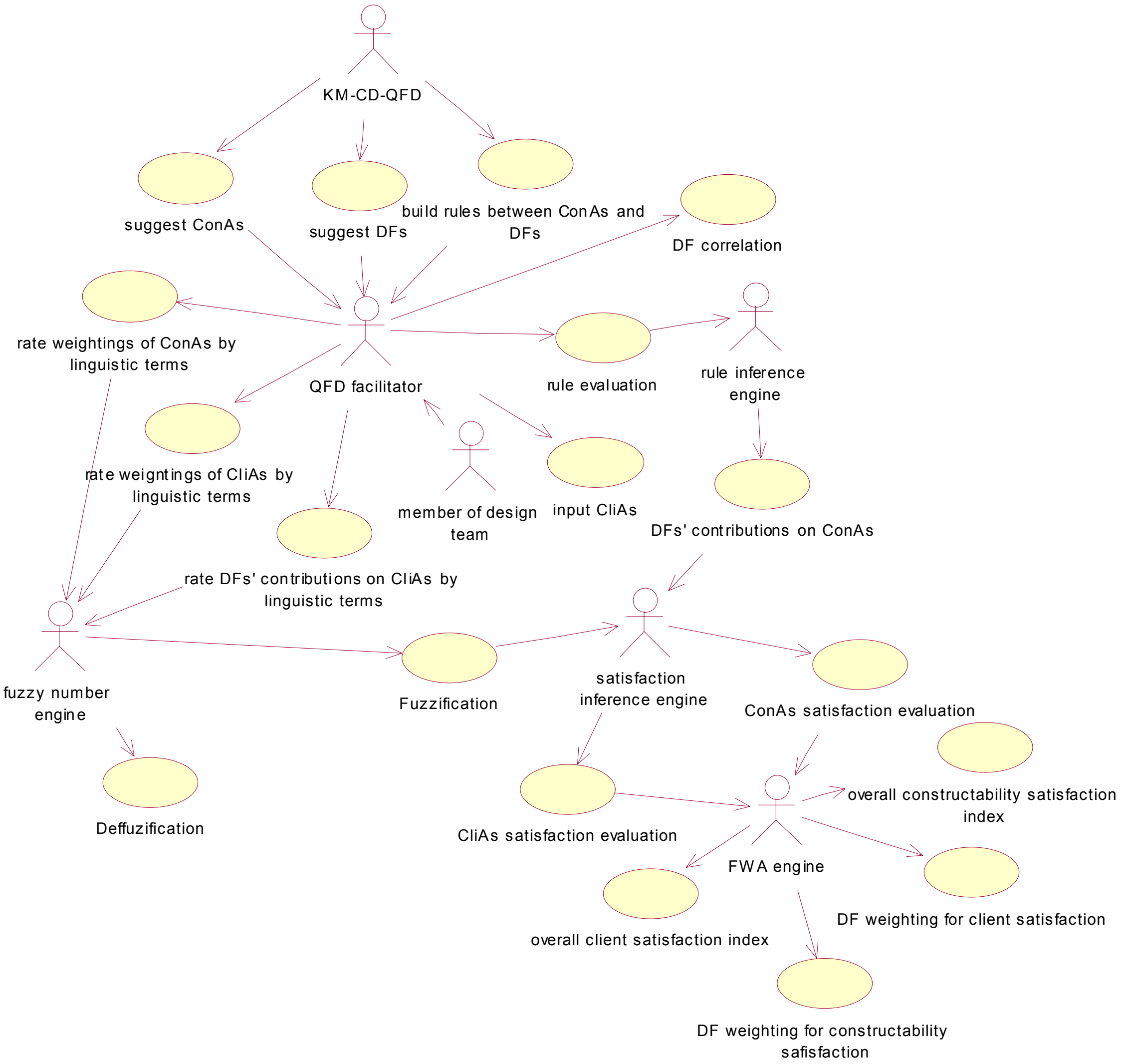

Figure 5 UML-based use case view of intelligent experts

SHARING CONSTRUCTABILITY INFORMATION WITHIN A CONCURRENT CONSTRUCTION ENVIRONMENT

The intelligent QFD system consists of many elements, including models (e.g., the HOQCD), algorithms and inference mechanisms (e.g., the FWA engine), knowledge bases (e.g., the KM-DF), and actors with different expertise (e.g., various members of the design team). An integrated environment is required to enable these elements to work together to achieve an improved constructable design. The common link between these diverse elements is that they all require and generate information. The information is usually generated by one element during the decision-making process of constructable designs, yet the resulting information may well be relevant to the whole design team, and thus should be shared. A product model is an information reservoir of complete product data to support activities at different product development phase (Krause, et al, 1993). The product model represents a product in a computer, and should contain adequate information about the product to satisfy the product information needs of all the project team members (Harding, et al, 1999). The Industry Foundation Classes (IFCs), developed by the Industry Alliance for Interoperability (IAI), is a building product model that aimed at sharing and exchanging building information between disciplines throughout the project life cycle (IAI, 2000). Thus, the IFC-based product model is used to build the concurrent information environment to support the development of a QFD-based decision support system (DSS) for constructable designs. Its architecture is represented in Figure 6, which shows that the client information and design-relevant constructability knowledge and information are combined with the IFC-based product model to form the concurrent information environment.

An example of sharing and exchanging information in the concurrent information environment using object-oriented techniques is shown in Figure 7. The key design features that affect the design for constructability of a beam are identified from IFCs, which include the dimensions, type, connections, location and materials of a beam. These features are stored and represented in the KM-DF. The class of constructability attribute, 'materials', contains the parameters (e.g., acquisition costs) that influence the constructability assessment of materials. Classes of constructability attributes are also derived from IFCs (e.g., from classes in the resource layer of IFCs) and are stored in the KM-ConA. Both beam class and materials class are associated with the beam_materials_relationship class that is included in the KM-ConA-DF. The beam_materials_relationship class builds the communication between beam class and materials class and includes functions to assess the beam's contributions on satisfaction of materials class. Similarly, the client attribute class, 'budget', which is derived from IFCs, is communicated with the beam class through the beam_budget_relationship class. The beam_budget_relationship class includes functions to assess the beam's contributions on satisfaction of the materials class. Client information (e.g., budget) and constructability knowledge and information (e.g., materials) are integrated together for exchange with each other through the IFC-based product model.

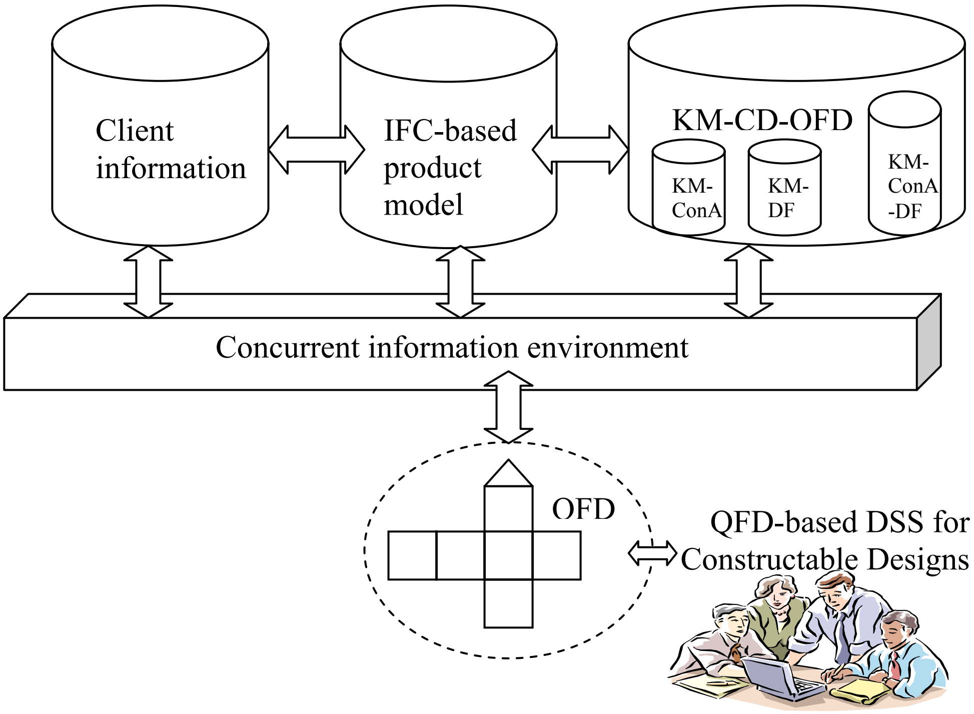

Figure 6 Architecture of concurrent information environment for constructable designs

CONCLUSION

The construction industry has recently adopted customer-driven strategies that deliver high quality projects in a safe manner, on schedule, and at the least cost to meet or exceed clients' expectations. This can be further achieved by raising design teams' awareness of integrated information, which includes the upstream client information and the downstream design-relevant constructability knowledge and information. Early and effectively sharing and utilizing the integrated information among members of the design team is critical to achieve an improved constructable design with a high client satisfaction.

This paper demonstrates an intelligent DSS to support constructable designs in the early design phase. The HOQCD is developed to facilitate the use of integrated client information and constructability knowledge and information. Under the HOQCD platform, intelligent design experts are constructed to support the sharing and processing of the integrated design-relevant QFD information. The integrated information is captured and stored within a concurrent information environment, which is supported by an IFC-based product model, so that a design team can easily acquire and share the information.

The system is already developed on a personal computer platform. Future research can focus on extending the system on the Internet platform and on further assessing and improving the information representation model, which was proposed to integrate the client information and constructability information within the IFC-based concurrent information environment.

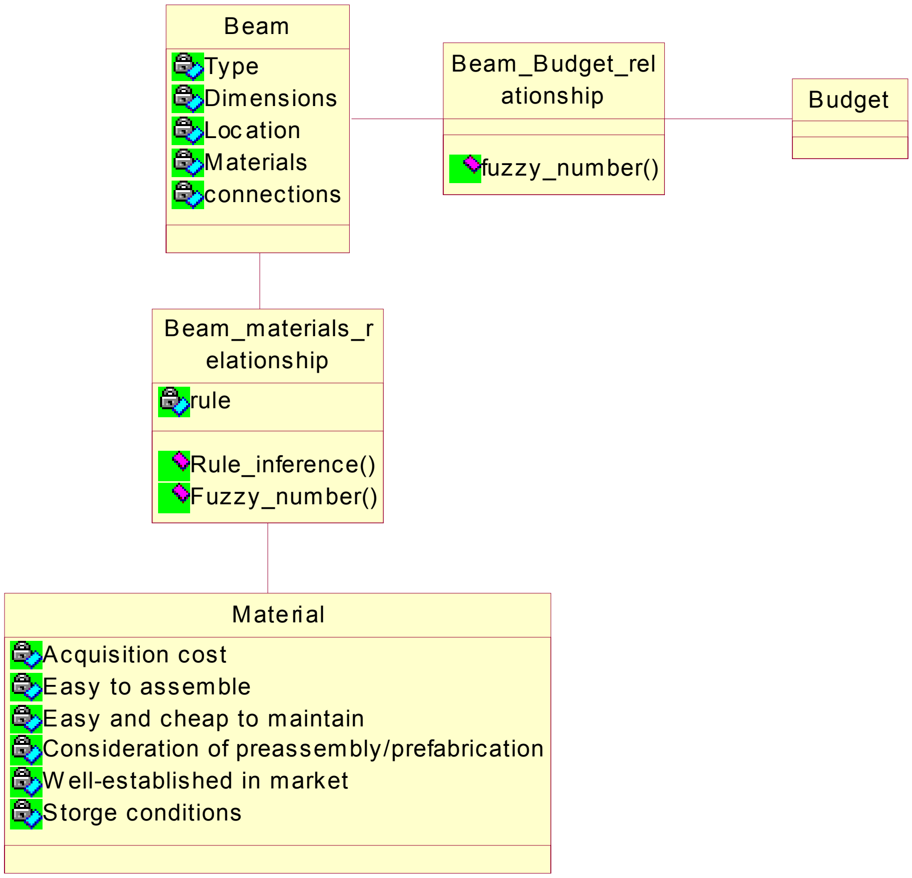

Figure 7 Example of information sharing and exchange in the concurrent information environment

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