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PROPOSED QUALITY FUNCTION DEPLOYMENT ENHANCEMENTS

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1 Introduction

The Quality Function Deployment (QFD) tool has been shown to have a significant positive impact on customer satisfaction, while reducing the associated design time and cost [1][2][3][4][5]. Observation of novice designers in tertiary engineering design courses identified a range of impediments to the robust transfer of QFD capabilities to the novice designers. These impediments appear to significantly limit the perceived value of QFD by the novice designers, and stymie its subsequent practical application.

The objective of this research is to propose a series of enhancements and to the traditional QFD tool to overcome the identified impediments. The influence of the proposed enhancements on QFD application by novice designers has been observed, including: the robustness of QFD application, and the perceived value of QFD. A teaching aid has been proposed to assist the transfer of QFD capabilities to novice designers by providing guidance to overcome commonly observed difficulties.

2 Background

The core intent of QFD is to quantify the relationship between design decisions and quality. These relationships are represented graphically in a form known as the House of Quality (HoQ) (Figure 1). QFD applies a series of matrices to produce quantified relationships, for example, relating customer requirements to technical requirements and then relating technical requirements to part characteristics [1]. A generic HoQ is presented in, based on material reviewed in a series of undergraduate level engineering design texts [6][7][8][9].

The initial input to the HoQ needs to be an unambiguous statement of the Customer Requirements (CRs) and their associated Importance Weighting (IW). Based on these CRs, which are often subjective, the designer defines a series of measurable Technical Requirements (TRs), and their preferred sense, i.e. to maximise (↑), minimise (↓), or target (○) a certain value. Correlations between the CRs and TRs are identified in the relationship matrix. The reviewed undergraduate level engineering design texts [6][7][8][9] apply the following correlation legend:

- A strong correlation (●) is assigned a weighting of nine;
- A moderate correlation (○) is assigned a weighting of three; and,
- A weak correlation (▲) is assigned a weighting of one.

This non-linear scaling of correlation between a relationship and the associated weighting prompts the designer to focus the allowable design effort on the CR that have the greatest influence on quality.

The Technical Importance (TI) associated with each TR is evaluated by summing the product of each importance weighting and the associated relationship weighting for each TR. For example, $TI_1 = IW_1 \bullet C_{11} + IW_2 \bullet C_{21} + \ldots + IW_n \bullet C_{n1}$ (Figure 1). Technical importance is one of the most useful outcomes of the HoQ as it identifies the most efficient means of enhancing customer satisfaction, and assists compromise between conflicting TRs.

The correlation matrix identifies correlation between the Technical Requirements (Figure 1). The reviewed design texts apply various legends to define the associated correlation between TRs, but unanimously allow five levels of correlation that range between: strong positive and strong negative. The correlation matrix outcomes are of significant importance to the designer, as they identify:

- Positive correlation, for example, in the bicycle suspension system assessed by Ullman there is a positive correlation between the allowable rider weight, and the allowable rider height [6]. Increasing one TR inherently increases the other, thereby providing an opportunity to efficiently enhance customer satisfaction.
- Negative TR correlation, for example, in the automatic iced-tea brewer assessed by Otto and Wood, there is a negative correlation between the TR associated with water temperature and housing temperature [8]. These conflicting TRs must be resolved, typically by biasing the solution toward the TR with the greatest technical importance.

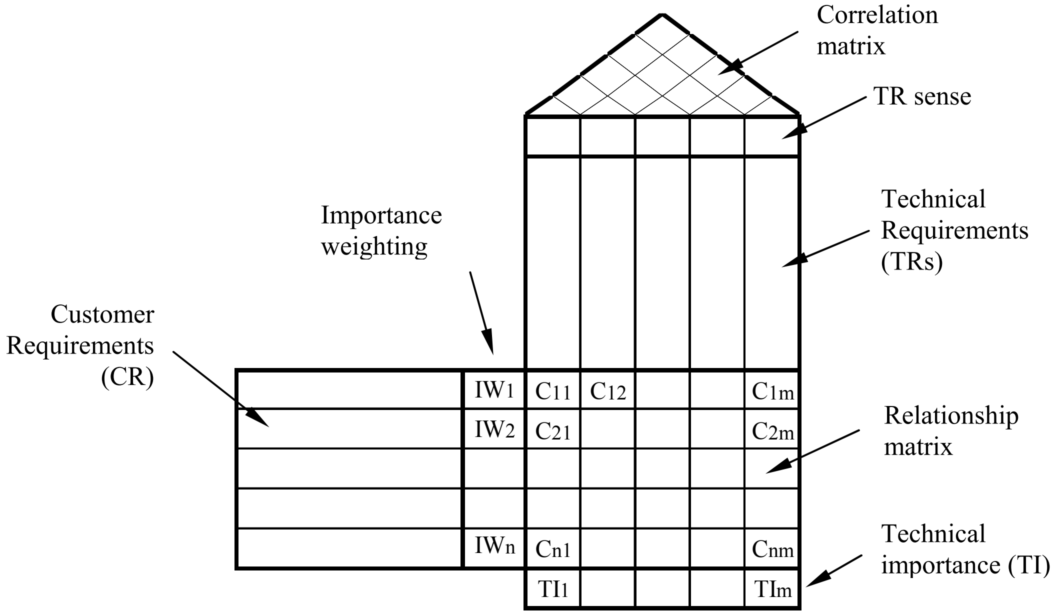

Figure 1. Generic House of Quality (HoQ) template.

3 Method

In recognition of the positive influence of QFD to the quality and efficiency of engineering design, the author has presented QFD to novice designers in tertiary engineering design courses at two Melbourne universities. The QFD syllabus is presented in conjunction with undergraduate level engineering design texts, such as [6][7][8][9]. The experiences of the novice designers with QFD were observed and evaluated during tutorial exercises, project reporting, and final examination. The QFD tasks were often completed poorly, and the novice designer's appraisal of the merit of QFD was typically negative.

The poor performance of novice designers to QFD tasks was identified at the end of the undergraduate design course, when the performance of assignment and final examination tasks was reviewed. In response to this poor performance it was decided to incorporate extended tutorial sessions in the following semester, thereby allowing active interaction between teaching staff and the novice designers as they responded to a series of QFD tasks. This strategy is labour intensive, but minimises the risk of students failing to become competent with QFD methods, and maximises the probability of identifying the basis of the limited transfer of QFD capabilities.

The novice designers were introduced to QFD and the HoQ by a series of formal lectures. The presented methods and case studies were based on a series of undergraduate level engineering design texts [6][7][8][9]. On completion of this lecture series, the novice designers were required to respond to a series of related tasks during extended tutorial sessions. During the observational study, teaching staff identified a series of impediments to the robust transfer of QFD capabilities. These impediments appear to significantly limit the perceived value of QFD, and stymie its subsequent practical application. These impediments were identified as either:

- Misunderstandings of the HoQ; or,
- Impediments inherent in the HoQ.

A series of enhancements to overcome these impediments were introduced, and are presented in the following sections.

4 Misunderstandings of the HoQ

Many of the difficulties identified in the observational study were due to misunderstandings of QFD, often associated with the HoQ structure. These misunderstandings could be overcome in future syllabus by a combination of extended presentation duration, and an increase in presentation effectiveness. As the current undergraduate engineering design course is highly time-constrained, any proposed syllabus enhancements are limited to those that increase presentation effectiveness. A novel HoQ template, and an associated expert system were developed to respond to the identified misunderstandings without extending the presentation time.

4.1 Novel HoQ template

A novel HoQ template was developed to mitigate common misunderstandings of the HoQ structure by the use of a self-explanatory nomenclature and presentation (Figure 2):

- A frequently observed misunderstanding was the difference between the Importance Weighting (IW), which identifies the importance of the Customer Requirements (CRs), and "technical importance", which identifies the importance of the Technical Requirements (TRs). This misunderstanding was overcome by applying the suffix "importance", i.e. as CR-Importance (CR-I) and TR-Importance (TR-I), respectively.
- As "relationship" and "correlation" are linguistically synonymous, there is a common misunderstanding between the intent associated with the "relationship matrix" and the "correlation matrix". This difficulty was overcome by identifying both matrices with the suffix "correlation", with an explicit prefix identifying the inputs to be correlated, i.e. CR-TR correlation and TR-TR correlation.
- Novice designers often reported that the HoQ as overwhelming and unintuitive. This difficulty was mitigated by physically separating the distinct elements of the HoQ: Customer Requirements, Technical Requirements, CR-TR correlation, TR-TR correlation and TR Importance (Figure 2).

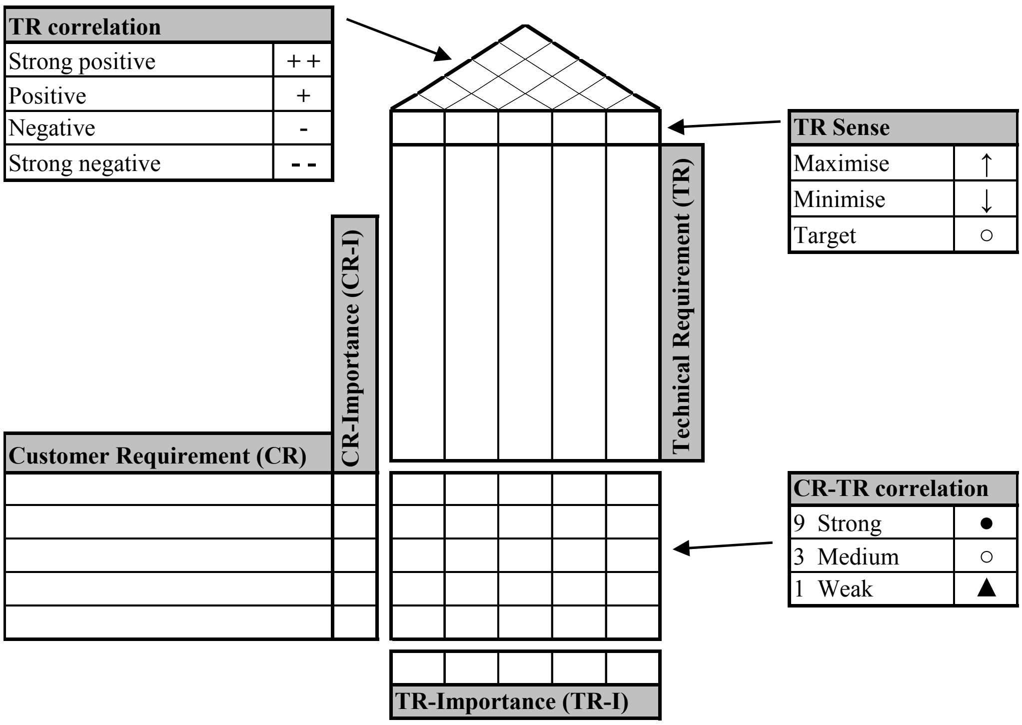

Figure 2. Modified HoQ template presented to novice designers.

4.2 HoQ expert system

In order to mitigate the misunderstandings of the HoQ, an expert system was developed that systematically defines the role of each element of the HoQ (Table 1). It is proposed that expert system will assist the robust transfer of QFD capabilities, and enhance the perceived value of QFD within the constraints of the available time-budget. For each HoQ element, the expert system identifies: the element intent, robust implementation strategies, and the important outcomes.

Table 1. Expert system presented to novice designers to assist robust HoQ development, and enhance the perceived value of the QFD process.

HoQ element	Robust implementation strategies	Important outcomes
Customer Requirements (CRs): Attributes that influence the customer's perception of product quality.	• CRs must be unambiguous e.g., "comfort" is ambiguous, "maximise comfort" is unambiguous. • CRs should be presented in the customers own words. • Excitement and Basic CRs are typically not verbalised by the customer – these must be actively identified by the design team. • Customers include all phases of the product life-cycle, including: design, production, end-use and recycling. • Group CRs according to affinities, e.g. aesthetics, ease of use, safety and production – this assists information management and CR generation. • Avoid CRs that are excessively broad, for example, "easy to use" may be more concisely represented by two CRs: "easy to clean" and "easy to operate".	• The CRs and associated Importance Weightings (IW) provide a formal definition of the needs of the customers, known as the design specification. • The design specification provides a basis for evaluating the proposed solutions.
Customer Requirement Importance (CR-I): A ranking of the relative influence of each CR to customer satisfaction.	• Choose an internally consistent ranking, e.g. scale linearly between: 1 – very minor, and 10 – non-negotiable. • The CR-I should have a tolerance that reasonably reflects the available level of certainty, e.g. using integer intervals: ranking from 1-5, the tolerance is ± 10 %; ranking from 1-10, the tolerance is ± 5 %.	• Assists in identifying the influence of each CR on quality.

CR-I (continued)	• When the level of certainty of a CR-I is greater than the chosen tolerance, the importance weighting should be defined as an appropriate range, e.g. IW $\in$ (5, 9). This range should propagate to the resulting DR-I. • Avoid excessive CR-I values. Typically the CR-I should be spread over the range of allowable values, rather than skewed toward the upper limit.	• The TR-I is a function of the CR-I, therefore the CR-I indirectly assists: compromise between conflicting DR, and prioritisation of the available design effort.
Technical Requirements (TR): Specification of parameters that measure the level of implementation of the CRs.	• TRs must be defined in measurable terms – explicitly identify the associated unit of measurement. • TRs should be orthogonal – i.e. there should be no overlap in the scope of each individual TR. • For subjective TRs, or, if no existing unit of measurement is applicable, a Customer Test (CT) may be specified. For example, appearance may be measured by the average response of a sample to the question: "Rate the appearance of this product from 0 (very poor) to 10 (excellent)". • TRs should not constrain the possible solutions – i.e. explicit reference to form should be avoided unless explicitly specified by a CR. • Identify the preferred TR sense as either: minimise (↓), maximise (↑), or target (0).	• Means of quantifying the attributes of a concept or product.

TR sense: Identifies the preferred sense of a TR.	• The TR sense may be ambiguous in certain scenarios. This ambiguity is eliminated if the proposed CR-TR legend is applied (Section 5.3).	• Allows the sense of the correlation matrix to be identified.

CR-TR correlation matrix:
 	
Rates the correlation between the CR and associated TRs.
	• Rate the magnitude and sense of the correlation (Section 5.2):
	  • Strong positive (+++)
	  • Medium positive (++)
	  • Weak positive (+)
	  • Weak negative (-)
	  • Medium negative (- -)
	  • Strong negative (- - -)
	• Focus on the strongest interactions; the interaction matrix should be between 60% and 70% blank.
		• Empty CR-TR row indicates insufficient TR to correlate with the CR.
		• Empty CR-TR column indicates either a redundant TR, or unidentified CR.

TR correlation matrix: Rates the correlation between TR.	• Identify the relationship between the TR. • Focus on the strongest correlations: The TR correlation matrix should be 60 – 70% blank.	• Identifies conflicting design requirements, i.e. negative relationship. • Identifies efficient means to providing quality, i.e. positive relationship.
Technical Requirement Importance (TR-I): A rating of the relative importance of each TR to customer satisfaction	• For each TR, sum the product of the CR and the associated CR-TR correlation magnitude. For example, $TI_1 = IW_1 \bullet C_{11} + IW_2 \bullet C_{21} + \ldots + IW_n \bullet C_{n1}$ (Figure 1).	• The TR-I quantifies the influence of TR on customer satisfaction.

5 Impediments inherent in the HoQ

Many of the difficulties identified in the observational study were due to impediments inherent in the HoQ as espoused in undergraduate level engineering design texts [6][7][8][9]. Three common impediments were identified:

- Uncertainty when a single TR correlates with multiple CRs in both a positive and negative sense;
- CR that represent constraints are not compatible with the HoQ; and,
- Uncertainty regarding the sense of a TR correlation when a TR is to “target” a nominated numeric value.

Proposed enhancements to the HoQ to overcome these impediments are presented in the following sections.

5.1 Proposed enhancements to the CR-TR correlation matrix

The CR-TR correlation matrix identifies the correlation between the Customer Requirements (CRs) and the Technical Requirements (TRs). As the correlation legend espoused in the reviewed texts allows only correlation of the positive sense (Section 2), the sense of the CR-TR correlation is embedded in the associated TR sense. Uncertainty arises when a single TR correlates with multiple CRs with both positive and negative sense. This contrasts with earlier published research, where the associated correlation legend allows the correlation sense to sense to be explicitly defined, for example [2].

As an example of this ambiguity, figure 3 shows a simplified HoQ for a “hypothetical rifle”. The designer has defined two TRs: mass and telescope magnification. Telescope magnification has no correlation with portability and has a strong positive influence on accuracy. Mass has a strong positive correlation with portability, as a lighter rifle is more portable. Therefore, the TR sense is set to minimise. Mass also has a strong correlation with accuracy, as recoil, i.e. the reaction of a firearm when discharged, is inversely proportional to mass. In this circumstance, the correlation is negative, as a lighter rifle has greater recoil and is therefore less accurate. However, there is no capability to account for this opposing sense in the common CR-TR correlation legend. It was observed in the novice designer case study (Section 3) that in response to this ambiguity, the novice designers typically maintained the initial sense assigned to mass, i.e. in this case, to minimise the mass.

The resulting TR-Importance (TR-I) for mass and telescope magnification is 90 and 45 respectively (Figure 3). This indicates that mass has a more significant influence on quality than telescope magnification. According to the espoused HoQ theory, the designer should bias the available design effort towards mass minimisation. This design strategy is flawed as, in this hypothetical scenario, the positive correlation between mass reduction and portability is countered by the negative correlation between mass reduction and accuracy, i.e. the customer dislikes the low portability of a heavy rifle, but this is offset by the increased accuracy, and vice versa. For the TR-I, and CR-TR correlations chosen for this hypothetical scenario, quality is independent of mass, but this independence cannot be explicitly integrated in the common HoQ.

To overcome the identified impediment to robust HoQ implementation, the CR-TR legend must explicitly allow correlations of both positive and negative sense. For example, the proposed CR-TR correlation legend presented in figure 4 allows the independence of customer satisfaction on mass to be accommodated. The resulting TR-I correctly identifies that for this hypothetical scenario:

- Net customer satisfaction is independent of mass; and,
- Telescope magnification has the greatest influence on customer satisfaction.

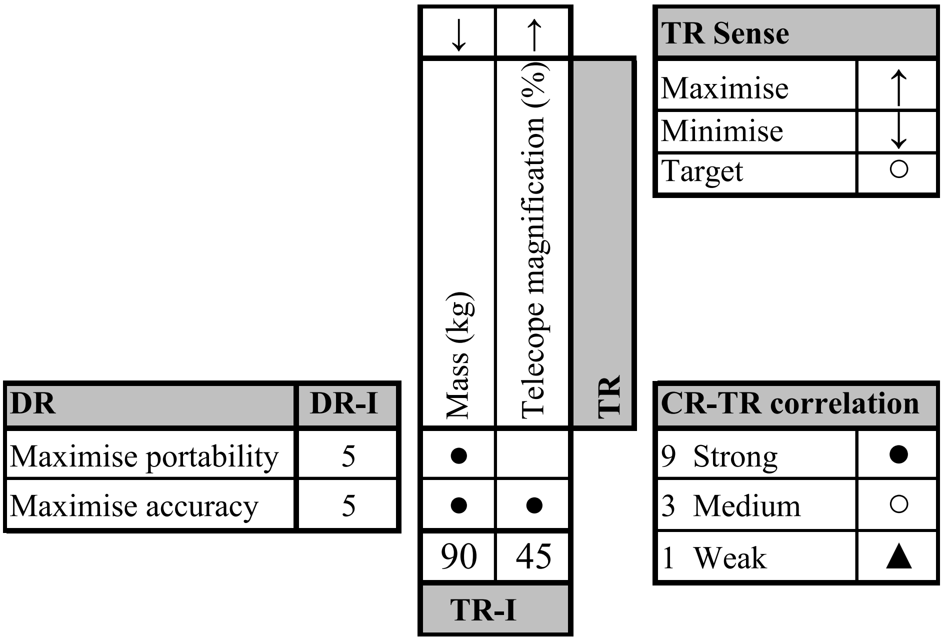

Figure 3. Simplified HoQ for a hypothetical rifle.

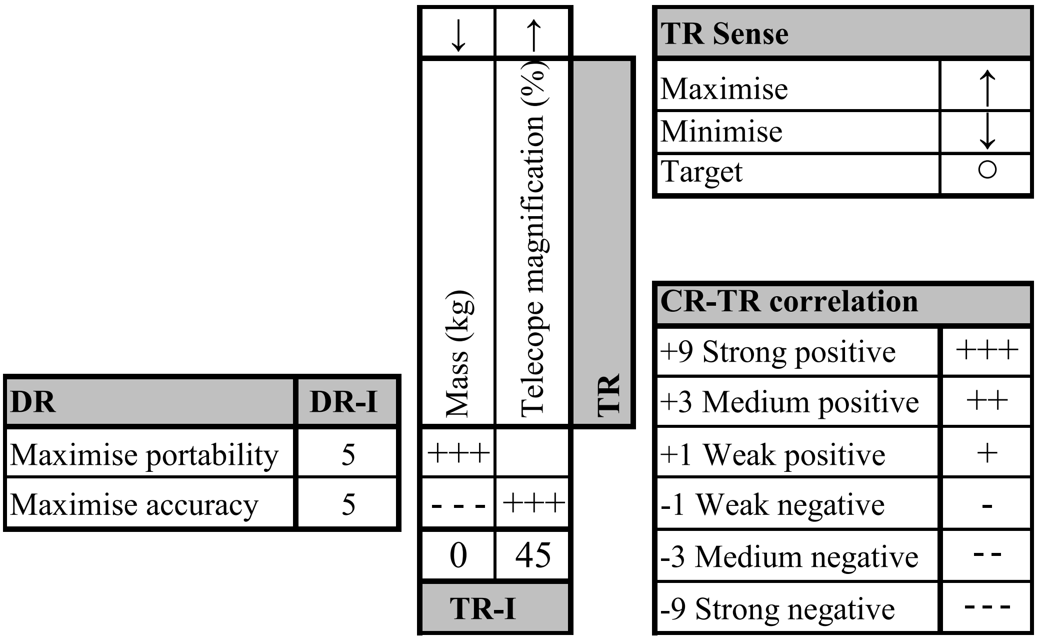

Figure 4. Simplified HoQ for a hypothetical rifle, incorporating the proposed enhancements.

5.2 Proposed enhancements to the allowable CR

Customer requirements may be categorised either as an objectives, or constraints [10]:

- An objective is a design requirement that is to be optimised, i.e. maximised or minimised. Objectives are optimised at global maxima or minima, or in the absence of such limits, objectives provide opportunity for continuous increase in customer satisfaction.
- A constraint is a design requirement limit. Constraints must be satisfied for a concept to be feasible, but, unlike objectives, do not influence performance once satisfied. When a design variable is subject to multiple constraints, the constraint that imposes the most stringent limit on the particular design variable is the "governing requirement".

The espoused HoQ only accommodates CR that are associated with objectives, i.e. define concept performance [6]. This limitation has been identified as an impediment to QFD application as:

- It is commonly misunderstood by novice designers, leading to unproductive design effort devoted to "optimising" constraints beyond those required for a concept to be feasible.
- Excluding constraints as valid CRs limits the applicability of the HoQ as an overarching design reference, i.e. an additional information repository is required to incorporate constraints.

In response to this impediment, a HoQ enhancement is proposed that allows all CR to be presented simultaneously. This enhancement incorporates a novel Differential Assessment (DA) method that acknowledges the performance differential that exists between objectives and constraints. This DA method applies measures that explicitly identify the contribution of constraints and objectives to the TR-I, i.e. the Constraint-Importance (C-I) and the Objective-Importance (O-I). The "raw" C-I and O-I values can be normalised to assist readability

When using the DA method in the concept evaluation phase, TR that correlate with a constraint, i.e. have a non-zero C-I, should be addressed first to ensure that the proposed concept is viable. Once the constraints have been satisfied, no further increase in quality can be achieved by responding to these constraints, and the available design effort should be engaged in maximising quality by optimising the TR associated with objectives, i.e. those with a non-zero O-I value.

The proposed DA method has been applied in a simplified HoQ implementation that links the CRs associated with "dynamically loaded automotive component design" with the associated TRs, i.e. the salient material properties. The HoQ includes two constraints, i.e. the component must not fail by fatigue or yield, plus a series of objectives associated with cost, recyclability and vehicle dynamics. Based on the enhanced HoQ (Figure 5), the design team is informed that:

- Based on the TR-I, fatigue strength has the greatest influence on customer satisfaction.
- The TR associated with: fatigue strength, hardness and yield strength, must be satisfied for a concept to be feasible, i.e. these TR have a non-zero C-I.
- The TR that influence concept performance, i.e. have a non-zero O-I, are: fatigue strength, density and the recyclability index. In this case the O-I indicates that the TR associated with fatigue strength and density have equal influence on performance. This outcome provides the design team with more meaningful information for design optimisation than

the TR-I alone, i.e. the TR-I identifies fatigue strength as a more important TR than density, but does not account for the differential role of fatigue strength in satisfying objectives and constraints.

The proposed enhancements allow the design team to implement all CR in a meaningful way, thereby overcoming the potential impediment that ensues when a constraints is entered in the HoQ, and allowing the HoQ to be used as a single reference document for the design process.

				Technical Requirements (TR)					
Customer Requirements (CR)	Sense	Type	Importance	Hardness	Fatigue strength	Yield strength	Density	Recyclability index	Raw material cost
No fatigue	○	C	9	3	9				
No yield	○	C	9			9			
Maximise handling	↑	O	6		9		9		
Maximise acceleration	↑	O	6		9		9		
Maximise efficiency	↑	O	7						
Maximise recyclability	↑	O	1					9	
Minimise material cost	↓	O	8		9		9		9
TR-Importance (TR-I)				27	261	81	180	9	72
Constraint Importance (C-I)				27	81	81			
Optimisation Importance (O-I)					180		180	9	72

Figure 5. HoQ for dynamically loaded automotive components.

5.3 Proposed enhancements to the TR-TR correlation matrix

The TR-TR correlation matrix identifies positive and negative correlation between Technical Requirements (Section 2). However, the sense of the TR correlation is ambiguous when one of the TRs seeks to "target" a certain value.

For example, consider, a designer involved in developing a HoQ for a hypothetical hydraulic switching device. The designer has decided to target a specific "actuation force", F, i.e. low enough such that a human operator can physically actuate the switch, i.e. $F < F_{max}$, and, simultaneously, high enough that the possibility of accidental actuation is acceptably low i.e. $F > F_{min}$. The actuation force correlates with "cylinder area", A, which is to be minimised. As the "actuation pressure", p, is constant, there is a linear correlation between F and A, i.e. $p = F/A$. The associated correlation sense is ambiguous, as it is dependant on the magnitude of A relative to the allowable range of F, i.e. $F \in (F_{max}, F_{max})$. For example, if A is chosen such that F exceeds the allowable range, i.e. $F \notin (F_{min}, F_{max})$, the associated correlation sense is positive only if further change in A tends to restore F to the allowable range. Otherwise the associated correlation is negative.

A proposed enhancement to the HoQ that will eliminate this ambiguity is to graphically identify that the TR correlation elements that are associated with a "target" value only have a correlation magnitude, with no associated correlation sense. The designer is then aware that a correlation exists but that no correlation sense can be inferred. For example, TR-TR correlation elements that are associated with a "target" can be shaded, to provide a visual cue that a correlation sense exists but is ambiguous.

6 Conclusions

The proposed QFD enhancements were implemented in the syllabus of the undergraduate level engineering design course. The observational study was repeated to allow the influence of the proposed enhancements to be assessed.

The proposed HoQ template and expert system dramatically reduced the frequency of erroneous QFD usage, and reduced the time required to present QFD by providing novice designers with tailored assistance to common difficulties. These enhancements are compatible with a time-constrained environment as they require no increase in presentation time.

The proposed enhancements to the HoQ assist in the transfer of robust QFD capabilities by minimising the probability of generating flawed outcomes. However, the enhanced HoQ methods require an increased presentation time, and are potentially incompatible with the associated time-constraints.

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