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HYBRID QUANTITATIVE–QUALITATIVE METHOD FOR TECHNOLOGY PORTFOLIO SELECTION: A CASE STUDY OF IRAN'S SPACE INDUSTRY

Emad Chizari[1], Seyed Hasan Sedighy[2,*], Mir Saman Pishvaee[3] and Adel Azar[1]

Abstract. The space industry is known as an economic driver for many world economies. In Iran, the acquisition of satellite technology knowledge is one of the achievements of the country's scientific and technological indicators in recent years, but the position and importance of optimal investment in this industry in Iran have been ignored. The optimal technology portfolio is one of the tools that can cover this gap and lead to better decision-making by policymakers. In this paper, the optimum technology portfolio determination regarding its goals, attributes and challenges is addressed for Iran's space industry with a hybrid quantitative–qualitative method in two short and medium-term periods. We formulate a technology portfolio selection model with these multi-objective functions: maximization of benefits in using different technologies comprising of both short and medium-term portfolios, maximizing the total summation of all Technology Readiness Levels (TRLs) of technologies, maximizing the acquisition speed for the technologies, and minimizing the acquisition risk of technologies in each portfolio. In the proposed model, the usability, acquisition cost, and complexity of each technology are considered meticulously. Also, the goal programming method is used to integrate the objective functions. Another novelty of this paper is the formulation of two portfolios with two different periods in which their corresponding inputs and outputs affect the other. This research can significantly help in directing the country's investment in the space industry, spatial ecosystem orientation, facilitating the creation of space-based businesses, improving economic growth, and also providing guidelines to improve the related policies in this area. In addition, this research can be an inspiration for other developing countries in the space industry.

Mathematics Subject Classification. 90B50, 90C29, 91G10, 97M50.

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1. Introduction

Extensive technological changes and globalization have influenced organizational structures and increased competition among organizations and countries. The importance of understanding the relationship between technological capabilities and organizational goals is increasing. As a result, technology and innovation management have played significant roles in decision-making processes [38]. Therefore, the importance of technology management makes the use of concepts such as "technology portfolio" more common.

Keywords. Technology portfolio, optimum portfolio, space industry, Iran.

[1] School of Progress Engineering, Iran University of Science and Technology, Tehran, Iran.

[2] School of Advanced Technologies, Iran University of Science and Technology, Tehran, Iran.

[3] School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran.

*Corresponding author: sedighy@iust.ac.ir

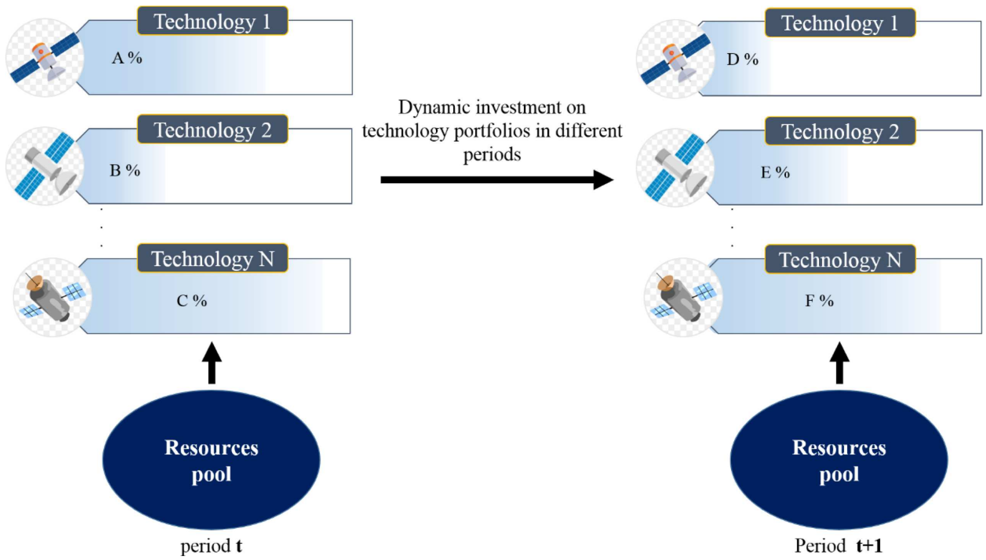

FIGURE 1. Producing dynamic technology portfolios.

In 1952, Markowitz designed a structure that known as the modern portfolio model [10]. The most important role of this theory was to provide a risk-efficiency framework for investors to make better decisions. By quantitatively defining the investment risk, Markowitz provided a mathematical approach for choosing assets and managing portfolios.

This model was based on the following assumption [10].

Investors are risk-averse with increasing expected desirability and a decreasing wealth marginal desirability curve, where they choose their investment portfolio based on expected mean-variance efficiency.

The goal was to minimize the portfolio variance subject to three constraints:

– The first constraint shows the expected efficiency of the portfolio, which is determined by the investor.
– The second one ensures that the total weight of the portfolio stocks is equal to 1.
– The third one dictates that the minimum weight of each stock be greater than or equal to 0.

In general, the selection methods of optimum technology portfolio determine how we get the highest efficiency and output with determined resources dedicated to several technologies. In other words, an optimum technology portfolio aims to maximize the total value of the portfolio technologies and minimize the total costs of the technology acquisition as well as technology transfer [10].

Regarding the reason for choosing the optimal technology portfolio in the space industry, it is important to mention that the revenue of the satellite market in 2014 was approximately 215 billion dollars, which was four times more than what resulted from the gas and oil export of Iran in the same year. Statistics show that the space satellite industry growth is more than the global economy [39]. In the worst case, experts predict that if the same growth continues for the next few years, the satellite technology market will get 700 billion dollars of revenue in 2024 [36]. However, along with this financial criterion, the security and military functions of satellites in critical conditions should not be ignored. The satellite images provided by Russia to prove their innocence in the Malaysian plane explosion over Ukraine in 2014 provide a great instance of a satellite's security function – a function that no economist may ever put a price on [43, 44].

As shown in Figure 1, since the created technology portfolio in this study is based on the country's space roadmap, which is a time-based tool, the created portfolio is changed at different periods. In fact, the output of this study is a portfolio of the products, services or technologies for the prioritized sectors of the space industry

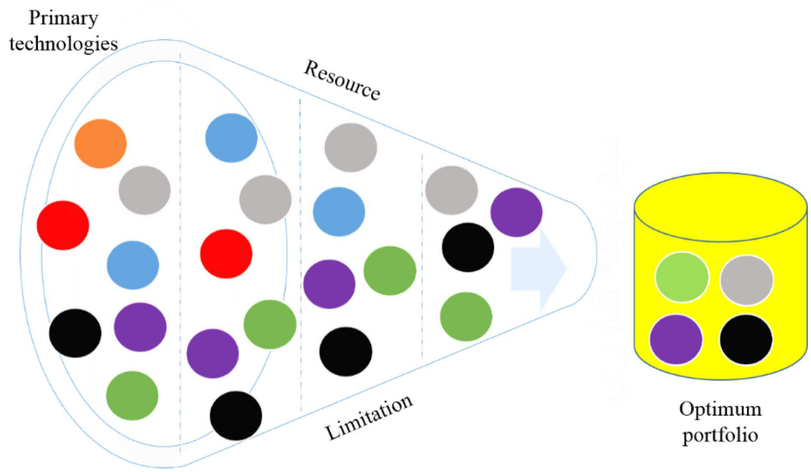

FIGURE 2. Schematic process of creating an optimum portfolio.

within a specified period. This output can direct investments in Iran's space industry and provides a guide for policymaking in this area. The improvement of factors such as technology strategy and technology economy in the space industry are some of the other benefits of this study. The creation of the optimum technology portfolio may have a significant effect on the mentioned technological areas and guiding resources in this industry.

As shown in Figure 2, the process of creating an optimum portfolio guided by resources and limitations.

The main objective of this research is to answer the question of "How the players in Iran's space industry should go along the development path to achieve optimum performance and enhance Iran's position in this industry?". The main contributions of this research are as follows:

(1) Development of a bi-budgetary framework for better decision-making in budget allocation to space technologies.
(2) Formulation of two portfolios at two different periods in which their corresponding inputs and outputs affect the other. For example, in the provided mathematical model, it is possible that part of the short-term budget (it is specified by the variable W in the model) allocated to some mid-term portfolio technologies. In this model, space area budgets in both terms, Technology Readiness Levels (TRLs), Technology Leverage factors (TLFs), etc. are considered.
(3) Considering all 4 indicators: complexity, usability, acquisition cost, and acquisition speed in the mathematical model, which have not been considered at the same time in any model.
(4) Complementary use of quantitative methods such as mathematical modeling and qualitative methods such as expert panels to cover the weaknesses of each method.
(5) Applying goal programming method to integrate objective functions and convert them into an objective function based on experts' panel weighting.
(6) Operational evaluation of the proposed model in a real case study (Iran's space industry).
(7) Analysis of short-term, mid-term and total portfolios, based on technological sub-areas.

The rest of the paper is organized as follows. After reviewing some knowledge about the technology portfolio and space industry in Section 2, the problem statement is reviewed and a technology portfolio model is provided with the hybrid quantitative–qualitative method in Section 3. In Section 4, at first the model is compared with some similar models to show the presented model outperforms. Then, an example is given to illustrate the proposed portfolio model using real data from Iran's space industry. Moreover, sensitivity analysis on important variables are also done in this section. Management practices obtained from the outputs and forward suggestions are presented in Section 5. A few concluding remarks are given in the last section.

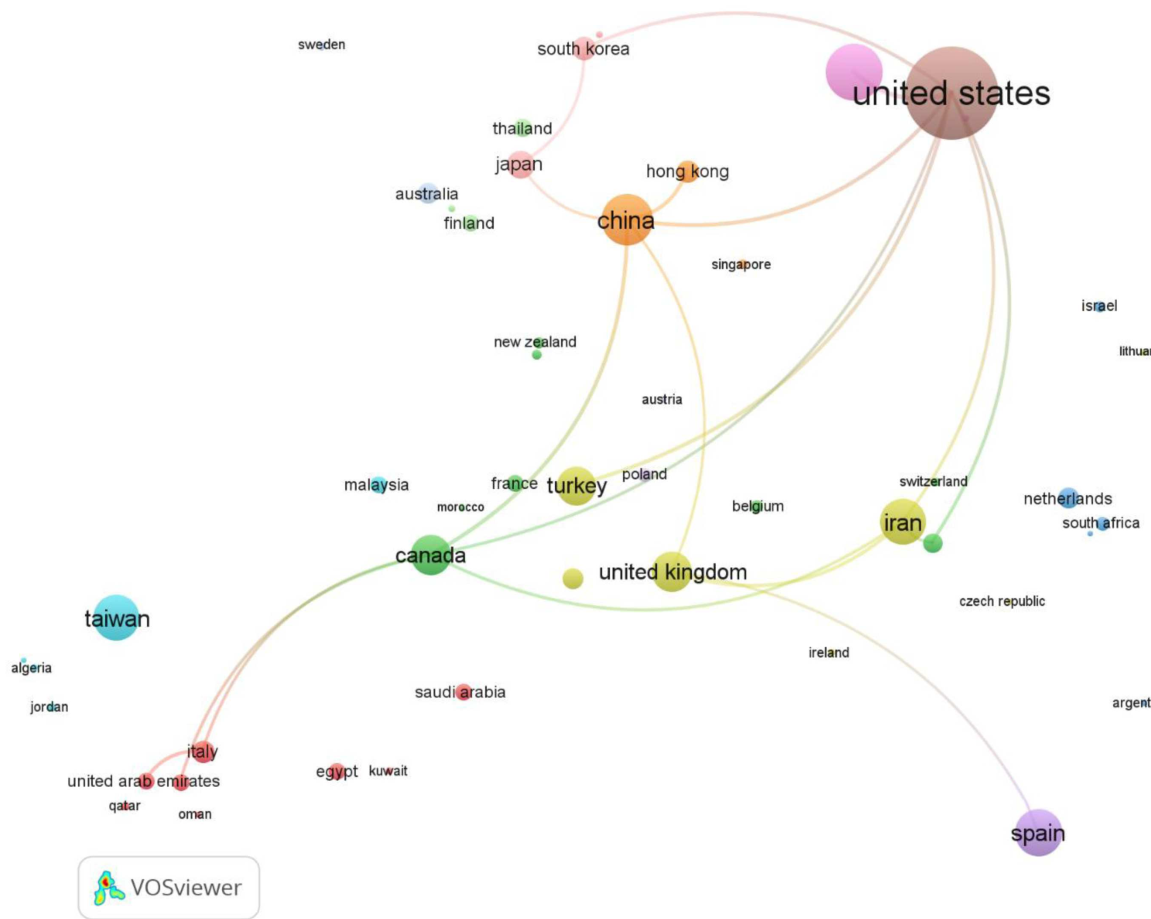

Figure 3. The connection density of the active countries in the field of technology portfolio.

2. Literature review

First, the functionality of the "technology portfolio" is evaluated *via* a scientometrics approach. Then, the latest findings on the importance and evolution of this concept are reviewed. At the end, different criteria used in creating a technology portfolio in the space industry are reviewed.

Scientometrics is one of the most common methods of assessing scientific activities. Scientometrics indices that describe research trends in different scientific communities can be useful tools for managing research and policymaking as well as identifying the level of acceptance and originality of different scientific fields.

The following scientometric information of the "technology portfolio" concept was extracted with no manipulations from Scopus and Web of Knowledge scientific databases and scientometrics softwares, such as VOS Viewer. This information is up to the end of 2021.

As shown in Figure 3, the US has the most activity in the field of technology portfolio. Also, Iran has scientific and research connections with countries such as the US, Canada, Britain, and Switzerland in the field of "technology portfolio". The amount of activities in the technology portfolio in Iran is higher than that of developed countries such as the Netherlands, Japan, France and many developing countries.

Figure 4 shows the relation between the technology portfolio concept and other keywords in scientific papers. The concept of "technology portfolio" is in the purple circle in the central right-angled part of the image. The

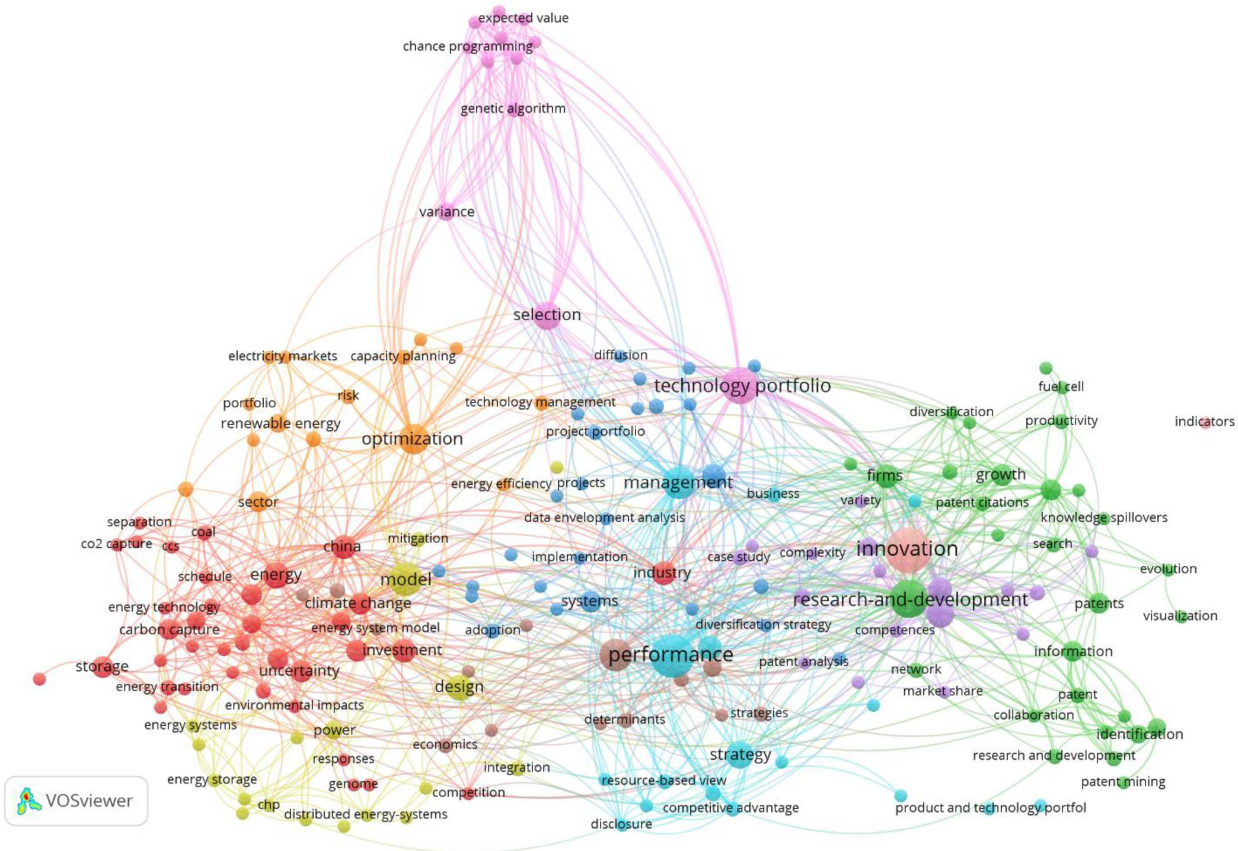

FIGURE 4. The relation between the technology portfolio concept and other keywords over time.

term "technology portfolio" has had a relation with concepts such as selection, expected value, optimization, model, and technology management. It should be mentioned that the frequency of use of keywords is determined by the diameter of the circle.

Technology development is a significant subject for technology researchers and policymakers. The technology portfolio process has been developed in this regard [41]. Technology development for great technology portfolios increases the number of layers, complexity, and uncertainty of the process. Heidenberger and Stummer described several methods for the quantitative assessment of the selection procedure and resource allocation to technology projects. They divided these methods into six groups: profit measurement techniques, mathematics planning, decision models and games theory, simulation models, heuristic methods, and cognitive simulations. Real choices analysis is another commonly used method that is employed by NASA for investment decision analysis [19, 20]; as it was primarily used to assess the investment in IT projects. It is also used for research and development in the automobile industry [3].

The selection of investment portfolios discusses how investors should dedicate their capital to different assets and how an efficient portfolio is created. Mean-variance model, presented by Markowitz, can be considered as a basis for modern portfolio theory. Different developments of Markowitz's mean-variance model were presented by different researchers, such as Giove *et al.* [17], Gupta *et al.* [18], and Yu and Li [50].

In the above models, a single-term horizon is assumed for investment. Whereas, in the real world, portfolio strategies are often multi-term and investors can alter their capital allocation at different periods. Therefore, the development of single-term models to multi-term ones seems quite normal. Multi-term portfolio selection was first introduced by Mossin (1968) and then examined by several researchers, some of them are introduced in the following [33].

Li and Ng (2000) presented an optimized analytical solution for the mean-variance model for a multi-term portfolio selection problem. Then, Leippold *et al.* (2004) employed a geometric approach to optimizing a multi-term portfolio of asset liability. Wei and Ye (2007) examined a multi-term mean-variance model for investment portfolio selection by controlling bankruptcy in a random market. Gulpınar and Rustem (2007) developed an optimization framework for a multi-term mean-variance model considering the random aspects of a decision tree. Pindoriya *et al.* (2010) used a multi-term portfolio with risk measurements of variance and skewness for an optimization problem in an electricity market. Huang and Qiao (2012) introduced a method for choosing a non-deterministic multi-term portfolio with trading costs. Considering different lending and borrowing rates, Sadjadi *et al.* (2011) presented a fuzzy multi-term investment portfolio [33]. Sun *et al.* developed the previous model using multi-periodic variables and probabilistic risk measures [45]. Berutich *et al.* (2016) used genetic programming for a multi-term portfolio. Qu *et al.* (2017) presented a normalized multi-objective evolutionary algorithm based on decomposition in a multi-term portfolio. Chen and Zhou (2018) developed a multi-objective particle swarm optimization in a multi-term portfolio [31]. Kamali *et al.* used a multi-period portfolio selection algorithm to maximize investor wealth using probabilistic risk measures [23]. Shaverdi *et al.* addressed a multi-objective technology portfolio optimization problem in a multi-period framework to maximize the created jobs, as a critical index in social welfare [42]. Yu *et al.* developed a fuzzy multi-objective multi-period portfolio selection problem. To obtain the optimal portfolio, they designed a hybrid intelligent algorithm by combining both the genetic algorithm and wavelet neural network algorithm [51]. Wei *et al.* presented a dynamic multi-period sparse portfolio selection model including asymmetric investors' sentiments on returns and risks [47]. Zhao *et al.* designed a portfolio selection model with extreme situations and extended it under the multi-period setting. Firstly, they established a new programming problem based on an optimization procedure. Secondly, they extend the model to a multi-period framework and show the outputs with a scenario tree, which solves the multi-period problems [52]. Wu *et al.* concentrated on environmental, social, and governance (ESG)-valued multi-period portfolio selection problem. They suggested an ESG-valued fused LASSO model to develop an optimal sparse multi-period portfolio process [49].

The difference between the current model and the mentioned conventional multi-period models, In addition to its quantitative–qualitative approach, is the use of two short and medium-term periods with the possibility of allocating part of the short-term budget to medium-term budget technologies (Eqs. (11) and (12) of the model). The reason for this possibility is the economic and strategic importance of some medium-term technologies, which require them to be addressed in the short-term to use their results in accelerating the acquisition of that technology in the medium term. Moreover, in addition to the high speed of technological changes in the space industry, in accordance with the major documents of Iran's space industry, the country's space goals have been drawn based on two short and medium-term time frames.

In Table 1, the general view of the research conducted in the technology portfolio area is shown. We tried to gather some papers with technology portfolios of all national, industry and business levels at different periods.

At the end of this section, in Table 2, different criteria used in creating the technology portfolio, especially in the space industry are presented.

As shown in Table 2, three criteria of technology readiness level (TRL), complexity, and effectiveness on space missions are the most frequent in the reviewed articles and selected scientific findings. However, as mentioned in NASA implementation guiding principles [46], the important point about the technology readiness level in portfolio creation is the investment balance in the technologies with different readiness levels, not low or high readiness criteria for an optimum technology portfolio. Due to limited space missions in the Iran's space industry, the "effectiveness on space missions" criteria is negligible. Therefore, regarding the Iran's space industry considerations, five criteria are assumed in this study: the variety of technology readiness levels, complexity, acquisition cost, acquisition speed, and usability.

Table 1. The research gap in technology portfolio studies.

References	Math planning	Fuzzy	Scenario planning	Statistical	Multi-term	Non-linear planning	Linear planning	MCDM	In major level	TRL[a]	TLF[b]	Complexity	Usability	Acquisition cost	Acquisition speed	Case study	Notes
Dickinson et al. [12]	⊠		⊠		⊠	⊠		⊠								Boing Company	–
Yu et al. [51]	⊠	⊠			⊠	⊠		⊠								–	–
Wei et al. [47]	⊠			⊠	⊠	⊠			⊠							Nasdaq	Capital market
Cedillos Alvarado et al. [1]	⊠		⊠	⊠	⊠	⊠		⊠						⊠		Energy systems business in England	–
Kucukbay and Araz [24]	⊠	⊠			⊠		⊠		⊠							–	Capital market
Li et al. [26]	⊠			⊠	⊠	⊠								⊠		–	–
Wu et al. [48]	⊠	⊠	⊠	⊠			⊠	⊠	⊠					⊠		Photovoltaic industry	Zhizhuang province in China
Gatzert et al. [16]	⊠		⊠	⊠	⊠	⊠			⊠					⊠		Renewable energies	
Depenbrock et al. [11]									⊠	⊠			⊠	⊠		NASA	–
Terrier [46]									⊠	⊠				⊠		NASA	
Pengra and Stofan [37]									⊠				⊠			NASA	NASA educational portfolio
Dubos et al. [13]	⊠			⊠	⊠	⊠			⊠	⊠						NASA	Spacecraft technology portfolio
Jesus et al. [22]									⊠	⊠		⊠			⊠	Brazil–China	Space industry
Shenhar et al. [43]									⊠	⊠		⊠	⊠		⊠	NASA	Project management framework
Shaverdi and Yaghoubi [41]	⊠			⊠	⊠		⊠	⊠	⊠	⊠	⊠			⊠		IPF (Iran's Innovation and Prosperity Fund)	–
Chavers et al. [7]					⊠				⊠				⊠		⊠	NASA	Human landing systems
This paper	⊠			⊠	⊠	⊠			⊠	⊠	⊠	⊠	⊠	⊠	⊠	Iran	Space industry

Notes. [(a)]Technology readiness level. [(b)]Technology leverage factor.

The TRL index was developed by NASA in the 1970s to measure technology maturity. Today, TRL is used as one of the most powerful tools for evaluating multi-million dollar decisions at NASA [14]. However, the use of this tool faces various challenges. In a study conducted by Olechowski *et al.*, the challenge of system complexity was considered the most important challenge for TRL users. Therefore, due to the importance of this index, the system complexity index was considered in addition to TRL in forming the technology portfolio. Also, TRL assessment is used as a tool to illuminate risk, but it is not enough to measure risk [35]. Therefore, the acquisition risk index was used in the current research. Regarding the acquisition speed index, research has been conducted

Table 2. The different criteria used in creating technology portfolios for the space industry.

References	Criteria										
	Usability	Feasibility	Viability	Effectiveness on space missions (plan)	Effective in meeting people's needs	Acquisition cost	Number of components	TRLs	Complexity	Acquisition rate	Uncertainty
Depenbrock *et al.* [11]	⊠	⊠	⊠	☐	☐	⊠	☐	⊠	☐	☐	☐
Terrier [46]	☐	☐	☐	⊠	⊠	⊠	☐	⊠	☐	☐	☐
Miranda [32]	☐	☐	☐	⊠	☐	⊠	☐	☐	☐	☐	☐
Pengra and Stofan [37]	☐	☐	☐	☐	⊠	☐	☐	☐	☐	☐	☐
Dubos *et al.* [13]	☐	☐	☐	⊠	☐	☐	⊠	⊠	☐	☐	☐
Jesus *et al.* [22]	☐	☐	☐	☐	☐	☐	☐	⊠	⊠	⊠	☐
Shenhar *et al.* [43]	☐	☐	☐	☐	☐	☐	☐	⊠	⊠	⊠	☐
Mihm *et al.* [30]	☐	☐	☐	☐	☐	☐	☐	☐	⊠	☐	⊠
Sauser *et al.* [40]	☐	☐	☐	☐	☐	☐	☐	⊠	⊠	⊠	⊠
Chavers *et al.* [7]	⊠	☐	☐	⊠	☐	⊠	☐	☐	☐	☐	☐

on the importance and improvement of this index in the space industry, among them, the research of Bahmani *et al.* regarding the improvement of the acquisition speed of GPS signals in the space industry [4], research Nie *et al.* discuss the development of a method for fast signal acquisition in GNSS [34], as well as Mariager *et al.*'s research on a new method for space mapping with a specified acquisition speed [27]. But in general, the use of the technology acquisition speed index in the formation of the technology portfolio has been unprecedented. Regarding the usability or ease of use index, research has been done on this index about technologies such as Ultrafast Lasers in Microfabrication [28], 3D printing technology [29], and Fused deposition modeling (FDM) [6] in the space industry. However, it has been used in a few research as criterion for forming a technology portfolio. Finally, the criterion of acquisition cost or cost, in general, has been chosen as one of the most repeated criteria for choosing the optimal portfolio.

3. Problem statement

Acquiring the knowledge of satellite technology was one of Iran's recent significant scientific and technological achievements. Despite the huge gap with the 50-year-old global space industry, Iran has successfully placed itself among the nine countries that own full-cycle satellite technology. Also, the significance and necessity of the space industry in Iran were studied in the two national strategic document viewpoints – "Comprehensive Document on Country Aerospace Development" and "Comprehensive Scientific Map of the Country" [8, 9]. However, the position of Iran's space industry can be enhanced with more accurate planning and technology management in accordance with the needs of the space market. This planning and management requires a standard management process agreed upon by all space industry actors. Therefore, in the current research, it has been tried to present a framework for better management of technology in the space industry with the participation of various actors in the country's space industry by using the technology portfolio method.

The current research framework can be explained in two quantitative and qualitative methodologies. The schematic view of the research methodology is presented in Figure 5.

In the qualitative phase, firstly, before designing the questionnaire, relevant international documents were reviewed and studied, including the 2020 NASA Technology Taxonomy as well as the ESA Technology Tree (version 4.0) [2, 32]. In addition, national documents such as the Tree of Iranian Space Research Center were

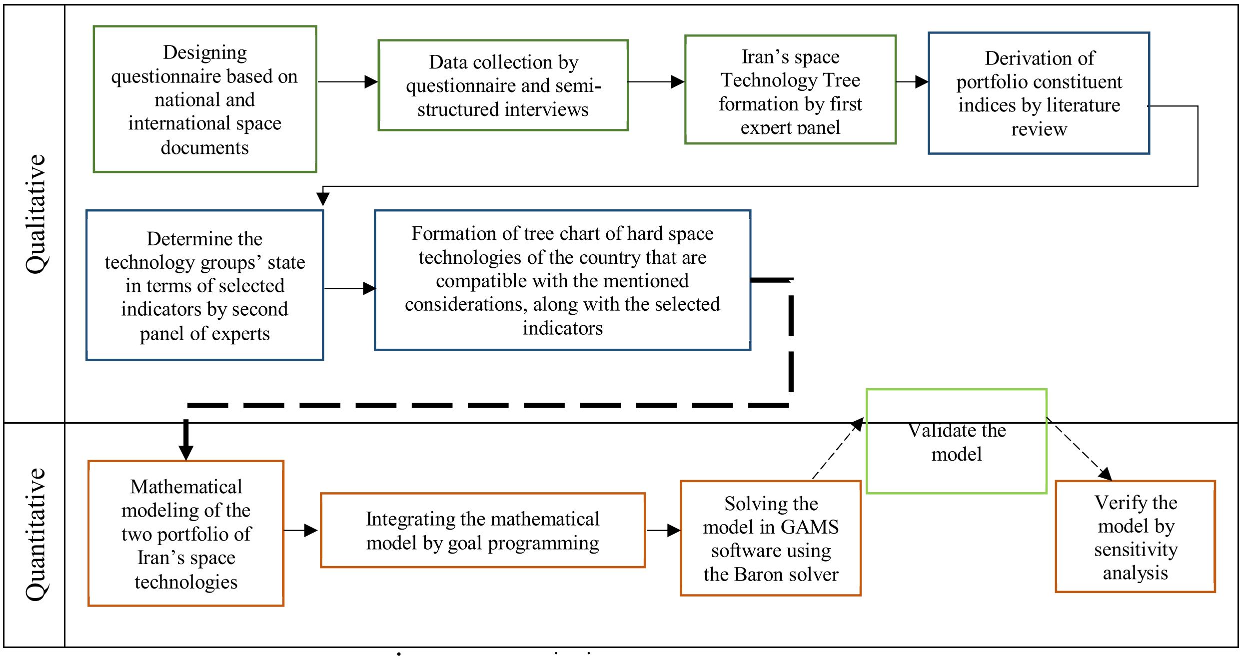

FIGURE 5. Schematic view of research methodology.

examined. The output of this analysis is the design of a hard technology[1] questionnaire for the space industry. In the second step, by means of the questionnaire from the previous step as well as semi-structured interviews, technology areas, technology sub-areas, and technology groups that were not relevant to the country's space industry from the point of view of the questionnaire completers and interviewees were filtered and removed. The output of this step is a set of selected technologies from the point of view of each of the respondents. In the third step, to form the tree of selected space technologies of the country, the output of the previous step was analyzed in the form of an expert panel (the characteristics of the members of the expert panel are specified in Appendix B) and based on the consensus process, the technologies in technology tree chart of Iran's space industry (Appendix A), which is in fact, the priority space technologies for the country are drawn. This tree chart was drawn in 3 layers; technology area, technology sub-area, and technology group. The consensus process refers to a maximal agreement on different items. For instance, if an expert disagrees with the others, they have to convince that expert with reasoning. Even, the expert's reasons may be convincing enough for the other experts to change their minds. In general, the expert panel is used for 3 purposes: reflections based on prior work, providing an updated view of the topic studied, and finally creating a ground for new discussions (disruptive innovation opinion) [5]. The current research can be placed in both categories 1 and 2. The current research can be placed in category 1 because the current case study, based on past studies about the space technology tree of NASA, ESA, etc., that needs customization. Placement in category 2 is also due to the fact that in the current research, the issue of Iran's space technology portfolio is addressed from a point of view that corresponds to the progress of this industry in the country.

In the fourth step, different criteria used in creating technology portfolios for the space industry are extracted according to Table 2. In the fifth step, the state of technologies in technology tree in the 4 selected criteria of complexity, acquisition cost, acquisition speed, and usability is asked the second panel of experts. The output

[1]Hard technologies are tangible components that can be purchased and assembled into assistive-technology systems. They include everything from simple mouth sticks to computers and software.

of this step is the tree chart of hard space technologies of the country that are compatible with the mentioned priorities and considerations, along with the complexity, acquisition cost, acquisition speed, and usability. In the last step of the qualitative phase, in line with validating Iran's space technologies tree and their status in the 4 selected indicators, the output of the previous step is again provided to several experts from panels one and two in order to confirm its final version. The quantitative phase steps are described in Section 3.1.

The expected benefits of this research are as follows:

– Making a framework to support space activities.
– Directing space activities (private or public) toward value-creating technologies.
– Identifying the priorities for investment in technologies in the space area.
– Directing government policymaking according to the created technology portfolios.
– Preventing the parallel and overlapping activities of the different sectors in the space industry.
– Avoiding sporadic activities and rising concentration by the created portfolios.
– Facilitating more objective investment by the government through the selected technology portfolios.

The country's policymakers in the space industry, the different players in this area, and the organizations in the value chain of the space industry that are active or are going to enter the business are among those who can use the results of this study. We hope that this study will be considered the initial step for research centers and researchers to be developed more thoroughly.

Regarding the practical objective and nature of data, this research is a quantitative–qualitative study.

3.1. Formulation of multi-period portfolio selection

In this section, we formulate a multi-period technology portfolio selection model with these multi-objective functions: maximization of benefits in using different technologies comprising both short and medium-term portfolios, maximizing the total summation of all Technology Readiness Levels (TRLs) of technologies, maximizing the acquisition speed for the technologies, and minimizing the acquisition risk of technologies in each portfolio. In this model, we consider decision makers of the country's space industry as an investor who want to optimize their technology portfolio over a planning horizon. The main objective of this model is to answer the question of "How the key players in Iran's space industry should invest and go along the development path to achieve optimum performance and enhance Iran's position in this industry in two mentioned periods?

In the following, the parameters and variables used in the space industry optimum technology portfolio, are provided below:

Symbols	**Description**
Indices	
i	Technology index
k	Technology sectors
l	TRL index
TRLset_l	Total TRLs
Parameters	
TLF_i	Leverage factor of technology i
R_i	Acquisition risk for technology i
U_i	Usability of technology i
C_i	Acquisition cost for technology i
TRL_i	Technological readiness level for technology i
S_i	Acquisition speed of technology i
CP_i	The complexity of technology i
Bs	Space area short-term budget
BL	Space area mid-term budget
	Amount of investment on portfolio 2 from the budget of portfolio 1
Ub	Optimum usability level

V	The maximum variety of the portfolio allowed for each sector
A	Maximum Acceptable complexity for the technologies
D	Minimum acceptable speed of acquisition for all technologies in the short-term portfolio
D'	Minimum acceptable speed of acquisition for each technology in the short-term portfolio
D''	Minimum acceptable speed of acquisition for each technology in the mid-term portfolio
M	A really big number
E	Minimum total number of the selected technologies in portfolios 1 and 2
Variables	
X_i	Percentile of the short-term portfolio allocated to technology i
Y_i	Percentile of the mid-term portfolio allocated to technology i
X_i'	If technology i is a member of the short-term portfolio, this variable is 1, otherwise, 0
Y_i'	If technology i is a member of the mid-term portfolio, this variable is 1, otherwise, 0
Z_i	Percentile of the cost allocated to technology i from the maximum cost allowed to be allocated to that technology
W	Amount of investment on portfolio 2 from portfolio 1 budget
STRL_l	If at least one of the selected technologies has TRL of l, this variable is 1, otherwise, 0

The basic optimization model is presented with objective functions and constraints as follow:

Objective functions

$$\text{Max } Z_1 = \sum_i \mathrm{TLF}_i(X_i + Y_i) \tag{1}$$

$$\text{Min } Z_2 = \sum_i R_i X_i + \sum_i R_i Y_i \tag{2}$$

$$\text{Max } Z_3 = \sum_l \mathrm{STRL}_l \tag{3}$$

$$\text{Max } Z_4 = \sum_i S_i X_i + \sum_i S_i Y_i. \tag{4}$$

Constraints

$$\sum_i X_i \leq 1 \tag{5}$$

$$\sum_i Y_i = 1 \tag{6}$$

$$\sum_i U_i X_i \geq Ub \tag{7}$$

$$\sum_i U_i Y_i \geq Ub \tag{8}$$

$$\sum_{i\in S_k} X_i \leq V \tag{9}$$

$$\sum_{i\in S_k} Y_i \leq V \tag{10}$$

$$\sum_i C_i Z_i X_i' + W \leq Bs \tag{11}$$

Table 3. Technology leverage factor [41].

Level TLF	TLF factor	Description
Low	10	Technology at the component level
Medium	30	Technology at the sub-system level
High	70	Technology at the system level
Empowering	100	Empowering technology

$$\sum_i C_i Z_i Y_i' \leq \mathrm{BL} + W \tag{12}$$

$$C_i Z_i \leq X_i Bs + Y_i(\mathrm{BL} + W) \qquad \forall i \tag{13}$$

$$Z_i \leq X_i \qquad \forall i \tag{14}$$

$$Z_i \leq Y_i \qquad \forall i \tag{15}$$

$$\sum_i \mathrm{CP}_i(X_i') \leq A \sum_i X_i' \tag{16}$$

$$\sum_i \mathrm{CP}_i(Y_i') \geq A \sum_i Y_i' \tag{17}$$

$$\sum_i S_i(X_i') \geq D \sum_i X_i' \tag{18}$$

$$\sum_{i \in \mathrm{TRLset}_l} X_i' + Y_i' \leq M\, \mathrm{STRL}_l \tag{19}$$

$$X_i' + Y_i' \leq 1 \qquad \forall i \tag{20}$$

$$D' X_i' \leq S_i \qquad \forall i \tag{21}$$

$$S_i Y_i' \leq D'' \qquad \forall i \tag{22}$$

$$0 \leq Z_i \leq 1 \qquad \forall i \tag{23}$$

$$0 \leq X_i \leq 1 \qquad \forall i \tag{24}$$

$$0 \leq Y_i \leq 1 \qquad \forall i \tag{25}$$

$$\sum_i X_i' + Y_i' \geq E. \tag{26}$$

Equation (1) is about maximizing the benefits of using different technologies comprising the short and mid-term portfolios. The benefits of each technology are characterized by the Technology Leverage factor (TLF). This factor is determined by the application domain of each technology and represents the potential of each technology for creating market and revenue. This factor is determined according to Table 3 [41].

Equation (2) is used to minimize the acquisition risk of technologies in each portfolio (either short or mid-term). Equation (3) is used to maximize the total sum of all technologies TRLs in each portfolio. Nine levels of TRL, included from basic principles (TRL-1) to operational systems (TRL-9). Equation (4) is about maximizing the acquisition speed for the technologies in each portfolio (either short or mid-term). Equation (5) ensures that the total shares of the different technologies comprising the short-term portfolio are not greater than 1. Equation (6) ensures the total shares of different technologies comprising the mid-term portfolio must be equal to 1. Equations (7) and (8) show that the usability or functionality must be greater than the minimum usability level according to their shares in technologies comprising short and mid-term portfolios, respectively. Equation (9) and (10) represent the maximum usage of the technologies in each sector of each short and mid-term portfolio, respectively. For instance, the maximum share of technologies related to the space propulsions subfield, in the short-term portfolio is 30%. Equation (11) shows the short-term portfolio budget limitation, where the related technologies acquisition cost, regarding the fraction of the cost they incur to their maximum allowable cost, plus the cost dedicated to the mid-term technologies in the short-term portfolio should not be greater than the budget allocated to the short-term portfolio. Equation (12) represents the mid-term portfolio budget limitation, where the related technologies acquisition cost, regarding the fraction of the cost they incur to their maximum allowable cost, plus the cost dedicated to the short-term technologies in the mid-term portfolio should not be greater than the budget allocated to the mid-term portfolio. Equation (13) shows that the acquisition cost of each technology, regarding the proportion of the cost allocated to technology to their maximum allowable cost, should not be greater than the total budget of the short and mid-term portfolios. Equation (14) and (15) respectively show that the percentage of the short or mid-term cost allocated to each technology must be greater than the percentage of its maximum allowable cost which is allocated. Equation (16) shows that the average technological complexity of all technologies in the short-term portfolio must not be greater than index A, because the acquisition time of each technology increases with the growth of its complexity. As a result, having highly complex technologies in short-term portfolios is not desirable. Equation (17) shows that the average technological complexity of all technologies in the mid-term portfolio must not be smaller than index A, because the acquisition time of each technology decreases with the reduction of its complexity. Therefore, having technologies with very low complexity in the mid-term portfolio is not desirable. Equation (18) shows that the average acquisition speed for the technologies in the short-term portfolio must be greater than index D. Because a lower acquisition speed for each technology increases the acquisition time for it. Therefore, having technologies with very low acquisition speed in short-term portfolios is not desirable. Equation (19) defines STRL_l and states that if the TRL of at least one of the technologies in either short or mid-term portfolios is l and that technology is selected, then STRL_l is equal to 1, otherwise 0. Equation (20) represents that each technology can be only in one of the short or mid-term portfolios. Equation (21) and (22) are for the acquisition speed for each technology – the minimum acceptable acquisition speed for the mid-term portfolio is index D', while the minimum acceptable acquisition speed for the short-term portfolio is index D''. Equation (23) shows that the maximum allowable cost dedicated to each technology should be between 0 and 1. Equation (24) represents that the percentage of the short-term portfolio dedicated to each technology must not be greater than 1 (equal to the whole portfolio). Equation (25) shows that the percentage of the mid-term portfolio dedicated to each technology must not be greater than 1. Finally, equation (26) shows that the sum of the selected technologies in both portfolios must be greater than a certain minimum. To solve the presented model, the objective functions must first be integrated and converted into an objective function; in this article, the goal programming method is used to integrate the objective functions. In this way, a weight is assigned to each of the objective functions according to the importance of the objective from the expert's point of view and the model seeks to minimize the amount of deviation from each objective from its goal [21]; using this planning, four objective functions of the current model became one objective function. For this purpose, the following positive variables and parameters are added to the model:

Parameters

G_k The goal of objective function k

Positive variables

g_k^- Amount of negative deviation from the objective function k

g_k^+ Amount of positive deviation from the objective function k

z_k^m Amount of objective function k, if the model is solved based on the objective function m

According to the added parameters and variables, the objective function is rewritten and equations (28)–(31) are added to the model:

$$\text{Min } z = \frac{g_1^-}{G_1 - \min\{z_1^2, z_1^3, z_1^4\}} + \frac{g_2^+}{\max\{z_2^1, z_2^3, z_2^4\} - G_2} + \frac{g_3^-}{G_3 - \min\{z_3^1, z_3^2, z_3^4\}} + \frac{g_4^-}{G_4 - \min\{z_4^1, z_4^2, z_4^3\}} \tag{27}$$

$$z_1 - g_1^+ + g_1^- = G_1 \tag{28}$$

TABLE 4. The technologies comprising each portfolio and the share of each technology.

Number	Short-term portfolio			Mid-term portfolio		
	Technology code	Technology title	Share	Technology code	Technology title	Share
1	Technology 5	Radars	0.7	Technology 3	Terrain mapping and classification	0.7
2	Technology 4	Atomic clocks	0.3	Technology 1	Human-rated advanced secondary chemistries beyond lithium-ion	0.29
3	–	–	–	Technology 6	Optical sensors	0.004
4	–	–	–	Technology 2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001

$$z_2 - g_2^+ + g_2^- = G_2 \tag{29}$$
$$z_3 - g_3^+ + g_3^- = G_3 \tag{30}$$
$$z_4 - g_4^+ + g_4^- = G_4. \tag{31}$$

4. Case study

To determine the optimum technology portfolio, as mentioned in Section 3, first, the expert panel was asked about the technology priority of Iran's space industry, based on a hard technology questionnaire supported by both national and international documents related to the space industry. The output is a tree chart for Iran's space industry technologies. It is drawn in 3 layers; technology area, technology sub-area, and technology group. Notice that the results provided in this section are manipulated for some national security implications and limitations.

It should be noted that the technological gap that exists between Iran's space industry and NASA and ESA should be considered in the designing of the hard technology questionnaire such that the technology areas, technology sub-areas, and technology groups mentioned in the form should be achievable in the schedule of the country's technology roadmap. Thus, regarding this gap and the priority of this industry in national strategic documents, only technology areas with short or medium-term gaps with Iran's space industry and justifiable from the strategic document's perspective were considered in the mentioned questionnaire. After filtering and finalizing this questionnaire, the second panel of experts was asked to fill out the form and determine the technology groups' state in terms of complexity, acquisition cost, acquisition speed, and usability. After answering and aggregating the questionnaire, the final form was extracted. After the completion of this process, the result is the tree chart of hard space technologies of the country that are compatible with the mentioned priorities and considerations, along with the complexity, acquisition cost, acquisition speed, and usability.

After obtaining this output, it was time to create the optimum technology portfolio for Iran's space industry.

After integrating the mathematical model, the proposed model is solved by GAMS software using the Baron solver, and the results are analyzed. Moreover, a sensitivity analysis is carried out on the most important parameters. In Table 4, the solving model results of the selected case study into short and mid-term portfolios were presented.

As the results show, the six selected technologies of the short and mid-term portfolios are from five sub-areas: electrochemical: batteries, sensing for robotic systems, onboard mapping and data analysis, timekeeping and time distribution, and orbital debris tracking. The share of each sub-area, in total and separately in the short and mid-term portfolio is provided in Figure 6.

As depicted in Figure 6, the short-term portfolio is equally distributed among two technology sub-areas – timekeeping and time distribution and orbital debris tracking. The mid-term portfolio is comprised of 4 technology sub-areas – electrochemical: batteries, onboard mapping and data analysis, sensing for robotic systems, and orbital debris tracking – where the share of all four technology sub-areas is equal. Some other points can be extracted from Figure 6:

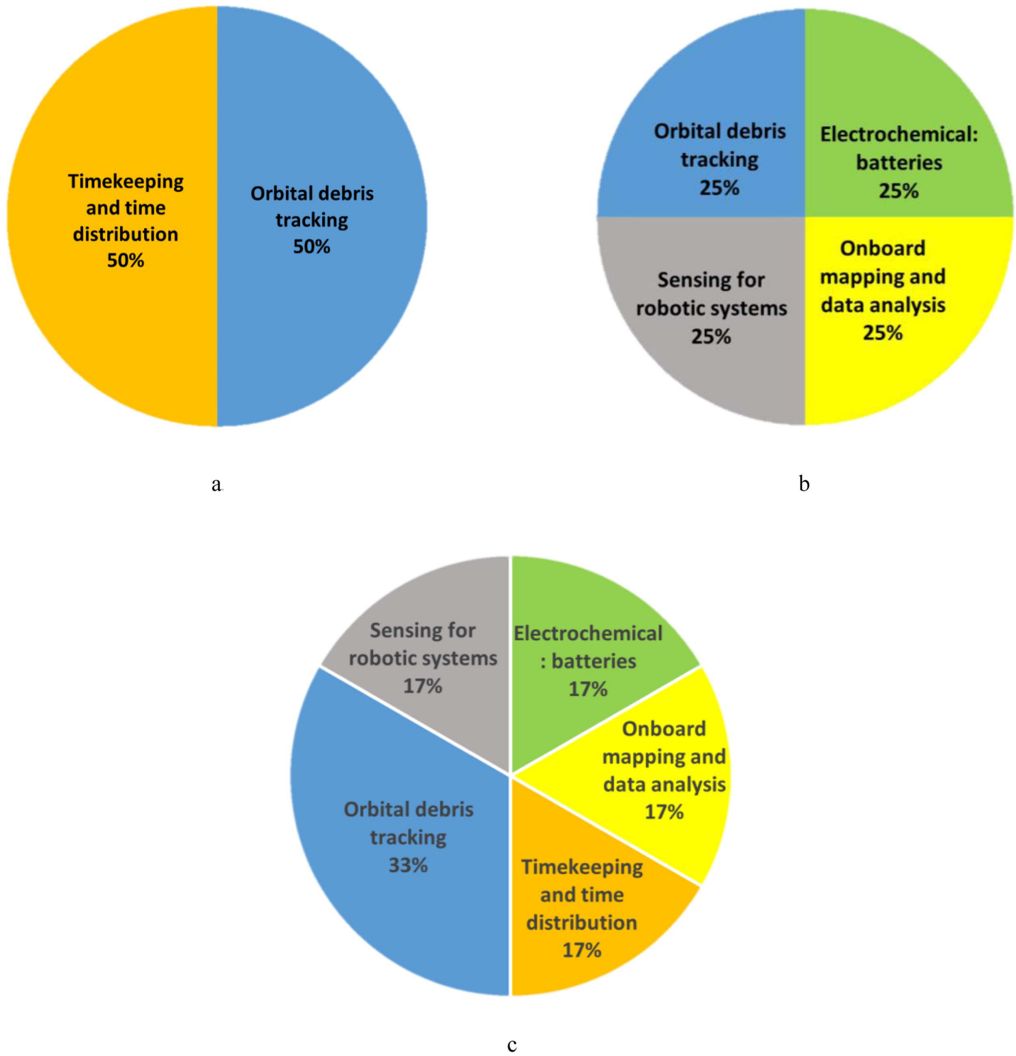

FIGURE 6. The share of each technology sub-area, in the short and mid-term portfolios individually and in total. (a) Short-term portfolio. (b) Mid-term portfolio. (c) Both portfolios' summation.

- The "orbital debris tracking" sub-area is the only one that is in both short and mid-term portfolios.
- In both portfolios' summation, the share of "orbital debris tracking" is twice as big as that of the four other sub-areas.
- The share of none of the technology sub-areas is over 50% in neither of the short and mid-term portfolios and the share of any sub-areas is over 33% in both portfolios summation. This represents the necessity of variety in the investment in different technology sub-areas.

4.1. Evaluating Iran's space industry optimum technology portfolio

To evaluate the impact of 5 indicators (variety of TRL, complexity, acquisition cost, acquisition speed, and usability), at first, the optimality of similar models (without considering the 5 indicators together) is compared

TABLE 5. Comparative analysis of results obtained from the model adopting different indicators of similar studies.

References	Criteria: TRL	TLF	Acquisition risk	Complexity	Acquisition cost	Acquisition speed	Usability	Short-term portfolio technologies	Mid-term portfolio technologies	Total number of technologies
Shenhar *et al.* [43]	✓		✓	✓	✓	✓*		Terrain mapping and classification Optical sensors	Radars	3
Depenbrock *et al.* [11]	✓		✓		✓		✓	*In-situ* camera geometric calibration diagnostics and self-calibration Mirrors, lenses, interferometers, gratings, prisms, and fiber	Atomic clocks Optical sensor	4
Shaverdi and Yaghoubi [41]	✓	✓	✓		✓			Terrain mapping and classification Laser ranging	Radars Atomic clocks	4
This paper	✓	✓	✓	✓	✓	✓	✓	Radars Atomic clocks	Terrain mapping and classification Human-rated advanced secondary chemistries beyond lithium-ion Optical sensors *In-situ* camera geometric calibration diagnostics and self-calibration	6

with the optimal solution of the presented model. Then the presented model is validated by comparing the current situation of Iran's space industry with the selected technology portfolio obtained from the presented model.

For example, in the research conducted by Shenhar *et al.* [43], four criteria of TRL, risk, acquisition cost, and complexity were assumed to form the portfolio of technological projects in NASA. In addition, two criteria of available time as well as innovation and newness degree of technology have also been considered. The first criterion overlaps with the acquisition speed criterion in the presented model to some extent, but the second criterion depends on the case study, which is not relevant to ours (Iran's space industry). Therefore, in addition to the 4 mentioned criteria and the acquisition speed criterion which is in common in both the presented model and Shenhar's model, it is worth noting that two criteria of usability and TLF have been considered in the present study in addition to the mentioned criteria.

In another similar study, Depenbrock *et al.* optimized the priority in NASA's technology portfolio by considering 3 main criteria: usability, feasibility, and viability, in which some criteria such as TRL, risk, and acquisition cost were considered as sub-criteria [11]. In addition to the mentioned criteria considered in Depenbrock's research, three other criteria; acquisition speed, complexity, and TLF are considered in the presented study.

Optimization of the technology portfolio by considering 4 criteria of TRL, TLF, risk, and acquisition cost under uncertainty was investigated in Shaverdi and Yaghoubi [41]'s research, also. In addition to the mentioned criteria, the moratorium period was also considered; however they did not assume the three criteria of acquisition speed, complexity, and usability, which are adopted in the present study. In the following, the results obtained from the recently reviewed model are compared with the obtained solution from the presented model (Tab. 5).

As shown in this table, considering different criteria leads to different results obtained from the present model. Assuming Shenhar *et al.* [43]'s criteria as the inputs of the presented model (neglecting the usability and TLF parameters), it results in the fact that radars technology, which has a high score in the mentioned criteria, is placed in the mid-term portfolio; while in presented portfolio (considering the usability and TLF parameters), the mentioned technology is placed in the short-term portfolio. In addition, the number of selected technologies of the Shenhar *et al.* [43]'s model is less compared to the presented model.

When it comes to the portfolio developed by Depenbrock *et al.* [11], two points should be noted: the first is that the portfolio obtained from their model has a smaller number of selected technologies compared to the portfolio obtained from the present model. The second is that atomic clocks technology, which is relatively fast to achieve

Table 6. Comparison of the two mentioned technology portfolios and their optimality under each objective function.

Portfolio code	Portfolio title	Short-term period		Mid-term period		Objective functions value		Normalized objective functions value	Aggregate
		Technology title	Share	Technology title	Share				
A	Proposed portfolio	Radars	0.7	Terrain mapping and classification	0.7	1	169.35	1	**3.74**
		Atomic clocks	0.3	Human-rated advanced secondary chemistries beyond lithium–ion	0.29	2	10.37	1	
		–	–	Optical sensors	0.004	3	4	0.8	
		–	–	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001	4	8.69	0.94	
B	Current portfolio	Navigation transponders and beacons	0.25	Electrical propulsion power processing units	0.2	1	109	0.64	3.5
		Monomethyl hydrazine	0.25	Distributed electronic propulsion	0.2	2	9	0.86	
		Star trackers	0.25	Radiators and radiator turn-down devices (*e.g.*, louvers, heat switches, variable conductance heat pipes)	0.2	3	5	1	
		Solar cells and panels	0.25	Direct numerical simulation, large eddy simulation, and detached eddy simulation	0.2	4	9.2	1	
				Autonomous high-accuracy star tracker	0.2				

Notes. The results are manipulated for some national security implications and limitations.

and has a normal complexity, is placed in the mid-term portfolio; while the presented model places the atomic clocks technology in the short-term portfolio. Moreover, it should be noted that the technologies of "*In-situ* camera geometric calibration diagnostics and self-calibration" and "Mirrors, lenses, interferometers, gratings, prisms, and fibers", which have the lowest acquisition speed compared to the other selected technologies, were placed in the short-term portfolio.

Comparing the presented portfolio with Shaverdi and Yaghoubi [41]'s demonstrates the importance of acquisition speed. In both models, the technologies of radars and atomic clocks are selected. However the mentioned technologies were placed in the mid-term portfolio in the Shaverdi and Yaghoubi [41]'s model, it seems reasonable that these technologies should be placed in the short-term portfolio due to their high acquisition speed, that the presented model has satisfied this matter. It is worthy note that the two technologies "Terrain mapping and classification" and "Laser ranging" placed in the short-term portfolio in the Shaverdi and Yaghoubi [41]'s model despite their lower technology acquisition speed in comparison with the two technologies radars and atomic clocks.

To validate the model, the selected technology portfolios in this model, are compared with the current situation of technology portfolios in Iran's space industry. As a result, the optimality of the technology portfolios obtained from solving this model in the present research in comparison with the current Iran's space industry technology portfolios was determined. In addition, all the constraints have been met in both technology portfolios.

In Table 6, the comparison of the two mentioned technology portfolios and their optimality under each objective function as well as their summation were shown. As it is clear from the index of the aggregate objective functions in the last column, the desirability of the proposed portfolio (A) is higher than the existing and current portfolio (B) of Iran's space industry. It should be noted that the weight of all 4 objective functions is equal to 0.25. These weights are extracted from the second panel of experts. The values of objective functions are normalized by Rumina's normalization method [15].

TABLE 7. The technologies comprising the short-term portfolio for different values of the short-term budget.

Different amounts of short-term budget (billion Rials)		1th Technology			2th Technology			3th Technology			4th Technology		
		Technology code	Technology title	Share	Technology code	Technology title	Share	Technology code	Technology title	Share	Technology code	Technology title	Share
Portfolio 1	1400	6	Optical sensors	0.29	4	Atomic clocks	0.7	1	Human-rated advanced secondary chemistries beyond lithium-ion	0.001	2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001
Portfolio 2	2000	5	Radars	0.7	4	Atomic clocks	0.3	–	–	–	–	–	–
Portfolio 3	2500	5	Radars	0.7	4	Atomic clocks	0.3	–	–	–	–	–	–
Portfolio 4	3000	5	Radars	0.7	4	Atomic clocks	0.3	–	–	–	–	–	–

4.2. Sensitivity analysis

To verify the model behavior and the effect of the different parameters on the results, a sensitivity analysis is conducted on two main parameters, *i.e.*, the short-term and mid-term budget parameters.

Short-term budget sensitivity analysis

As can be seen from the developed mathematical model, regarding the budget trend analysis of the country's space industry in the past 10 years, the short-term budget of this industry is estimated at 2000 billion Rials. In Table 7, the technologies comprising the short-term portfolio for different values of the short-term budget were shown. It is worth mentioning that the mid-term budget has remained static at 2300 billion Rials. The output of the portfolio for different values of the short-term budget, from 1400 to 3000 billion Rials, has been shown. The two numbers of 1400 and 3000 billion Rials, as the range for the budget parameter, are based on the historical data of the country's space budget for the past 10 years and the optimistic regression of this trend in the future. In general, the country's space budget has never been less than 1400 billion Rials in the past 10 years, and with an optimistic estimation and the increase in the country's space budget, the short-term space budget of the country will never exceed 3000 billion Rials. Therefore, nothing out of this range is probable.

Some results of the sensitivity analysis on the short-term budget are as follows:

– Technology group 4, atomic clocks technologies, has been selected by the model in all budget levels. This highlights the importance of this technology for the country's space industry. Moreover, this technology group has at least a 30% share of the short-term portfolio at all budget levels.
– The model is sensitive to the budget range of 1400–2000 Rials; *i.e.*, if the budget exceeds this amount, the model behavior does not change. However, the model behavior for the 1500 billion Rials budget is much different from the 1800 billion Rials budget.
– No change in the model behavior in the range between 2000 and 3000 billion Rials shows the high importance and also the capacity for investment in the two selected technologies, as foundational and infrastructural technologies.

Mid-term budget sensitivity analysis

As can be seen in the developed mathematical model, regarding the budget trend analysis of the country's space industry in the past 5 years, the mid-term budget of this industry is estimated at 2300 billion Rials. In Table 8, the technologies comprising the mid-term portfolio for different values of the mid-term budget are shown. The short-term budget has remained static at 2000 billion Rials. The obtained portfolio for different values of the mid-term budget, from 2000 to 5000 billion Rials, has been considered. The two numbers of 2000 and 5000 billion, as the range of mid-term budget parameters, are based on the historical data of the country's

Table 8. The technologies comprising the mid-term portfolio for different values of the mid-term budget.

Different amounts of mid-term budget (billion Rials)		1th Technology			2th Technology			3th Technology			4th Technology		
		Technology code	Technology title	Share	Technology code	Technology title	Share	Technology code	Technology title	Share	Technology code	Technology title	Share
Portfolio 1	2000	1	Human-rated advanced secondary chemistries beyond lithium-ion	0.29	2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001	3	Terrain mapping and classification	0.7	6	Optical sensors	0.004
Portfolio 2	2300	1	Human-rated advanced secondary chemistries beyond lithium-ion	0.29	2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001	3	Terrain mapping and classification	0.7	6	Optical sensors	0.004
Portfolio 3	3000	1	Human-rated advanced secondary chemistries beyond lithium-ion	0.29	2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001	3	Terrain mapping and classification	0.7	6	Optical sensors	0.004
Portfolio 4	4000	1	Human-rated advanced secondary chemistries beyond lithium-ion	0.29	2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001	3	Terrain mapping and classification	0.7	6	Optical sensors	0.004
Portfolio 5	5000	1	Human-rated advanced secondary chemistries beyond lithium-ion	0.29	2	*In-situ* camera geometric calibration diagnostics and self-calibration	0.001	3	Terrain mapping and classification	0.7	6	Optical sensors	0.004

space budget for the past 5 years and an optimistic regression of this trend in the future. In general, the country's space budget has never been less than 2000 billion Rials in the past 5 years, and with an optimistic estimation and increase in the country's space budget, the mid-term space budget will never exceed 5000 billion Rials. Therefore, nothing out of this range is probable. The reason for considering the last 10 years to determine the short-term budget sensitivity analysis period and the last 5 years to determine the medium-term budget sensitivity analysis period is the time difference between the two budgets.

Some results of the sensitivity analysis on the mid-term budget are as follows:

- The objective function is not sensitive to the mid-term budget in the intended range.
- The selection of each 4 technology groups (1, 2, 3, and 6) in all 5 mid-term budget milestones shows the strategic importance of these technologies for Iran, because of the changes in the budget between 2000 and 5000 billion Rials, although the budget increases by 150%, no change occurs in the selected technology groups and even in their shares. This can represent the necessity of these technology groups for the country's space industry and the capacity for investing in these technology groups and using its unused capacity for the country.
- In general, the model is much more sensitive to the short-term budget. After getting more outputs from the objective functions for different values of the short and mid-term budget, we found that major changes in the number of the selected technology groups in the short and mid-term portfolios happen in the 5000 billion Rials budget level for the short-term portfolio. The number of selected technology groups in both short and

mid-term portfolios changes significantly from this budget level. For instance, if the short-term budget is 5000 billion Rials and the mid-term budget is a low value like 600 billion Rials, the number of selected technology groups in both portfolios summation will increase by 100%; indeed, with this assumption, the number of selected technology groups becomes 12 technology groups; while with a more realistic and likely estimated budget for the short and mid-term portfolios, there will be 6 group technologies in both short and mid-term portfolios summation. This means that if we desire comprehensive development in the country's space industry, a 5000 billion Rials budget for the short-term portfolio seems essential.

5. Managerial insights

Hearing that each dollar invested in the space industry has a return of dozens of dollars, may change one's mindset about this industry. Investing in the space industry is a long-term and costly investment. But, what makes it intriguing for investors is the high profitability per dollar invested. Along with this financial importance, the security and military functions of the space industry in critical conditions should not be ignored. Therefore, the management of limited resources and its optimal allocation to the space industry of each country, especially developing countries that are facing more financial and technological resource limitations, is of great importance. Iran, as one of the developing countries, is not exempt from this rule. In general, the current research can significantly help in directing the country's investment in the space industry, spatial ecosystem orientation, facilitating the creation of space-based businesses, improving economic growth, and also providing guidelines to improve the related policies in this area.

Also, policymakers and managers of technology-oriented industries, especially the space industry, can use the proposed framework and selected criteria of the current model in prioritizing and allocating budgets to technologies and as a result make better decisions based on the potentials and uncertainties of their environment.

The following three practical suggestions can be considered for further studies:

(1) Developing a strategic pattern for dedicating the selected technologies to the players in the space industry according to the share of each technology in the space technology portfolio and the capacity and capabilities of each player in the space industry.
(2) To extend the model, the long-term budget parameter can be considered uncertain. Because due to the political, economic, and social changes caused by the change of governments, it is not possible to precisely predict the long-term budget.
(3) Determining acquisition methods for each selected technology and planning for each technology transfer method for technologies that cannot be developed endogenously. Choosing the method of technology acquisition or transfer can lead to more accurate budget allocation.

6. Conclusions

Technology development is a time-consuming, costly, and at the same time strategic process. This process is especially sensitive and important in developing countries such as Iran, which face more resource constraints. Therefore, in this research, for better management of resources for technology development, the method of selecting the optimal technology portfolio has been used. The aim of the proposed method was to determine the development path in Iran's space industry to achieve optimum performance and enhance Iran's position in this industry. Therefore, according to the limitations, available resources, goals, needs, and challenges of Iran's space industry, as well as the characteristics of each technology, an optimal technology portfolio has been provided. In fact, using mathematical modeling and its innovative combination with expert-oriented qualitative methods, the output of this research is a set of key technologies in the priority sectors of the space industry in two short and medium-term periods.

The proposed model was a four-objective-function model with the objectives of maximizing the benefits of using different technologies comprising the short and mid-term portfolios, maximizing the total sum of all technologies TRLs, maximizing the acquisition speed for the technologies, and minimizing the acquisition risk of technologies in each portfolio. In the mentioned model, we took the usability, acquisition cost as well as complexity of each technology, etc. into consideration. Considering all 4 indicators: complexity, usability, acquisition cost, and acquisition speed in the mathematical model, which have not been considered at the same time in any model. It is worth mentioning, that another advantage of the proposed model, is the formulation of two portfolios with two different periods in which their corresponding inputs and outputs affect the other. In fact, in the designed mathematical model, it is possible that part of the short-term budget is allocated to some mid-term portfolio technologies. After integrating the mathematical model with the goal programming method, the proposed model is solved in GAMS software using the Baron solver and the results are as follows: the selection of two technology groups of radars and atomic clocks in the short-term portfolio and 4 technology groups: Terrain mapping and classification, Human-rated advanced secondary chemistries above lithium-ion, optical sensors, and in-situ camera geometric calibration diagnostics and self-calibration, in the mid-term portfolio, Which shows the necessity of acquisition and the importance of investing in selected technologies in the two-time-frame studied. To validate the model, the selected technology portfolio in this model is compared with current Iran's space industry technology portfolios. As a result, the optimality of the technology portfolio obtained from present research in comparison with current Iran's space industry technology portfolios was determined. Then, to verify the model behavior, sensitivity analysis was performed on two important parameters of the model, namely short-term and medium-term budget; the results show the importance and criticality of the country's short-term space budget. Major changes in the optimal space portfolio, due to changes in this parameter.

Finally, 3 suggestions were recommended for future studies, assigning tasks and technologies to space actors, developing the model in the long term, taking into account uncertainty, and assigning acquisition and technology transfer methods to portfolio technologies.

Appendix A.

Table A.1. A part of "Iran's space industry prioritized hard technologies tree chart".

Technology taxonomy	Technology area	Technology sub-area	Technology group
Tx04 robotic systems	Sensing and perception	1. Sensing for robotic systems	Space-qualifiable force and torque sensors Space-qualifiable tactile sensor Three-dimensional (3D) range imaging sensors for surface mobility, above-surface mobility, and manipulation *In-situ* camera geometric calibration diagnostics and self-calibration
		2. State estimation	Vision-based aiding of dead reckoning for navigation of surface vehicles Map-based position estimation for navigation of surface vehicles Vision-based aiding of dead reckoning for above-surface vehicles Map-based position estimation for navigation of above-surface vehicles Radio frequency (RF) navigation aiding for above-surface vehicles
		3. Onboard mapping and data analysis	Terrain mapping and classification Landmark mapping from image sequences and other navigation data Three-dimensional (3D) modeling from multiple observations
		4. Object, event, and activity recognition	Natural object recognition Human-made object recognition Event recognition

Table A.1. Continued.

Tx08 sensors and instruments	Remote sensing instruments and sensors	1. Detectors and focal planes	Back short Undergirds bolometer arrays Mercury cadmium telluride and strained super lattice arrays Charge coupled devices
		2. Electronics	Analog and mixed-signal instrument front-end electronics application-specific integrated circuits (ASICs), Field Programmable Gate Arrays (FPGAs) and discrete components *e.g.*, radio frequency (RF) System on Chip, Multi-Channel Digitizer (MCD) Control and bias voltage electronics Low noise amplifiers Multi-channel A/D and D/A Converters Space cube Nano electronics
		3. Optical components	Mirrors, lenses, interferometers, gratings, prisms, and fibers Dynamic pointing components (*e.g.*, field steering mirrors) Advanced surface technologies (*e.g.*, frequency selective surfaces and composites)
		4. Microwave, millimeter-, and submillimeter-waves	Laser heterodyne and gas correlation radiometers Low noise receivers Transmit/receive modules Couplers/combiners, isolators, amplifiers, filters, antennas, and waveguide components
		5. Lasers	Pulsed lasers and the electro-optical components that support them like fibers, gratings, crystals, laser diodes, electro-optical modulators, Nano lasers
		6. Cryogenic/ thermal	Adiabatic demagnetization refrigerators Dilution refrigerators Sorption coolers and supporting components Cryocoolers, like Starling refrigerators, Brayton Cycle refrigerators, pulse tube refrigerators, Joule-Thomson coolers

Appendix B.

The characteristics of the panel members are mentioned in the Table B.1.

Table B.1. Members of the expert's panels.

Number	Education	Experience in the space industry (years)
1	P.H.D	About 10 years
2	P.H.D	About 10 years
3	P.H.D	About 10 years
4	P.H.D	More than 10 years
5	Masters	More than 10 years
6	Masters	About 10 years
7	P.H.D	More than 10 years
8	P.H.D	More than 10 years
9	P.H.D	About 10 years
10	P.H.D	More than 10 years
11	P.H.D	More than 10 years

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