Research Article

Faris M. AL-Oqla* and Mohammed T. Hayajneh

Hybrid material performance assessment for rocket propulsion

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Abstract: Fuel based on hybrid green material is of paramount importance for various military and civilian purposes. This work presents a novel expert-based multi-criteria hierarchy and decision-making model to evaluate various chemical rocket propulsion technologies with different fuel material types under an uncertain environment. This helps select the most appropriate fuel material types according to the performance requirements considering various evaluation criteria toward achieving better performance economic benefits of the sustainable hybrid green material-based fuel for various applications. Here, the analytical hierarchy process model was utilized to enhance more informative decisions from both numerical and linguistics information regarding the performance of the fuel based on hybrid green material under an uncertain environment. The model considers various simultaneous evaluations and conflicting criteria to practically demonstrate economic, technical, and sustainable issues for the decision makers in this field. Results demonstrate that cost and size criteria are the most important in the evaluation process from experts' points of view for the rocket propulsion technology. The fuel based on hybrid green material has the highest priority regarding the whole evaluation criteria. The sensitivity analysis illustrates the robustness of the model as well as the reliability of the drawn decisions.

Keywords: hybrid materials, green fuel, rockets, sustainable technology, hybrid fuel, environment

*** Corresponding author: Faris M. AL-Oqla,** Department of Mechanical Engineering, Faculty of Engineering, The Hashemite University, P.O box 330127, Zarqa 13133, Jordan, e-mail: Fmaloqla@hu.edu.jo
Mohammed T. Hayajneh: Industrial Engineering Department, Faculty of Engineering, Jordan University of Science and Technology, Jordan, e-mail: hayajneh@just.edu.jo
ORCID: Faris M. AL-Oqla 0000-0002-6724-8567; Mohammed T. Hayajneh 0000-0001-8328-2071

1 Introduction

Significant efforts have been made worldwide to practically prepare green propellants for rockets to replace hydrazine. These hybrid green materials have the potential to provide high-density impulse surpassing the performance of the most commonly used toxic monopropellants [1–4]. In the last four decades, rockets have been utilized increasingly to explore our atmosphere as well as outer space. Many of such uses have been beneficial for civilization, such as placing satellites and tethered satellite systems into orbit [3,5–7]. These satellites have been used for various scientific investigations, communication weather monitoring, and the investigation of the solar system, whereas other types of rockets have been used to explore asteroids, planets, and outer space. Different models and computer calculations are utilized by rocket scientists to predict rocket performance. Simulating launches to test ideas is considered much cheaper and faster than building a new rocket each time. Several factors and criteria can influence the performance of rockets, which is a kind of multi-criteria problem. One of the major criteria that influence chemical rocket technology as well as their overall performance is the type of fuel used whether it is liquid, solid, or hybrid [7,8].

Chemical rocket engines use fuel and an oxidizer that reacts with the fuel to form the propellant. Once the propellant reacts inside the combustion chamber, hot gasses are produced and utilized to create the rocket [1,2,9,10]. The fuel and oxidizers can be kept in different forms such as solids, liquids, or a mixture of both as a hybrid. The main three types of chemical rocket propellants are shown in Figure 1, which shows how the fuel and oxidizer are pumped together into the combustion chamber. Hybrid solid fuel grains are typically produced in the shapes of long cylinders with internal ports that run the length of the grain. The liquid oxidizer then runs through these ports to balance the fuel and oxidizer like nitrous oxide. Then the produced heat makes the mixture produce high chamber pressures to yield thrust. The two different states of the liquid oxidizer and solid fuel make a hybrid rocket, which

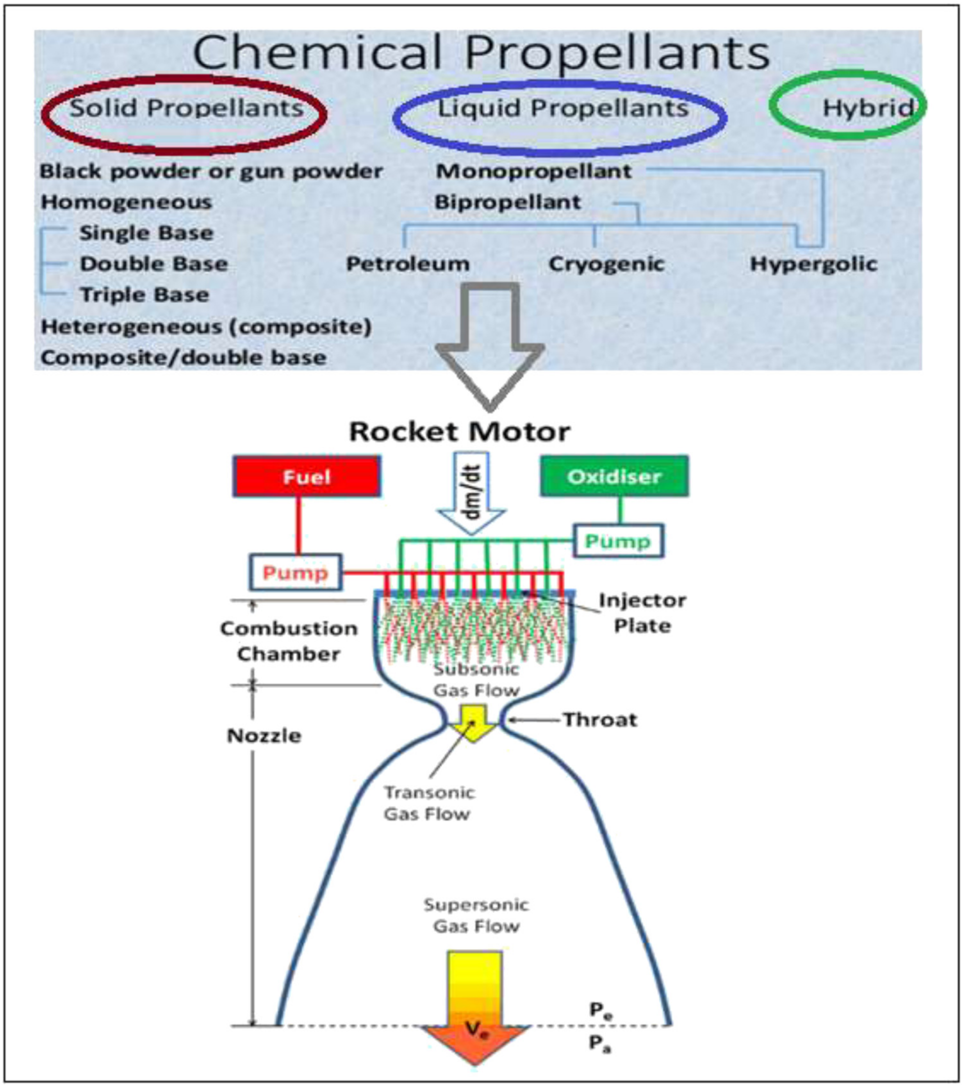

Figure 1: Classification and schematic diagram of rocket propellants.

is much safer than other rocket types. Recent research focuses on producing and developing new material types suitable for high-tech applications including hybrid rocket propulsion. Serving this objective, natural fiber composites are one potential alternative not only for automotive, green factories, and aerospace structure [11–20], but also may be very attractive for the fuel of hybrid rockets, particularly those produced from polypropylene/natural fibers such as the core of rocket's solid-type fuel [21–29].

There are various advantages and disadvantages of these different propellant rockets. For instance, according to typical data that were taken from existing engine [16,25,30–33], the high-performance liquid rockets offer a sea-level specific impulse in the range 270–360 s, whereas hybrid and solid rocket motors offer a specific impulse in the range of 230–270 and 210–265 s, respectively. On the other hand, from a flexibility standpoint, for the solid type, the extinction and re-ignition are hard to realize whereas hybrid and liquid rocket types are much easier to shut down and re-start. On the other hand, the selection of proper fuel was found in the literature using decision-making tools. For instance, Ren and Liang [34] have performed measuring for the sustainability of marine fuels using a fuzzy group multi-criteria decision-making (MCDM) approach. However, other related aspects like gas stations, renewable energy systems, and automotive-related applications were also reported in the literature [35–39].

Thus, it can be deduced that each type of rocket propulsion technology has various responses and characteristics regarding different performance criteria, such as size, range of specific impulse, stability, safety, etc., which affect its overall desired performance. Therefore, this work aimed to implement the analytical hierarchy process (AHP) as an MCDM tool to select the most appropriate rocket propulsion technology in a fairly optimized manner regarding various evaluation criteria.

2 Methodology

This work introduces a multi-criteria hierarchy model that assists in the selection of the most applicable rocket propulsion technology according to the performance requirement regarding various evaluation criteria. Here, the AHP as a tool designed to solve the MCDM problems is utilized.

In decision-making problems, it is common that the information is provided by humans, which is inherently non-numeric. Preferences, partial evaluations, and weights are usually expressed linguistically. Linguistic terms like high and medium are commonly used. It is not clear, however, the way they have to be explained into the entities that can be more flawlessly treated using the formalisms of sets, fuzzy sets, rough sets, and alike. Also, it is not clear what optimization criterion can be intended when reaching the formalization of the linguistic terms through information granules. Here, the AHP model was utilized to enhance more informative decisions from both numerical and linguistics information regarding the performance of the fuel based on hybrid green material under uncertain environment.

2.1 AHP

AHP is a widely used MCDM tool. Unlike the conventional techniques, AHP uses pairwise comparisons which allow verbal judgments that enhance the precision of the result by deriving accurate ratios and scales [40–43]. The AHP method can analyze both personal and impartial assessment methods to enhance the evaluation consistency and minimize bias in decisions [41–46]. For creating complex decisions with multiple criteria, the goal has to be divided into various sub-goals. Therefore, the model has to have at least a goal, evaluation criteria, and various alternatives in three hierarchy levels.

The relative weights in a certain level lead in fact to a matrix of scores $a(i, j)$ that contains the judgment of the pairwise comparisons. Such a matrix must be consistent [43]. Accordingly, a test for ensuring such consistency has to be performed before accepting the matrix to validate the expert knowledge in what is called an

Table 1: Primary information utilized for generating judgment matrix of the rocket substitutions

		Rockets with solid propellants	Rockets with liquid propellants	Rockets with hybrid propellants
Performance (specific impulse range in a s)		210–265	270–360	230–270
Size (mass density kg/m^3)		1,500–1,900	1,000–1,350	1,000–1,200
Stability (ease of starting and steering)		Moderate–difficult	Easy–easy	Easy–difficult
Safety	Explosion sensitivity	Moderate	High	Low
	Controlling the ignition	Difficult	Easy	Easy
	Toxicity	Less harmful	Sever	Moderate
Cost		Cheap	Costly	Moderate
Operability		Needs short time operation	Needs long time operation	Needs moderate operation

inconsistency test. Such a test is valuable for recognizing possible errors in judgments. A matrix $a(i, j)$ is believed to be reliable with no high inconsistencies if all its elements attain the transitivity and reciprocity rules given as follows:

$$a_{i,j} = a_{i,k} \cdot a_{k,j}, \tag{1}$$

$$a_{i,j} = 1/a_{j,i}, \tag{2}$$

where i, j, and k are any options in the judgment in the matrix.

The pairwise comparison matrices can also be represented as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix}. \tag{3}$$

A consistent matrix can be shown to satisfy that:

$$A \cdot w = nw, \tag{4}$$

where A is the evaluation matrix, w is the eigenvector, and n is the size of the matrix. Eq. (4) is a typical eigenvalue problem. For such gained reciprocal matrix, the consistency can be attained if the maximum eigenvalue equals the number of comparisons, i.e., $\lambda_{\max} = n$ [43,47]. Accordingly, a Consistency Index was introduced to measure the deviation from consistency as in Eq. (5):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}. \tag{5}$$

A comparison between the judgment consistency generated from Eq. (6) and the random index leads to the Consistency Ratio as in formula (6):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{6}$$

If the CR value is less than or at a maximum of 0.1, then the judgment inconsistency is acceptable. But, if it is greater than 0.1, the subjective judgment should be revised.

3 Results and discussion

For conducting pairwise comparisons between the alternative rocket types considered in this study, the criteria affecting the rocket performance from different standpoints were determined. The used criteria in this study were namely: the performance (specific impulse [range in a s]), the size (mass density kg/m^3), the stability (ease of starting and steering), the safety, the cost, and operability. The primary information utilized for generating a judgment matrix of the rocket substitutions is demonstrated in Table 1. To ensure the relevance of the evaluation criteria used in the model, a pilot questionnaire was built and sent to 15 experts in the world to be evaluated. For the hybrid fuel performance evaluation, the generalized performance gain of hybrid fuel is usually unlike solid propellants, since it is not achieved when a polymeric hybrid fuel is improved by hydrides. Best configurations that maximize specific impulses are found in many works in the literature [9,24]. However, to generate a baseline for the experts to compare hybrid and traditional solid fuel performance, the flame temperature, and molar mass that are interpreted in ref. [24] were utilized taking into account the particular ingredients that may be involved for certain details according to testing issues.

In the questionnaire, experts were kindly asked to suggest comments regarding the proposed criteria and to rank their importance in the evaluation process according to their best knowledge. Comments of eleven filled questionnaires were returned. After carrying out the inconsistency assessments, only nine were used in the further calculation for the current model since they demonstrated a high level of consistency. Several considered feedbacks were found sufficient to conduct the analysis using the AHP approach [42,48]. The weight of the evaluation criteria was calculated as shown in Figure 2. It can be seen that the cost criterion has the highest weight in the selection process with a weight of 26.2% followed by the size with a weight of 19.7%, whereas the operability criterion has the lowest weight of

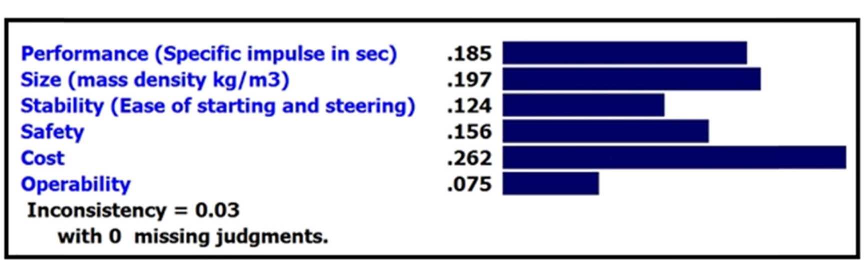

Figure 2: Weights of the main factors with respect to the main goal with inconsistency values.

7.5% leaving only the performance, safety, and stability in intermediate priorities.

The hierarchy model of the current problem with the main goal, criteria, and alternatives is illustrated in Figure 3.

After that, the alternatives were compared with each other for every single criterion used in the hierarchy model as a pairwise comparison scheme. This was performed with the help of typical data that were taken from the existing engines found in the literature [24,25,30–33].

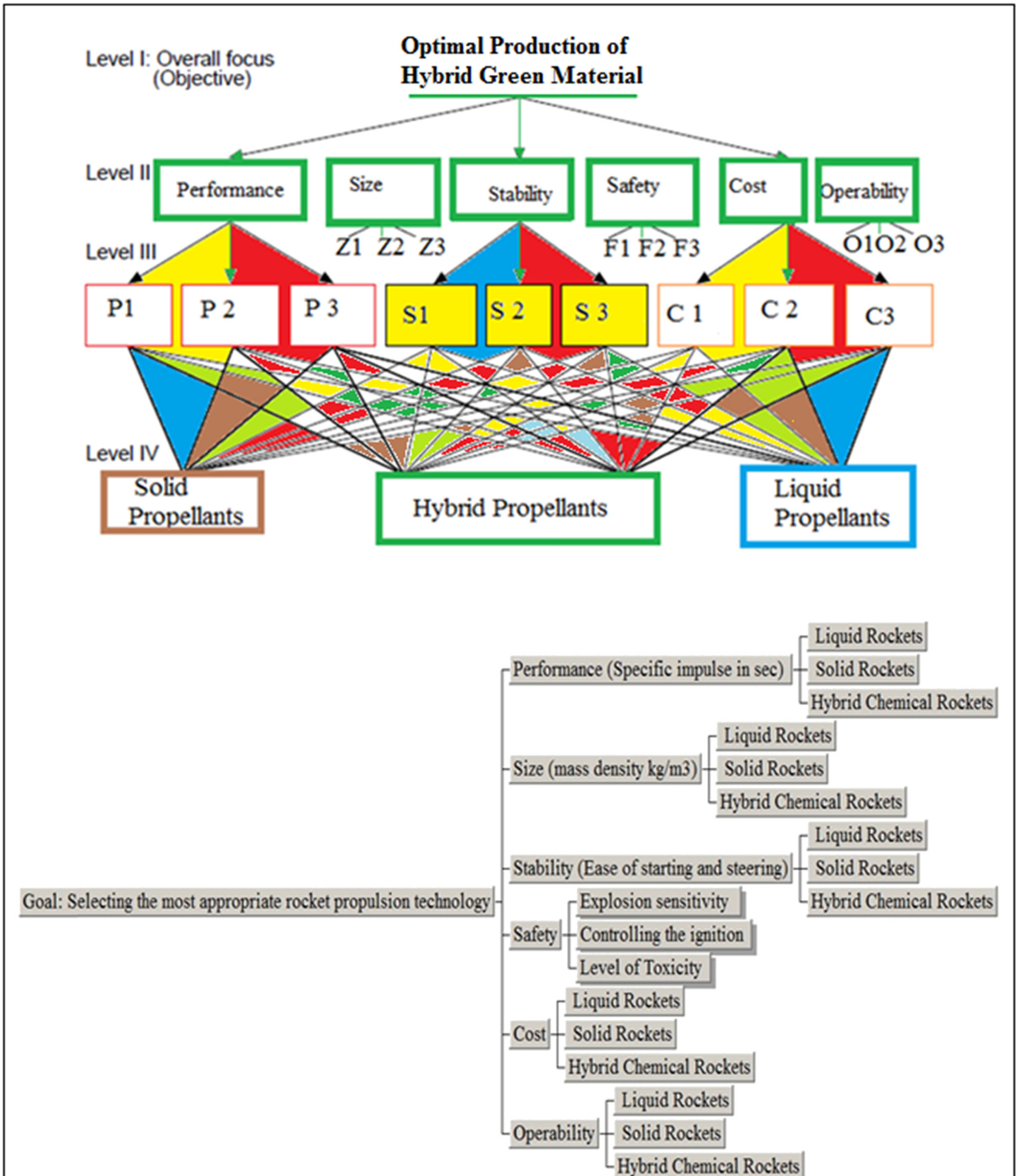

Figure 3: The structure of the model with a tree hierarchy nature.

	Performan	Size (mass	Stability (E	Safety	Cost	Operability
Performance (Specific impulse in sec)		1.0	1.0	1.0	1.0	3.0
Size (mass density kg/m3)			2.0	2.0	2.0	2.0
Stability (Ease of starting and steering)				2.0	2.0	2.0
Safety					2.0	2.0
Cost						3.0
Operability	Incon: 0.03					

Figure 4: Judgment matrix of the main criteria with respect to the goal (Red values mean reciprocals, i.e., the value of 2 in red color means ½.).

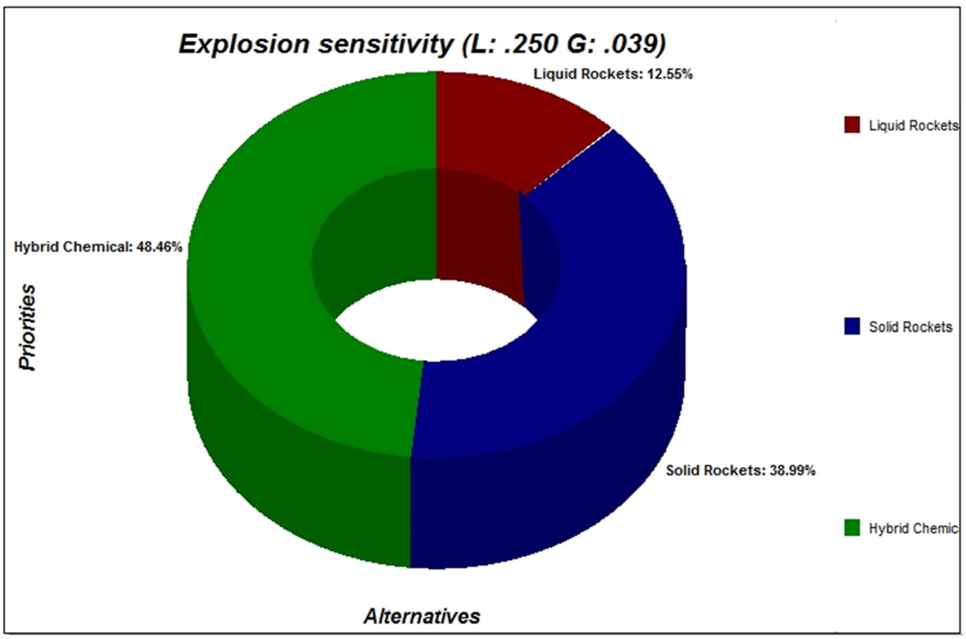

Figure 5: Priorities of the alternatives with respect to the expulsion sensitivity sub-criterion.

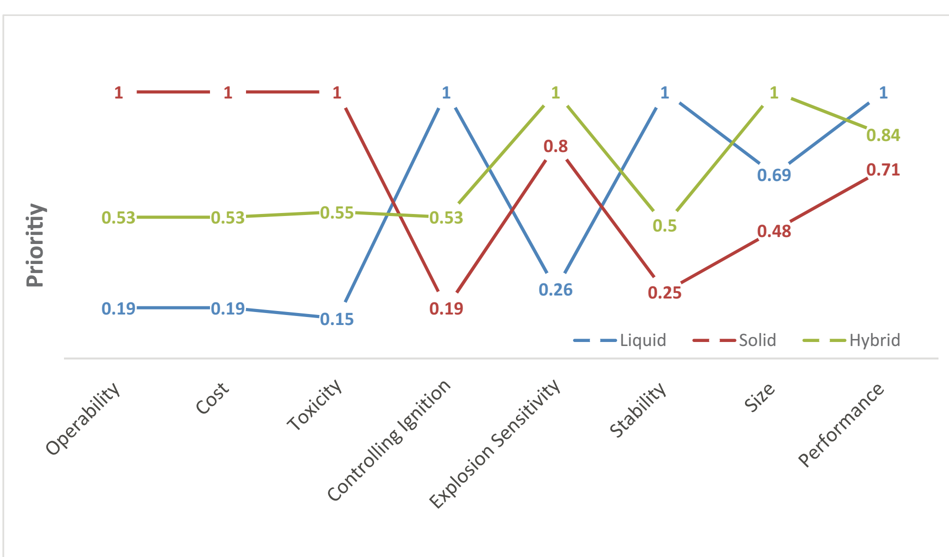

Figure 6: Relative priorities of the alternatives with respect to all criteria in the model.

Table 2: The local and global contributions of each property of the model and their sums

Alt.	Level 1	Total weight	Alt.	Level 1	Total weight	Alt.	Level 1	Total weight
HC	Co.	0.07	**LR**	Co.	0.025	**SR**	Co.	0.133
	Oper.	0.02		Oper.	0.007		Oper.	0.038
	Perf.	0.079		Perf.	0.094		Perf.	0.066
	Saf.	0.052		Saf.	0.047		Saf.	0.043
	S	0.1		S	0.069		S	0.048
	Sta.	0.031		Sta.	0.062		Sta.	0.016

It can be noticed here that 15 judgments wanted to complete the pairwise comparison for major evaluation factors according to the goal for the main six criteria.

The pairwise comparison of the main criteria concerning the goal is illustrated in Figure 4. It can be noticed here that 15 judgments are needed to fill this pairwise comparison matrix for the main six criteria. It can be demonstrated that the judgment matrix used in the evaluation process was consistent with an inconsistent value of 0.03. This value is still less than 0.1, and thus the judgment is acceptable.

Figure 5 demonstrates the priorities of the rocket alternatives regarding the expulsion sensitivity sub-criterion, which contributes immediately to the safety main criterion with 25% and to the whole model with a global priority of 3.4%. Hybrid-type rockets are the most preferable among others with a priority of 48.46% from the explosion sensitivity standpoint, whereas the liquid rocket types have the least priority of 12.55% only. This in order indicates that hybrid types have major advantages regarding not being easily explosive in harsh environments compared to other types.

The relative priorities of the rocket types regarding each criterion used in the model are similarly established in Figure 6. It can be seen that the liquid rocket type is the preferable one regarding the performance, stability, and controlling of the ignition criteria, but the least important one regarding explosive sensitivity, level of toxicity, and operability. Moreover, the solid rocket kind is the best concerning the level of toxicity, cost, and operability criteria but it is the worst regarding the performance, size, stability, and the controlling of the ignition criteria. Furthermore, the hybrid rocket type is the best regarding size and explosion sensitivity but not the worst of any.

In addition, the local (weight of each criterion concerning its direct parent criterion) as well as the global contributions of each property of the model and their overall sums are demonstrated in Table 2.

The final ranking of the alternatives is illustrated in Figure 7. It can be clearly shown that the best choice is in favor of the hybrid chemical rockets with an overall aggregated weight of 35.2% leaving other alternatives behind with weights of 34.3 and 30.5% for both the solid

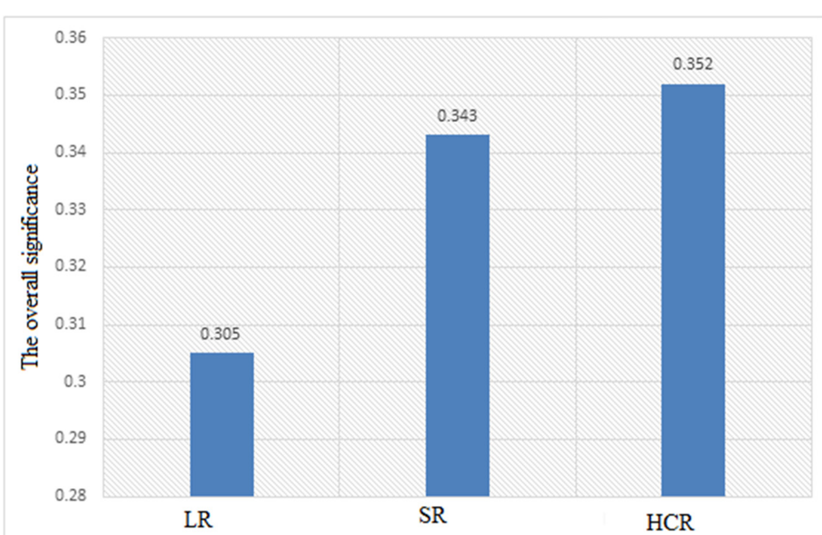

Figure 7: The overall significance of the alternatives regarding the goal.

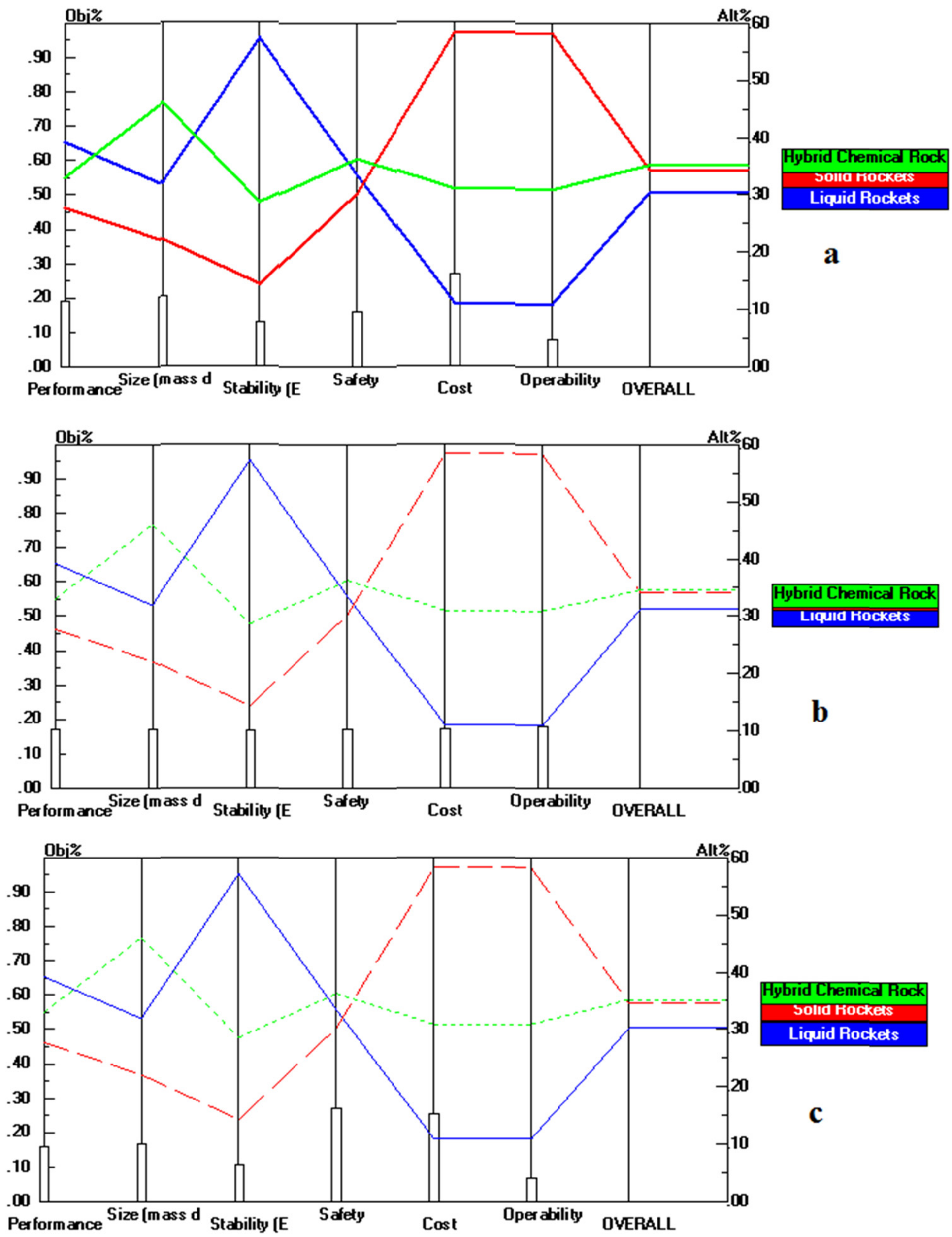

Figure 8: Sensitivity analysis after changing the weights.

and liquid rockets, respectively. It is a worthy noting here that the closeness of the substitutions of the final imports proves that selecting the most appropriate rocket type considering the whole criteria simultaneously is a complex matter and is not an easy job without using such a decision-making model that can reduce error as well as bias in the final decision.

To demonstrate the reliability of the used expert-DM model, a sensitivity analysis was performed. This analysis can answer a systematic question of how will the model respond if the importance of the assessment elements were slightly changed. Performing such sensitivity will start with the current priorities resulting from the expert's feedback on the evaluation criteria. This is illustrated in Figure 8a where the hybrid type is the preferable choice. In a scenario of making the whole evaluation criteria have the same weights (which demonstrates unreasonable changes), the response of the model was stable and kept the hybrid type as the most preferable choice (although the priority values were changed as a response to weigh changing) as seen in Figure 8b. Such response demonstrates that the drawn decisions are reliable and the model is insensitive to a slight change in the criteria weights. Another scenario is illustrated in shifting the importance of both the cost and safety main criteria to exaggerated values (unreasonable change). This is demonstrated in Figure 8c. The hybrid rocket type is still the best choice with a weight of 34.9%. This demonstrates that the gained results are reliable and the decision was consistent.

4 Conclusions

The built hierarchy decision-making model was capable of better evaluating the performance of various types of fuel materials as well as selecting the most appropriate one for the rocket propulsion technology. The model considered various simultaneous evaluations and conflicting criteria to practically demonstrate economic, technical, and sustainable issues for the decision maker in this field. Expert feedback was an extra outcome of this study by capturing the weight of each evaluation criterion. Chemical rocket type with hybrid fuel materials was illustrated to be a potential alternative to the current solid and liquid ones due to its various advantages that were expressed here in a rational base scheme. That is, it was demonstrated by the current expert decision-making model that the hybrid rocket type is the best regarding size and explosion sensitivity but not the worst regarding any of the considered criteria. Moreover, it was shown that the liquid rocket type is the preferable one regarding the performance, stability, and controlling the ignition criteria, but the worst regarding explosive sensitivity, level of toxicity, and operability. Furthermore, the solid rocket type is the best regarding the level of toxicity, cost, and operability criteria but it is the worst regarding the performance, size, stability, and controlling of the ignition criteria. The proposed hierarchy model was successfully implemented to solve the current conflict multi-criteria problem as well as providing a valuable instrument for testing the consistency of the assessment and alternatives, thus, reducing the bias in decision making regarding evaluating different propulsion technologies for chemical rockets.

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