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Application of Quality Function Deployment And Axiomatic Design For Design Choice of Intercity Bus Seats

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Abstract — *Competition between companies is increasing due to a rapidly developing global market. Companies that want to be a leading competitor have embarked on new quests and begun to strengthen their R&D activities. Currently, customer satisfaction has a significant impact on the work of designers. A company that satisfies customer requests is always one step ahead of its competitors. The purpose of this paper is to select a suitable design for an intercity bus seat that meets the highest level of customer requests. First, the quality function deployment (QFD) methodology is applied to consider the "voice of the customers," and the expected features of the seat are determined. Then, an axiomatic design (AD) is used, and the seat that meets the highest number of customer requests among the three designed seat alternatives is obtained. As a result, a roadmap for achieving the best design that satisfies the end user's requests is presented.*

Keywords — *axiomatic design, design for six sigma, house of quality, intercity bus seats, quality function deployment*

I. INTRODUCTION

The design process involves complex decision-making. Decision-makers must frequently analyze a combination of criteria. Each alternative design possesses different properties, technical capacities, and costs. Considering that multiple decision-makers evaluate more than one criterion, the difficulty of rendering an optimal decision that is accepted by all decision-makers is distinct.

Design methods that have been developed by scientists provide ease in terms of time and effort via an explanation of the design method that should be followed. To determine which method should be employed in each step, the designer must properly implement this method.

In literature, axiomatic design (AD) applications can be found in different areas [1]. [2] proposed an axiomatic design approach for hybrid manufacturing systems. In another research, [3] studied small and medium-sized enterprises to design flexible and changeable manufacturing systems. In aerospace engineering, the axiomatic design methodology is used to map the design process of a reflective multilayer high-temperature insulator [4]. In another area, [5] conducted research to apply a fuzzy axiomatic design approach for selecting the design alternatives of an overflow valve. In the automotive sector, [6] developed interchangeable production units. They showed that complexity causes high investment costs. [7] presented a kinematic design methodology of suspension systems. They compared McPherson strut, double wishbone, and multilink and found that multilink's functional requirements (FRs) were decoupled and could be minimized. In robotic systems, [8] used axiomatic design principles for robot arm selection. They concluded that axiomatic design methodology is better than the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. Axiomatic design is also used for the optimization of patient flows in hospitals [9].

By implementing quality function deployment (QFD), an analysis of the relationship between customer requirements and technical requirements was performed in this study. Thus, the priority design criteria were provided at the initial stages of the design.

II. MATERIALS AND METHODS

In this section, relevant tools that are used for the application are introduced for completeness. First, the quality function deployment and then the axiomatic design is given in brief.

A. Quality Function Deployment (QFD)

QFD, which is utilized in the design of new products or the development of current products to reflect the customer requests and requirements for a product, is a quality improvement method [10]. QFD has the following objectives:

- To convert customer requirements to the technical characteristics of a company,
- To increase horizontal communication by creating a communication environment for different functions of the same products,
- To prioritize improvements for a product,
- To determine target innovations,

- To provide the opportunity for comparison with competitors and competing products,
- To identify areas of target cost reduction [10].

With this method, customer requests and requirements are prioritized according to the customer and are related to the product specifications. Thus, when the designer has to choose between the demand and the needs of the customers due to technical or aesthetic aspects of the product design, the designer analyses this sequence and designs the product according to this sequence. As a result, time loss is prevented, and a product is designed and fabricated according to the most requested properties [11].

Akao suggested quality function deployment theory in 1966 and published it in 1967 [12]. In 1972, Akao systematically explained this approach in his paper "New Product Development and Quality Assurance – Quality Deployment System," which was published in the journal "Standardization and Quality Control"; it combined the concept and experiences of previous publications. Akao's approach remained insufficient for the creation of design quality. This inadequacy was resolved in 1972 by quality tables created by Dr. Mizuno and Dr. Furukawa in the Kobe shipyard of the Mitsubishi Heavy Industries. These tables (customer requirements) illustrate the systematization of the actual quality based on the functions and the relationship between the quality characteristics and these functions [13, 14]. QFD is a process that consists of four phases [15]:

- Planning: The planning step involves the identification of customers.
- Collecting the "Voice of the Customer": In this stage, the customers' requests are collected. The most commonly used method is a survey. After determining the voice of the customer, their priorities need to be identified. In the design phase, two customer requirements with equivalent costs are prioritized by weight.
- The creation of quality house: The quality house is a set of matrices that are used to associate the customer requirements with the quality characteristics that are specified to satisfy the criteria, to compare the quality characteristics based on objective measures, and to determine the correlations [16]. The quality house is obtained using four different types of information. This information consists of answers to the following questions:
- What is essential to the customers?
- How should factors that are important to the customers be provided?
- Is there a relationship between "what" and "how"? If so, what is their power?
- How many "how" factors should be used to satisfy the customer?

The steps in the creation of a quality house are as follows:

(1) Determination of customer requirements and degree of importance,

(2) Creation and analysis of the matrix of planning,

(3) Determination of technical requirements,

(4) Determination of the relationship between customer requirements and technical requirements,

(5) Determination of the correlation among the technical requirements,

(6) Technical assessments and identification of targets,

(7) Planning of development project based on the results,

(8) Analysis and interpretation of the results: Using the matrix that is obtained from the quality house, the priorities of the project are determined.

A sample representation of the quality house structure is given in Fig. 1.

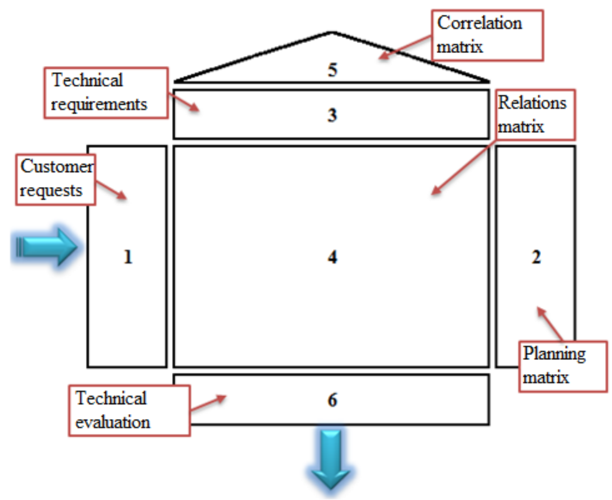


Fig. 1. Quality house structure.

B. Axiomatic Design (AD)

The approach of axiomatic design (AD) was developed by Dr. Nam P. Suh in the mid-1970s with the goal of developing a scientific, generalized, codified, and systematic procedure for design [17]. Axiomatic design is the experimental design field for products, systems, and processes. The domain on the left relative to the domain on the right represents "what we want to achieve," whereas the domain on the right represents the design solution of "how we propose to satisfy the requirements specified in the left domain." The customer domain is characterized by the customer attributes (CAs), which comprise what the customer is looking for in a product, process, system, or other design objects. In the functional domain, customer attributes are specified in terms of functional requirements (FRs) and constraints (Cs). The functional requirements represent the actual objectives and goals of the design. The design parameters (DPs) express how we want to satisfy the functional requirements. To realize the design solution specified by the design parameters, the system variables (SVs) are stated in the process domain [17].

The design approach provides the systematic process of searching with axioms in the design domain. The systematic search process, which minimizes a random search and

simplifies the selection of the best alternative design solutions [18]. Some of the term definitions used in the axiomatic design are as follows:
Axiom: No proof or exception; distinct and gospel truth. An axiom cannot be revealed from laws and principles of nature [19].
Theorem: Proposal, which is not proven; however, it can be evidenced with accepted axiomatic and is determined as a law or specialty [16].
Functional Requirements (FR): Completely describes the functional requirements of products (software, organizations, and systems) in the functional domain; consists of a minimum set of independent requirements [11].
Constraint (C): Constraints are essential limitations for acceptable solutions. Constraints can be classified as input constraints, which limit design characteristics and system constraints that limit the production system [20].
The most crucial concept in axiomatic design is the concept of design axioms [18]. These axioms are as follows:
Independence Axiom: Maintain the independence of the FRs.
Information axiom: Minimize the information content in design.

According to the axiomatic design approach, all designs consist of four different domains. These domains are defined as the "Customer" domain (CA), the "Functional" domain (FR), the "Physical" domain (DP), and the "Process" domain (PV). They continuously provide processing of information within themselves and between each domain [19]. Customer requirements are introduced in the customer domain and are subsequently formulated in the functional domain. A set of the functional requirements (FR) that require a solution and are independent of each other is defined in the functional domain.

Design occurs in the planning process of the relationships between the functional domains, which asks the question "What do we want?" and the physical domain, which asks the question "How can we do?" that consists of the design parameters (DPs) [1].

Fig. 2 illustrates the relationship between the domains. The domain on the left side answers the question "what," and the domain on the right side answers the question "how" [7]. The transition between these questions is referred to as "mapping."

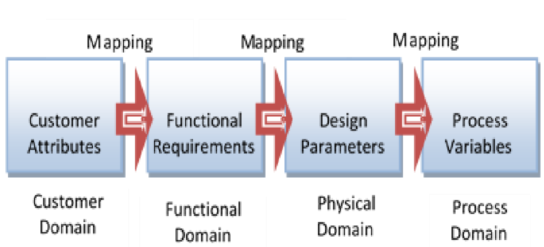


Fig. 2. Mapping in axiomatic design domains.

In the axiomatic design approach, the designer passes to the physical domain to implement and create the necessary physical structure after determining the set of functional requirements (FR_i) in the functional domain. In this stage, if a set of design parameters (DP_i), which correspond to a set of obtained functional requirements, cannot be applied or clearly articulated, a set of one lower-level functional requirement (FR_i) will be created and returned to the functional domain. This "decomposition" with "zigzags" will continue to the point at which solutions to problems identified in the lower levels are established [3]. The decomposition of the design with zigzags is shown in Fig. 3.

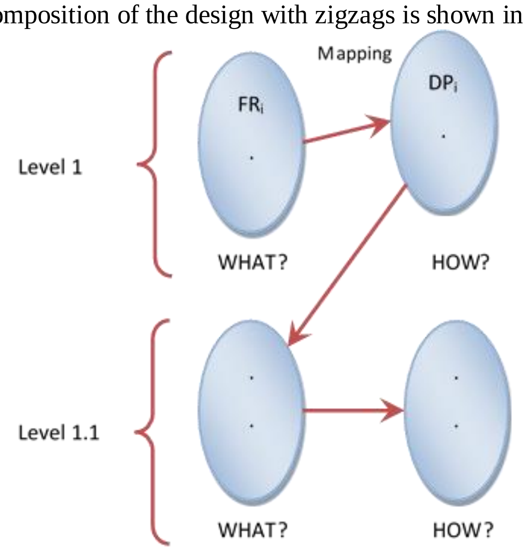


Fig. 3. Decomposing of the design with zigzags.

An independence axiom can be described as a path to be followed during the zigzag process from the functional requirements (FRs) in the functional domain to the design parameters (DPs) in the physical domain [6]. The independence axiom defines the independent relationship between the functional requirements (FRs) and the design parameters (DPs). According to axiom 1, each functional requirement should be associated with only one design parameter without affecting other design parameters [21].

The design described as a mapping process can be mathematically expressed. In this expression, functional requirements can be represented by the vector "FR" with "m" elements, and the design parameters can be represented by the vector "DP" with "n" elements [22]. A design matrix (A) defines the relationship between the functional requirements (FRs) and the design parameters (DPs) [15].

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ . \\ . \\ . \\ FR_n \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{21} & . & . & . & A_{1n} \\ A_{12} & A_{22} & . & . & . & A_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ A_{1n} & A_{2n} & . & . & . & A_{nn} \end{bmatrix} \times \begin{Bmatrix} DP_1 \\ DP_2 \\ . \\ . \\ . \\ DP_n \end{Bmatrix} \quad (1)$$

The shape and dimension of matrix A are used to classify the design into one of the following categories: 1) Uncoupled design, 2) Decoupled design, and 3) Coupled design. A design that completely complies with the independence axiom is referred to as an uncoupled (independent) design.

An uncoupled design is an ideal (square matrix) design. The resulting design matrix—in this case, A—is a square-diagonal matrix, where m = n and Aij is not zero when i = n but zero elsewhere [22]. This design is possible for each design issue, but their detection is critical. However, due to environmental conditions or creation restrictions, these designs may not be possible [12].

A matrix is also considered as the sensitivity matrix that represents the physical mapping with [22, 23]

$$\mathrm{A}_{ij} = \frac{d\mathrm{FR}_i}{d\mathrm{DP}_j} \tag{2}$$

According to the uncoupled design matrix,

$$\{\mathrm{FR}\}=[\mathrm{A}]\{\mathrm{DP}\} \tag{3}$$

The visual representation of the uncoupled design is shown in Fig. 4.

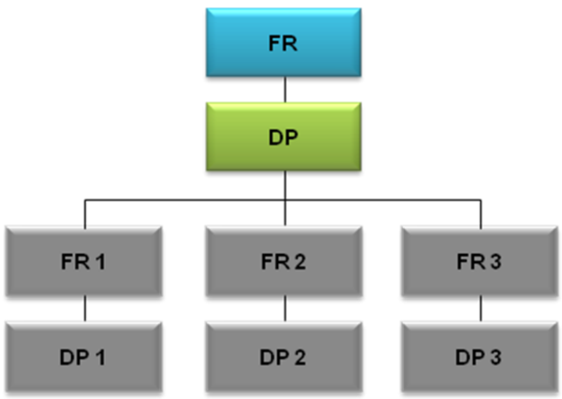


Fig. 4. The uncoupled design

The information axiom enables the selection of the best design among all design alternatives that satisfy the requirements of the independence axiom by converting the design requests to the quantitative measurement. Besides, the information axiom prepares a theoretical substructure about design optimization and creating a robust design [19]. According to Suh, the solution that contains the least amount of information is the best solution within all solutions that satisfy the requirements of the functional requirements (FRs). Less information (less complex designs) will increase the chances of success of the solution [19].

The information content is shown as Ii and is expressed as the probability of realization of the functional requirements (FRs) with the most straightforward definition. The information content is calculated with [18]

$$\mathrm{I}_i = \log_2 \frac{1}{p_i} \tag{4}$$

where p_i indicates the possibility of satisfying the functional requirements. If the system contains n functional requirements in the system, the total information content is the sum of all possibilities. If I_i goes to infinity, the system cannot satisfy the functional requirement that is determined by the designer. If the probability value is one, the information content will be zero [18, 24, 25].

The probability of success in any design is dependent on the level (design range) and the system capacity (system range), which the designer wants to attain on the basis of tolerance.

Correspondingly, the uniform probability distribution function can be written as [23, 24, 26]

$$\mathrm{P}_i = \left(\frac{\text{Common range}}{\text{Design range}}\right) \tag{5}$$

In this case, the information content can be calculated as

$$\mathrm{I}_i = \log_2 \left(\frac{\text{Design range}}{\text{Common range}}\right) \tag{6}$$

As a result, the design that contains the smallest amount of total information is selected as the best design. Design range, system range, and a common range of functional requirements are shown in Fig. 5.

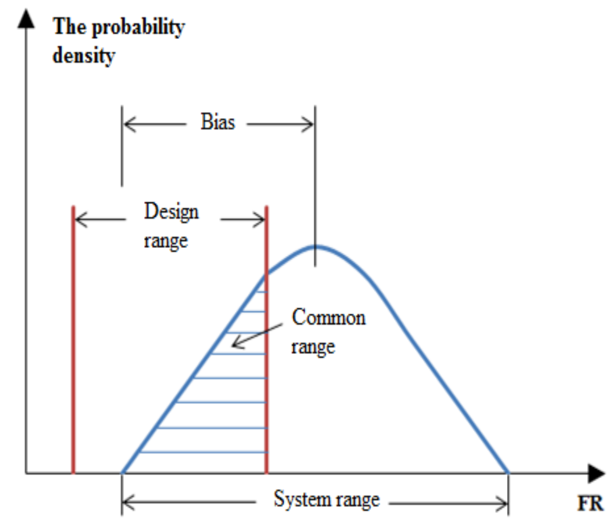


Fig. 5. Design range, system range, and a common range of functional requirement

In the next section, the application and results of the axiomatic design of a passenger bus seat are given in detail.

III. RESULTS

In this paper, passengers who commute a significant distance were defined as the primary customer group, and the specifications of the seats during the trip were determined. All specifications that can be included have been identified. A survey was prepared using the Likert five-point scale, where A indicates strongly disagree, and E indicates strongly agree. The surveys were conducted to passengers who will make a long-distance journey from Bursa Intercity Bus Terminal. The surveys, which contained 19 questions, were completed by 58 people; the results and calculated ratios of the answers were given in Table I.

Table I. Survey results and data set for QFD analysis.

		A	B	C	D	E	Total Score	% rate	Mean	StDev
Q1	Soft upholstery	0	1	3	29	25	252	**5.78**	4.328	0.659
Q2	Fabric newspaper pocket	6	9	29	10	4	171	3.92	2.948	1.016
Q3	Newspaper pocket with cells	2	5	19	25	7	204	4.68	3.517	0.96
Q4	Tiltable backrest	2	1	0	13	42	266	**6.10**	4.586	0.879
Q5	Footrest	2	0	7	16	33	252	**5.78**	4.345	0.983
Q6	Vertical adjustable headrest	0	2	9	19	28	247	**5.67**	4.259	0.849
Q7	Horizontal adjustable headrest	0	2	8	22	26	246	**5.64**	4.259	0.828
Q8	Not to slide from seat	0	0	6	23	29	255	**5.85**	4.397	0.674
Q9	Leg support	0	4	20	24	10	214	4.91	3.69	0.842
Q10	Side sliding	1	8	20	20	9	202	4.63	3.552	0.994
Q11	Independent tablet	1	5	10	21	21	230	**5.28**	3.966	1.025
Q12	TV monitor	0	4	2	20	32	254	**5.83**	4.362	0.852
Q13	Reading light	2	8	9	17	22	223	5.12	3.862	1.191
Q14	Mid armrest	3	4	12	26	13	216	4.96	3.707	1.06
Q15	Large seat	0	2	7	20	29	250	**5.74**	4.276	0.874
Q16	Plug	2	6	13	20	17	218	5.00	3.759	1.097
Q17	Cup holder on armrest	1	5	11	26	15	223	5.12	3.81	0.963
Q18	Handle	1	5	23	16	13	209	4.79	3.569	0.993
Q19	Bag hook	1	5	13	18	21	227	5.21	3.845	1.04

The specifications, which have a rate above average, which is 5.26% (given in boldface), were used to create a quality house, shown in Table 1. All questions were analyzed in MINITAB16 statistical software prior to the elimination of the questions. According to the correlation analysis of the survey data, there is no significant relationship between the questions, and all results are independent and therefore analyzed separately. Results of the correlation analysis are given in Table II.

Table II. Correlation analysis results.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18
Q2	-0.11																	
Q3	0.01	0.48																
Q4	-0.10	0.07	0.01															
Q5	-0.12	0.26	0.35	0.37														
Q6	0.13	-0.05	0.18	0.40	0.33													
Q7	0.00	-0.07	0.27	0.10	0.34	0.50												
Q8	-0.18	-0.28	-0.08	0.31	0.37	0.28	0.32											
Q9	-0.07	0.10	0.20	0.16	0.20	0.21	0.09	0.04										
Q10	-0.15	0.15	0.10	0.45	0.27	0.16	0.14	0.22	0.23									
Q11	0.04	0.20	0.27	0.24	0.08	0.05	0.05	0.05	0.19	0.29								
Q12	0.10	0.08	0.20	0.51	0.37	0.28	0.01	0.14	0.16	0.32	0.34							
Q13	0.15	0.04	0.16	0.10	-0.20	0.24	0.06	-0.17	0.20	0.29	0.51	0.26						
Q14	-0.11	0.20	0.10	-0.04	0.15	0.16	0.25	0.14	0.17	0.54	0.23	0.04	0.33					
Q15	0.30	0.02	0.06	0.27	0.21	0.21	0.26	0.29	-0.14	0.31	0.11	0.17	0.12	0.07				
Q16	0.11	0.02	0.05	0.13	-0.25	0.18	0.11	-0.18	0.11	0.25	0.21	0.21	0.39	0.15	0.16			
Q17	0.10	0.21	0.34	0.07	0.07	0.02	0.15	-0.07	0.12	0.24	0.37	0.13	0.34	0.31	0.08	0.26		
Q18	0.11	0.31	0.31	0.07	0.08	0.09	0.29	0.18	0.26	0.30	0.49	0.02	0.23	0.38	0.22	0.02	0.43	
Q19	0.13	0.18	-0.01	0.06	0.14	0.25	-0.01	0.14	0.06	0.17	-0.01	0.05	-0.09	0.20	0.01	-0.25	0.01	0.46

The consistency of the survey answers is validated by performing a reliability analysis. For this purpose, the initial Cronbach's alpha is calculated as 0.7788. After elimination of the questions with larger standard deviations (Q1, Q19, and Q16 subsequently) final alpha value has reached the value of 0.7901. The final analysis results are given in Table III.

Table III. Final reliability analysis results.

Cronbach's Alpha = 0.7901

Omitted Item Statistics

Omitted Variable	Adj. Total Mean	Adj. Total StDev	Item-Adj. Total Corr	Squared Multiple Corr	Cronbach's Alpha
Q2	60.155	7.093	0.2519	0.5093	0.7899
Q3	59.586	6.971	0.4076	0.4749	0.7775
Q4	58.517	7.022	0.3961	0.5886	0.7785
Q5	58.759	6.959	0.4072	0.569	0.7775
Q6	58.845	7.036	0.3973	0.5214	0.7786
Q7	58.845	7.078	0.357	0.4708	0.7813
Q8	58.707	7.245	0.2075	0.4781	0.7898
Q9	59.414	7.118	0.2999	0.2557	0.7851
Q10	59.552	6.816	0.5549	0.5792	0.7656
Q11	59.138	6.853	0.495	0.5141	0.7703
Q12	58.741	7.025	0.4086	0.4308	0.7778
Q13	59.241	6.911	0.3514	0.5789	0.7836
Q14	59.397	6.903	0.4239	0.564	0.7762
Q15	58.828	7.113	0.2898	0.3124	0.7859
Q17	59.293	6.974	0.4027	0.3367	0.7779
Q18	59.534	6.857	0.5110	0.5452	0.7692

Based on the results of the reliability analyses, Question 1, Question 16, and Question 19 were removed from the list.

As a second step, customer requests, which will be employed in the quality function deployment (QFD) analysis, are listed in Table IV.

Table IV. Customer requests to be used in the quality house.

Question Number	Customer Request	Total Rate	Percentage Rate	Customer Severity Rating
Q-4	Tiltable backrest	266	13.30	92
Q-5	Footrest	252	12.60	87
Q-6	Vertically adjustable headrest	247	12.35	85
Q-7	Horizontal adjustable headrest	246	12.30	85
Q-8	Not to slide from the seat	255	12.75	88
Q-11	Independent tablet	230	11.50	79
Q-12	TV monitor	254	12.70	88
Q-15	Large seat	250	12.50	86

By the current capacity of the company at hand, responses that can be given to the determined customer requests are given in Table 5. Also, rival companies' ability ratios to meet these requests are shown. The target rate that meets the customer requirements is determined. With each increase of rate in these targets, the expected rate of increase in sales is calculated. Severity rating was found by multiplying customer severity rating, progress rate, and point of sale. For example, the severity rating of the tiltable backrest is 92x1x1.1=101.2. Then, the normalized scores of severity ratings were calculated, and the percentage of severity rating for tiltable backrest was found to be 4.48. All data derived for all customer requests are given in Table V.

Table V. Percentage of Severity Ratings.

Customer Request	Customer Severity Rating	Company	Rival A	Rival B	The target of the company	Progress rate	Point of sale	Severity Rating	Percentage of Severity Rating
Tiltable backrest	92	5	5	5	5	1	1.1	101.2	4.48
Footrest	87	5	5	5	5	1	1.1	95.7	4.24
Vertically adjustable headrest	85	1	1	4	5	5	1.2	510	22.57
Horizontal adjustable headrest	85	1	1	4	5	5	1.2	510	22.57
Not to slide from the seat	88	4	1	3	4	1	1.2	105.6	4.67
Independent tablet	79	3	3	3	4	2	1.1	173.8	7.69
TV monitor	88	3	1	2	5	5	1.5	660	29.21
Large seat	86	4	3	5	5	1	1.2	103.2	4.57
Total								2259.5	100

Degrees of correlation are defined as in Table VI.

Table VI. Degrees of correlation.

Degree of correlation	Symbol	Number
Strong	Θ	9
Moderate	O	3
Weak	Δ	1

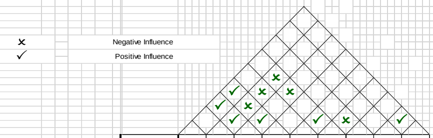
Fig. 6 lists the results of the QFD analysis of the quality house. Because the QFD analysis results should be given priority for the realization of customer requests, which include a vertically adjustable headrest, a horizontally adjustable headrest, an independent tablet, and a TV monitor, all have a high percentage rate. The development of technical requirements for the specifications of the seat, which include the accessory assembly, the welding operation, the foam preparation process, and the headrest pre-assembly, are important. In addition to these specifications, tiltable backrest and footrest properties can be optionally added to each model seat. Therefore, these two specifications will be added to the seat design.

In the next stage, the selection of the best design among three seat designs benefited from an axiomatic design is performed. Because the customer determines what constitutes the system characteristics, QFD analysis results obtained in the previous step were employed. System ranges were created for the four selected specifications. The information for the specification of each seat was calculated. A summary of information about the seats is shown in Table VII.

Table VII. The information contents table.

	ΣI_1 (bit)	**ΣI_2 (bit)**	**ΣI_3 (bit)**	**ΣI_4 (bit)**	**ΣI (bit)**
A	8.62	4.38	6.75	0.82	**20.57**
B	infinite	infinite	6.75	3.46	**infinite**
C	infinite	2.36	infinite	infinite	**infinite**

As the information content suggests, the most beneficial specification from a design point of view is the vertical



Customer Requests	Customer Severity Rating	Chassis assembly	Accessories assembly	Welding operation	Seat assembly	Foam preparation process	Headrest pre-assembly	Accessories preparation process	Sewing process	Upholstery operation	Percentage Rate
Tiltable backrest	92	9			1						4.48
Footrest	87	9									4.24
Vertical adjustable headrest	85		3	9		1	9				**22.57**
Horizontal adjustable headrest	85			9		9			1	1	**22.57**
Not to slide from seat	88	3		9							4.67
Independent tablet	79		3		9			9			**7.69**
TV monitor	88		9			1					**29.21**
Large seat	86	1			1	9			1	1	4.57
Technical Severity Rating		97	354	448	78	296	203	69	27	27	**100%**
Normalized Severity Rating		6.1	22.1	28	4.9	18.5	12.7	4.3	1.7	1.7	

Fig. 6. Quality House

Adjustable headrest, and therefore it is chosen for the rest of this study. In the next subsection, design features of the vertically adjustable headrest are given.

A. Design Features

Design features of the vertically adjustable headrest are shown in Fig. 7. Three seats' (A, B, and C) parameters and the desired system range for vertically adjustable headrest are given in Table 8. For completeness, the other three specifications are also added to Table VIII.

Table VIII. Design ranges and parameters.

Vertically adjustable headrest				Horizontal adjustable headrest			Independent tablet			TV monitor	
Distance of increase in height (mm)	Number of levels	Width of the headrest (mm)	Height of the headrest (mm)	Headrest Ear Closing Angle (°)	Headrest Ear	Headrest Ear Angle (°)	Side Opening Angle (°)	Depth (mm)	Width (mm)	Opening angle (°)	Width of the monitor (inch)
0 - 60	0 - 6	420 - 430	220 - 230	0 - 20	Yes	45	0 - 46	0 - 50	400	0 - 45	7
0 - 50	0 - 5	450 - 475	195 - 210	0 - 20	Yes	27	0 - 46	0 - 50	410	0 - 21	10
0 - 50	No	440 - 450	250 - 260	0 - 30	Yes	40	0 - 40	No	420	0 - 15	7
55 - 80	5 - 10	400 - 450	230 - 250	20 - 25	Yes	30-45	45 - 65	40 - 60	400 - 420	20 - 50	7 - 10

As indicated above, the vertically adjustable headrest that useful changes can be made was selected as the main design feature. After determining which features can be altered, the design ranges are shown in Table IX.

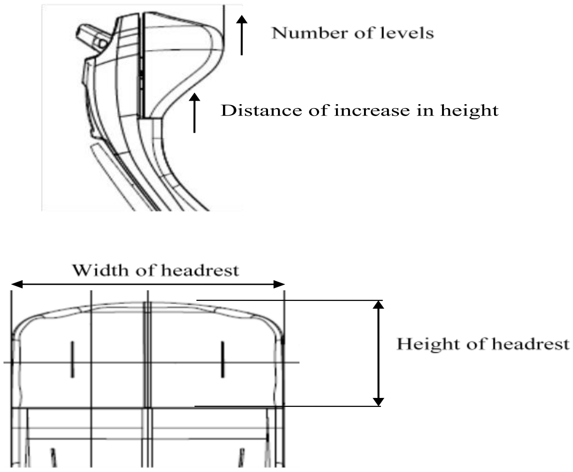


Fig.7. Design features of the vertically adjustable headrest.

Table IX. Design ranges of the vertically adjustable headrest.

	The distance of increase in height	Number of levels	Width of headrest	Height of headrest
Seat A	0-60 mm	0-6	420-430 mm	220-230 mm
Seat B	0-50 mm	0-5	450-475 mm	195-210 mm
Seat C	0-50 mm	-	440-450 mm	250-260 mm

On the other hand, the system ranges are:

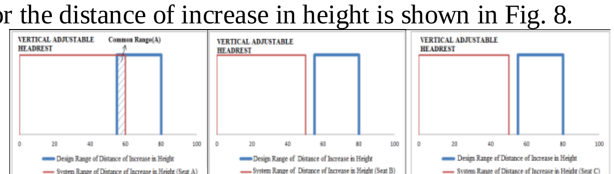
- 1,1= Distance of increase in height: 55-80 mm
- 1,2= Number of levels: 5-10
- 1,3= Width of headrest: 400-450 mm
- 1,4= Height of headrest: 230-250 mm

$$P = \frac{\text{Common range}}{\text{System range}} \tag{7}$$

$$I = \log_2 \frac{1}{P} \tag{8}$$

Note that as the limit values are also accepted in the given ranges, they will be considered in the calculation.

Vertical adjustable headrest's probability density function for the distance of increase in height is shown in Fig. 8.



Seat A	Seat B	Seat C
(a)	(b)	(c)

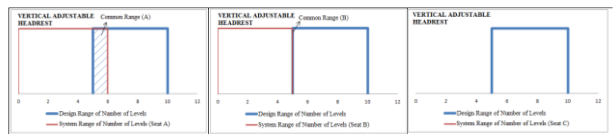
Fig. 8. Vertical adjustable headrest's probability density function for the distance of increase in height.

Probability and information content is given in Table X. Calculations were done according to Fig. 8.

Table X. Probability and information content

Seat A	Seat B	Seat C
$P_{1,1,A} = \frac{(60-55)+1}{(60-0)+1} \cong 0.098$	$P_{1,1,B} = \frac{0}{(50-0)+1} = 0$	$P_{1,1,C} = \frac{0}{(50-0)+1} = 0$
$I_{1,1,A} = \log_2 \frac{1}{0.098} \cong 3.35$	$I_{1,1,B} = \log_2 \frac{1}{0}$ = **Infinite**	$I_{1,1,C} = \log_2 \frac{1}{0}$ = **Infinite**

Vertical adjustable headrest's probability density function for the number of levels is shown in Fig. 9.



Seat A	Seat B	Seat C
(a)	(b)	(c)

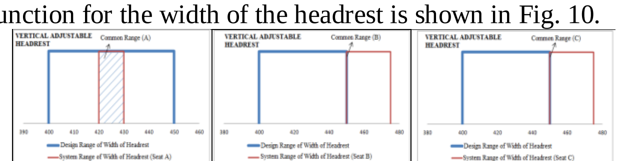
Fig. 9. Vertical adjustable headrest's probability density function for the number of levels.

Probability and information content is given in Table XI. Calculations were done according to Fig. 9.

Table XI. Probability and information content.

$P_{1,2,A} = \frac{(6-5)+1}{(6-0)+1} \cong 0.286$	$P_{1,2,B} = \frac{(5-5)+1}{(5-0)+1} \cong 0.167$	$P_{1,2,C} = \frac{0}{0} = 0$
$I_{1,2,A} = \log_2 \frac{1}{0.286} \cong 1.81$	$I_{1,2,B} = \log_2 \frac{1}{0.17} \cong 2.58$	$I_{1,2,C} = \log_2 \frac{1}{0}$ = **Infinite**

The vertical adjustable headrest's probability density function for the width of the headrest is shown in Fig. 10.



Seat A	Seat B	Seat C
(a)	(b)	(c)

Fig. 10. Vertical adjustable headrest's probability density function for the width of the headrest.

Probability and information content is given in Table XII. Calculations were done according to Fig. 10.

Table XII. Probability and information content.

$P_{1,3,A} = \frac{(430-420)+1}{(430-420)+1} = 1$	$P_{1,3,B} = \frac{(450-450)+1}{(475-450)+1} \cong 0.038$	$P_{1,3,C} = \frac{(450-440)+1}{(450-440)+1} = 1$
$I_{1,3,A} = \log_2 \frac{1}{1} = 0$	$I_{1,3,B} = \log_2 \frac{1}{0.038} \cong 4.72$	$I_{1,3,C} = \log_2 \frac{1}{1} = 0$

The vertical adjustable headrest's probability density function for the height of the headrest is shown in Fig. 11.

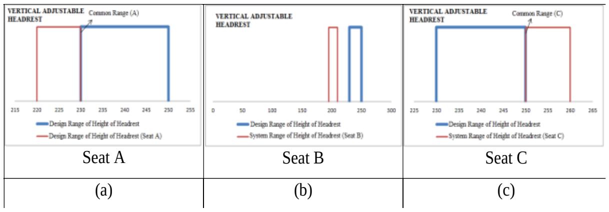


Fig. 11. Vertical adjustable headrest's probability density function for the height of the headrest.

Probability and information content is given in Table XIII. Calculations were done according to Fig. 11.

Table XIII. Probability and information content.

$P_{1,4,A}=\frac{(230-230)+1}{(230-220)+1}\cong 0.091$	$P_{1,4,B}=\frac{0}{(210-190)+1}=0$	$P_{1,4,C}=\frac{(250-250)1}{(260-250)+1}\cong 0.091$
$I_{1,4,A}=\log_2\frac{1}{0.091}\cong 3.46$	$I_{1,4,B}=\log_2\frac{1}{0}=\textbf{Infinite}$	$I_{1,4,C}=\log_2\frac{1}{0.05}\cong 3.46$

The resulting information contents of the vertically adjustable headrest are given in Table XIV. The design which has the minimum information is considered the best design. From Table XIV, design A is found to be the best design.

Table XIV. The information contents of the vertically adjustable headrest.

Vertical adjustable headrest	$I_{1,1}$ (bit)	$I_{1,2}$ (bit)	$I_{1,3}$ (bit)	$I_{1,4}$ (bit)	ΣI_1 (bit)
Seat A	3.35	1.81	0	3.46	8.62
Seat B	Infinite	2.58	4.72	Infinite	Infinite
Seat C	Infinite	Infinite	0	3.46	Infinite

IV. CONCLUSION

The specifications for seats A, B, and C (design ranges) were analyzed according to the requested system specifications (system ranges). Although Design C yielded the best results in the design of a horizontally adjustable headrest, it did not provide other features. Design B satisfied the specifications of an independent tablet and TV monitor at a level but did not meet the requests for a vertically adjustable headrest and a horizontally adjustable headrest. By making improvements on the system specifications that did not meet the design range for B and C seats, the requested results can be obtained.

As a result, Design A contains the least amount of information. Design A provides more requested design specifications than the designs for the remaining seats. According to the information, the improvements yield better results. The best design is shown in Fig. 12. The results of the analysis show that a seat design that includes a vertically adjustable headrest and an independent tablet (an independent tablet can also be installed in seat B), TV monitor designs for seat A, and a horizontally adjustable headrest design for seat C yield the best results. In future designs and improvements, the results provided in this paper can be used as a guideline, and better designs that meet most of the customer requirements can be obtained.

Fig. 12. The best design (Design A)

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