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BUILDING A DESIGN DECISION METHODOLOGY BY COMBINING QUANTITATIVE AND QUALITATIVE METHODS - A CASE STUDY FOR CENTRAL CYLINDER DESIGN SELECTION

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ABSTRACT

Showed and used methodology herein provides a new perspective for designers and researchers to distinguish the best design, by using Hierarchical Tree, Belief Map, Decision Matrix and Eleven Point Scaling methods. In this study, the aforementioned methods are improved by a combination of quantitative evaluation techniques to obtain a complete decision making methodology. This methodology is specifically designed for the case of selecting the best option between various central cylinder types for communication satellite.

Objective of the study is to determine a selection methodology amongst various design options of a central cylinder (CC), which is used as main structural element of the satellite primary structure. In this study, designed CC is expected to be used in a communication satellite. The study also aims to improve the objectivity of design option selection methodologies in the field. The most commonly used method, Decision Matrix, is improved by using analysis results in the evaluation of the measurable criteria. In order to be compatible with space systems design applications, Eleven Point Scaling categories are redefined. A belief map is planned to use for subjective evaluation of the design options and search for team consensus.

INTRODUCTION

The structural subsystems of a spacecraft should be designed according to low weight, high strength and local and global stiffness considerations in order to withstand the static, dynamic, acoustic, thermal and shock loads, which intensely occur during and after launch phase. To carry aforementioned loads without causing a malfunction, the primary structure of the spacecraft is designed according to the operational margins. In order to construct the primary structure, various structural elements can be used: ADM-AELOUS Earth Explorer [ESA, 2005], uses truss structures, Jason-1 Satellite [CNES, 2016] using Proteus platform, skin-frame structures, GSAT-9 [ISRA, 2017], tubular structures can be investigated as sample cases. In this particular study, cylindrical structures are chosen as the most appropriate type of structural elements for a communication satellite, supported with large panel and deck segments. The central cylinder structures have high stiffness, high strength, good rigidity and a compatible cross sectional shape with the launch vehicle adapters and rings. Therefore, the central tube configurations can easily be assembled to the launchers with simple design modifications. Different central tube configuration applications are available, such as Space Systems Loral (MDA) SSL-1300 [RSDO, 2016] communication satellite as a CFRP structure, Express-2000 ISS-Reshetnev [Morozov, 2017] as a grid structure and INTELSAT 4 [Anonymous, 1971] as an aluminum structure representative. Therefore, a unique selection methodology must be generated to determine the appropriate type of central structure that is in accordance with the reference mission.

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METHOD

The selection of the most appropriate concept amongst design options can be divided into six operational steps, which are demonstrated in Figure 1.

Detailed Problem Definition ⇨ Design Option Generation ⇨ Evaluation Criteria Selection ⇨ Robust Decision Making ⇨ The Decision Matrix ⇨ Best Concept

Figure 1: The flowchart for a design option selection process

The process starts with the definition of requirements, which are generally provided to the structural design teams via requirement sets. After the requirement definition, by considering the technological trends and historical development of the technology, design options are generated by the structural design team. In this case study, there exists three kind of design options taken into consideration, which are made of Aluminum, CFRP sandwich and CFRP Grid. These three design configurations are shown representatively in Figure 2.

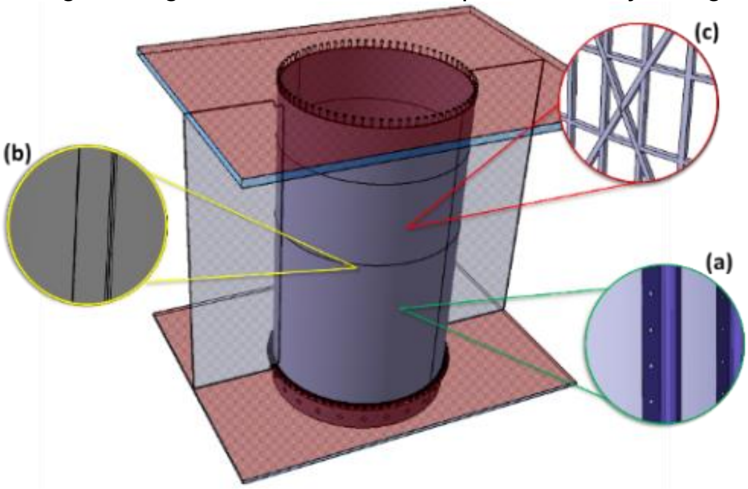


Figure 2: Design options: (a) Aluminum CC, (b) CFRP CC, (c) Grid CC

Based on the requirements and in-house procedures of Turkish Aerospace (TA), such as production capabilities and project management practices, four main evaluation criteria are generated and divided into groups and sub-groups, shown in Figure 3.

Central Cylinder Design Options Selection Criteria

- Overall Structural Properties
  - Weight
  - Stiffness
  - Mass Optimization Capability
  - Thermoelastic Stability
- Material and Physical Properties
  - Environmental Awareness (Outgassing)
  - Environmental Sensitivity
  - Grounding
  - Design Modification Convenience
  - Radiation Shielding
- Production
  - Assembly Integration
  - Structural Unity
  - Damage Tolerance
  - Material Cost
  - Domestic Production Availability
- Technology
  - Know-How
  - Potential Use for Future Projects
  - Market Trend

Figure 3: Selection Criteria of Design Options for Central Cylinder

The relative importance of each criterion to the overall project requirements is determined by using Hierarchical Objective Tree method. The Weighting Factors related to evaluation criteria are defined in a detailed manner and represented in Table 6. The criteria are ordered according to their contribution to the overall evaluation and the ones that have highest contribution are used in a robust decision making methodology called Belief Map to observe whether there exists group consensus. The design solutions are evaluated by using Pugh's Method (Decision Matrix), the weighting factors and Eleven-Point Rating Scales. The rating scales are redefined in accordance with the spacecraft applications and are given with the verbal definitions in Table 3. For measurable (objective) criteria, analysis and calculations on the design options are performed and the results are included instead of the rating scales on the decision matrix, given in Table 7. The highest scored overall concept is chosen as the best one.

The Evaluation Criteria Modifications

Material Cost Criterion Evaluation: The cheapest material cost value between the design options is rated "10" in the decision matrix. The design option that uses the most expensive material is rated "0". The rating values for mid-values of material cost are determined by linear interpolation.

Weight Criterion Evaluation: A benchmark study is performed over 11 composite central cylinder structures being already used in the market and produced by RUAG, TAS, SAFRAN-AIRBUS and MELCO. The found mass/length ratios of commercial composite cylinders are used as average values for grid structures. For CFRP average value, design margin of 15% is added whereas margin of 30% is added for the Aluminum average value. Since the products on market are already optimized solutions, for a conceptual design solution, average mass limit is increased by 6% and this value is taken as mass upper limits. The upper limits are assigned with rating of 0 whereas the average mass values have rating of 2 in the evaluation. The rating value of 10 is assigned to the mass lower limits and they are calculated by using linear extrapolation between mass upper limit and average mass values. The mass limits and average values are calculated by using equation (1) and presented in Table 1.

$$\mathbf{Mass_{limit}} = \left(\mathbf{mass}/\mathbf{length}\right) \times \mathbf{length} \qquad (1)$$

Table 1: Mass limit conditions for weight criterion evaluation.

Cylinder Design Option	Mass/ Length Ratio	Mass Upper Limit (kg)	Mass/ Length Ratio	Average Mass (kg)	Mass Lower Limit (kg)
Aluminum	27.6	77.3	26	75	65.8
CFRP	24.4	68.3	23	65	51.8
Grid	21.2	59.4	20	56	42.4
RATING	**-**	**0**	**-**	**2**	**10**

In this study, mass values are calculated without considering the fasteners and other joining elements such as brackets, inserts. All rating values for design options are assigned by using linear interpolation between exact value and the average / limit values.

Stiffness (Rigidity) Criterion Evaluation: Natural frequency analysis is performed for each design option. Vega, Soyuz, Atlas, Ariane 5, Proton M and Falcon 9 are determined as launcher candidates. The maximum and minimum values for lateral and axial frequencies are taken as the rating boundaries for evaluation. For the mid-values of natural frequencies, linear interpolation is performed to assign a rating value. The results are given in Table 2.

Table 2: Frequency boundaries of selected launchers and corresponding rating values.

Cylinder Design Option	Lateral Frequency [Hz]	Rating	Axial Frequency [Hz]	Rating
Maximum - boundary	15.0	**7**	35.0	**3**
Minimum - boundary	8.0	**0**	15.0	**0**

Table 3: Modified Eleven-Point Scale Verbal Definitions

CRITERION	Eleven - Point Scale 10	9	8	7	6	5	4	3	2	1	0
Design Modification Convenience	Easy to modify				Requires additional analysis			Requires re-production			Not appropriate for modification
Assembly Integration	Single part			Standard parts				Special design parts			Process details are not known yet
Thermoelastic Stability	Perfect stability		High stability		Moderate stability			Low stability		Unstable	Not predictable
Radiation Shielding	Perfect shielding			Good shielding			Moderate shielding			Poor shielding	Not predictable
Structural Unity	Compact design					Few sub-components					Too many sub-components
Potential Use for Future Projects	Being already used in current projects	Appropriate for current projects		Planned to be used			May be used due to market trend				No use in upcoming projects
Market Trend	Suggested as the future technology		High demand potential			Moderate demand potential			Low demand potential		Outdated
Mass Optimization Capability	Easy optimization				Requires additional effort			Limited optimization			Cannot be optimized
Environmental Sensitivity (Moisture, Cleanliness)	Not sensitive		Low sensitivity		Moderate sensitivity			Special requirements		High sensitivity	Cannot be predicted
Environmental Awareness (Outgassing)	Very low outgassing rate				Moderate outgassing rate					High outgassing rate	Cannot be predicted
Grounding	Does not require	Good conductive		Semi-conductive		Poor Conductive		Grounding required	Special design needed		Cannot be grounded
Know-How	Already exists	Current study		Global technology trend		May improve company abilities					Not useful
Domestic Production Availability	All parts are available	Onlyonly in-house production		Only local subcontactors available			Only international subcontractors				Cannot be produced without further development
Damage Tolerance	Very high capability		High capability		Moderate Capability			Reinforcement needed	Low capability		No capability

Decision Matrix and Calculations

A representative decision matrix is given in Table 4. The criteria groups are given in the first column whereas each sub criteria is given in the rows of the sheet. There exists eight parameters included in the decision matrix which are represented in Table 5.

Table 4: Representative Decision Matrix

Criteria Group	Criteria	Weight	Concept 1						Concept 2							Concept o					
			Score	Rating	Evaluator 1	Evaluator 2	…	Evaluator p	Score	Rating	Evaluator 1	Evaluator 2	…	Evaluator p		Score	Rating	Evaluator 1	Evaluator 2	…	Evaluator p
Criteria Group 1	Criterion 1	Wc_1	S_1	r_1	r_{11}	r_{12}	⋯	r_{1p}	S_1	r_1	r_{11}	r_{12}	⋯	r_{1p}		S_1	r_1	r_{11}	r_{12}	⋯	r_{1p}
	Criterion 2	Wc_2	S_2	r_2	r_{21}	r_{22}	⋯	r_{2p}	S_2	r_2	r_{21}	r_{22}	⋯	r_{2p}		S_2	r_2	r_{21}	r_{22}	⋯	r_{2p}
	Criterion 3	Wc_3	S_3	r_3					S_3	r_3					…	S_3	r_3				
Criteria Group 2	Criterion 4	Wc_3	S_4	r_4	r_{41}	r_{42}	⋯	r_{4p}	S_4	r_4	r_{41}	r_{42}	⋯	r_{4p}		S_4	r_4	r_{41}	r_{42}	⋯	r_{4p}
	Criterion 5	Wc_5	S_5	r_5	r_{51}	r_{52}	⋯	r_{5p}	S_5	r_5	r_{51}	r_{52}	⋯	r_{5p}		S_5	r_5	r_{51}	r_{52}	⋯	r_{5p}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮		⋮	⋮	⋮	⋮	⋱	⋮
Criteria Group m	Criterion n	Wc_n	S_n	r_n	r_{n1}	r_{n2}	⋯	r_{np}	S_n	r_n	r_{n1}	r_{n2}	⋯	r_{np}		S_n	r_n	r_{n1}	r_{n2}	⋯	r_{np}
	SUM	1.00	CS_1						CS_2							CS_o					

Table 5: Decision Matrix member definitions

Member of Decision Matrix	Abbreviation	Calculated by
The weighting factors for the evaluation criteria groups	$W_{j,}$	Table 6
The weighting factors for each criterion	w_i	Table 6
Each evaluation criterion being evaluated by the k^{th} group member	r_{ik}	-
Rating value: average of each team member's individual rating	r_i	Equation 2
Weighted rating for each criterion	R_i	Equation 3
Weighted contribution of each criterion	Wc_i	Equation 4
Overall score of each criterion	S_i	Equation 5
Overall score of a concept	CS_l	Equation 6

In equations (1) to (5):

- "i" represents the i^{th} criterion, ranging from 1 to number of criterions used during evaluation, "n"
- "j" represents the j^{th} criteria group, ranging from 1 to number of criteria groups used during evaluation, "m"
- "k" represents the k^{th} evaluator, ranging from a single evaluator, 1 to number of team members evaluating the criteria, "p"
- "l" represents the l^{th} concept amongst the number of concept being evaluated, "o".

$$\boldsymbol{r_i = \frac{\sum_{k=1}^{k=p} r_{ik}}{p}} \quad (2)$$

$$\boldsymbol{R_i = r_i \times w_i} \quad (3)$$

$$\boldsymbol{Wc_i = w_i \times W_j} \quad (4)$$

$$\boldsymbol{S_i = R_i \times Wc_i} \quad (5)$$

$$\boldsymbol{\sum_{i=1}^{i=n} S_i = CS_l} \quad (6)$$

The weighted contribution of each criterion are demonstrated in Table 6. The weighted contribution is the indicator of individual contribution of a single criterion to the overall evaluation process. By going over the results, it can be concluded that Weight and Stiffness have the highest contribution to the overall evaluation process (1/5 in total), followed by Design Modification Convenience, Assembly Integration and Material Cost.

Table 6: The weighting factors and weighted contribution values.

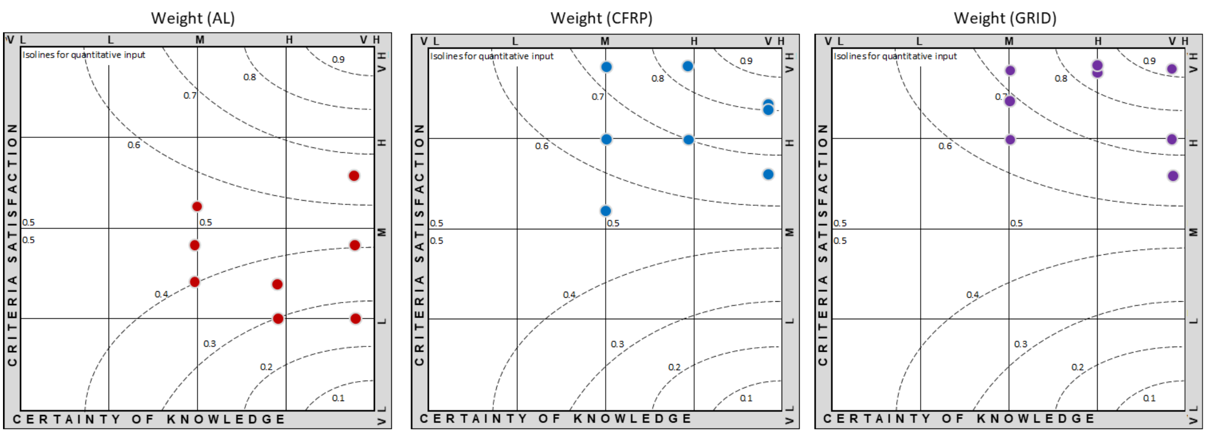
Criteria Group	Criteria		Weighted Contribution
Overall Structural Properties	Weight	0,30	0,10
	Stiffness (Rigidity)	0,30	0,10
0,33	Mass Optimization Capability	0,18	0,06
	Thermoelastic Stability	0,22	0,07
Material and Physical Properties	Environmental Awareness (Outgassing)	0,14	0,04
	Environmental Sensitivity	0,20	0,05
	Grounding	0,12	0,03
0,27	Design Modification Convenience	0,28	0,08
	Radiation Shielding	0,26	0,07
Production	Assembly Integration	0,30	0,08
	Structural Unity	0,25	0,06
	Damage Tolerance	0,05	0,01
0,25	Material Cost	0,30	0,08
	Domestic Production Availability	0,10	0,03
Technology	Know-How	0,20	0,03
0,15	Potential Use for Future Projects	0,40	0,06
	Market Trend	0,40	0,06
		SUM	1,00

RESULTS AND DISCUSSION

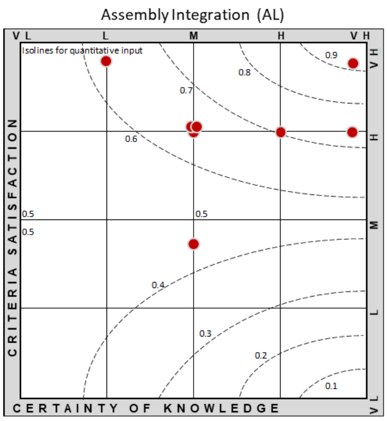
Robust Decision Making: Belief Maps

In belief maps, the horizontal axis represents expertise level of evaluator whereas the vertical axis is the rating value assigned by the evaluators. There exist contour lines between the values of 0.1 to 0.9. These contour lines indicate the average rating value of evaluators. For the evaluation results of a sub criterion, if many of the rating points are accumulated around a contour line, it means that the evaluation group has a consensus on the score value of the design alternative. If there exists a rating point separate from the others, it indicates that this rating value must be questioned and (may be) omitted. If the rating points are scattered on the graph, it means that the group has different ideas on the satisfaction of the criteria and either the criteria must be re-explained to the group or additional evaluators who are experts on that significant field must be invited in the project group.

Amongst seventeen evaluation criteria, the ones that have the major contribution to the overall evaluation are weight, assembly integration, stiffness, design modification convenience, structural unity, thermoelastic stability and radiation shielding. These criteria results are chosen to be demonstrated as belief maps in Figure 4 (a-w).



(a) (b) (c)



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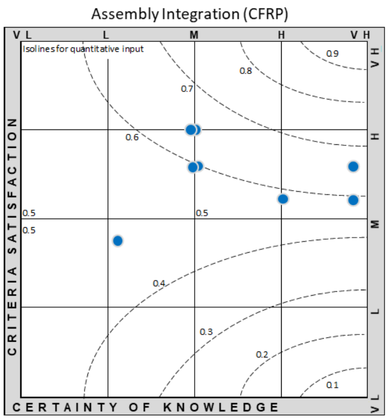

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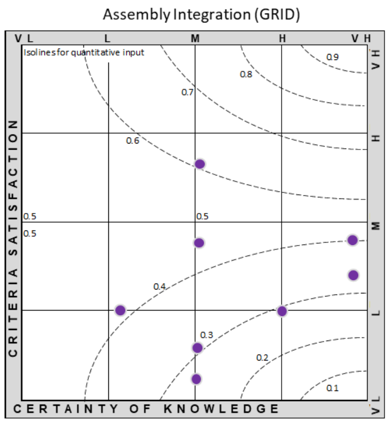

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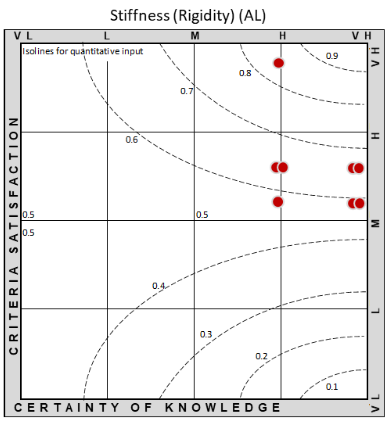

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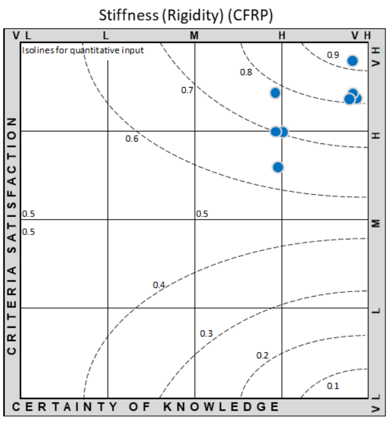

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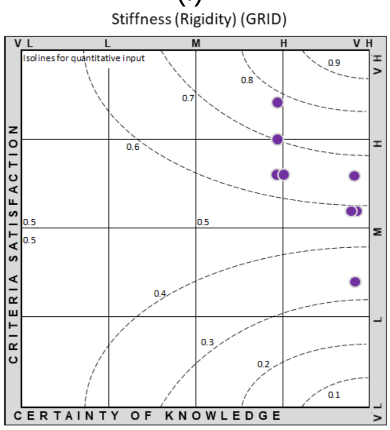

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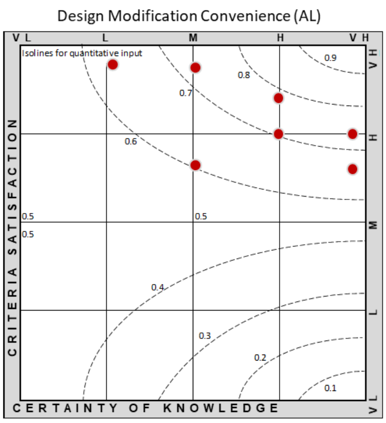

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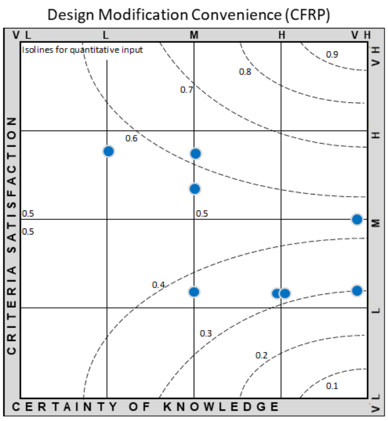

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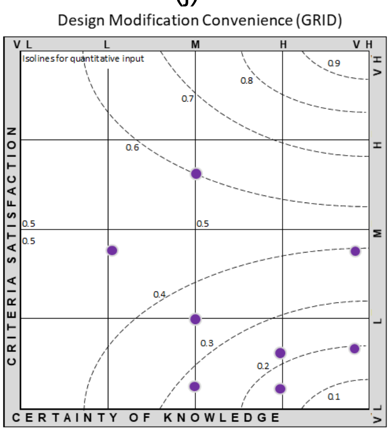

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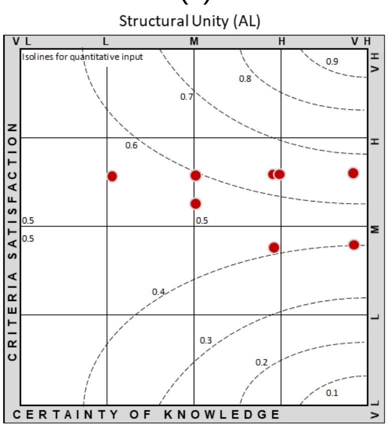

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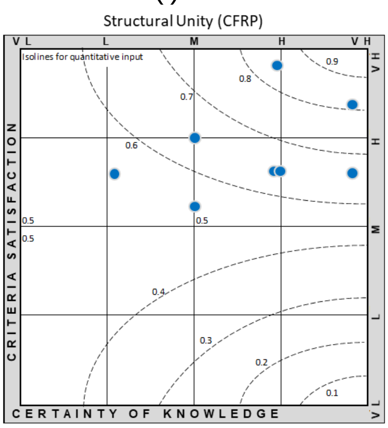

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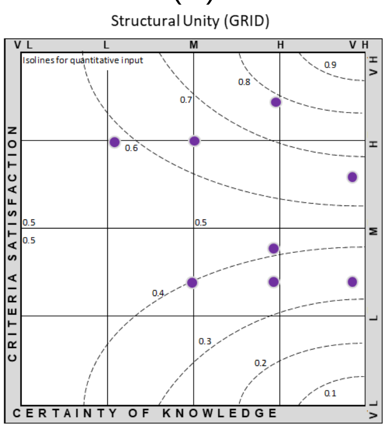

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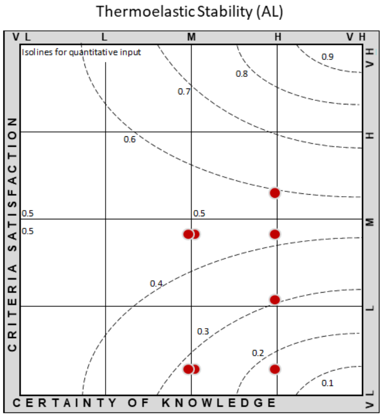

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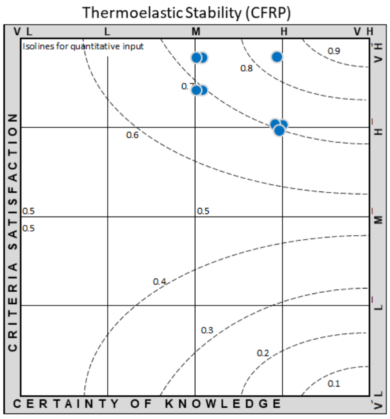

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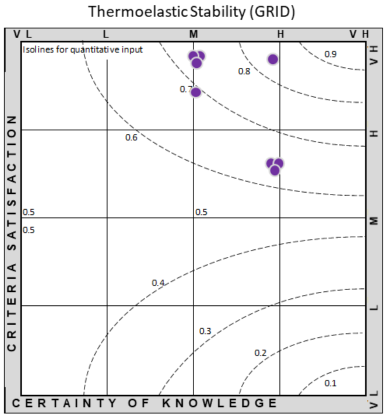

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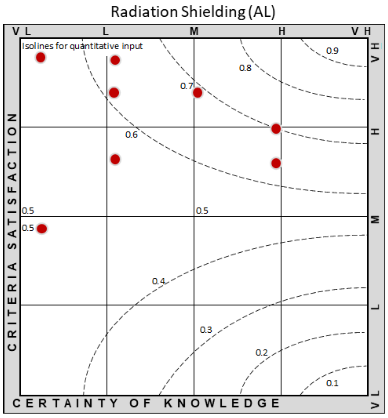

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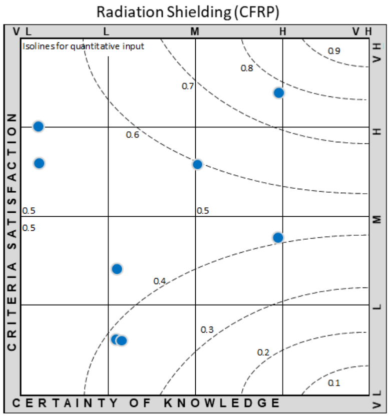

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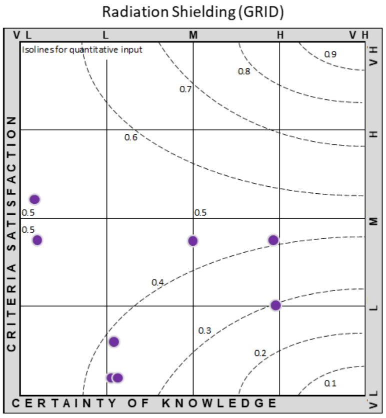

(w)

Figure 4: (a-w) belief maps of selected evaluation criteria.

<u>Weight</u>

The group decision for the weight criterion is that the most convenient option for a lightweight central cylinder is CFRP Grid configuration followed by the CFRP. Aluminum concept does not satisfy the group expectations on weight.

<u>Assembly Integration</u>

The evaluation group is mostly satisfied with the aluminum Central Cylinder on assembly integration whereas the opposite stands for Grid Central Cylinder. Regarding the CFRP configuration, the satisfaction level of evaluation group is slightly positive.

<u>Stiffness (Rigidity)</u>

The individual evaluations for stiffness (rigidity) of the group for all design concepts are consistent with each other. The order of design concepts by decreasing satisfaction level is CF followed by Aluminum and Grid.

<u>Design Modification Convenience</u>

The criteria satisfaction levels of individuals are scattered through the map, which indicates that evaluation group has no consensus on the design modification. However, a rough ordering from the most satisfactory design option to the least one can be given as followed: Aluminum, CFRP and Grid.

<u>Structural Unity</u>

The evaluation group has slightly positive belief in Aluminum Central Cylinder configuration on structural unity whereas CFRP Central Cylinder design option is satisfactory on the evaluation group expectations. The responses for Grid Central Cylinder appear to be scattered through the map which indicates that the group has a low level of knowledge on the field. Therefore, evaluation of the Grid configuration can appear highly subjective on the following steps.

Thermoelastic Stability

It can be seen from the belief map that there exists no expert on thermoelastic stability in the evaluation group. However, the individual responses of the evaluators are accumulated in certain belief levels for the Grid and CFRP design options. The group satisfaction on CFRP Central Cylinder is slightly stronger than the Grid one. For the Aluminum Central Cylinder option, the group has no consensus and low trust in the design for thermoelastic stability.

Radiation Shielding

Similar to thermoelastic stability, there exists no expert on this field in the evaluation group. Even though the group has no consensus on the radiation shielding criterion for CFRP design, the group appears to be neutral for using CFRP central cylinder for radiation shielding. In contrast with the Grid Central Cylinder configuration, the group belief on using Aluminum Central Cylinder is positive.

The Decision Matrix Results

In this study, the evaluation team consists of eight people: E_1, Structural Design Engineering Manager, E_2, System Engineering Manager, E_3, Assembly and Integration Head Engineer, E_4, Senior Analysis Engineer, E_5, Experienced Structural Analysis Engineer, E_6, Experienced Structural Design Engineer, E_7, Structural Design Engineer, E_8, Structural Analysis Engineer. The Decision Matrix results are given in Table 7.

Table 7: The Decision Matrix Evaluation Results for Central Cylinder Design Options

CRITERIA GROUP	CRITERIA	Wc_i	Alternative 1 (AL)										Alternative 2 (CFRP)										Alternative 3 (Grid)									
			S_i	r_i	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	S_i	r_i	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	S_i	r_i	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
Overall Structural Properties	Weight	0,10	0,69	7,00									0,89	9,00									0,89	9,00								
	Stiffness	0,10	0,99	10,00									0,99	10,00									0,79	8,00								
	Mass Optimization Capability	0,06	0,44	7,38	8	6	10	7	7	7	7	7	0,45	7,50	9	8	10	8	7	5	5	8	0,33	5,50	5	10	5	3	4	6	7	4
	Thermoelastic Stability	0,07	0,25	3,38	6	5	5	3	1	1	1	5	0,65	9,00	8	10	10	8	10	9	9	8	0,64	8,75	7	9	10	7	10	10	10	7
Material and Physical Properties	Environmental Awareness	0,04	0,33	8,75	9	10	10	8	8	9	8	8	0,20	5,25	5	8	5	3	1	7	7	6	0,18	4,88	3	7	5	3	1	8	7	5
	Environmental Sensitivity	0,05	0,45	8,25	8	9	10	8	8	7	8	8	0,30	5,50	5	6	5	5	7	6	5	5	0,26	4,75	7	7	5	4	4	3	4	4
	Grounding	0,03	0,31	9,50	8	10	10	10	10	10	9	9	0,11	3,38	5	5	5	3	1	1	2	5	0,09	2,88	2	5	5	3	1	1	2	4
	Design Modification Convenience	0,08	0,63	8,38	8	7	10	7	10	8	9	8	0,35	4,63	5	7	7	3	3	3	3	6	0,25	3,25	2	7	5	5	1	1	2	3
	Radiation Shielding	0,07	0,57	8,13	7	9	10	8	7	10	9	5	0,39	5,50	9	7	7	5	4	2	2	8	0,25	3,50	5	5	5	3	1	1	2	6
Production	Assembly Integration	0,08	0,61	8,13	8	8	10	8	10	8	8	5	0,51	6,75	6	8	7	6	5	7	7	8	0,28	3,75	4	5	5	3	3	1	2	7
	Structural Unity	0,06	0,40	6,38	7	7	7	5	5	7	7	6	0,48	7,63	9	7	10	7	7	7	6	8	0,38	6,13	4	8	5	7	4	9	8	4
	Damage Tolerance	0,01	0,11	8,88	8	8	10	7	10	10	10	8	0,07	5,25	6	7	7	4	5	3	3	7	0,04	2,88	2	5	3	3	1	2	3	4
	Material Cost	0,08	0,75	10,00									0,53	7,00									0,23	3,00								
	Domestic Production Availability	0,03	0,19	7,75	8	8	9	8	7	7	8	7	0,18	7,25	8	7	9	7	8	6	6	7	0,11	4,38	5	6	4	4	3	4	5	4
Techno logy	Know-How	0,03	0,28	9,25	7	10	10	10	10	9	9	9	0,20	6,50	8	9	7	8	6	3	4	7	0,11	3,63	9	1	5	6	1	1	2	4
	Potential Use for Future Projects	0,06	0,46	7,63	9	8	7	4	8	8	9	8	0,48	8,00	7	8	10	8	7	8	7	9	0,26	4,38	4	7	5	7	3	2	3	4
	Market Trend	0,06	0,31	5,13	8	5	7	3	7	2	3	6	0,43	7,13	7	6	7	8	7	7	7	8	0,44	7,38	8	6	5	9	2	10	10	9
	SUM	1,00	7,76										7,18										5,52									

Selected Design Option

The best concept is determined as the Aluminum Central Cylinder structure. Since the concept score of CFRP Central Cylinder Structure is close to the best one, it is useful to re-evaluate some of the criteria or improve a detailed criteria list specifically to compare these two design options.

CONCLUSION

The most important finding of this study is combining four main methodologies of concept evaluation and decision making in one complete methodology: The Decision Matrix, Hierarchical Tree Method, Belief Map and Eleven-Point Scaling. Even though this project is specifically generated for spacecraft design, the methodology can be used in any field with modifications.

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