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An approach for space launch vehicle conceptual design and multi-attribute evaluation

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ABSTRACT

This paper presents an approach for space launch vehicle conceptual design and evaluation using multi-attributes decision making analysis. The approach is comprised of morphological matrix method to improve the brain storming process by efficiently identifying potential space launch vehicle design concepts. The potential concepts are screened for compatibility and are then sized for desired mission using Tsiolkovsky ideal velocity rocket equation. The Tsiolkovsky ideal velocity rocket equation supported by mass and propulsion modeling is found to be fast and efficient and is applied for sizing and performance modeling of space launch vehicle at the conceptual design phase. Based on the performance parameters, program related issues and cost attributes, the candidate design concepts are subjected to multi-attribute decision making analysis. This is to rank the alternative design concepts and identify the most promising ones for further considerations. The successful application of the proposed approach in conceptual design and evaluation of space launch vehicle has demonstrated its utility in the early phase of the aerospace system design and decision making.

1. Introduction

Space launch vehicle (SLV) is the key technology to transport satellites from the earth surface to the outer space and position them in specified orbits. In addition to availability of a large number of different SLVs and a large amount of expertise as noted by [21], many new concepts are evolving as the future launch vehicles are being developed. It has been widely recognized that substantial part of the overall product development cost is committed at the conceptual design phases [29,30]. For instance, Qazi and He [26] noted that at least 80% of life-cycle cost of SLV is locked in by the concept that is chosen. Moreover, Koelle [16] pointed out that a future new launch vehicle program will require a clear economic justification. Modern space launch vehicle cannot be designed, built and sold on performance alone and other life-cycle issues must be a fundamental part of the design considerations [28]. Hence, the engineers involved in generating these new concepts not only need to consider the required technical performance of SLV but also need to consider cost, manufacturability, reliability, environmental friendliness and quality of the end product. Most of these issues are dictated by the design concept taken up during the concept generation phases. Thus, the strong effect of concept generation phase on the technical and programmatic aspects entail to adopt various concept generation and evaluation methods. The objective of using such methods is to enrich the existing concept generation approaches and thus be able to select the best design concept at first time and avoid the costly design changes at a later stage. It is in this context that the present study provides a systematic approach of generating and evaluating SLV concepts while simultaneously considering technical performance, program related issues as well as cost attributes. The present work extends our previous research work [35] with the addition of cost modeling approach and an improved evaluation methodology supported by the sensitivity analysis.

2. Literature survey

Space launch vehicle concept generation and evaluation has been the focus of several research studies. Muller and Sebastian [21] developed an approach for preliminary design and configuration task of space launch systems. In the proposed approach knowledge-based system is combined with fuzzy multi-attribute decision making. The approach is intended to provide the design engineer with a tool to support the selection process of optimal alternatives from a set of feasible design alternatives. Dorrington [8] conducted a qualitative study to select the space launch vehicle architecture for the European space agency. Various launch vehicle alternatives were considered and it was concluded that space launch vehicle architectures are difficult to compare qualitatively, yet the various launch vehicle options must be analyzed

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Nomenclature

A^+	Positive ideal solution
A^-	Negative ideal solution
$C_{DDT\&E}$	Design, development, testing and engineering cost of SLV
C_{TFU}	Theoretical first unit cost of SLV
C_f	Thrust coefficient
C^*	Propellant characteristic velocity
cc	Closeness coefficient
d	Distance measure
e	Information entropy
$F_{S/E}$	Stage/engine theoretical first unit cost
f_s	Structural mass ratio
f_p	Propellant mass fraction
g_o	Gravitational acceleration
$H_{S/E}$	Stage/engine development cost
h	Deviation degree
Isp	Specific impulse
M_e	Flow Mach number
m_E	Engine mass
m_N	Mass of nozzle
m_T	Mass of tank
m_{SC}	Mass of stage connections
m_{TF}	Mass of the thrust frame
m_A	Mass of avionics
m_{CAB}	Mass of cables
m_{IF}	Mass of insulations and fitting
m_s	Structural mass
m_{pl}	Payload mass
m_{TVC}	Mass of thrust vector control
m_p	Propellant mass
m_i	Initial mass
m_f	Final mass
P_e	Nozzle exit pressure
P_c	Chamber pressure
r_{ij}	Normalized decision matrix
V_{ij}	Weighted normalized decision matrix
v^+	Best rating of criterion
v^-	Worst rating of criterion
w	Criteria weight
ΔV	Velocity gain
μ	Mass ratio
ε	Expansion ratio
λ	Payload ratio
γ	Specific heat ratio

Acronyms

AP	Ammonium per chlorate
CER	Cost estimating relationship
DOF	Degree of freedom
EW	Entropy weight
HTPB	Hydroxyl-terminated polybutadiene
LH2	Liquid hydrogen
LOX	Liquid oxygen
MY	Man-Year
MADM	Multi-attribute decision making
NIS	Negative ideal solution
PIS	Positive ideal solution
SLV	Space launch vehicle
RP-1	Rocket Propellant-1
WS	Weight scenario

concurrently to select the proper launch vehicle architecture. Villeneuve [36] developed a methodology for quantitative and simultaneous exploration of concept and technology alternatives during the conceptual design phase of space launch vehicle. Several other concept selection methodologies have been adopted for engineering system design concept generation which are likewise applicable to SLV such as decision matrix-based methods [25,22]. Besides there are optimization-based approaches applied to SLV design such as reported in [26,27,14,3,13], etc. Unfortunately, the decision matrix-based methods alone are unable to perform quantitative design space exploration and hence are inefficient for concept selection. On the other hand, optimization-based methods are efficient in dealing with continuous design space exploration but lacks the capability to deal with discrete alternatives.

In present work we strive to improve the SLV concept generation and evaluation approach. Specifically we focus on the following three aspects:

First we assert that during the conceptual design phase, one is concerned to establish the performance trade space for a number of space launch vehicle design concepts, so the vehicle technical performance need to be determined using medium to high fidelity physics-based methods. The use of Tsiolkovsky ideal velocity rocket equation which is applied for launch vehicle staging by a number of studies such as [28,13,34,18] is proposed (see Section 3.4). This will improve the efficiency of the conceptual design process by avoiding three or six DOF trajectory simulations. The velocity losses caused by the external disturbances such as aerodynamic drag, gravity, steering, etc., can be accounted for by introducing reasonable estimates for them which will add up to the required velocity gain and will result in more realistic calculations. Moreover, Jamilnia and Naghash [13] found that the SLV staging based on Tsiolkovsky ideal velocity rocket equation leads to very similar results as compared to the staging based on actual velocity and details of three DOF trajectory optimization.

Secondly, we declare that during conceptual design phase, many criteria (performance and cost) have to be all simultaneously taken into account while some of them are conflicting in nature and hence a compromise becomes essential. This is in contrast to the traditional single objective of maximum performance. With these characteristics, the concept selection problem can be best modeled as multi-attribute decision making (MADM) problem. The MADM methods take into account every single criterion independently and hence are more superior to the traditional overall evaluation criteria (OEC) method.

Thirdly, we believe that conceptual design phase of SLV is characterized by the uncertainties in relevant data and hence the evaluation methodology must be accompanied by sensitive analysis to check the robustness of the results for possible ranges of quantitative data.

3. The proposed approach

The proposed approach as shown in Fig. 1 consists of a number of sequential steps. (1) The mission requirements are defined. (2) A morphological matrix is constructed which contains all possible sub-system level components which when put together form the SLV architecture. (3) The non-compatible architectures which might result from the morphological matrix are excluded. (4) The compatible design concepts are sized and their performances including technical and program related parameters are calculated. (5) Cost calculations are done. (6) Based on performance and cost attributes, the candidate design concepts are subjected to multi-