Integrating Value Analysis and Quality Function Deployment for Evaluating Design Alternatives

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Abstract: This paper presents a hybrid framework that integrates value analysis and decision making for eliciting and evaluating design alternatives. Value analysis approach relies on the integration of the functional analysis through the systematic use of the functional analysis system technique and quality function deployment. This value analysis methodology enables customer requirements to be linked to specific design alternatives during the project design stage. The degree of project complexity will affect the number of design alternatives to be evaluated. As such, the data envelopment analysis (DEA) is incorporated as a decision support tool to evaluate the degree to which each design alternative satisfies the customer requirements. DEA is used to calculate a customer requirement efficiency index for each alternative. This index is a measure of how well a particular alternative achieves the requirements taking into account its overall cost. The framework was successfully used on a high-tech research facility construction project.

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Introduction

Achieving end-user satisfaction and optimizing the total value of a project design is a major goal of facility owners and developers. After identifying design objectives, a multitude of products/ options with varying costs can be used to create alternatives that meet the design objectives. Owners have to carefully select the most optimum design alternative that combines the most valuable options and realize the design objectives within the project budget (or life-cycle costing). This paper presents a framework for a decision support system to help owners identify the most valuable design alternative. The proposed approach uses value analysis (VA), quality function deployment (QFD) and data envelopment analysis (DEA) to optimize the owner decision.

The underlying scenario of this paper is as follows: "A developer or a facility owner wants to build (redevelop/rehab) a facility that will be used by customers (for example tenants or employees), who have a set of end-user requirements. The developer wants to select the design features (such as components and finishes) that meet the customer requirements, present the most valuable components (from engineering/functional view) and optimize/meet budget requirements."

A functional analysis system technique (FAST) diagram is first used to define the "value" map of the design. i.e., What are the objectives of the design/facility? This relates mainly to the engineering aspect of the "function" of the facility under design. To achieve these functions or objectives, a set of different "products/ options" can be acquired at varying "costs." QFD is used to establish a matrix that helps define the value of each option (the degree by which each option satisfies the design objectives). Different combinations of available options constitute viable design alternatives. Each alternative has a value which is based on the value of the options included. DEA is then used to find the design alternative that optimizes the values within a certain budget.

The value of the integrated framework lies in its ability to: (1) elicit customer requirements (the "WHATs") through the use of FAST; (2) relate various design options (the "HOWs") to each customer requirement through the use of QFD; and (3) provide a decision-support environment to the project decision maker to assist in selecting the most suitable alternative (the "WHY"). This integrated framework was successfully applied during the design stage of a smart research facility at the University of Toronto.

Background

Value analysis (also referred to as value engineering) is an organized, systematic, and multidisciplined team approach that analyzes the functions of systems, equipment, facilities, services, and supplies for the purpose of eliminating unnecessary costs, while maintaining the required performance, quality, and safety of the functions required by the customer (Dell'Isola 1998). At the core of VA lies the process of extracting the fundamental functions expected by the product/service. The functions of a facility (or a product) are defined through careful investigation and analysis of "what is it supposed to do?" Basic functions of a facility can be implemented through innovative use of different alternatives or deign components. FAST builds upon VA by linking the functions

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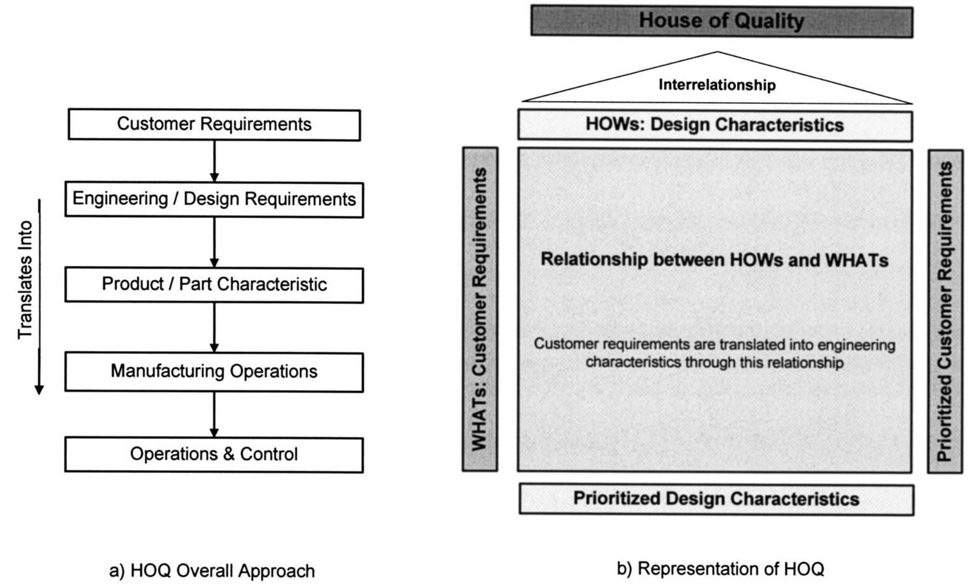

Fig. 1. QFD methodology

of a product into a network/hierarchy of basic and secondary functions (normally expressed in a verb-noun fashion). The functional model provides a graphical representation of the functions of the product or service under analysis and the relationship between each function. FAST should not be considered an end product or result, but rather a beginning. It describes the item or system under study, and causes the team to think through the functions that the item or system performs. This forms the basis for a wide variety of subsequent approaches and analysis techniques.

QFD is defined as deploying the attributes of a product or service desired by the customer throughout all the functional components of an organization (Xie et al. 2003). QFD is used as a tool for satisfying customers through design targets and quality assurance points used throughout the production phase (Akosa et al. 1995). It is important to emphasize that QFD is not a solution, but rather a systematic process towards finding one, thereby achieving a more satisfied customer. As such, QFD should not be considered an end in itself, but rather a means to an end, a more satisfied customer (Mallon and Mulligan 1993). Benefits of QFD are both tangible and intangible (ReVelle et al. 1998). Tangible benefits include: Lowering design costs, elimination of most late design changes, early identification of high risk areas, up-front determination of product process requirements, significant reduction in development time, and a more efficient allocation of resources. Intangible benefits include: Increase customer satisfaction, facilitation of multidisciplined teamwork, establishment of knowledge transfer by maintaining documentation, and encouragement of transfer training to other projects by teammates.

The QFD methodology is illustrated in Fig. 1 consists of a structured multiple matrix-driven process that could be explained through a step translation operation. (Shillito 1994). The QFD procedure is best explained graphically through the house of quality (HOQ). The HOQ is the engine that drives the entire QFD process, and it provides means for combining planning, and communications. The structure of the HOQ takes the shape of a house [Fig. 1(b)]. The exterior walls of the house describe the customer requirements known as the WHATS. The ceiling of the house describes the design characteristics known as the HOWS. The interior of the house describes the relationship between the customer requirements and design characteristics known as the *WHYS*. The roof of the house contains the correlation or interrelationships between the design characteristics. Finally, at the foundation of the house lie the prioritized engineering design characteristics (Xie et al. 2003).

QFD has been successfully utilized in a multitude of domains. The most extensive use of QFD has been in the manufacturing sector. Recently, some researchers have used QFD in construction research. A study by Mallon and Mulligan, (1993) applied QFD to the design and construction process of renovating a hypothetical personal computer workroom facility. In this study, the goals of the QFD exercise were to decide if improvements were desirable or even needed, and to focus on the design elements of the proposed improvements. The study concluded that QFD can be successfully implemented if a company-wide commitment to quality and improvement is in place. Furthermore, they argue that the immediate effect of QFD on the design process will not be a reduction in the cost or time required for the initial design; instead, the immediate effect will be a more focused conceptualization. The use of QFD in the capital project planning process was proposed by Ahmed et al. (2003). Capital project planning is divided into four development phases: Project requirement, feasibility study, preliminary design, and detailed design. QFD is used in parallel with the respective phases of the project planning process to enhance the quality of the output from each phase. The use of QFD helped in keeping track of the customer requirements, enhanced communication between client and design team, and supported the evaluation of the project alternatives.

The application of QFD in strategic construction planning was first examined by Dikmen et al. (2005). The study argues that although it is better to implement QFD as early as possible in a construction project, it is not too late to benefit from it even after the construction stage is over. This "post analysis" determines the best marketing strategies to transfer experience gained from a current project to forthcoming projects. According to the findings of the case, QFD can be utilized to determine the right marketing strategy, to make a comparison with the competing alternatives, and to collect data which could increase the client satisfaction

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level in future projects. Finally, the study suggests that the assignment of the relationships and weights in the matrices is an important limitation of the QFD methodology, since the inaccuracy and vagueness in the inputs reduces the reliability of the decisions.

DEA is a nonparametric linear programming framework that is used to assess the relative efficiency of a particular solution with respect to a group of peer solutions. In this regard, DEA is useful in identifying solutions that are performing with an inferior level of efficiency and those that are, theoretically, superiorly efficient. Applications of DEA are quite diverse and can be found in domains where the problem can be formulated in an input-to-output efficiency framework. DEA applications can be found in healthcare management (Steinmann and Zwrifel 2003), educational policy (Coates and Lamdin 2002), and advertising (Luo and Donthu 2001) to mention a few. Within the domain of civil engineering, DEA has been utilized in efficiency assessment of: (1) irrigation systems (Rodriguez-Díaz et al. 2004); (2) public transit systems (Boilé 2001); (3) construction prequalification (McCabe et al. 2005); (4) water supply and sanitation systems (Akosa et al. 1995); and (5) industry-level construction productivity (Li et al. 2005).

A DEA formulation evaluates the efficiency of each solution as the weighted sum of outputs divided by inputs [Eq. (1)]. In DEA terminology, a solution is usually referred to as a decision-making unit (DMU) The mathematical formulation of input-oriented DEA is given by the following set of equations:

$$\text{Maximize}: E_k = \frac{u_1 O_{1,k} + \ldots + u_M O_{M,k}}{v_1 I_{1,k} + \ldots + v_N I_{N,k}} \tag{1}$$

Such that

$$E_i^k = \frac{u_1 O_{1,i} + \ldots + u_M O_{M,i}}{v_1 I_{1,i} + \ldots + v_N I_{N,i}} \leqslant 1, \quad i = 1, \ldots, N \tag{2}$$

$$u_1, \ldots, u_M, \quad v_1, \ldots, v_N \geqslant 0 \tag{3}$$

where M=number of output attributes; N=number of input attributes, $O_{i,j}$=value of output attribute number i for unit k; $I_{i,j}$ =value of input attribute number i for unit k; u_i=output weight for output attribute number i; v_i=input weight for input attribute number i; E_k=efficiency of the current DMU_k; and E_i^k =efficiency of DMU_i that is calculated for DMU_k maximization. The variables in these equations are u_i, v_i, while E_k, $O_{i,j}$, and $I_{i,j}$ must be known for each DMU. This DEA formulation strives to maximize the efficiency of DMU_k, while maintaining the efficiency of all other DMU's $\leqslant 1$. Some of the strengths that DEA exhibits as a decision tool include (Thanassoulis 2001):

- The ability to deal with inputs and outputs that have heterogeneous units. For example, in a project optimization/evaluation scenario, the units of input could be project cost and time, while the output could include items like quality and environmental impact; and
- DEA does not need to have a functional form that relates inputs and outputs. This is specifically useful for applications where no formal models exist.

On the other hand, some of the key issues that must be considered with DEA include:

- DEA only estimates a relative measure of efficiency for a DMU. Hence, it is only able to assess how an alternative performs in comparison to its peers not against a "hypothetical" optimum solution.
- DEA cannot deal with uncertainty in the input or output variables; and
- Large problems can be computationally complex.

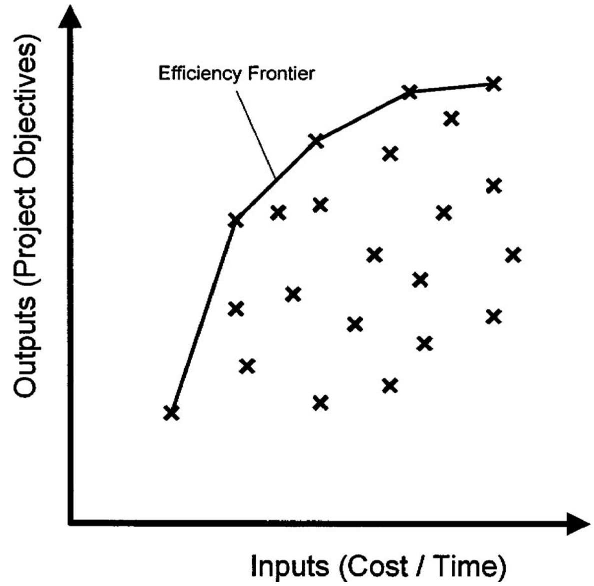

Fig. 2. Efficiency frontier in DEA

Proposed Approach

The proposed integration approach between FAST, QFD, and DEA relies on utilizing the output of one method as a necessary input for the following method. FAST diagrams help identify design objectives, while QFD can be used to compare the degree by which each design option satisfies these objectives. As such, there is a need to complement these two tools with a decision support tool. DEA is used to evaluate how each design alternative (i.e., a combination of options) attains the various objectives elicited through the use of FAST and QFD. DEA evaluates how a particular solution performs with respect to a measure of efficiency, which is generically the ratio between outputs and inputs. Respective to evaluating the design alternatives, outputs could represent various customer requirements/project objectives, while the inputs could represent the total cost and/or time for a project completion. Fig. 2 depicts the efficiency frontier for the DEA approach to evaluating the design alternatives. The benefit of this approach is its ability to short-list a set of design alternatives that best meet the customer requirements (those lying on the efficiency frontier). This reduces the solution space by filtering out "inefficient" solutions. In this regard, DEA is utilized as a decision-support rather than a decision-making tool, as the decision-maker still retains the final decision for selecting the most appropriate solution from those that lie on the frontier. In essence, integrating DEA with FAST and QFD closes the decision-making loop by answering the questions of:

1. What are my objectives? (FAST).
2. How can I attain them? (QFD).
3. Why should I select a particular alternative(s) (DEA)?

The major steps for integrating FAST, QFD, and DEA are depicted in Fig. 3:

1. Define the objectives (the WHATs): FAST is used to formalize a set of tangible objectives (J) that the project should aspire to attain.

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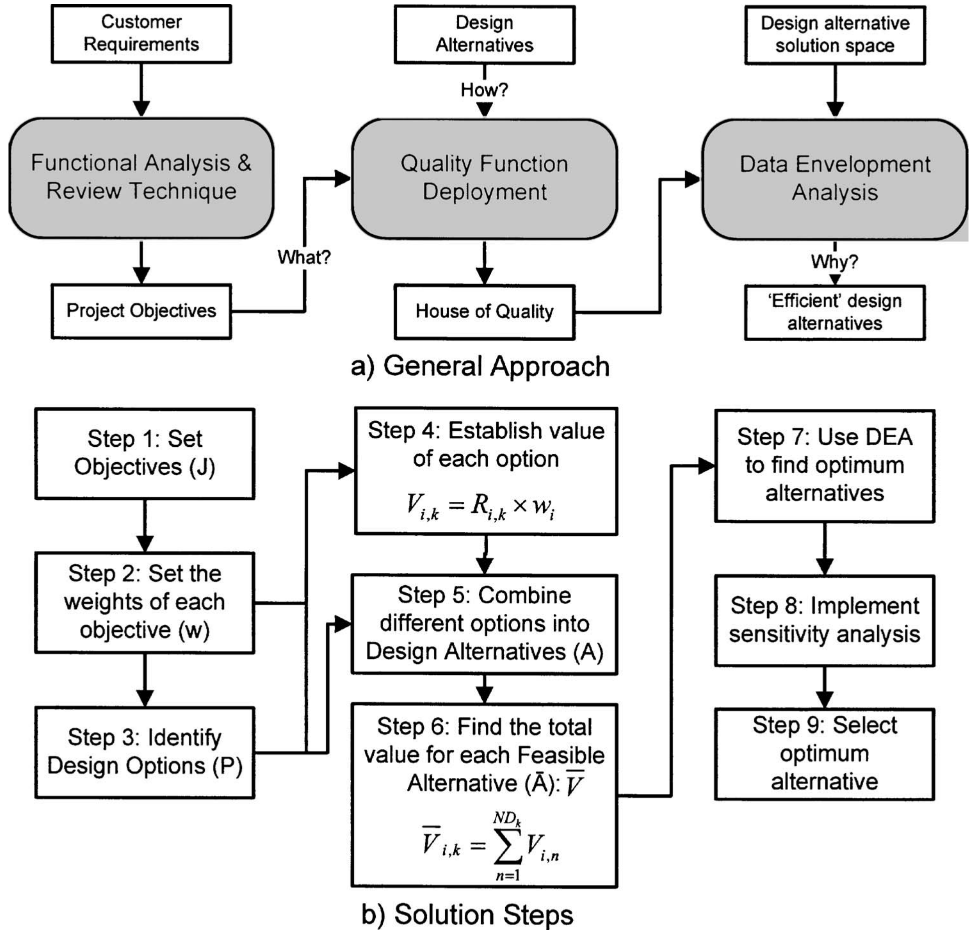

Fig. 3. Proposed integration framework

2. Assign relative weights for each objective (w): This is done through pairwise comparison between the objectives. Typically, this is done through interaction and collaboration between the owner, the designer, facility users, and maybe a VA consultant. The analytical hierarchy process (AHP) is used in this research to obtain the weights based on the pairwise comparison of objectives. Discussion of AHP is beyond the scope of this paper. The interested reader is referred to Saaty (1980).
3. Identify the options: Any project can be broken down into a set of constituent design components (D), normally for each design component (such as building envelop, flooring system, and finishes) there are a set of different products/options (ND_i) available in the market to implement the component (or achieve the design intent). For example, the lighting system for a facility can be executed using an elaborate/customized light system, or using simple off-the-shelf lights. It also can be executed using different wiring *configuration* and styles. In total, there exists P design options where $P = \sum_{i=1}^{D} ND_i$. Each available and suitable option should be considered by the owner.
4. Find the value of the options:
   - Establish the HOQ: QFD serves as the enabling mechanism to contrast/compare several design options to the objectives set forth by the FAST diagram. This is done by establishing the HOQ using the objectives in the left column (the WHATs) and the options in the top row (the HOWs);
   - Populate the HOQ: In each cell of the HOQ matrix establish the value relationship between each option and each objective. How much does each option satisfy each objective? The relationship strength ($R_{i,k}$) between "the WHATs" and "the HOWs" is assigned a value of 9 if the relationship is strong, 3 if medium, 1 if weak, and 0 if no relationship. $R_{i,k}$ refers to the relationship strength between objective i and option k; and
   - Find the value of each option: The value ($V_{i,k}$) of each option (P_k) respective to an objective (J_i) is determined by multiplying the relationship strength ($R_{i,k}$) by the weight (w_i) of each corresponding objective (J_i)

$$V_{i,k} = R_{i,k} \times w_i \tag{4}$$

5. Define the alternatives: The owner and the design team should develop a set of alternative designs (A). An alternative design is a complete design *configuration* that is composed by selecting a complementary set of products/options. Theoretically speaking, the total number of design alternatives available will depend on how many design elements (D) and options per design elements (ND_i) are available. The maximum number of design alternatives that can be generated is A, where

$$A = \prod_{i=1}^{D} ND_i$$

For example, assume that a project has 5 main design components (D) and each component has 3 design options

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(ND). Then we would have 15 total options (P). In addition, theoretically, the total number of option combinations or alternatives (A) would be $3^5=243$ alternatives. Of course, in actual life, a more limited number of alternatives (the actual set of alternatives $\bar{A}$) can be identified as the really feasible alternatives, such that $\bar{A} \subset A$. The set of feasible alternatives is generated via a compatibility matrix that indicates which design options are compatible within any single design alternative. A binary compatibility value $CV_{i,j}$ refers to the compatibility between option i and j. If $CV_{i,j}=1$ the options are compatible, whereas a value of 0 indicates incompatibility. The set of feasible alternatives $\bar{A}$ is generated such that for all design options $CV_{i,j}=1$. For each feasible alternative ($\bar{A}$), develop an estimate of the total life-cycle cost (LCC).

6. Find the total value of each feasible alternative ($\bar{V}_{i,k}$) respective to each objective J_i: For every feasible alterative $\bar{A}_k$, add the values of each of its constituent design options respective to the same objective

$$\bar{V}_{i,k} = \sum_{n=1}^{ND_k} V_{i,n} \tag{5}$$

7. Apply DEA:
   - Formulate the DEA: The total LCC of the alterative $\bar{A}_k$ is selected as the input of the DEA, whereas the value matrix for each alterative $\bar{V}_{i,k}$ is selected as the output. It should be noted that other input variables (e.g., total project duration, energy consumption, etc.) can be used if the decision framework so requires; and
   - Find the optimum frontier: Use DEA to find the combination of alternatives that best optimize the total project budget (B) and maximize the values of all the alternatives (in achieving the objectives).
8. Sensitivity analysis: Given that all costs are estimated costs, it is prudent to conduct a sensitivity analysis (to compare all the options on the frontier) before selecting the single most optimum alternative(s).
9. Final selection: The most optimum alternative should be selected either through DEA or through subjective consideration based on the sensitivity analysis.

Implementation

The framework for QFD and DEA integration was implemented in a simple easy-to-use programmable spreadsheet (Figs. 5–7). The spreadsheet provides the following functionality:

1. Elicitation of the weights for each objective based on a pairwise AHP, comparison.
2. Generation of the HOQ based on objectives, design components, and options for each component.
3. Automatic generation of the set of feasible alternatives $\bar{A}_k$ and their associated value matrix for each objective $\bar{V}_{i,k}$.
4. Integration with an out-of-the-box DEA software (WinDEAP 1.10).
5. Capability to easily perform sensitivity analysis due to the automated nature of the process.

Case Study

The proposed approach was used to optimize the design of a smart laboratory at the University of Toronto. The project involved the creation of a new research facility: The Center for Information Systems in Infrastructure and Construction (i2c). The center encompasses a state-of-the-art computer lab, board room, and lab for smart systems. The facility is equipped with various sensors and actuators, and houses a green bio-wall that acts as a miniature ecosystem. The analysis procedures were as follows:

1. **FAST diagram:** The FAST diagram was developed through the help of a VA consultant. Fig. 4 shows a summary of the FAST diagram for the facility. The process involved developing basic functions through several meetings with the owner, architect, and construction manager. This was followed by an open house meeting with prospective users (graduate and undergraduate students). In this meeting, the students were introduced to the concept of VA, participated in identifying several additional functions, and assisted in the development of a preliminary FAST diagram. A set of meetings with the owner and the architect culminated in the development of the final FAST diagram. The basic function of the space is to "conduct research." The nonbasic functions shown in the diagram were used as objectives in the HOQ. These include:
   - Provide smartness: Create a responsive workspace, house smart infrastructure systems facility, and portray an image of a smart facility;
   - Attract new students;
   - Attract collaborating partners;
   - Offer aesthetics;
   - Conserve energy;
   - Maintain flexibility: Provide a multiuse space that can be easily reconfigured to accommodate various user needs; and
   - Provide a comfortable space: Offering users of the facility a comfortable and relaxing work environment.

   These functions act as the objectives that should be met by the facility.
2. **Weights:** A team composed of a representative set of potential users and the owner of the facility were involved in selecting the weights for the objectives. A scale of 1–5 was used to assess the relative importance between objectives (with 5 being extremely important). These importance values were achieved via a consensus process. Fig. 5 shows the pairwise comparison of these objectives and the resulting weights that were calculated using AHP.
3. **Option development:** Five main design components were selected by the architect for option development. They were categorized as follows:
   - External glass: The facility main façade is designed as a curved façade. The three main options for this category are: (1) Use butt-connected curved glass; (2) use small straight glass panels with aluminum frames; and (3) remove the curve from the design and use straight glass. The costs of the options were estimated at \$78,700, \$38,200, and \$34,900, respectively;
   - Internal glass: There were two options for internal glass: (1) Use retractable glass panels; and (2) use fixed glass panels with doors. The cost of each option was \$42,000 and \$18,000, respectively;
   - Lighting: The proposed two options in this category are: (1) Elaborate lighting *configuration*; and (2) a regular lighting

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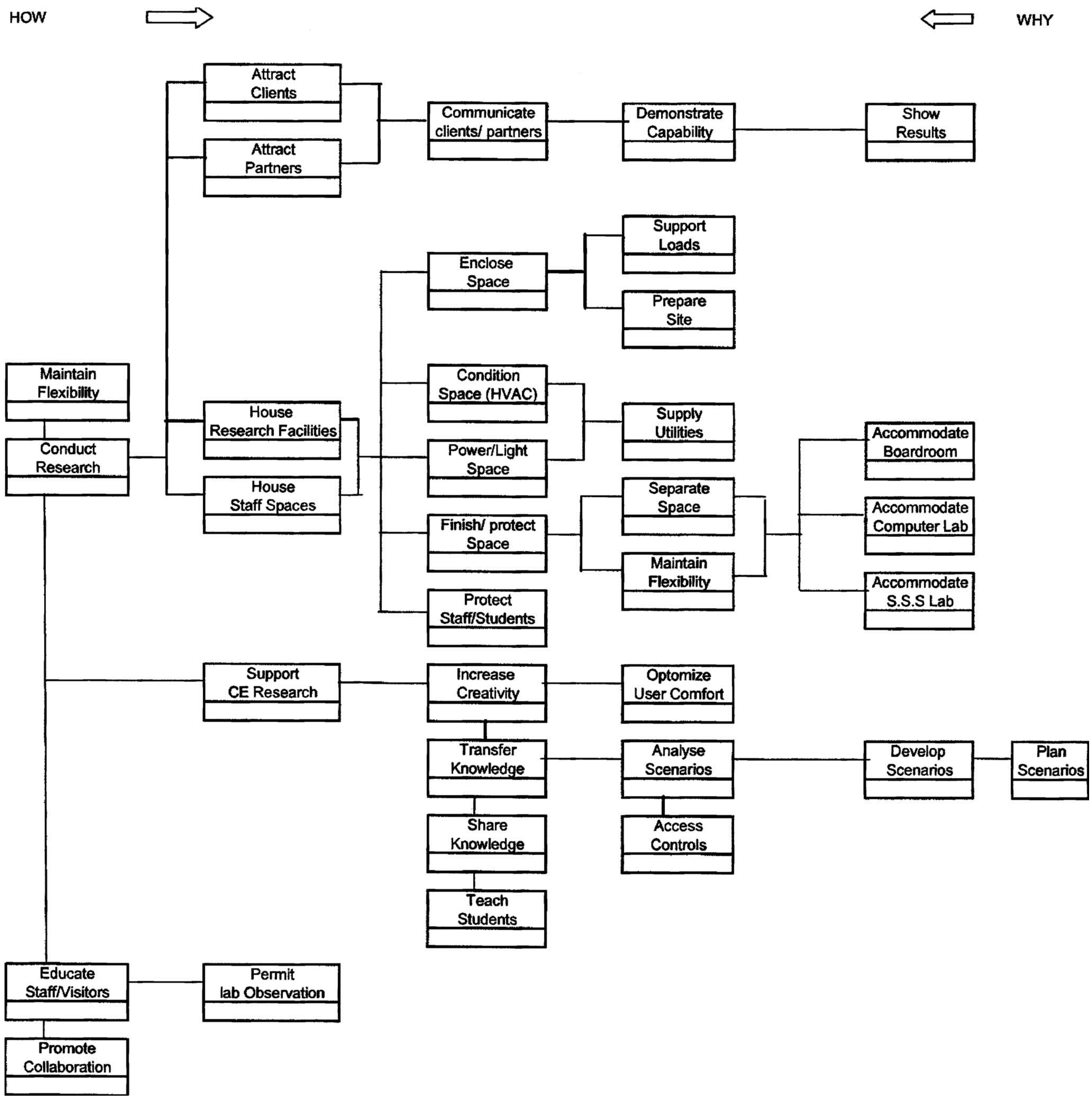

Fig. 4. FAST diagram for the i2c facility

configuration. The costs of these options were $76,750 and 65,600, respectively;

- Furniture: This category included two main options: Expensive furniture and simple furniture. The estimated costs for these two options were $15,000 and $10,500, respectively; and
- *HVAC*: This category included two main options: (1) Allowing for individual controls of HVAC systems, and (2) limited control of HVAC system. The estimated costs for these two options were $47,000 and $35,000, respectively.

4. **Populate the HOQ**: Table 1 shows the simplified HOQ. The first two columns represent the objectives and the relative weight of each objective. The remaining columns represent the relationship strength between each objective and each option ($R_{i,j}$: nonbold numbers), and the value of each alternative with respect to the objectives ($V_{i,j}$: bold numbers). For example, the option of "Individual HVAC Control" has a relationship strength of 5.4 and value of 98.3 (shown in bold face) with respect to the objective of "Provide Smartness." The bottom row shows the estimated cost for each design option. The values of each option were developed based on the average assessment of a team composed of the architect, the owner, and a set of students.
5. **Alternative generation**: Using the compatibility matrix approach, the compatibility of various design elements is assessed by the architect. Fig. 6 shows the compatibility of the 11 design elements. In this example, all possible combinations were assumed feasible, and, hence, all compatibility values are "1." Fields marked "N/A" refer to the compatibility of elements within an individual design component (and,

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	Provide Comfortable Space	Maintain Flexibility (Multiuse Space)	Conserve Energy	Offer Aesthetics	Attract Colaboration Partners	Attract New Students	Provide Smartness	Overall Weight (%)
Provide Smartness	2	3	3	2	0.5	2		18.2
Attract New Students	2	2	3	3	0.33			12.8
Attract Colaboration Partners	2	3	4	3				31.7
Offer Aesthetics	0.33	0.25	2					7.6
Conserve Energy	0.333	0.5						5.1
Maintain Flexibility (Multiuse Space)	1							11.3
Provide Comfortable Space								12.5

Fig. 5. Pairwise comparison of objectives for the i2c facility

hence, cannot simultaneously exist in an alternative). Because the design options were mutually exclusive, the available combinations of all these options were 48 alternative designs ($3\times2\times2\times2\times2$). The architect confirmed that all 48 were viable alternatives and worthy of consideration. Although this example did not demonstrate the applicability of the compatibility matrix (all values were 1), it is very common for architectural design components to be incompatible. For example, some flooring options might not be compatible with lighting or furniture options for aesthetic considerations. The compatibility matrix allows these combinations to be excluded from the feasible alternatives set before performing DEA. Fig. 7 shows design alternative numbers 27 and 28. The shaded column to the right shows values of $\bar{V}_{i,k}$. For example, alternative number 28 has a cost of \$175,510 and has a value of 43.9 with respect to the objective of energy conservation.

6. **DEA calculations**: For all 48 design alternatives a single input (cost) and seven outputs (objectives) were compiled. Together, these eight attributes constitute the attributes of a DMU that is used in DEA analysis. An input-oriented DEA with variable returns to scale was conducted on the 48 DMUs. The efficiency frontier was found to be comprised of 14 design alternatives. These alternatives have a superior measure of efficiency (output/input) compared to other alternatives in the solution space. The weighted efficiency calculated in Eq. (1) can be considered a customer requirements efficiency index (CREI). The index ranges in value from

Table 1. HOQ for the Five Main Design Elements

		Design elements										
		Exterior glass			Internal glass		Lighting		Furniture		HVAC	
Objective	Weight	Curved	Straight with framing	Remove curvature from design	Retractable	Fixed	Elaborate	Regular	Expensive	Simple	Individual control	General control
Provide smartness	18.2	0.6	0.6	0.6	0.4	0.4	4.2	0.8	0.2	0.2	5.4	0.8
		10.9	**10.9**	**10.9**	**7.3**	**7.3**	**76.4**	**14.6**	**3.6**	**3.6**	**98.3**	**14.6**
Attract students	12.8	5.0	5.4	3.8	0.8	0.4	3.2	1.2	3.0	1.2	6.6	1.2
		64.0	**69.1**	**48.6**	**10.2**	**5.1**	**41.0**	**15.4**	**38.4**	**15.4**	**84.5**	**15.4**
Attract collaboration partners	31.7	3.8	3.8	3.8	0.8	0.4	3.8	1.2	4.2	1.2	5.4	1.2
		120.5	**120.5**	**120.5**	**25.4**	**12.7**	**120.5**	**38.0**	**133.1**	**38.0**	**171.2**	**38.0**
Offer aesthetics	7.6	7.8	5.0	5.4	3.0	1.8	4.8	1.4	6.6	1.6	0.6	0.2
		59.3	**38.0**	**41.0**	**22.8**	**13.7**	**36.5**	**10.6**	**50.2**	**12.2**	**4.6**	**1.5**
Conserve energy	5.1	0.0	0.0	0.0	1.8	1.8	6.0	1.6	0.0	0.0	6.0	0.8
		0.0	**0.0**	**0.0**	**9.2**	**9.2**	**30.6**	**8.2**	**0.0**	**0.0**	**30.6**	**4.1**
Maintain flexibility	11.3	0.0	0.0	0.0	5.4	1.0	0.8	0.4	0.8	0.4	0.6	0.2
		0.0	**0.0**	**0.0**	**61.0**	**11.3**	**9.0**	**4.5**	**9.0**	**4.5**	**6.8**	**2.3**
Provide comfortable space	12.5	0.2	0.2	0.2	0.2	0.2	0.8	0.4	9.0	2.6	6.0	2.4
		2.5	**2.5**	**2.5**	**2.5**	**2.5**	**10.0**	**5.0**	**112.5**	**32.5**	**75.0**	**30.0**
Cost (\$)		38,200	34,900	78,700	42,000	18,000	76,750	65,600	15,000	10,500	47,000	35,000

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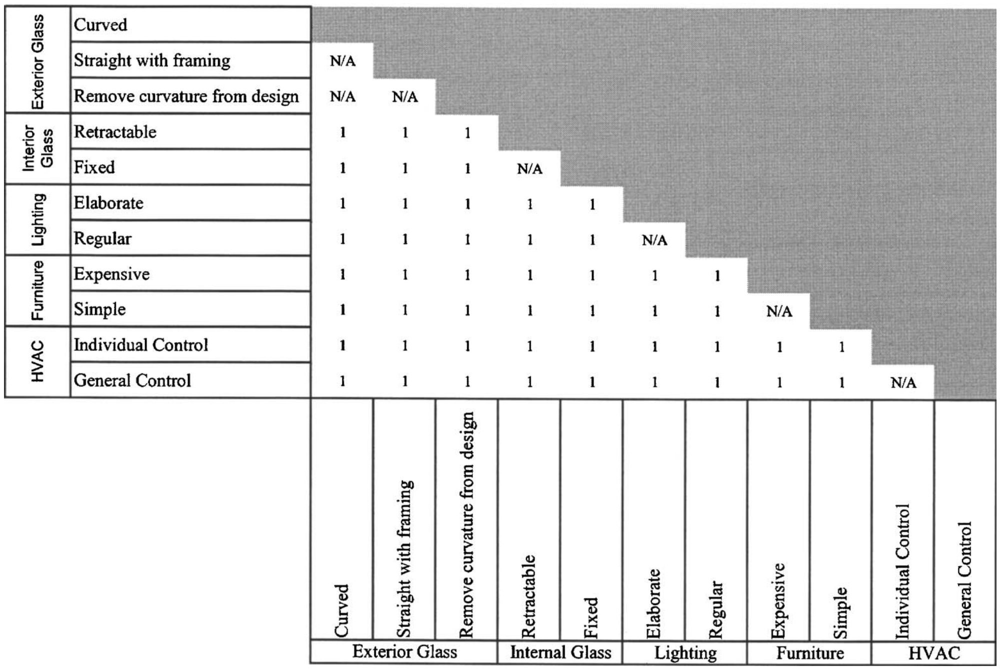
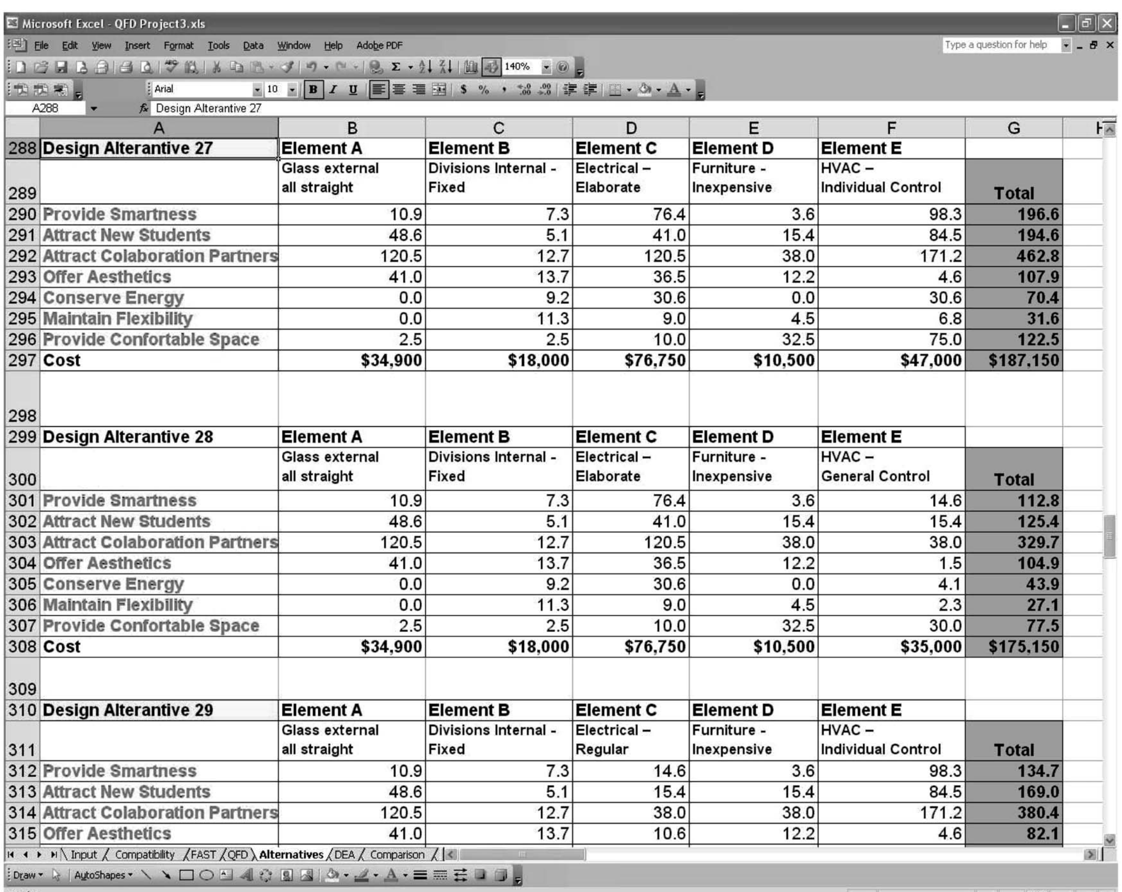
This Matrix describes the compatibility of various design options. A Value of "1" indicates that these two design elements are compatible and can be included in any single design alternative whereas a value of "0" indicates that the elements are incompatible.



		Curved	Straight with framing	Remove curvature from design	Retractable	Fixed	Elaborate	Regular	Expensive	Simple	Individual Control	General Control
Exterior Glass	Curved											
	Straight with framing	N/A										
	Remove curvature from design	N/A	N/A									
Interior Glass	Retractable	1	1	1								
	Fixed	1	1	1	N/A							
Lighting	Elaborate	1	1	1	1	1						
	Regular	1	1	1	1	1	N/A					
Furniture	Expensive	1	1	1	1	1	1	1				
	Simple	1	1	1	1	1	1	1	N/A			
HVAC	Individual Control	1	1	1	1	1	1	1	1	1		
	General Control	1	1	1	1	1	1	1	1	1	N/A	
		Exterior Glass			Internal Glass		Lighting		Furniture		HVAC	

Fig. 6. Compatibility matrix for various design elements



Microsoft Excel - QFD Project3.xls

A288 Design Alterantive 27

	A	B	C	D	E	F	G
288	Design Alterantive 27	Element A	Element B	Element C	Element D	Element E	
289		Glass external all straight	Divisions Internal - Fixed	Electrical – Elaborate	Furniture - Inexpensive	HVAC – Individual Control	Total
290	Provide Smartness	10.9	7.3	76.4	3.6	98.3	196.6
291	Attract New Students	48.6	5.1	41.0	15.4	84.5	194.6
292	Attract Colaboration Partners	120.5	12.7	120.5	38.0	171.2	462.8
293	Offer Aesthetics	41.0	13.7	36.5	12.2	4.6	107.9
294	Conserve Energy	0.0	9.2	30.6	0.0	30.6	70.4
295	Maintain Flexibility	0.0	11.3	9.0	4.5	6.8	31.6
296	Provide Confortable Space	2.5	2.5	10.0	32.5	75.0	122.5
297	Cost	$34,900	$18,000	$76,750	$10,500	$47,000	$187,150
298							
299	Design Alterantive 28	Element A	Element B	Element C	Element D	Element E	
300		Glass external all straight	Divisions Internal - Fixed	Electrical – Elaborate	Furniture - Inexpensive	HVAC – General Control	Total
301	Provide Smartness	10.9	7.3	76.4	3.6	14.6	112.8
302	Attract New Students	48.6	5.1	41.0	15.4	15.4	125.4
303	Attract Colaboration Partners	120.5	12.7	120.5	38.0	38.0	329.7
304	Offer Aesthetics	41.0	13.7	36.5	12.2	1.5	104.9
305	Conserve Energy	0.0	9.2	30.6	0.0	4.1	43.9
306	Maintain Flexibility	0.0	11.3	9.0	4.5	2.3	27.1
307	Provide Confortable Space	2.5	2.5	10.0	32.5	30.0	77.5
308	Cost	$34,900	$18,000	$76,750	$10,500	$35,000	$175,150
309							
310	Design Alterantive 29	Element A	Element B	Element C	Element D	Element E	
311		Glass external all straight	Divisions Internal - Fixed	Electrical – Regular	Furniture - Inexpensive	HVAC – Individual Control	Total
312	Provide Smartness	10.9	7.3	14.6	3.6	98.3	134.7
313	Attract New Students	48.6	5.1	15.4	15.4	84.5	169.0
314	Attract Colaboration Partners	120.5	12.7	38.0	38.0	171.2	380.4
315	Offer Aesthetics	41.0	13.7	10.6	12.2	4.6	82.1

Input / Compatibility / FAST / QFD / Alternatives / DEA / Comparison

Fig. 7. Sample alternatives

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Table 2. DEA Results of First Ten Design Alternatives

	Customer requirements/objectives (outputs)								
	Provide smartness	Attract new students	Attract collaboration partners	Offer aesthetics	Conserve energy	Maintain flexibility	Provide comfortable space	Cost	Customer requirement efficiency index
Alternative 1	196.56	238.08	570.6	173.28	70.38	85.88	202.5	218,950	1
Alternative 2	112.84	168.96	437.46	170.24	43.86	81.36	157.5	206,950	1
Alternative 3	196.56	215.04	475.5	135.28	70.38	81.36	122.5	214,450	0.991
Alternative 4	112.84	145.92	342.36	132.24	43.86	76.84	77.5	202,450	0.95
Alternative 5	134.68	212.48	488.18	147.44	47.94	81.36	197.5	207,800	1
Alternative 6	50.96	143.36	355.04	144.4	21.42	76.84	152.5	195,800	0.986
Alternative 7	134.68	189.44	393.08	109.44	47.94	76.84	117.5	203,300	0.947
Alternative 8	50.96	120.32	259.94	106.4	21.42	72.32	72.5	191,300	0.946
Alternative 9	196.56	232.96	557.92	164.16	70.38	36.16	202.5	194,950	1
Alternative 10	112.84	163.84	424.78	161.12	43.86	31.64	157.5	182,950	1

0–1.0, with an index value=1.0 indicating a superior efficiency. Table 2 shows the results for the first ten design alternatives.

7. **Sensitivity analysis**: Design alternatives with CREI=1.0 formed a short-list that was subjected to a sensitivity analysis by the decision-maker for the final selection.

The design alternatives that had a CREI=1.0 ranged in price from \$180,500–\$218,950, whereas all 48 feasible alternatives ranged in price from \$164,000–\$259,450. The results seem to indicate that very costly alternatives did not contribute much to an increase in overall attainment of the customer objectives. On the other hand, alternatives that lay on the lower-end of the cost spectrum were significant underperformers in achieving the customer requirements compared to their slightly more expensive counterparts. DEA revealed that none of the efficient alternatives (CREI=1.0) had the option of the curved exterior glass. Evidently, the superiority of this option compared to other glass options was not out-weighed by its relatively high cost. The design alternative that was implemented was that involving straight glass with framing, fixed internal glass, regular lighting, expensive furniture, and a individual HVAC control. This also happened to be the least expensive design alternative that had a CREI=1.0. The constrained budget available to the facility, coupled with the user's desire to attain the design objectives in a reasonable manner drove the facility owner to select this design alternative. One of the noteworthy limitations of the proposed approach is its inability to deal with uncertainty. This is a specific concern for cost data that is usually very preliminary during the early design stages. One approach currently under investigation by the authors is the incorporation of the probabilistic LCC in the FAST-QFD-DEA framework.

Summary

One of the most important tasks that face facility owners during the design phase is how to select an optimum mix of design options that would optimize the value of the facility under a limited budget. This paper presents an approach to integrate VA (FAST diagram), QFD, and DEA to help owners in the selection process. The integrated framework is able to: (1) Elicit customer requirements (the WHATs) through the use of FAST; (2) Relate various design options (the HOWs) to each customer requirement through the use of QFD; and (3) Provide a decision-support environment to assist in selecting the most suitable alternative (the WHY). The framework was implemented in a programmable spreadsheet environment to provide an easy user interface. The methodology was tested on a project that involved the creation of a smart workspace and graduate lab at the University of Toronto. The proposed approach can be helpful in pre-project planning activities. Through engaging owners and facility users in the development of a value function for all design options/alternatives, designers can gain insights into how to optimize the design of a facility.

Notation

The following symbols are used in this paper:

A = Set of all possible design alternatives;
$\bar{A}$ = Set of feasible design alternatives;
$CV_{i,j}$ = Compatibility value between design option i and j;
D = Number of constituent design components;
E_k = Efficiency of the current DMU_k;
E_i^k = Efficiency of DMU_i that is calculated for DMU_k maximization;
$I_{i,j}$ = Value of input attribute number i for DMU_k;
J = Set of customer objectives;
ND_i = Number of available design options for design component i;
$O_{i,j}$ = Value of output attribute number i for DMU_k;
P = Set of design options for all design components,
$R_{i,k}$ = Relationship strength between objective J_i and option P_k;
u_i = Output weight for output attribute number i;
$V_{i,k}$ = Value of option P_k respective to an objective J_i;
$\bar{V}_{i,k}$ = Value of feasible design alternative $\bar{A}_k$ respective to an objective J_i;
v_i = Input weight for input attribute number i; and
w = Set of importance weights for customer objectives.

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