Concept Selection

Introduction

Within concept generation, Team 517 narrowed the field from 100 to eight fidelity concepts. These choices were based on which solutions the team thought would best meet critical targets and metrics. The current goal is to narrow the field to a single concept. Starting with a ranking of customer needs and their impact on functionalities, concept selection begins with the House of Quality. Following this, direct comparison is then conducted using Pugh Charts where the fidelity concepts will be evaluated against a datum. This iterative process will further narrow the field, leaving the team with only a few final concepts to choose from. To select a final concept, the team will then employ the alternative hierarchy process. All these processes are outlined further in the following sections.

As a final note, this process primarily serves to reduce bias in decision-making. By using a mathematical approach to eliminate options, the process remains impartial. Also, this process was conducted during a series of team meetings where certain engineering characteristics were refined to provide a better basis for comparison.

House of Quality

The first step in concept selection is to determine a hierarchy for the customer requirements. Knowing what requirements are most important to the customer allows for a quantification of needs, which will be continuously used to assign value to each concept and determine a winner. Binary pairwise determines this hierarchy by comparing each customer's need to each other, with the better requirement receiving a (1), and the less favorable requirement getting a (0). This is done on the table by listing the customer needs in both the major rows and columns of the table and at each intersection assigning a (1) if the row value is more important than the column value. This does mean that each requirement is compared to itself at some point, but these cells are ignored. At the end of this process the totals of each row can be found, and the requirements with the highest numbers are the most important.

Binary Pairwise											
Customer Requirements	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
1 Measures Thrust		1	1	1	1	1	1	1	1	1	9
2 Measures Temperature	0		1	0	0	1	0	0	0	1	3
3 Measures Pressure	0	0		0	0	0	0	0	0	1	1
4 Performs Uncertainty Analysis	0	1	1		0	1	1	1	1	1	7
5 Stores data	0	1	1	1		1	1	1	1	1	8
6 Easily cleaned	0	0	1	0	0		0	0	0	1	2
7 Reproducible by University	0	1	1	0	0	1		1	0	1	5
8 Visible from viewports	0	1	1	0	0	1	0		1	1	5
9 Accessible	0	1	1	0	0	1	1	0		1	5
10 Scalable	0	0	0	0	0	0	0	0	0		0
Total	0	6	8	2	1	7	4	4	4	9	n - 1 = 9

In the House of Quality, Customer Requirements are placed in each row with Engineering Characteristics in each column. Each intersection is then rated based on the contribution of the column to the row. This uses the following scale: 0 (blank) – not at all, 1 – slightly, 3 – moderately, and 9 – significantly. The Importance Weight Factor is then multiplied across the rows and each column is summed to generate a weighted raw score for individual Engineering Characteristics. Relative weight percent and overall rank of importance are tabulated as well.

Using the House of Quality generates a numerical representation of the significance of Engineering Characteristics to a project. For Team 517, these values are used to identify what Engineering Characteristics within a concept are the most critical to the overall design by keeping a mindset of the design requirements, assumptions, and key goals. Because "Scalable" is a secondary goal, it was not considered significant as a customer requirement. Shown in the figure below, from left to right, Processing Rate and Uncertainty are the most significant Engineering Characteristics as they both directly contribute the most to the Customer Requirements.

House of Quality																
	Engineering Characteristic (how?)															
Improvement Direction	↓↑	↑	↓	↑	↑	↑	↑	↓	↑	↓	↑	↓	↑	↑	↑	↓
Units		Hz/Bytes	%	N	Hz/Bytes	%	Gb	Kg	%	USD	%	Days	#	C	Torr	min
Customer Requirements	Importance Weight Factor	Sampling/ Processing Rate	Thrust Sensor Uncertainty	Maximum Thrust Allowed	RAM Allocation	Connections directed through terminal blocks	External Drive Capacity	Stand Mass	Accessibility to wires	Structural Cost	Accessible Materials	Build Time	Viewports with direct sightlines	Temperature Accuracy	Pressure Accuracy	Cleaning Time
Measures Thrust	9	9	9	9	1	1		1								
Measures Temperature	3	3			1	1								9		
Measures Pressure	1	3			1	1									9	
Performs Uncertainty Analysis	7	9	9	3	9			1						1	1	
Stores data	8	3	3	1	3		9							1	1	
Easily cleaned	2							3	1	1	3					9
Reproducible by University	5	1		1		3	1	1	3	9	9	9				
Visible from viewports	5					1				1			9			
Accessible/ Manueverable	5					9		9	9	1	1					
Scalable	0			9		1		3	1	3	1	1				1
Raw Score	(1144)	185	168	115	100	78	77	72	62	57	56	45	45	42	24	18
Relative Weight %		16.2	14.7	10.1	8.7	6.8	6.7	6.3	5.4	5.0	4.9	3.9	3.9	3.7	2.1	1.6
Rank Order		1	2	3	4	5	6	7	8	9	10	11	11	13	14	15

Pugh Charts

Pugh Charts are a method to narrow down the design choices by comparison between concepts. High and medium fidelity concepts are compared against a datum, using the Engineering Characteristics found most important from the House of Quality. The datum chosen is an existing product that is similar to the team's design. To best compare the concepts generated, the NASA MSFC current Green Propellant Thrust Stand was used as the datum.

CONCEPT KEY								
Concept #	**Force Sensor**	**Temp sensor**	**Material**	**Remote Calibration**	**Cleaning**	**Error Code**	**Mount**	**Type**
1	Piezo	Thermocouple	SS	Wire	Modular design, drainage compabilities, smooth surfaces	ECC, Feedback, Data Validation	Vertical	Vertical
2	Strain	Thermocouple	SS	Wireless	Modular design, drainage compabilities, smooth surfaces	ECC, Feedback, Data Validation	Vertical	Seesaw
3	Strain	Thermocouple	SS/AL	Wireless	Modular design, drainage compabilities, smooth surfaces, coating	ECC, Data Validation, SF	Vertical	Seesaw
4	Piezo	Thermocouple	SS	Wire	Modular design, drainage	Data Validation,ECC	Vertical	Vertical
5	Piezo	Thermistor	Comp	Wirless	Modular design, smooth surfaces	Data Validation,ECC	Vertical	Vertical
6	Strain	Thermocouple	Comp	Wire	Drainage, coating	Data Validation,ECC	Vertical	Seesaw
7	Capactive Force	Infared	SS	Wireless	Coating, smooth surfaces	Data Validation,ECC	Horizontal	Torsional
8	Strain	Thermistor	SS	Wireless	Modular design, coating	Data Validation,ECC	Horizontal	Horizontal

The concept key shows the specifics of each medium and high fidelity concept. SS represents stainless steel, AL represents aluminum and ECC represents error correcting codes. This concept key will be useful for the following stages of concept selection, and concept numbers should be referred to from it.

The Engineering Characteristics, or the Selection Criteria, are listed on the rows of the Pugh Charts, and the Concepts are listed on the columns. Each concept is compared to the datum by going down the rows and determining if the concept performs better (+), worse (-), or the same as (S) the datum for each Engineering Characteristic. The sums of the pluses, minuses and

S's are found at the bottom of the table to compare concept performance. The first Pugh Chart compares the 8 high and medium fidelity concepts to the datum of the NASA MSFC current thrust stand. Once underperforming concepts are eliminated, the second Pugh Chart is created by taking one of the highest performing concepts from the first, and using it as the datum to compare the remaining concepts to. This datum, along with 2 other concepts that perform well in comparison, are chosen to begin the Analytical Hierarchy Process.

Pugh Chart 1									
Engineering Characteristics	Concepts								
	Datum	1	2	3	4	5	6	7	8
Sampling/ Processing Rate	**Current MSFC Green Propellant Thrust Stand**	S	S	S	S	S	S	S	S
Thrust Sensor Uncertainty		+	+	+	+	+	+	+	+
Maximum Thrust Allowed		+	-	-	+	+	-	-	-
RAM Allocation		S	S	S	S	S	S	S	S
Connections directed through terminal blocks		S	S	S	S	S	S	S	S
External Drive Capacity		S	S	S	S	S	S	S	S
Stand Mass		+	-	-	-	+	+	-	-
Accessibility to wires		+	+	+	-	-	+	-	-
Structural Cost		-	-	-	-	-	-	-	-
Accessible Materials		-	-	-	-	-	-	-	-
# of pluses	0	4	2	2	2	3	3	1	1
# of minuses	0	2	4	4	4	3	3	5	5
# of satisfactory	0	4	4	4	4	4	4	4	4

From Pugh Chart 1, concepts 7 and 8 were determined to be removed due to the significant number of minuses and least amount of pluses. Concept 1 was chosen to be the new datum due to the having the highest number of pluses and the least amount of minuses. This concept as the datum will be useful in comparing the remaining concepts due to its high performance and setting the bar to beat currently. Concepts 3 and 4 were chosen to be removed because of having minimal pluses and substantial minuses.

Concept 2 was chosen to stay rather than either 3 or 4 because while they all had pluses compared to the datum, the Error Codes concept 2 has, such as Feedback and Data Validation, are more beneficial to the Thrust Sensor Uncertainty than the other two concepts that were removed. This was how it was decided for moving forward to Pugh Chart 2.

Pugh Chart 2				
Engineering Characteristics	Concepts			
	datum	2	5	6
Sampling/ Processing Rate	Concept 1	S	S	S
Thrust Sensor Uncertainty		S	-	-
Maximum Thrust Allowed		-	S	-
RAM Allocation		S	S	S
Connections directed through terminal blocks		S	S	S
External Drive Capacity		S	S	S
Stand Mass		-	+	+
Accessibility to wires		S	S	S
Structural Cost		-	+	+
Accessible Materials		S	-	-
# of pluses	0	0	2	2
# of minuses	0	3	2	3
# of satisfactory	0	7	6	5

From Pugh Chart 2, concept 6 was chosen to be removed due to having the least number of S's and tied for most minuses. This concept was chosen to be removed rather than concept 2 because it had pluses only in areas that weren't as important to the project like Stand Mass and Structural Cost. While concept 2 had 0 pluses, the S's in Thrust Sensor Uncertainty and Accessible Materials are what deemed it more important to consider going forward, because these Engineering Characteristics were more important to the project success and the sponsor.

The outcome from the Pugh Charts is that concepts 1, 2 and 5 are to be used in the Analytical Hierarchy Process to select the final concept.

Analytical Hierarchy Process

Compared to the first steps of selection, the analytical hierarchy process (AHP) is more mathematically involved. Like the House of Quality and Pugh Charts, it serves as another bias limiter when determining what concept best fulfills design requirements. The first step involves establishing the selection criteria for which each concept will be evaluated against. For Team 517, these criteria are documented in the table below.

Selection Criteria
Sampling/ Processing Rate
Thrust Sensor Uncertainty
Maximum Thrust Allowed
RAM Allocation
Connections directed through terminal blocks
External Drive Capacity
Stand Mass
Accessibility to wires
Structural Cost
Accessible Materials

Once these criteria are chosen, each of the criteria are evaluated against one another in a criteria comparison matrix. This process employs methods like those used in the House of Quality, specifically pairwise comparison and a skewed ranking system. Comparing column to row, the matrix describes how much more or less important one criteria is than another. However, the ranking system used here employs a 1-3-5-7-9 scaling as opposed to the 1-3-9 scaling from before. If the row is less important than the column, the value taken is the inverse. For example, if criteria 1 is a 9 when compared to criteria 2, then criteria 2 compared to criteria 1 would be 1/9. For Team 517, the selection criteria and associated matrix comparison are outlined in the table below.

[C] Criteria Comparison Matrix												
	Analytical Hierarchy Process	A	A	A	A	A	A	A	A	A	A	
B	Selection Criteria	Sampling/ Processing Rate	Thrust Sensor Uncertainty	Maximum Thrust Allowed	RAM Allocation	Connections directed through terminal blocks	External Drive Capacity	Stand Mass	Accessibility to wires	Structural Cost	Accessible Materials	Average
B	Sampling/ Processing Rate	1	5.000	0.143	1.000	0.333	0.200	0.143	0.040	0.003	0.000	0.786
B	Thrust Sensor Uncertainty	0.200	1	0.143	0.200	0.143	0.143	0.143	0.111	0.111	0.143	0.234
B	Maximum Thrust Allowed	7.000	7.000	1	3.000	3.000	0.333	3.000	3.000	0.333	0.333	2.800
B	RAM Allocation	1.000	5.000	0.333	1	1.000	0.333	0.333	0.200	0.333	0.333	0.987
B	Connections directed through terminal blocks	3.000	7.000	0.333	1.000	1	0.333	0.333	1.000	0.333	0.333	1.467
B	External Drive Capacity	5.000	7.000	3.000	3.000	3.000	1	1.000	3.000	3.000	5.000	3.400
B	Stand Mass	7.000	7.000	0.333	3.000	3.000	1.000	1	1.000	0.333	0.333	2.400
B	Accessibility to wires	5.000	9.000	0.333	5.000	1.000	0.333	1.000	1	0.333	0.333	2.333
B	Structural Cost	7.000	9.000	3.000	3.000	3.000	0.333	3.000	3.000	1	3.000	3.533
B	Accessible Materials	7.000	7.000	3.000	3.000	3.000	0.200	3.000	3.000	0.333333	1	3.053
	Total	43.200	64.000	11.619	23.200	18.476	4.210	12.952	15.351	6.114	10.810	32.099
	Average	4.320	6.400	1.162	2.320	1.848	0.421	1.295	1.535	0.611	1.081	

Following this, the table is then normalized into the normalized criteria comparison matrix where criteria weights are then established and documented in the column on the far right of the matrix. This table is shown below.

norm[C] Normalized Comparison Matrix												
	Analytical Hierarchy Process	A	A	A	A	A	A	A	A	A	A	
B	Selection Criteria	Sampling/ Processing Rate	Thrust Sensor Uncertainty	Maximum Thrust Allowed	RAM Allocation	Connections directed through terminal blocks	External Drive Capacity	Stand Mass	Accessibility to wires	Structural Cost	Accessible Materials	Critical Weight {W}
B	Sampling/ Processing Rate	0.023	0.078	0.012	0.043	0.018	0.048	0.011	0.003	0.000	0.000	0.024
B	Thrust Sensor Uncertainty	0.005	0.016	0.012	0.009	0.008	0.034	0.011	0.007	0.018	0.013	0.013
B	Maximum Thrust Allowed	0.162	0.109	0.086	0.129	0.162	0.079	0.232	0.195	0.055	0.031	0.124
B	RAM Allocation	0.023	0.078	0.029	0.043	0.054	0.079	0.026	0.013	0.055	0.031	0.043
B	Connections directed through terminal blocks	0.069	0.109	0.029	0.043	0.054	0.079	0.026	0.065	0.055	0.031	0.056
B	External Drive Capacity	0.116	0.109	0.258	0.129	0.162	0.238	0.077	0.195	0.491	0.463	0.224
B	Stand Mass	0.162	0.109	0.029	0.129	0.162	0.238	0.077	0.065	0.055	0.031	0.106
B	Accessibility to wires	0.116	0.141	0.029	0.216	0.054	0.079	0.077	0.065	0.055	0.031	0.086
B	Structural Cost	0.162	0.141	0.258	0.129	0.162	0.079	0.232	0.195	0.164	0.278	0.180
B	Accessible Materials	0.162	0.109	0.258	0.129	0.162	0.048	0.232	0.195	0.055	0.093	0.144
	Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

As a further check against bias, the criteria weights are then checked for consistency using the process outlined below.

The first step involves finding the weighted sum vector. The formula for this is shown below.

Weighted Sum Vector (WSV) = [Criteria Comparison Matrix] *{Criteria Weights} (1)

This equation resulted in a 10 x 1 vector for Team 517 that shows the relative importance of each of the team's selection criteria. A consistency vector is then created by using the formula shown below.

Consistency Vector (CV) = {Weighted Sum Vector}/{Criteria Weights} (2)

This results in another 10 x 1 vector for Team 517. The average consistency value (λ) is then calculated by averaging the values from the consistency vector. Using λ, the consistency index (CI) is calculated using the formula below.

$$\mathrm{CI} = \frac{\lambda - n}{n-1} \quad (3)$$

In this equation, n represents the number of selection criteria. Then, as the final step, the consistency ratio (CR) is calculated using the formula below.

$$CR = \frac{CI}{RI} \quad (4)$$

RI represents the random index value, which for Team 517 is 1.49 because the number of selection criteria is 10. This value is referenced from a table documenting RI values corresponding to the number of selection criteria, specifically for the alternative hierarchy process (Yap & Ho, 2017). This process is documented in the table below.

Consistency Check					
Weighed Sum Vector {Ws} = [C]{W}	{W}	Consistency Vector (CV) = {Ws}./{W}	Average Consistency (λ)	Consistency Index (CI)	Consistency Ratio (CR)
0.233	0.024	9.867	11.240	0.138	0.093
0.150	0.013	11.289			
1.438	0.124	11.588			
0.465	0.043	10.813			
0.608	0.056	10.857			
2.72976007	0.224	12.195			
1.120553396	0.106	10.601			
0.9246192	0.086	10.732			
2.217171757	0.180	12.319			
1.752263204	0.144	12.144			

After the criteria have been checked for consistency, each of the final designs is then compared against each criterion individually. Consistency is checked in the same way using CR, and the only value that changes is RI since the number of selection criteria now corresponds to the number of concepts being analyzed. These comparisons and consistency checks are shown in Appendix F to avoid overcrowding the document. However, the final chosen concepts are outlined in the table below as a refresher.

Concept (Reference #)	Concept Description
1	This thrust stand measures thrust with a piezoelectric force sensor and monitors temperature using a thermocouple, all constructed from stainless steel with smooth, non-porous surfaces. It features a modular design with drainage capabilities and calibrates through wireless communication protocols. To ensure accuracy, the system employs error-correcting codes, feedback control systems, and data validation, mounted vertically on a vertical stand for precise measurements.
2	This thrust stand measures thrust with strain gauge load cells and monitors temperature using a thermocouple, all constructed from stainless steel with smooth, non-porous surfaces. It features a modular design with drainage capabilities and calibrates through wireless communication protocols. To ensure accuracy, the system employs error-correcting codes, feedback control systems, and data

	validation, mounted vertically on a seesaw stand for precise measurements.
5	This thrust stand uses a piezoelectric force sensor to measure thrust and a thermistor for plume temperature, with the thruster vertically mounted to compress the sensor for voltage output. Constructed from composite materials, it includes wireless calibration, error correction, data validation, and a modular design with drainage surfaces for easy cleaning.

Once the normalized comparison tables for each criterion are created, the design alternative priority (Pi) values are listed out in a final rating matrix. These Pi values are representative of the criteria weights associated with the initial comparison matrix. The final rating matrix for Team 517 is listed below.

[Pi] Final Comparison Matrix				
	Analytical Hierarchy Process	A	A	A
B	**Engineering Charactersitic**	1	2	5
B	Sampling/ Processing Rate	0.333	0.333	0.333
B	Thrust Sensor Uncertainty	0.692	0.231	0.077
B	Maximum Thrust Allowed	0.455	0.091	0.455
B	RAM Allocation	0.333	0.333	0.333
B	Connections directed through terminal blocks	0.333	0.333	0.333
B	External Drive Capacity	0.333	0.333	0.333
B	Stand Mass	0.260	0.106	0.633
B	Accessibility to wires	0.429	0.143	0.429
B	Structural Cost	0.633	0.260	0.106
B	Accessible Materials	0.429	0.429	0.143

This matrix is then manipulated into a final rating matrix using the equation below.

$$\text{Alternative Value} = [Final\ Rating\ Matrix]^T .* \{W\} \quad (5)$$

Here the final rating matrix gets transposed and multiplied by criteria weight vector established during the initial criteria comparison matrix. The following table documents the outcome of this process.

Concept	Alternative Value
1	0.421
2	0.262
5	0.317

According to the table, concept 1 fulfills the design criteria the best. This concept is discussed and shown below in the final selection section. By comparing criteria against one another and then weighing those criteria in terms of each concept, Team 517 was able to find what concept they will use to further development of this project.

Final Selection

A conceptual rendering of concept 1 is shown in the figure below.

References

Yap, Jeremy & Ho, Chiung Ching & Yee, Ting. (2017). Analytic Hierarchy Process (AHP) for business site selection. AIP Conference Proceedings. 2016. 10.1063/1.5055553.