Application of House of Quality Matrix to Material Selection for Engineering Designs

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Aims: The paper developed a strategy that apply the house of quality (HOQ) matrix for selecting appropriate engineering materials for use in engineering designs. The HOQ matrix provides a means for translating customer needs into appropriate technical requirements for effective product planning.
Study Design: Development of strategy for material selection and comparison using HOQ Computer Assisted Materials Selection (HCAMS) Software.
Place and Duration of Study: Department of Mechanical Engineering, Federal University of Technology, Akure, Ondo State, Nigeria, between January 2014 and May 2015.
Methodology: The HOQ concept was used for determining and selecting the best material available that is suitable and which can adequately be used to manufacture a designed component. It was employed for screening and ranking of materials in a quantitative manner, within the strategy developed prior to selection. The strategy was then implemented through a software that was developed using Visual Basic programming language nested with Python. The software was

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developed to run on microsoft windows operating platform and to be interractive and user-friendly. It processed specific informations supplied by the users in respect of a designed product into standard requirements useful in quantitatively determining the materials that are best fitted for the manufacture of the product.

Results: Recommendation of materials best suited for the manufacturing of the designed product was provided by the material selector software developed. The software was validated and evaluated using practical examples from past engineering design work. Also, a comparison of the time it takes to finish the process of material selection using manual approach to the one when HCAMS is used revealed that the software is two hundred and three times faster.

Conclusion: Materials recommendations for design by the software in respect of the case studies are the same with the ones recommended from manually conducted material selection exercise using the developed strategy.

1. INTRODUCTION

Material selection involves seeking the best match between the property-profiles of the materials and that required by the design. Engineering materials play a vital role in modern technologies and manufacturing processess. They are important in everyday life because of their versatile structural and physical properties and the selection of the engineering materials is dependent on their structural and physical properties [1]. It is of necessity therefore that the designer of any product get involved with material selection because of the huge number of issues to consider in selecting the best material for a particular design.

The choice of material however has implications throughout the life-cycle of a product, influencing many aspects of economic and environmental performance. In other words, different challenges on material are needed to be dealt with during material selection if the product is to be commercially successful and competitive in the market [1]. Furthermore, material engineering decisions have impacts on the consumption of raw materials and energy, on the contamination of our water and atmosphere, and on the ability of the consumer to recycle or dispose off spent products [2]. Selecting the optimum combination of material and process can therefore not be performed at one certain stage in the history of a project, it should gradually evolve during the different stages of product development. It is imperative to get this selection right the first time by selecting the optimal combination for the design. This would have enormous impact and benefits to any engineering-based business. Such benefits however include lower product costs, faster time-to-market, and a reduction in the number of in-service failures as well as significant advantages in respect of product competition [3].

As the world advance in age, there is a continuous increase in the amount of materials available for engineering application. To select the best material suitable for one process or product as the case may be, there are a vast considerations to look at. This poses a complex problem for the engineer. Selection of materials and manufacturing processes for industrial applications is a long-standing, complex decision-making problem with potential impact on the entire life cycle of a product including manufacturing, distribution, consumer use, recycling, and disposal [4]. However, no engineer can expect to know more than a small subset of this ever-growing body of information on engineering materials.

This implies that a technique needs be designed to translate design requirements into quantitative requirements for decision making on material selection for manufacturing of product from engineering designs. Such technique should be able to handle large data available on engineering materials during material selection. Therefore, the house of quality which is a kind of conceptual map that provides the means for inter-functional planning and communications [5] was employed for ranking of materials towards selecting any particular one for engineering design.

Many literatures utilized different approaches in their pursuit of the best optimum material that can do a specified job effectively because of the very many engineering materials available. In

designing a cassava milling machine, Nwaigwe et al. [6] selected the materials without any vivid analysis. The material selection which was done by mere considering previously utilized materials for similar purpose showed that it is technically unacceptable. To select materials in the design of a medium scale ginger pulveriser, Aderemi et al. [7] also used a grading system that was not considered as a good representative of a technically sound material selection approach. This method which involves deciding material that is good or bad without any mathematical approach or property comparisom is subjective and could not be adequate for the selection of materials for product design. In designing a small-scale manually operated hydraulic oil press, the selection of materials performed by Reddy and Bohle [8] were mainly based on the previously utilized materials. In designing a multi-application seed oil expeller, selection of materials performed by Aviara et al. [9] were based on stress-strain analysis of each component. Generally, it could be inferred that there is lack in dedicated tool/method for material selection towards product development.

Hence, this paper was aimed at developing a strategy based on house of quality matrix that would facilitate adequate selection of engineering materials for design purpose. The House of quality matrix was employed for screening and ranking of materials in a quantitative manner within the strategy being developed, prior to material selection.

2. MATERIALS AND METHODS

2.1 The Method of Material Selection

The material selection process was designed to proceed from translation of design requirements into a set of material specification to a screening stage wherein the materials that fail design constraints are screened out. Afterwards, the materials that sailed through screening were then ranked in respect of their ability to meet the design objectives. This is referred to as the ranking stage of the approach. It is however worthy of note that while screening eliminates materials that can't do the job, ranking finds the material that does the job best.

The screening and the ranking stages pose a big challenge and the estimation necessary at these stages is complex since they involve several technicalities required to be considered for precise selection of materials. In this paper,

some factors were considered in screening and ranking materials. The first of such factors is the amount of engineering materials available around the world. The next factor is the number of constraints that have an effect on the type of materials to be used. Another factor is that of cost of raw material and associated cost of material processing as well as the mechanism usable in incorporating cost decisions in material selection.

2.2 The HOQ Matrix and Its Application to Material Selection

The matrix is called House of Quality due to a roof-like structure in its top. The house is divided into six rooms namely (1) The voice of Customer (VOC), (2) Design Requirements, (3) Relations Matrix, (4) Benchmarking, (5) Importance level and (6) Correlation matrix (Fig. 1).
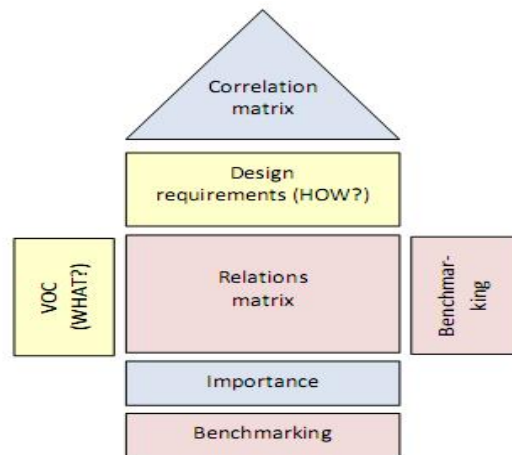
Fig. 1. Structure of house of quality
(Source: Bernal et al., 2009 [10])

The house of quality matrix concept was used in determining the best material available that is suitable to manufacture the desired product. The HOQ matrix was introduced at the screening and ranking stage of the material selection process. Hence, two HOQ matrix Tables were used. To facilitate selection of material from the properties of the available material, the first HOQ matrix was employed and adjusted to determine which material properties are important in the pursue of the design. This forms the first stage of the developed strategy wherein the HOQ matrix table was assembled and executed to determine the material properties that are important to satisfy the voice of customer towards the production of the required product. The result of

the HOQ matrix is a list consisting of five important properties from all properties of material considered. In order to achieve this result, only 4 rooms on the HOQ Table are utilized as shown in Fig. 2.

Fig. 2. Structure of HOQ matrix as applied in the developed strategy

The first room of the HOQ matrix used is the voice of customer (VOC). Here, a set of customer requirement (i.e design constraints) which are expected to be met by the design would be provided by the designer after appropriately carrying out the activities at the requirements analysis stage of the design process.
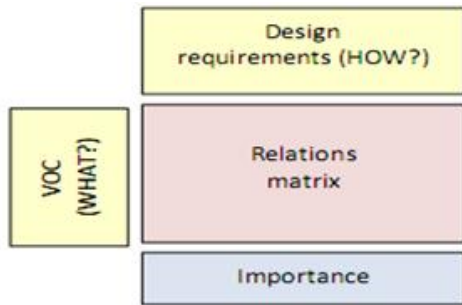
The second room used is the design requirement. In this room, the various material properties that are important to the design are considered. The material properties are provided in groups. A single design may require one or all of the properties within a group. The purpose of this is to determine which properties is allowed to exist at the design requirement section.

The third room of the HOQ as used in this study (Fig. 2) is the relations matrix. The matrix requires quantitative values that represent the relationships between elements in the first room (i.e the design constraints) and the second room (material properties). The values are taken between 0 and 5 where 5 represents very high dependence, 4 represents high dependence, 3 represents average dependence, 2 represents low dependence, 1 represents very low dependence while 0 represents no dependence.

The fourth room is the importance level. This is calculated as the sum of the product of the value of the rank given to each design constraints criteria obtained from VOC and the values given to the relationships between each design constraint and material property (design requirements). The resulting values (i.e. the quantitative values obtained in the importance level room) are used to select and rank the material properties important to the design.

The top five material properties are taken, and then translated to become the customer requirement/design constraints for the second HOQ table while all the engineering materials available (known) is taken as the design requirement and used to populate the second room for this Table. The result of the second HOQ tables would be the top five materials that can perform the job required. For the second HOQ table, the two other rooms (i.e. relations matrix and importance level) utilized in the first HOQ table is also used.

For the second HOQ Table, Renard value of preferred number series was used in setting a value for the importance (i.e. relations matrix) between the required material properties and the actual material properties of the available materials being considered. The Renard number designated as R5, R10, R20, R40 or R80 is a set of preferred numbers wherein the interval from 1 to 10 is divided into 5, 10, 20, 40 or 80 steps respectively. The factor between two consecutive numbers in a Renard series is constant, namely the 5th, 10th, 20th, 40th or 80th root of 10, which leads to a geometric sequence.

However, when a finer grade is needed (as in the case of this study), the R20, R40 and R80 series can be applied. Hence the first 6 values of the R80 preferred number series (rounded) is employed to categorize and apportion relation matrix between material property recommended for selection and the available materials in respect of the value of the material property that is required for the design. These R80 values are 1, 1.03, 1.06, 1.09, 1.12 and 1.15. Therefore, the relations matrix between each material property being used for selection purpose and the available materials is populated using the following relationships when the value of a material property of the materials to be selected is to be greater than or equal to the actual value of the material property required for the design.

$a = x \leq 1.03a$ The relationship is taken as 5
$1.03a < x \leq 1.06a$ The relationship is taken as 4
$1.06a < x \leq 1.09a$ The relationship is taken as 3
$1.09a < x \leq 1.12a$ The relationship is taken as 2
$1.12a < x \leq 1.15a$ The relationship is taken as 1
$x > 1.15a$ The relationship is taken as 0
$x < a$ The relationship is taken as -1

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             ╱  INPUT DESIGN CONSTRAINT AND           ╲
            ╱   RANK THEM                              ╱
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          ╱   SELECT AS INPUT, MATERIAL PROPERTY       ╲
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        │  GENERATE THE FIRST HOQ TABLE HAVING THE   │
        │  CUSTOMERS NEED AS THE CONSTRAINTS (VOC)   │
        │  AND MATERIAL PROPERTIES AS THE DESIGN     │
        │  REQUIREMENTS.                             │
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        ╱  INPUT THE RELATIONSHIP (I.E. RELATION     ╲
       ╱   MATRIX) BETWEEN THE CONSTRAINTS AND       ╱
      ╲    THE MATERIAL PROPERTIES                   ╱
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        ┌───────────────────────────────────────────┐
        │  CALCULATE THE IMPORTANCE LEVEL OF         │
        │  MATERIAL PROPERTIES AND RANK THEM         │
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        ┌───────────────────────────────────────────┐
        │  RECOMMEND THE FIVE MOST RELEVANT MATERIAL │
        │  PROPERTIES TO BE USED FOR SELECTION PURPOSE│
        └──────────────────┬────────────────────────┘
                           ↓
      ╱─────────────────────────────────────────────╲
     ╱  INPUT THE QUANTITATIVE VALUES REQUIRED BY THE ╲
    ╱   DESIGN IN RESPECT OF THE MATERIAL PROPERTIES  ╱
   ╲    RECOMMENDED FOR SELECTION PURPOSE            ╱
    ╲─────────────────────┬─────────────────────────╱
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      ┌─────────────────────────────────────────────┐
      │  GENERATE THE SECOND HOQ TABLE HAVING THE    │
      │  MATERIAL PROPERTIES AS THE DESIGN CONSTRAINT│
      │  (VOC) AND THE MATERIALS AVAILABLE AS THE    │
      │  DESIGN REQUIREMENTS                         │
      └──────────────────┬──────────────────────────┘
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    ┌───────────────────────────────────────────────┐
    │  DETERMINE THE RELATIONSHIP (RELATIONS MATRIX) │
    │  BETWEEN THE MATERIAL PROPERTIES AND THE       │
    │  AVAILABLE MATERIALS                           │
    └──────────────────┬────────────────────────────┘
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      ┌─────────────────────────────────────────────┐
      │  CALCULATE THE IMPORTANCE LEVEL OF THE       │
      │  AVAILABLE MATERIALS AND RANK THEM           │
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    │  RECOMMEND NOT MORE THAN FIVE MATERIALS FOR    │
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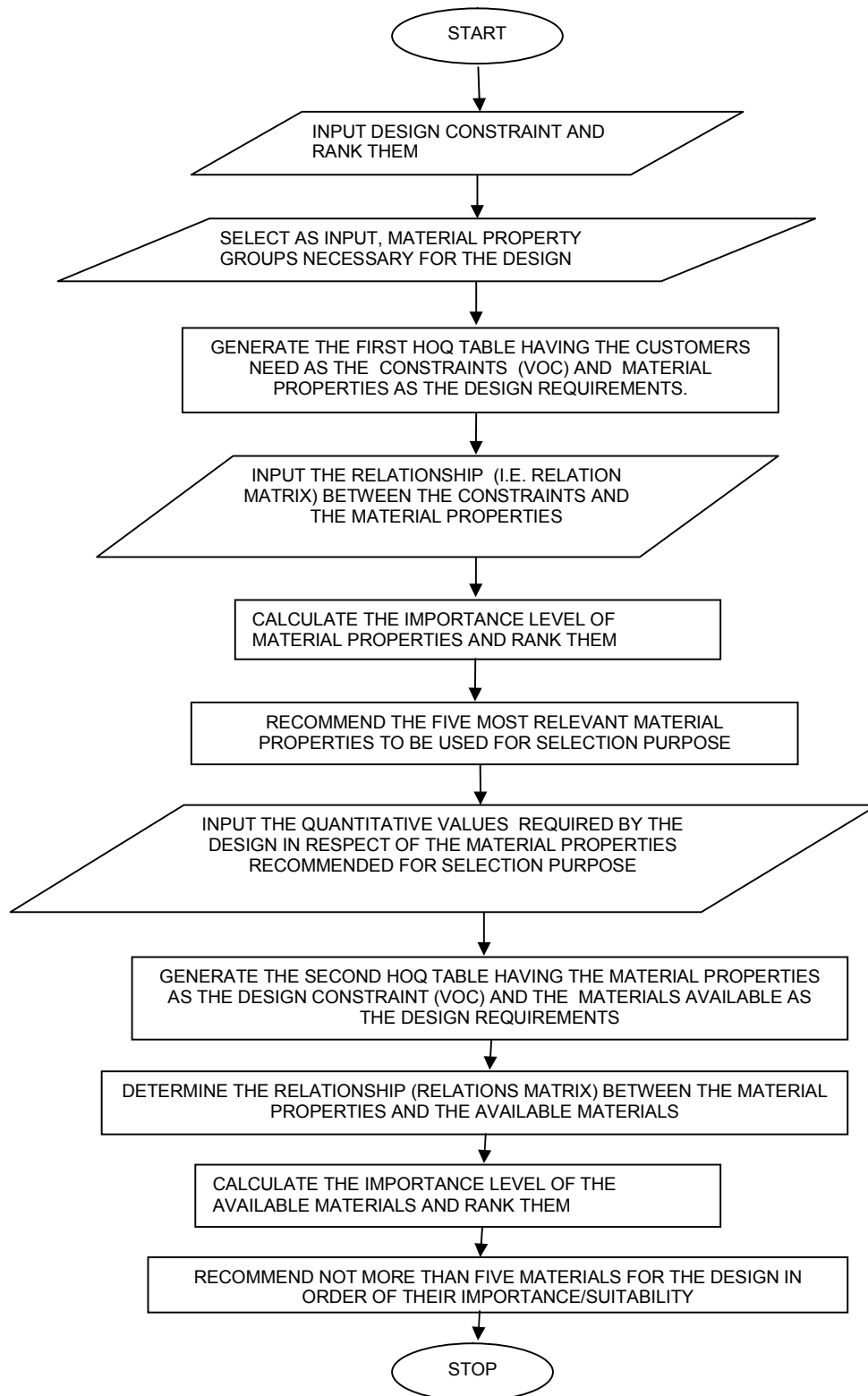
Fig. 3. Flowchart of material selector software

Also, the relation matrix room of the HOQ matrix can be populated using the following relationships when the value of a material property of the materials to be selected is to be less than or equal to the actual value of the material property required for the design.

a =x ≥ 0.97a   The relationship is taken as 5
0.97a>x≥0.94a The relationship is taken as 4
0.94a>x≥0.91a The relationship is taken as 3
0.91a>x ≥0.88a The relationship is taken as 2
0.88a>x≥0.85   The relationship is taken as 1
x < 0.85a   The relationship is taken as 0
x> a   The relationship is taken as -1

where,

"x"is the quantitative value of a particular property of a material available for selection and "a" is the value of the property of material required for the design.

As documented herein, the values of the relation matrix are assigned to be between -1 and 5 where 5 represents very high closeness of values, 4 represents high closeness of values, 3 represents average closeness of values, 2 represents low closeness of values, 1 represents very low closeness of values, 0 represents no closeness and -1 represents an undesirable relation situation where the quantitative value of a particular property of a material available for selection (x) is negative in respect of the selection inequality requirement and the value of the property of a material required for the design (a). The -1 set as the relation matrix was used to filter the material being selected for recommendation, such that, any material that has the value of -1 set for the relation matrix in respect of any of the material properties being used in the second HOQ Table, based on the comparison set up, will not be considered or selected as one of the materials to be recommended irrespective of the value of its importance calculated.

The preferred number was employed and implemented to arrive at a decision on how close the quantitative value of the property of a material is to the required value so that an appropriate value can be assigned to the relations matrix in respect of the actual value of the property of material and the required value. The flowchart used to implement the material selector software is as presented in Fig. 3. The flowchart explains the various decisions taken in the material selection.

3. RESULTS AND DISCUSSION

3.1 The HOQ Computer Assisted Materials Selection (HCAMS) Software

Having developed an appropriate strategy for the selection of materials for engineering design, the flowchart, Fig. 3 was implemented in a software called material selector using visual basic 6.0 programming language nested with python. The interface was designed with HTML 5.0. The .exe file is about 50 MB of software which requires a little above 120 MB data space in a computer before it can be installed. The software can run on all microsoft windows operating platform. It is highly interactive and user-friendly.

Several design case studies (twenty-two of them) have been employed and used to test and validate the developed strategy and software. However, for the purpose of this paper only two are presented. The first case study is used to facilitate the description of the function of the developed software in line with the selection strategy. Also, it was used to depict the validation of the software. Only the design information required for material selection and the materials recommended by the software to the designer are produced on the second case study.

The first case study which was used to validate the software is centered on the selection of material for a column section. It has the following constraints:

a) The material is to carry a 50 kN force;
b) The material should be of light weight of 40 g or below; and
c) The material may be transparent

The material properties recommended for selection in respect of the case study are the young modulus, tensile strength, density and transparent. The calculation of these important material properties was done manually and the actual material selections from the software are based on the values obtained.

3.2 The Software Description

Presented in Figs 4-8 are pictorial views of some of the user interfaces of the software and the results obtained from it in a bid to solve the first case study. Fig. 4 shows the project launch

screen where a new session can be opened or an existing session can be opened.

This screen permits the user to start either a new session or load a previous session of material selection project. Fig. 5 shows a graphical user interface (GUI) on which provision is made to enter the design constraint and rank them in the order of importance relative to one other. After entering the constraints and their ranks as shown in Fig. 5 and after clicking the confirm button, the software go to the next step shown in Fig. 6. Here, the user is allowed to select the group of properties that are related to the design in question. For example, the case study used would require, general, mechanical and optical properties. Hence, they were selected as shown in the Figure and this action would populate the selected properties of material as those factors in respect of which the engineering materials in the database would be screened out and narrowed down.

Table 1 shows the first HOQ Table generated after the users of HCAMS proceed from Fig. 6. It contains columns for the design constraints, rank and material properties. After completing the table by inputting the necessary rank and the relationship between the material properties and the constraints (i.e. the relation matrix), the completed HOQ Table is saved and then the user proceed to generates the top five material properties, as must have been recommended, and discards the remaining.

Fig. 7 depicts the GUI showing the most relevant material properties that was selected and recommended for selection purpose at the end of the analysis done on the first HOQ. This user interface also allows the user to input the desired values for each of the material properties according to the design requirement and specification, the material properties having being ranked, in respect of their relevant to the design, from previous operations.

Fig. 4. Project launch graphical user interface (GUI)

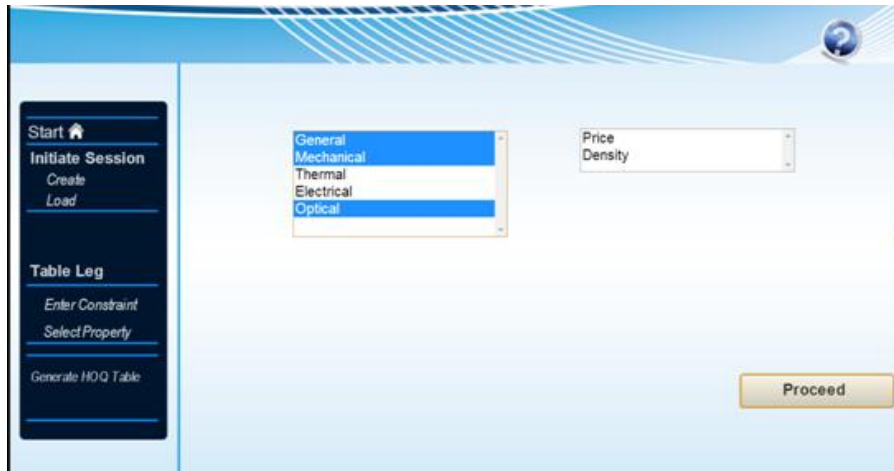**Fig. 5. Completed constraint input GUI**

Fig. 6. Group property selector GUI

Fig. 7. Completed material properties recommendation GUI

The software processes the value entered for each material property, determines the relations matrix between each material property and the available materials, calculate the importance level of each materials and recommend the best materials that are good for the design. The material properties generated for the case study considered to validate the software in this study are the young modulus, tensile strength, density and transparent as shown in Fig. 7.

Manual analysis and computation was also done, following the developed strategy, to select the appropriate materials for the first case study. The summary of the result obtained from manual computation and that obtained from the software in respect of the material properties recommended to be used for material selection using the first case study is presented in Table 2. Also, a comparison of materials recommended

for the design after analysis of the second HOQ Table is as presented in Table 3.

Tables 2 and 3 show that the results generated from manual analysis and computation exercise, using the developed strategy, are in agreement with the ones generated by the developed software (HCAMS) thereby validating the software. Also, a comparison of the time it takes to finish the process of material selection using manual approach to the one when HCAMS is used revealed that the software is ninety percent faster. The second HOQ Table generated before the final recommendation of materials is as presented in Table 4, which provide a recommendation of the materials best suited for the design. The recommendation of best materials (in ranking order with scores) suited for the design in respect of the first case study of a column section is as presented in Fig. 8.

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Table 1. The first HOQ table generated

S/N	Constraints	Rank	General			Mechanical									
			Price	Density	Bulk Modulus	Shear Modulus	Young's Modulus	Compressive Strength	Tensile Strength	Hardness	Elongation	Fracture Toughness	Loss Coefficient	Transparency
1	Carry a 50 KN force	4					4		4					
2	A light weight of 40g or below	3		4										
3	The material may be transparent	1												4
	Importance level			12			16		16					4

The first HOQ table generated

Fig. 8. Material recommendation GUI for the first case study

Table 2. Comparison of material properties recommended for material selection after analysis of the first HOQ Table in order of importance

S/N	Material properties recommended from manual computation	Material properties recommended by the software (HCAMS)
1	Young's modulus	Young's modulus
2	Tensile strength	Tensile strength
3	Density	Density
4	Transparency	Transparency

Material Properties Recommended by Manual Computation and Software

Table 3. Comparison of material recommended for the design after analysis of the second HOQ table

S/N	Material Recommendation from Manual Computation and Selection Exercise	Material Recommendation by the Software (HCAMS)
1	Fibreboard, medium hard, parallel to board	Fibreboard, medium hard, parallel to board
2	Antimony metal, commercial purity, regulus	ANTIMONY metal, commercial purity, regulus
3	High density wood (Transverse) (0.85 – 1.43)	High density wood (Transverse) (0.85 – 1.43)
4	Alkali barium glass	Alkali barium glass
5	Aluminoborosilicate – G20	Aluminoborosilicate – G20

Materials Recommended for the Design through Manual Computation and Software

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Fig. 9. Material recommendation GUI (as obtained for the second case study)

Table 4. The second HOQ table as generated for the first case study

S/n	Material Properties	Values	Rank	Fibreboard, medium hard, parallel to board	Antimony metal, Commercial Purity, Regulus	High Density Wood (Transverse) (0.85 –1.43)	Alkali Barium Glass	Aluminoborosilicate – G20	Soda lime - 0070	Borosilicate – KG33	Potash Soda Zinc	Soda Borosilicate	Borosilicate - 7740
												Materials	
1	Young's modulus	1.9998	5	0	0	0	0	0	0	0	0	0	0
2	Tensile Strength	11.43	5	4	4	4	0	0	0	0	0	0	0
3	Density	61	3	0	0	0	0	0	0	0	0	0	0
4	Transparent	0	2	0	0	0	5	5	5	5	5	5	5
	Importance Level			20	20	20	10	10	10	10	10	10	10

The second HOQ table as generated for the first case study

The second case study involves material selection for the design of a multi-application seed oil expeller. It has the following constraints:

a) The material is to carry a 25 N force;
b) The design should be for light weight automobile of 50 g or below;
c) The material may be opaque and
d) The material has hardness of 165

Following the same process as for the first case study, a recommendation of best materials (in ranking order with scores) suited for the required design in respect of the second case study as obtained from HCAMS is presented in Fig. 9 above.

This material recommendation is also in agreement with the one done manually in line with the developed strategy. The designer can

then select any of these materials depending on the local availability of such materials in the market.

4. CONCLUSION

The house of quality matrix was introduced and used in this study to facilitate material selection decision for mechanical engineering designs. This involves developing a strategy that utilizes HOQ for screening and ranking engineering materials towards adequately selecting them for engineering design. The strategy was implemented through the development and use of material selector software. The developed strategy was used, as implemented in the material selector software, in determining the best material available in the database that can adequately be used to manufacture the required design.

The recommendation of appropriate engineering materials suited for a particular design was made easy by the material selector software developed which is highly interactive and user-friendly. The software generates the first HOQ Table which examines the relationships between the material properties that are most important in the production of the required product and the design constraints so that the five top most material properties in term of relevance are recommended and translated to become the customer requirement for the second HOQ table. The results of the second HOQ Table are the top five materials that can perform better in respect of the engineering design being considered and the available engineering materials.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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