Space Elevator - Concept, Technology, Financial Viability & Safety Issue

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Abstract

A space elevator has primarily been a feature of fictional films. However, this has changed significantly, with an increasing focus on evaluating the viability of such infrastructure to enable cost-effective space travel. To that effect, the current study seeks to establish a contemporary understanding of the current research regarding the underpinning science and technology, financial viability, and safety issues associated with a space elevator. The study comprises a systematic review of literature relevant to the research topic, based on this approach's ability to reduce instances of bias and thus offer reliable findings that can inform the drawing of reliable and accurate conclusions. The study's key objectives include determining the managerial, financial, and safety risks and evaluating the overall viability of undertaking such a megaproject.

From the findings, relevant managerial risks include an inability to register and communicate an exciting vision essential for obtaining the project's goodwill from all relevant stakeholders and the need to build a successful collaborative camaraderie among the different nations central in realising the project. The financial risks include a high risk of overspending when obtaining the needed materials since they may be costly. The safety concerns include potential collisions between the space elevator and orbital debris and extreme

environments, including high radiation levels. Despite these challenges, the completion of the megaproject would present unique benefits for space exploration like reducing over 4,000 per cent in the cost of undertaking space travel compared to the current chemical-based approach that uses rockets.

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1. Introduction

1.1 Background Information

Space elevators, like many other novel ideas, have featured extensively in fictional films, but interestingly, only a small number of people are conversant with the concept. In its most basic description, a space elevator is a cable with one end attached to the Earth, while the other end extends to about 90,000km into space [1]. It would serve as an enormous infrastructure, designed to leverage Earth's rotation in raising payloads from the planet's surface towards space and other destinations within the solar system. For years, rockets have been the method used for both people and payloads to travel into space, and they currently remain the only means through which humans can access the outer expanses of the solar system. However, the use of rockets presents numerous challenges, including the enormous costs of powering the rockets and the expensive infrastructure needed to launch them, particularly considering the relatively low returns in terms of payload capacity. Furthermore, numerous safety risks are presented by the use of rockets: for every launch, depending on the type of launcher employed and its reliability, there is a 30 per cent or more probability of the rocket exploding [2]. With the increasing interest in space travel for exploration, adventure and economic reasons, there is a need for a reliable and low-cost method of accessing space.

The space elevator concept stands out as the most daring and extensively challenging proposal in pursuit of a low-cost, reliable means of accessing space, but also as the one that would have the highest impact and offer the most benefits if actualised. Primarily, a space elevator would be used to deliver payloads such as satellites into space. Following the initial development and construction costs, the infrastructure would have the advantage of dramatically reducing the recurring costs associated with space activities such as launching satellites [3]. From an economic standpoint, a space elevator also promises the potential for a range of applications and activities, including space tourism. Meanwhile, reducing the price of undertaking space missions would offer more people and countries opportunities to obtain an income from infrastructure such as satellites and space applications [1]. As a result, there is a growing body of research aimed at determining how such a project could be actualised. In the same vein, the current research focuses on establishing a contemporary perspective on the current state of the art regarding the underpinning science and technology, financial viability and safety issues associated with a space elevator from a managerial perspective.

1.2 Definitions of Terms

1.2.1 Space elevator

The idea of a space elevator was first proposed by Constantin Tsiolkovsky, a Russian rocket scientist, in 1895. From Constantin’s original ideas, the concept eventually became a mainstay of science fiction books and films in the 1970s, but only garnered attention from academic scholars as a valid scientific and engineering concept in the 1980s [4]. However, in recent decades, the project has gained increasing attention within scientific and engineering circles, and it is now perceived as a viable project and one that could be accomplished within the 21st century. One of the most recent developments in the concept of space elevators is the work of Edwards and Westling, who developed an engineering template for a space elevator comprising a ribbon 1 metre wide and mere molecules thick, stretching from the Earth's surface to beyond the geosynchronous altitude [4]. As a conceptual design, the concept's main benefit is that it would make it possible for climbers to cover great distances in a way that mimics how railroads traverse continents. Figure 1 below displays the conceptual design of a space elevator as envisioned by Edwards and Westling.

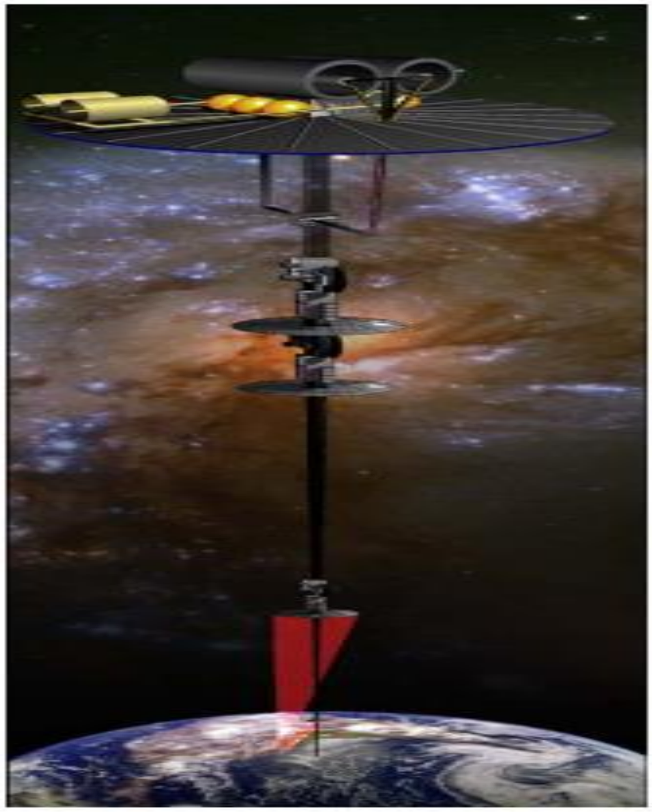

Figure 1: Space elevator concept design [4]

The contemporary understanding of a space elevator refers to a geostationary connection built from the Earth's surface to an orbit altitude of approximately 36,000km. Its centre of mass would need to have an orbit of 24 hours and would have to stay at a geostationary position above the equator while at the same time rotating around the axis of the Earth. The infrastructure would be used to move people and cargo from the Earth’s surface into space, acting as a transportation service [1]. One of the plausible orbits that could be utilised is similar to that of a satellite 36,000km away from the planet: if a satellite were to be launched to this height above the equator, it would orbit the Earth every 24 hours [1], coinciding with the rotation of the Earth around its axis. As a result of the coinciding period of rotation, the satellite would remain fixed at a specific point in the skies relative to the planet’s surface. Lowering cables from the satellite to the surface would result in a system that could be thought of as a cable car. Figure 2 below presents the basic concept of a space elevator.

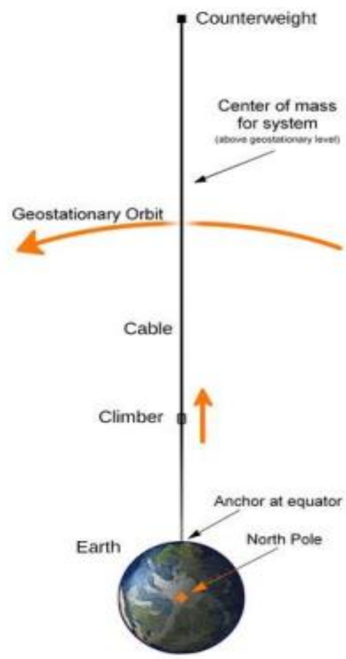

Figure 2: Basic space elevator concept [1]

1.3 Rationale of the Study

The concept of a space elevator is informed by the desire to establish a more sustainable way of travelling from the Earth into space. The main aim is to lower the recurring costs associated with space travel, including those of launching satellites. This is alongside the goal of making it possible to commence a range of different applications and activities in space, including space tourism. Furthermore, reducing the price of undertaking space missions would offer more people and countries opportunities to obtain an income from infrastructure such as satellites and space applications [2]. The idea of some type of space elevator has been around for a while, with the idea of creating a structure to reach from the Earth’s surface to the outer realms of the world dating back to some of the earliest known manuscripts [3]. For instance, the Book of Genesis in the Bible details the story of Babel, a city whose residents decided to build a structure that would reach the skies, bringing about what is now commonly referred to as the Tower of Babel.

In more recent times, it was Konstantin Tsiolkovsky who, in 1895, taking inspiration from the Eiffel Tower in Paris, came up with the concept of a tower whose top extended to space. He envisioned a celestial castle situated at the top of a cable shaped in the form of a spindle, with the castle maintaining a geosynchronous orbit with the Earth. Since objects would attain orbital velocity as they moved up the cable, once they were released at the top of the tower, they would possess the velocity required to persist in a geosynchronous orbit [3]. At the time, Konstantin's idea was deemed unrealistic as no material had adequate compressive strength to support the structure's weight under the conditions within which it would have to operate. However, over the past few decades, there has been a growing interest in the space elevator concept; for instance, in 1959, Yuri N. Artsutanov proposed a more feasible concept. His elevator would feature a space tower that would utilise a geosynchronous satellite as the base from which the tower would be constructed [3].

Following Yuri's concept, there have been further ideations of a space elevator; for example, an American scientist, Jerome Pearson, suggested an integrated profile with a tapered cross-sectional area, which would be a better approach for the design of the elevator. His design featured a proposal for incorporating a counterweight that would gradually stretch out up to 14,400km [5].

The pursuit of feasible space elevator concepts has been driven by the high costs currently involved in moving people and payloads from Earth into space, a model which is proving unsustainable. With the multiple existing ideations of space elevators, there is currently no standard strategy for developing the concept. The development of new technologies has made it possible to generate new materials such as carbon nanotubes (CNTs), which would make the space elevator project more feasible [1], [4], [6]. However, owing to the rapidly changing variables as new studies are undertaken, there is currently a lack of any concrete estimate regarding the cost implications of such a project and its benefits [1]. As such, this study intends to present the viability of a space elevator for offering space travel in the near future, based on the perspective of the current state of research regarding the underpinning science and technology, safety issues and financial viability concerns associated with such a project.

1.4 Research Objectives

While the theoretical objective of this study is to offer an integrated understanding of the space elevator concept in terms of the underpinning science and technology, the practical role of the research lies in offering a managerial perspective on the viability of such a megaproject by considering the financial and safety factors involved. The relevance of such an undertaking is that the current research on the concept remains largely fragmented, lacking the kind of cohesion that would establish an understanding of whether it is a viable megaproject, and if so, what needs to be done to ensure it is realised. Chiefly, the current study considers some of the more recently proposed concepts, including the modern elevator and the climbing approaches, where once the elevator cable is in place, the climber vehicles would be designed in such a way that they could effectively carry payloads up the elevator [7]. For propulsion, these vehicles would require a sustainable energy source, and following an analysis of the possible modes, laser technology emerges as the most suitable alternative. Crucially, there is a growing consensus on the viability of a space elevator as a suitable solution for addressing the challenges associated with space travel [8]. In the context of the need to develop an in-depth understanding of the existing body of knowledge relating to the space elevator as well as to offer a clear managerial perspective on the viability of such a megaproject, this study's objectives are broken down into the following primary research question and subquestions:

What is the current state of the research in terms of the underpinning science and technology, financial viability and safety issues associated with a space elevator?

1. What are the managerial risks currently associated with the construction of a space elevator?
2. What are the financial risks associated with the construction of a space elevator?
3. What are the existing safety risks associated with space elevators, and what are their remedies?
4. To what extent is a space elevator project financially viable?

2. Review Design

The development of research based on the existing body of knowledge relating to a particular topic is a key building block for virtually all academic research activities, regardless of the discipline. Undertaking research accurately to derive reliable deductions should be a key consideration for academicians. However, such an undertaking is becoming increasingly complex due to the rapid changes that keep occurring in various disciplines, especially due to technological advancements [9]. Consequently, despite the extensive growth witnessed in the research on science and especially space and extra-terrestrial studies, these fields remain largely fragmented, especially due to the inter-disciplinary nature of much of the research. Hence, it is becoming increasingly difficult to monitor the latest research and remain at the vanguard of a research domain by evaluating the collective evidence pertaining to the field of interest. It is due to such challenges that literature review (LR) has obtained increased relevance as a viable research method, even in fields such as the sciences that have traditionally predominantly involved primary research.

An LR can be briefly defined as a methodical way of obtaining and amalgamating previous research. A literature review that is effective and well-conducted, when utilised as a research method, thus offers a solid foundation upon which to grow knowledge and fast-track the process of developing new theories [10]. The appeal of LR emanates from the fact that, through the synthesis of findings and ideas from a diverse portfolio of empirical studies, it enhances a researcher's ability to address multiple research questions in ways that no single study can. Furthermore, LR offers the possibility of determining areas in which the research is disparate and involves multiple disciplines. It is an excellent way of synthesising research findings, identifying meta-levels and uncovering elements within the body of knowledge that might benefit from additional primary research. These factors are all crucial both in the development of theoretical frameworks and in instituting conceptual models.

Utilised in conjunction with other research methods, LR is a crucial tool for the determination of what has been studied in the past on a certain research topic and for understanding the level to which the existing work on the topic illustrates patterns that can be analysed to provide insights. Furthermore, it offers a way of integrating the various empirical findings accrued to address a specific research question that has been narrowed down, as a way of supporting evidence-based practice [9]. It is also a suitable method for identifying topics that require further analysis, which is the basis of research as an incremental process. Within academic research, one of the most common applications of LR is as a section within academic works such as journal articles or graduate papers. The LR section typically integrates the existing research relating to a particular field and outlines the gaps that exist, some of which the study is intended to address. In this way, LR can be used to present the theoretical basis for a study and to offer support for the existence of a research problem, as well as to establish the study as one that offers a new contribution to the incremental body of knowledge [10]. Alongside this, it can also help to substantiate the researcher's selected methods for their study.

The alternate approach to LR, which is adopted as the basis of the current study, recognises the review as a primary and worthwhile research work in itself. In contrast to serving as a base for further empirical work by a researcher, this approach provides a solid commencement point for a researcher aiming to comprehend a specific area of study. In this context, a review article is a complete research paper with the primary role of synthesising the existing studies in a certain field, without the collection or analysis of original primary data. When undertaken effectively, LR research papers can serve as invaluable sources of information for researchers who are interested in recent evidence that they can use as a guide when making decisions and undertaking their work practices [10]. In addition, top-quality LR articles are now frequently cited as useful research work, indicating that scholars can utilise them to obtain an outline of the relevant literature when undertaking empirical studies. This is because such reviews provide an in-depth analysis of a study topic through the provision of a wide range of references on the most useful primary studies that have been undertaken on that topic. There are different forms of LR articles, which are outlined in the following sections.

2.1 Descriptive Reviews

Descriptive, or mapping, LRs focus on determining the extent to which the body of knowledge that pertains to a certain research topic discloses patterns that can be analysed within the current propositions, theories, methodologies and findings. To that effect, such reviews incorporate a methodical and clear procedure, which involves locating, screening and categorising the relevant studies [11]. Crucially, within mapping reviews, structured methods are utilised in the creation of a representative sample for a larger collection of the published literature. The authors of mapping reviews usually seek to draw pertinent features of interest from each study, including the publication year, the research methods and data collection techniques employed, and the weight and direction of the research outcomes, with a view to employing this information in undertaking a qualitative analysis. Each study used in creating a descriptive review is viewed as a unit of analysis, and the entire literature provides a database for the author, from which they can identify the explicable themes. Furthermore, the author can derive the overall conclusions made in relation to the advantages of existing ideations, propositions, approaches and findings [12]. Hence, descriptive reviews are perceived as tools used to present findings that illustrate the state of the existing literature within a certain field.

2.2 Narrative Reviews

Narrative reviews are a suitable way to review extant literature in terms of establishing a qualitative comprehension of the existing body of knowledge in a specific field. Simply put, a narrative review is used to summarise and incorporate the research undertaken in a certain field, but it is not meant as a way of developing generalisations or an incremental comprehension of knowledge across different fields [10]. Narrative review authors primarily utilise this approach to accumulate and synthesise relevant existing literature as a way of depicting the value held by a specific view in relation to the selected research topic. As such, researchers will often be highly selective or limit their attention to a certain study, with a view to making a certain point [13]. This makes the narrative method a somewhat unsystematic approach to reviews, since the selection of information from primary sources is in most cases subjective and devoid of a clear criterion upon which the selection is based. As a result, there is a tendency for narrative reviews to feature extensive biases from the reviewer in arriving at certain inferences. That said, narrative reviews present a suitable approach by which researchers can synthesise sizeable volumes of literature on specific topics.

Narrative reviews are often used among faculty teams due to the ability they offer to present recent information on research topics and provide a valuable range of peer-reviewed literature. The presence of an extensive range of credible sources in narrative reviews makes them especially suitable for offering researchers an avenue to identify gaps and irregularities in different bodies of knowledge, thus highlighting the importance of undertaking new research. Furthermore, narrative reviews provide researchers with information that is adequate for them to utilise in arriving at research questions as well as formulating hypotheses. Recently, there has been a growing trend of a more thorough approach to narrative reviews, with a view to addressing the more apparent pitfalls associated with these reviews and to bringing about positive changes in terms of the standards of publications. To that effect, one suggestion that has been made includes a proposal for the development of a comprehensive framework within which to develop such reviews [14]. The framework comprises three crucial steps: literature research and screening, followed by the extraction and analysis of data, and finally writing the literature review. Conversely, [15] proposes a structured tool that could be employed in identifying primary studies within a feasible scope, which would make it easier to obtain the relevant content from the articles.

2.3 Realistic Reviews

Realistic reviews are primarily theory-driven, interpretive reviews, which are developed with the aim of informing, enhancing and building upon traditional systematic reviews. The aim of this approach is to make sense of the disparate evidence pertaining to complex interventions employed in various contexts as a way of guiding decision-making in relation to policies [16]. The origins of realistic reviews can be traced to the criticism of positivist systematic reviews, which are largely based on simplistic assumptions. The primary goal of realistic reviews is to determine causation, and the approach is effective in certain fields such as education. In these studies, findings of random samples from controlled trials can be easily collated to identify ways in which a new approach can improve outcomes. However, critics of this approach assert that it is essentially impossible to pinpoint direct causal links between approaches and outcomes in certain fields, such as management and information systems, in which it is not necessarily the case that a certain action will result in a regular outcome. In a bid to overcome such limitations, [16] proposes an approach that incorporates the synthesis of knowledge by unpacking the ways in which complex interventions function in different situations. Hence, the key research question of ‘what works’, which is the basis of realistic reviews, is replaced with ‘what aspect of the intervention works’, for whom, and in which situations. Chiefly, realistic reviews do not bear any preference for either qualitative or quantitative evidence; in contrast, as a theory-building approach, these reviews initially seek to outline the possible mechanisms underlying the issue under analysis, followed by scrutinising the underlying mechanisms identified in accordance with the available evidence to determine where the mechanisms apply. Essentially, primary studies in the existing body of literature are viewed as case studies on which initial theories can be tested and improved.

2.4 Scoping Reviews

Scoping reviews are primarily used as preliminary indicators of the volume and nature of the present literature pertaining to a certain research subject, with a particular preference for emerging topics. Hence, a scoping review can be undertaken to comprehend the scale, range and nature of the research activities undertaken in relation to a specific field, and to determine the value that will be obtained from conducting a full systematic review. Furthermore, this type of review allows for identifying the research gaps that exist within the present literature [10]. As such, scoping reviews often end with the presentation of a conclusive research agenda that should guide future research, in addition to outlining the possible effects of the existing gaps in both research and practice. In contrast to narrative and mapping reviews, scoping studies are meant to be as conclusive as possible in reviewing the existing literature, including relevant grey literature [17]. Furthermore, inclusion and exclusion criteria should be established to help researchers filter out studies that do not align with the stated research focus.

2.5 Systematic Reviews

Researchers in fields such as health are often confronted with extensive amounts of information, especially research-based evidence, from a variety of sources [18]. As such, it cannot be expected that all professionals in these fields will possess the requisite skills, resources and time to sift through the available evidence within their field of research and incorporate it accurately in their decision-making. Hence, systematic reviews represent a strategy incorporating the extensive utilisation of scientific procedures, with the intention of limiting instances of bias and subjectivity in the analysis. As a result, systematic reviews incorporate, review and synthesise into a single source all empirical evidence pertaining to a certain topic that meets the set criteria. The aim of this approach is thus to respond to narrowed-down research questions, and these reviews follow distinct scientific principles and methodological guidelines to reduce random and systematic errors, which are often the reason behind departures from a factual basis in the process of arriving at inferences.

The incorporation of explicit methods within systematic reviews serves as an effective way of synthesising an extensive body of evidence and identifying in which ways the effects or interactions align. In addition, this approach makes it possible to outline possible inconsistencies between study findings and outline the value added to the wider body of knowledge on a certain topic based on the outcomes under review [19]. The main procedure employed in undertaking systematic literature reviews involves formulating the review question, determining inclusion criteria and developing a search strategy with a view to identifying the relevant studies. The second step is to search for suitable studies using different databases and information sources, including grey literature resources, making certain that the language used in the analysis is one that all the researchers understand. The third step entails selection of the studies to be included, obtaining data from these studies and mitigating the risk of bias in a duplicate manner by utilising independent reviewers as a way of avoiding both random and systematic errors within the research process. The fourth step comprises the analysis of data using qualitative and quantitative approaches and detailing the results in a summary of the findings. Finally, the findings are interpreted with a view to arriving at conclusions.

The methodology chosen for undertaking the current research is a conceptual one involving a blend of scoping and systematic LRs, thus making it a hybrid approach. The main aim of the study is to obtain a contemporary perspective on the current state of the research relating to the underpinning science and technology, financial viability and safety issues associated with a space elevator. Since the study has not been undertaken before, it could be viewed as an explanatory form of research [20]. This informs the basis of undertaking the scoping review to obtain an understanding of all published studies that are relevant to the research topic and thus illustrate the existence of a research gap. Crucially, in this case, the scoping review functions as the pre-cursor for the systematic LR by presenting the existing situation within the research topic, from which the consistent, precise and concrete interpretations of the initial findings are taken up for more detailed analysis in the systematic review. Furthermore, the scoping review serves to confirm the suitability of the inclusion criteria and research questions, which is essential for undertaking an effective systematic review [21]. The systematic LR then considers the pertinent empirical evidence that fits into the pre-determined inclusion criteria to answer specific research questions [22].

The appeal of the systematic review element of the current study emanates from its framework: by employing a systematic and explicit approach in reviewing the literature, it is possible to reduce instances of bias and thus offer reliable findings that can inform the process of arriving at valid and accurate conclusions [9]. Furthermore, the ease of applying the approach and its efficacy in promptly offering extensive information regarding the chosen research topic increases the appeal of a systematic LR as a suitable methodology for undertaking the current study. The study presents a review of different articles relevant to the topic of space elevators, and especially to the viability of a space elevator as a suitable way of undertaking space travel from managerial, financial and safety perspectives. To achieve this, a search protocol is developed and utilised in the analysis of multiple databases, including journal article resources and institutions including the International Space Elevator Consortium (ISEC) and the National Aeronautics and Space Administration (NASA), which are the leading organisations in space elevator research. The articles included in the review are limited based on the time, language and the relevant search phrases employed. The source materials are grouped into those which are concerned with the current science and technology underpinning the research into space elevators and those that explore how the existing science and technology literature impacts on the viability of such a megaproject, from managerial, financial and safety perspectives. Our analysis of the existing literature based on these guiding procedures helps to inform an in-depth understanding regarding the viability of a space elevator project. Crucially, only credible and peer-reviewed sources are incorporated into the systematic LR.

3. Scoping Review

3.1 Background

Scoping reviews serve as highly effective tools for mapping the underlying concepts that guide a certain area of research. They are especially valuable in supporting the process of amalgamating the pertinent literature within disciplines that feature extensive emerging evidence, as they allow for addressing questions beyond those relating to effectiveness or the experience associated with an interventional measure. The current study aims to offer a managerial perspective on a space elevator by presenting insights on the viability of such a megaproject through a consideration of the financial and safety factors, based on the underpinning science and technology behind such an undertaking. To that effect, the relevance of the scoping review is to function as a pre-cursor for the systematic LR, which is presented in the next chapter. The scoping review aims to map out a body of knowledge with relevance to the context as well as the source.

Concerning the context, the scoping review focuses on the existing science and technology research behind space elevators that considers the viability of such a megaproject from a managerial perspective by factoring in the financial and safety factors that would hamper or support its construction. After the synthesis of the relevant literature, an extensive review and analysis is conducted with the aim of determining the viability of such a space elevator megaproject from the managerial perspective. Crucially, there are existing peer-reviewed sources detailing both the science and technology pertaining to the development of space elevators; however, this information is highly fragmented and lacking in direct insights on the viability of space elevators from the managerial perspective, i.e. factoring in financial aspects and safety factors. Thus, the scoping review aims to collate a diverse body of knowledge on this subject, with a view to supporting the making of relevant deductions in the systematic LR phase.

3.2 Objectives

The primary objective of this scoping review is to function as a pre-cursor for the subsequent processing of a precise and robust systematic LR. This aim is achieved through the presentation of an understanding of the scale, range and nature of the research activities undertaken to date within the field of space research, specifically space travel involving a conceptualised space elevator. Furthermore, the scoping review aims to determine the value that will be added to the field by undertaking a full systematic review on the topic. Crucially, the scoping review is also guided by the overall objectives of the study, as detailed by the research questions:

What is the current state of the research in terms of underpinning science and technology, financial viability and safety issues associated with a space elevator?

1. What are the managerial risks currently associated with embarking on the construction of a space elevator?
2. What are the financial risks associated with on the construction of space elevator?
3. What are the existing safety risks associated with space elevators, and what are their remedies?
4. To what extent is a space elevator project financially viable?

3.3 Inclusion Criteria

It is important to note that not all studies that have been undertaken on the topic of space elevators are considered within the current review. With the vast bodies of both peer-reviewed and grey literature featuring this topic, it is important to apply criteria to inform the decisions of which sources to consider, and which to ignore, in a bid to obtain relevant and applicable insights into the concept from the existing literature. Hence, the inclusion criteria serve as a guide for decisions about which sources should be included in the scoping review. There is a strong need for congruence among the essential elements of the objectives, the research questions and the inclusion criteria for the scoping study to be effective. In elaborating the inclusion criteria, the 'population, concept, context' model as outlined by the Joanna Briggs Institute (JBI), proves to be an invaluable tool [50]. On this basis, the inclusion criteria should provide the basis for the population to be included, the underlying factors behind the uptake of the space elevator concept, and the managerial hurdles pertaining to financing and safety that are at play.

3.3.1 Population

The key aim of this scoping review is to establish an understanding of the underlying factors associated with the concept of a space elevator as a plausible means of space travel, and its viability as a megaproject in a near future. Since this study does not feature individual respondents, the inclusion criteria focus mainly on the concept and context. As a result, the main point of emphasis for the inclusion criteria are the literature sources selected to guide the discourse. Moreover, the study is not aimed at analysing demographic factors; rather, it aims to establish an understanding of the main factors surrounding the concept of a space elevator, and especially the viability of undertaking such a megaproject, from a managerial perspective. Hence, the review is focused on offering a managerial perspective on the viability of such a megaproject by considering the financial and safety factors involved.

3.3.2 Concept

The core concept to be examined by a scoping review should be clearly outlined to provide a guide for both the scope and the breadth of the enquiry. Primarily, the concept aspect of this refers to the elements to be detailed in the systematic review afterwards, including interventions and the phenomenon of interest. The current scoping review is not intended to ascertain an interventional measure, but to review a phenomenon of interest. The phenomenon in question here is how space elevators, a novel concept, could be developed as a tool for facilitating effective space travel. At present, rockets continue to dominate the field of space travel in terms of enabling the movement of people and payloads into space. However, rockets feature numerous disadvantages as a method of space travel, including high costs, high safety risks (including those of using rocket fuel), and the limited capacities of current models in terms of payloads and ease of use. A space elevator would provide a truly sustainable way of accessing space, which could offer extensive economic benefits. Some current estimates set the potential cost reduction for launching people and payloads into space at $250 per kg [23].

3.3.3 Context

In a scoping review, the context element is entirely dependent on the objective and the research questions that the study seeks to address. The context, which should be defined clearly, may feature, but is not limited to, consideration of cultural factors, physical factors such as geographic location, and societal interests. It may also encompass the actual setting of the topic that is under review. The current study focuses on space travel, a matter that is of interest in society, and on ways of increasing its efficiency through the novel concept of the space elevator. The analysis of the concept is especially focused on determining the viability of such a project by factoring in the scientific and technological resources that exist to enable its realisation as well as considering both financial and safety concerns.

3.4 Search Strategy

A comprehensive search strategy for a scoping review should identify both the published and the unpublished (grey literature) primary studies relevant to the topic that is under study. There are several approaches that could be employed in the search strategy of a scoping review, but the model proposed by the JBI is especially useful in presenting a framework that is ideal for developing the strategy for the current study. The JBI framework features a three-step process, with each stage having to be outlined in depth to enhance clarity and make certain that there are no errors [24]. The current study is focused on a management perspective regarding the viability of a space elevator megaproject as a suitable way of effecting space travel. In that regard, the online databases from which the initial limited search was undertaken to find relevant sources on the topic included Science Direct and Springer. In addition, with a view to obtaining as much information on the space elevator as possible, the search was extended to various organisations that are involved in studies relating to space, and specifically space elevators. The organisations included in the search included the ISEC and NASA.

As the topic of space elevators is a novel one, whose nature has constantly shifted over the past few decades due to rapid technological innovations, the search strategy was also extended to independent peer-reviewed journal articles on the topic, to avoid neglecting pertinent information. As a result, the databases from which individual sources were obtained included Elsevier and the Journal of Aviation and Aerospace Studies. From the primary studies, it was possible to obtain a suitable initial comprehension of the concept of space elevators, the underlying science and technology and the financial and safety factors pertaining to their development, and their viability as a megaproject that could be undertaken in the near future. The initial search was followed by the analysis of words contained in the titles of the sources, the abstract sections of the retrieved papers and the index terms used in describing the articles. A second search utilised all the identified keywords and index terms across the selected databases [24]. After the completion of the second search, a third search was conducted, encompassing all the identified reports and articles, with the goal of finding additional studies.

Where relevant, a researcher should indicate their intent to contact the authors of the primary studies for further insight on their work. For the current review, the authors of the primary studies will not be contacted, and their work, which has been peer-reviewed, is taken as is for the scoping review. Another essential point when outlining the search strategy is the language preferences that will guide decisions on the inclusion of sources in the study. English is the primary communication language for the majority of the relevant studies, and even for those featuring a different language, there are translations into English. Moreover, the databases that inform the study, i.e. Science Direct, Springer, Elsevier, as well as the professional organisations NASA and the ISEC, all publish in English. Therefore, the language of choice for the study is English, and for its inclusion into the review, a study must be written in English. Furthermore, in instances where the review question is broad, it would be appropriate to search for all types of evidence, including primary studies as well as opinion articles, simultaneously within a single search strategy. However, in this scoping review, the review question is straightforward, which removes the need to use opinion articles, as does the fact that the scoping in this case acts as a pre-cursor for the systematic review in which concrete inferences will be made, with the intention of employing the insights practically in outlining the viability of space elevators.

For the current scoping review, the search strategy entailed searching through specific databases, Science Direct, Springer and Elsevier, as well as organisational sources from NASA and the ISEC. As there has not been an overwhelming body of studies on the topic of space elevators over the past decades, and as the existing studies feature an incremental development of knowledge, all relevant studies from 2000 up to 2021 were considered, with the search narrowed down to only those sources written in English. Keywords used for the search included ‘space elevators’, ‘space elevator development’, ‘Earth–space infrastructure’, ‘physics of space elevator’, ‘viability of space elevator’, ‘safety considerations for space elevators’ and ‘futuristic materials for modern space travel’. On Science Direct, the search returned 5,875 initial sources, of which, following a review, 254 relevant articles were identified. On Springer, the search resulted in 1,247 initial findings, of which 25 were selected. The Elsevier search resulted in 3,285 initial findings, of which 10 were selected. The search criteria and the search findings from the databases are detailed in Tables 1 and 2 below, respectively.

Table 1: Inclusion and exclusion criteria for source materials

Inclusion	**Exclusion**
Research topic and scope of the research are relevant to the research questions.	Research topic and scope are not relevant to the research questions.
The concepts and definitions outlined in the source are relevant to the research questions.	Concepts and definitions are not relevant to the research questions.
Qualitative studies, quantitative studies, observations, case studies, experimental studies, action research, reports on status of the topic relevant to research questions, conceptual and theoretical frameworks.	Articles without any concrete research design, i.e. concept papers, proposals.
Studies on space elevators with a focus on the science and technology underlying the elevators and possible development of the technology.	Studies on space elevators but outside the scope of ascertaining the viability of a megaproject from a scientific, technological and/or managerial perspective.
Articles published from 2000 to date.	Studies published prior to 2000.

Table 2: Search details for the scoping review

Database	**Sub-headings and Keywords Used**	**Articles Searched (Initial Findings)**	**Articles Identified**
Science Direct	Space elevators, space elevator development, Earth–space infrastructure, physics of space elevator, viability of space elevator, safety considerations for space elevators, futuristic materials for modern space travel	5,875	254
Springer	Space elevators, space elevator development, Earth–space infrastructure, physics of space elevator, viability of space elevator, safety considerations for space elevators, futuristic materials for modern space travel	1,247	25
Elsevier	Space elevators, space elevator development, Earth–space infrastructure, physics of space elevator, viability of space elevator, safety considerations for space elevators, futuristic materials for modern space travel	3,285	10

The search process thus resulted in a total of 289 sources from which to select relevant studies for review. A step-by-step screening process was used in a further examination of the identified studies, and Figure 3 below depicts the flow chart of the different stages of the literature search, adopted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) low diagram [49]. The first step entails the analysis of the relevance of the identified sources based according to their titles and abstracts. In this study, 289 articles were screened for relevance, of which 158 abstracts were excluded due to limited conformity with the review objectives. Out of the remaining 131 articles, 34 were discovered to be duplicates and thus omitted from the review, leaving a total of 97 articles that were eligible for the complete screening, which is the next step in the model.

After undertaking the screening process to determine the articles that were ideal for the scoping review, 46 further articles were eliminated due to various factors, including limited emphasis on the viability of space elevators from a managerial perspective and offering a historical perspective on space elevators as opposed to a contemporary view on the concept with the aim of ensuring its realisation. Following the inclusion and exclusion criteria outlined in Table 1 above, the final output of the screening process consists of 51 articles, of which 45 are primary studies and six are review articles, to utilise for data synthesis.

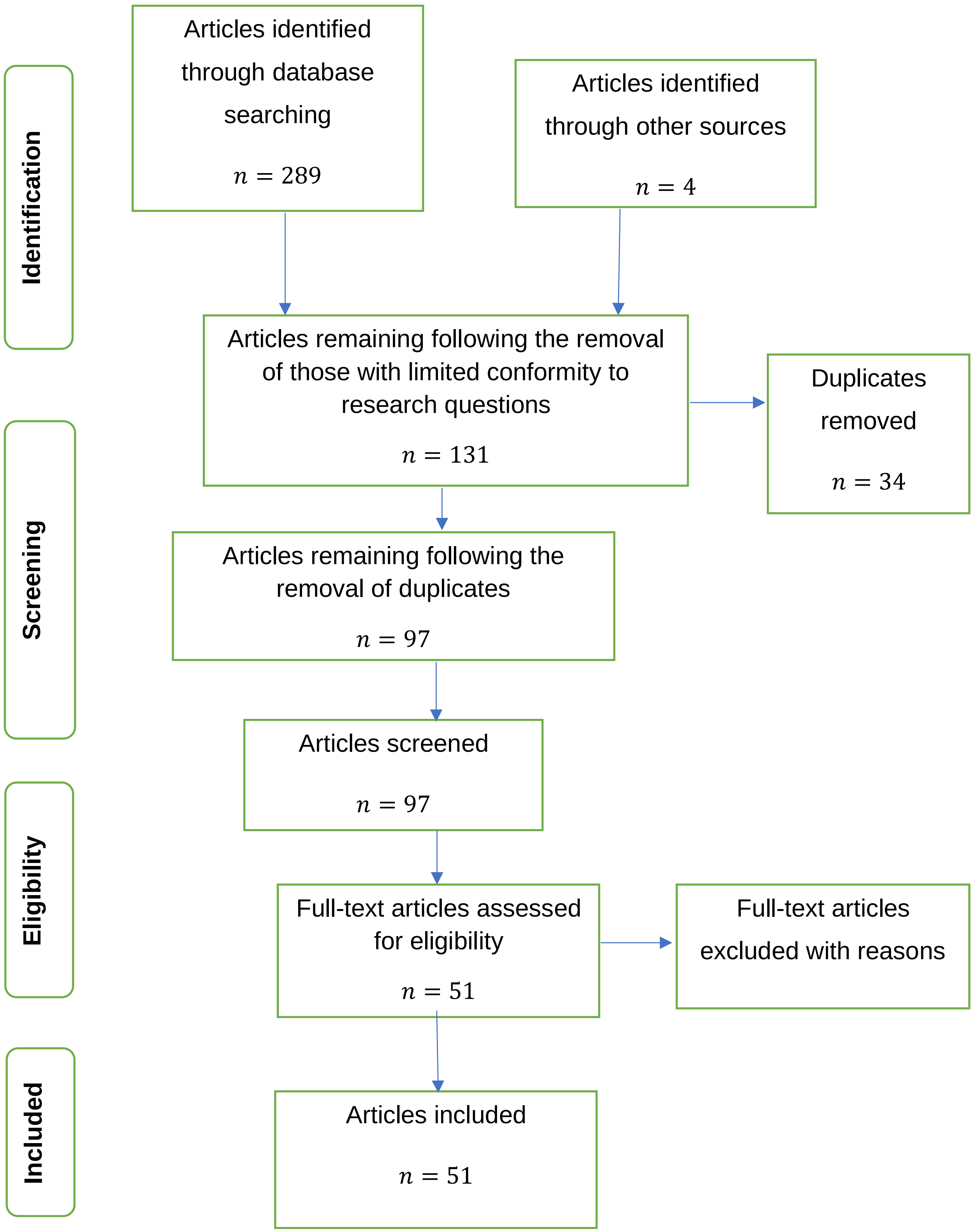

Figure 3: PRISMA flow diagram for scoping review [49].

3.5 Extraction of Results

After searching for the articles and settling on the most suitable ones for data extraction, the next step was to carry out the data extraction. The types of data to be extracted were based on the review questions as specified in the previous section. The aim of the review is to offer an integrated comprehension of the space elevator in terms of the underpinning science and technology as well as a managerial perspective on the viability of such a megaproject by considering the financial and safety factors involved. Hence, the relevant information to be extracted included the setting and the design of the study. The extraction fields used for each source thus included author, year of publication, country of origin, aim or purpose, methodology, key findings, and research gaps identified by the study.

3.6 Presentation of Results

The review was undertaken in accordance with several considerations, among them the number of articles that have been published from 2000 to date and the countries from which the articles were published. Of the 51 included articles, in-depth analysis of a total of 15 articles was undertaken to determine the trends in the research on space elevators. From the reviewed studies, the USA emerged top with eight articles [25], [26], [27], [28], [29], [37], [38], [39], followed by one each from China [34], Turkey [30], Canada [36], Japan [35], Austria [32], the Czech Republic [31] and Italy [33]. Moving on to the year of publication, six of the 15 articles were published between 2008 and 2017, five were published between 2000 and 2008, and four from 2017 to date, as depicted in Figure 4 below. This is indicative of a growing interest in the topic, which could have been partly fuelled by technological advances that have resulted in the development of super-strong materials such as CNTs, which have increased the likelihood of realising a space elevator within the 21st century. Despite the concept having been around for over a century, the idea of space elevators could be viewed largely as a new concept, particularly since it is only now that the technology that could make the megaproject a reality is being developed and launched for mainstream use. Due to space elevators being largely a new concept, there is a need for additional studies to establish a fuller understanding. The set of sources selected for the current study featured both primary research articles and review articles. Of the 15 articles reviewed in depth, two were critical reviews, while the other 13 were primary research articles.

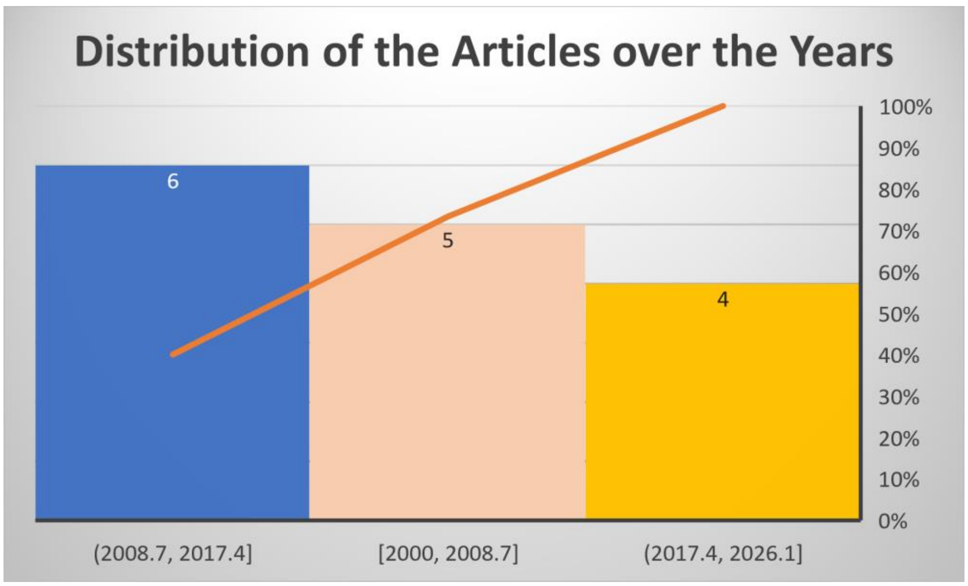

Figure 4: Distribution of articles over the studied period

3.7 Discussion and Conclusion

3.7.1 Discussion

The reviewed sources encompass primary research involving analysis of the space elevator concept from the perspective of physics, and especially engineering, to offer guidance regarding plausible designs and avenues for addressing some of the challenges that are envisioned to arise in the development of this type of megaproject. From the reviewed sources, the underlying themes pertaining to space elevators include plausible designs, modern materials that could be employed in the realisation of the megaproject, and ways of overcoming the possible challenges and perils that would emanate from this mode of travel into space. Concerning the materials, according to [25], the concept of a space elevator concept as a suitable method of getting into space emerged in the 1960s, and early studies outlined a basic concept comprising of a cable strung between Earth and space. However, at that time, the conclusion was that there were no available materials with the requisite properties to be employed in feasibly constructing such a cable. The discovery of CNTs in the early 1990s raised the possibility of a material that could be suitable for use in the development of a space elevator [25]. Furthermore, in [26], it is asserted that the space elevator is an advanced space transportation system that could one day replace chemical rockets as the primary means of transportation from Earth to space.

However, realising that possibility is dependent upon the development of the enabling technologies as well as upon addressing relevant questions regarding the economic perspective of the megaproject and the existing policies relating to space travel [26]. In an analysis of current proposed designs of a space elevator for their suitability, [27] presents a life cycle assessment to quantify, assess, compare and propose improvements to the potential environmental and financial performance of the existing space elevator design proposals. Based on this analysis, the One-Tether Space Elevator has the lowest environmental impact, while the Two-Tether Initial Space Elevator offers the lowest production cost per unit mass delivered to orbit [27]. It is important to note the assertions in [37] that the pursuit of a megaproject often relies on the capacity to leverage technical knowledge, political goodwill and management skills. Thus, in the case of a space elevator, the success of the megaproject would rely on the ability to capitalise on an exciting vision to pull the programme together and drive it forward [37].

3.7.2 Conclusion

This scoping review analysis presents a concrete argument that there is an increased emphasis on finding alternative means of realising space travel in place of the conventional rockets. This is reflected by the finding that the number of studies being undertaken in relation to the concept of a space elevator has increased significantly over the past decade. There is thus a case for seeking to establish a thorough comprehension of the viability of space elevators as the primary means of fulfilling space travel in the future. Crucially, the majority of studies on this topic have been undertaken in the USA, which indicates the growing interest in space elevators by organisations such as NASA and the ISEC. Furthermore, as the majority of studies on this subject to date have been primary studies, there is a case for undertaking a systematic LR as a way of amalgamating the existing research to arrive at a coherent conclusion regarding the current state of development of the space elevator concept, and especially its viability as a megaproject in the near future.

4. Systematic Review

4.1 Background

Conducting LRs is one of the most effective ways of developing knowledge as it facilitates uncovering studies that would otherwise remain unutilised, while also making it possible to advance new theories. Crucially, this systematic review, as opposed to the scoping review section carried out in the previous chapter, delves into the themes that exist within the selected literature. Specifically, the aim is to review the concept of space elevators and their viability from a managerial perspective, factoring in the financial aspects as well as the safety concerns of such a megaproject. The appeal of undertaking a systematic review compared to other LR methods such as mapping reviews is that it is an exhaustive method for reviewing literature, using a replicable approach [19]. Furthermore, it makes it possible to minimise any element of bias in the process of selecting, identifying and evaluating the appropriate sources. Of relevance for the current study is a qualitative systematic review approach of combining, reviewing and synthesising into a single source the empirical evidence that meets defined eligibility criteria. The aim is to respond to clearly formulated, defined and narrowed-down research questions pertaining to a specific topic.

The scoping review chapter presented the distribution of the various articles that were included in the analysis after undertaking a thorough screening process that reduced an initial sample size of over 8,000 articles to 51, from which a study sample of 15 articles was selected. Hence, there is no need for a further overview of the distribution of the source materials; rather, the focus of the systematic review is to provide a deeper contextual analysis of the articles' findings, with the aim of providing an in-depth insight into the research topic. This chapter thus employs a qualitative systematic review of the included literature as a way of exploring the concept of space elevators from a managerial perspective, in terms of the viability of a megaproject from financial and safety standpoints. The methodology entails an integration of findings from different sources, as opposed to formally aggregating the findings from within the selected sources [38]. For the current study, a qualitative systematic review makes it possible to explore the context within which the findings in the selected sources are situated. There is then a need to employ a conclusive approach to summarising as well as extracting the findings from literature, while also making certain to maintain the context as well as the nature of the qualitative research to remain objective.

Several approaches have been developed to help researchers in the process of conducting a meta-synthesis of qualitative research. For the current study, the approach employed in undertaking the thematic synthesis is that outlined in [39]. The method first entails a preparatory phase, comprising a literature search and a review of the quality of available sources, followed by the extraction of data from the selected literature. After the preparatory phase, the next stage is thematic synthesis, which encompasses the coding of the text, developing the descriptive groupings and generating the analytical themes. Vitally, the thematic synthesis stage involves considering the context, accuracy and quality of the studies documented in the selected sources. This systematic review section follows this approach to provide structure and support the flow of the review.

4.2 Objectives

The primary objective of a qualitative systematic review is to investigate the fundamental complexities that exist within people’s experiences by integrating findings across different studies. Within the current study, this is carried out by providing an overview of the underlying themes associated with the concept of space elevators, and specifically an understanding of the viability of this type of megaproject from a managerial perspective, by factoring in the financial and safety factors that would be involved in the project. Vitally, the qualitative systematic analysis will also be guided by the overall objectives of the study as well as those that guided the scoping review, as detailed by the research questions repeated below:

What is the current state of the research in terms of underpinning science and technology, financial viability and safety issues associated with a space elevator?

1. What are the managerial risks currently associated with embarking on the construction of a space elevator?
2. What are the financial risks associated with on the construction of space elevator?
3. What are the existing safety risks associated with space elevators, and what are their remedies?
4. To what extent is a space elevator project financially viable?

4.3 Preparing for Thematic Synthesis

4.3.1 Literature search

With a view to obtaining as many relevant sources as possible for the review, multiple published and peer-reviewed sources were searched across different electronic databases. The databases selected for the review were Science Direct, Springer and Elsevier, as well as those of professional organisations including NASA and the ISEC. The search was narrowed down to the key concept of a space elevator, with a particular focus on reviewing this concept from a managerial perspective regarding viability in terms of financial and safety considerations. As the topic of space elevators has only featured in a limited number of studies over the past few decades and the existing studies feature an incremental development of knowledge, all relevant studies from 2000 up to 2021 were considered, with the search narrowed down to only those sources written in English.

This search was guided by the following keywords: ‘space elevators’, ‘space elevator development’, ‘Earth–space infrastructure’, ‘physics of space elevator’, ‘viability of space elevator’, ‘safety considerations for space elevators’ and ‘futuristic materials for modern space travel’. On Science Direct, the search resulted in 5,875 initial sources, from which 254 relevant articles were identified.

On Springer, the search resulted in 1,247 initial findings, from which 25 articles were selected. On Elsevier, the search resulted in 3,285 initial findings, from which 10 articles were identified. The identified articles were analysed and their consistency with the search requirements was reviewed. Following the omission of studies having only limited consistency with the study's requirements, a total of 15 sources were selected from across the different databases for a systematic review. In addition, five source papers from the research organisations focused on the analysis of the space elevator concept – NASA and the ISEC – were selected.

4.3.2 Screening and Quality Assessment

All the sources obtained from the search were reviewed and screened in detail to elucidate any elements of doubt that emerged. However, within qualitative systematic reviews, the question of whether to undertake a quality assessment as part of the review remains an area of contention with scholars holding differing perspectives on this issue [40]. As outlined in [39], there is at present no universally accepted way of classifying qualitative studies based on their quality. Due to the variations in conducting qualitative methodologies, conducting quality review within a qualitative systematic review is a complex undertaking. This is emphasised by the consideration that the utilisation of a standardised research criterion might lead to the exclusion of certain studies that are otherwise fully suited for consideration in the review.

This would be case, for instance, where a study fails to outline its research methodologies conclusively, but otherwise features high-quality material that would offer invaluable insights to the review [41]. In full comprehension of the complexity associated with integrating a full-fledged quality assessment criterion within the qualitative systematic review process, as well as the need to obtain a broad understanding of the space elevator concept within the guidelines of the stated objectives, the current study employed an approach similar to that proposed in [38]. Consequently, no standard criterion was set for reviewing the quality of the sources used. However, the sources identified for the study included peer-reviewed journal articles as well as work from leading organisations in the field of space research. Vitally, no study was excluded from the research based on methodological criteria used or design methodology, unless it did not conform to the inclusion criteria previously detailed in Table 1.

4.3.3 Obtaining data from the selected articles

Each of the 20 selected articles was read carefully, and the findings relating to the development of space elevators, Earth–space infrastructure, the physics of the space elevator, viability of the space elevator as a megaproject, safety considerations and risks associated with space elevators, and futuristic materials for use in modern space travel were reviewed. In this process, emphasis was placed on the extraction of information relating to the managerial and financial risks associated with undertaking a space elevator construction project. Focus was also placed on determining the existing safety risks associated with space elevators and on some of the remedies proposed for addressing those risks. Finally, the financial viability of a potential space elevator project was analysed based on the findings from the reviewed sources to offer insights regarding how viable such a project would be from a financial viewpoint. The key indicators on which the study was focused were entered into a template through the incorporation of as much of the original text as possible from the reviewed sources, while incorporating concepts akin to those utilised by the different authors.

4.4 Thematic Synthesis

4.4.1 Coding the text and identifying descriptive categories

Following the entry of text into the template, it was coded. Initially, broad coding categories were utilised, to be narrowed down later using more refined and specific codes. For example, data relating to the underpinning science and technology associated with space elevators were initially entered under a broad heading of current developments in the research on the construction of a space elevator. This code was later broken down to incorporate subheadings such as preliminary viable designs for the space elevator, ideas on climber propulsion design for a space elevator, and the physics of a space elevator. Eventually, the analysis resulted in the development of ten descriptive categories to be employed in the initial coding. These were as follows: feasibility of a space elevator, viable designs for a space elevator, futuristic material for the construction of a space elevator, economic viability of space elevators, consolidated approach to the development of a space elevator, challenges of current space elevator designs, safety risks associated with a space elevator, engineering and programmatic factors associated with a space elevator, performance requirements for an effective space elevator, and the managerial risks associated with space elevators.

4.4.2 Generating analytical themes

After coding the text and generating the categories, the third stage of the thematic synthesis entailed an in-depth analysis of the ten descriptive categories, which were then combined to define five analytical themes: current viable designs for the development of an effective space elevator, existing and futuristic materials for the construction of a space elevator; the economic viability of space elevators; the managerial risks associated with the development of a space elevator, and the safety risks associated with the development of a space elevator. These themes were developed through a refined coding process, which also entailed an analysis of the findings obtained from the 20 articles selected for the review. The following sections present the ideas pertaining to these themes in the reviewed literature, with the aim of presenting as much information as possible about the individual studies to help understand the context within which they were developed.

4.4.3 Analytical themes

4.4.3.1 Viable designs for the development of an effective space elevator

The idea of a space elevator that could be used for lifting payloads into space is an appealing concept that could offer unique benefits from an economic standpoint. This is because a space elevator would eradicate the need to use sizeable launch vehicles for escaping from Earth's gravity, hence making it possible to carry large payloads into space at a much lower cost than is currently involved [27]. However, despite the evident appeal of such a structure, there is a lack of consensus regarding the most appropriate concept for its development, especially due to the lack of all the requisite materials that would make it a success. To that effect, several concepts have been put forward for the development of a complete space elevator by factoring in the requisite components. These include the modern elevator concept, the climber concept and the base station concept, in addition to approaches involving space elevator astrodynamics.

The modern elevator concept was developed with a view to mitigate the weaknesses identified in previous space elevator concepts. One of these earlier models was that of Tsiolkovsky, and its failing was that, using any known materials, the base of the tower would lack the necessary strength to support the weight of the rest of the structure [23]. For the modern space elevator model, the tension in the cable can be determined by calculating the apparent gravitational field exerting its force on each section of the cable. Thus, the gravitational field is the summation of the forces of the Earth's gravity acting on the cable as well as the centrifugal force generated by the cable. From an analysis of the distribution of masses, it is evident that if the centre of mass is above the altitude of the geostationary orbit, the structure will be in tension [23]. The centre of mass of the system can be raised above the geostationary altitude by incorporating a counterweight into the free end, as illustrated in Figure 5 below.

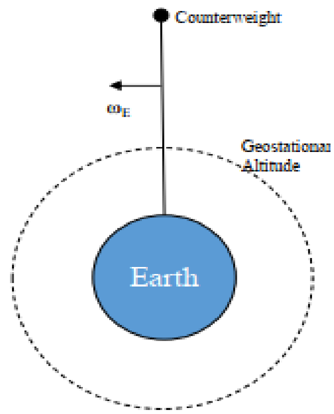

Figure 5: Modern space elevator concept

In this case, the centre of mass must be high enough within the geostationary orbit to offer adequate tension to support the weight of the structure itself as well as any vehicles climbing on the cable.

An important consideration in the design of a space elevator is that the gravitational field varies with the height of a structure in space; thus, the cross section of the cable must be tapered, i.e. it must be wider at some heights than others. The maximum tension would occur at the height of the geostationary orbit, with the minimum tension being at the Earth's surface [43]. Crucially, the ratio of the cross section of the area of the cable at the surface of the Earth to that of the part of the cable in geostationary orbit is largely dependent on the strength-to-density ratio of the material used. The higher the ratio, the smaller the taper ratio will need to be, and due to costs and construction challenges, the aim is to have as small a taper as possible. Presently, only CNTs, which have a yield strength of around 100GPa and a low density (1.3–1.4 g/cm^3), offer a taper ratio that is realistic, i.e. 1:9. Consequently, CNTs are the most suitable material for the development of a space elevator according to the modern concept [7].

Following the development of a suitable space elevator concept, the ideation process for a complete space elevator project proceeds to the climber concept, which is focused on how the climbing vehicles would need to be designed to carry payloads up the cable. As a way of minimising the required cable length, the elevator would not feature moving cables that raise the payload; rather, it would have one fixed cable, while the climbers would supply the power needed to move up and down the cable [23]. Based on the significant distance that the climbers would need to travel, storing a propellant on board would result in a prohibitively large mass, in terms of both development complexity and cost implications. A suitable solution would be the use of an electric motor on the climber, accompanied by a system that transfers power to the motor wirelessly using laser technology. The power that would need to be provided by the laser would be determined by the speed of the climber. According to current estimates regarding energy requirements, a suitable laser would provide about 200kW of power, which would make it possible for the climber to reach the geostationary orbit within four days [23]. The capacity of the load that the space climber can handle is informed by the engine design, and practical estimates have placed the carrying capacity of the climber at approximately 13 tonnes.

Following the development of the space elevator and climber concepts, the next crucial element of the design is the base station. Due to astrodynamics factors, the base station of the space elevator would need to be anchored at the equator so that the cable can remain stationary with respect to the Earth's surface. Additionally, it would be advisable to have the anchor point able to move slightly so that it could avoid orbital collisions. The base station would also need to be of a significant size to enable it to accommodate the delivery of payloads, stage the climber and host the power-beaming stations [23]. Based on these underlying considerations, the most realistic concepts of a base station for use with the space elevator comprise a floating base station, as depicted in Figure 6 below. Vitally, the determination of the appropriate location for the base station would be based on several factors, including weather patterns, which would need to be as mild as possible to minimise the potential risk of damage to the cable. Furthermore, easy access to the area is a key consideration – the location would need to offer easy access to shipping facilities.

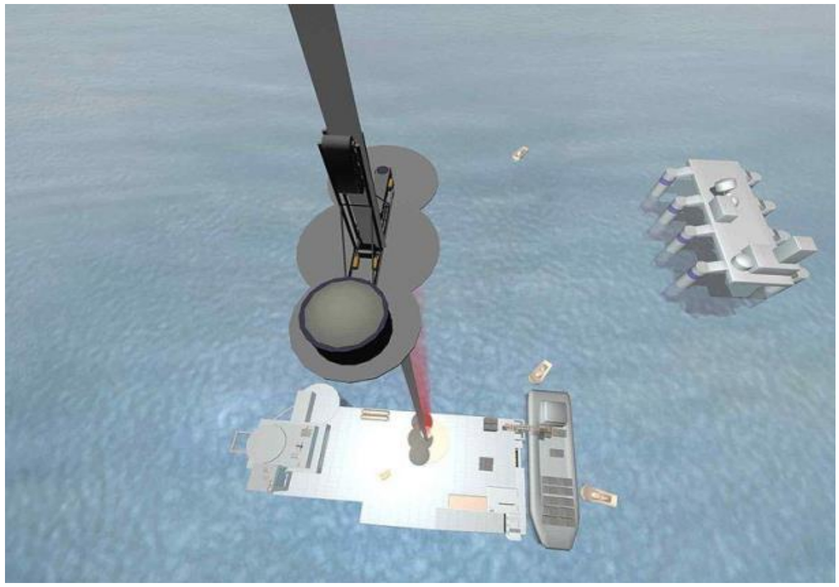

Figure 6: Space elevator base station concept [23]

4.4.3.2 Existing and futuristic materials for the construction of a space elevator

The ideation of a space elevator is a process that has been ongoing for some time, despite a feeling of its being somewhat more aligned to science fiction. However, the development of this type of megastructure has been hampered by several factors over the years. One of these factors is unrealistic designs, and the second, which represents the most significant challenge, is the lack of suitable materials to bring about the realisation of the project. In [44], the four basic elements of a space elevator are identified as the base station and anchor, the counterweight and orbital space station, the tether, and the climber. According to an interview detailed in [44] with one of the leading researchers in the field, at present, given adequate money and time, all components apart from the tether could be created using existing technology; however, no material has yet been developed that is strong enough to be used in making the tether. In a study by NASA seeking to determine the state of research [48] CNTs are the only material that offer the requisite high-strength, low-density combination for the tether.

At present, the production of CNTs is an expensive process due to the limited demand for them. However, there are numerous possible commercial applications of CNTs within existing markets that would significantly increase the demand for CNTs and result in a significant reduction in their price. Some of these possible applications include use of CNTs in pressure vessels for flight vehicles, in electronic circuit devices with densities four orders of magnitude greater than present ones, in power transmission lines and towers, and in super-flywheel energy storage devices [8]. As outlined in [7], taking a cable with constant section as well as a vanishing tension at the Earth's surface, the maximum stress that would be achieved at the geosynchronous orbit point is approximately 63GPa. Only in recent times, with the discovery of CNTs, have such significant levels of strength been observed experimentally [7]. Additional research in the field of carbon nanostructures has resulted in the emergence of graphene as a suitable material for use in the construction of a tether for use on the space elevator [33].

The appealing features of graphene as a suitable material for the space elevator include that it is 200 times stronger than steel [44]. However, the main hindrance to its extensive application in the development of a space tether is that, at present, graphene can only be produced commercially in tiny pieces, typically 400 nanometres long [45]. Various proposals have been made regarding how to make graphene suitable for the development of space elevator tethers. As the tether needs to be as strong as possible, it is paramount that the structure's entire length should be made from single sheets of defect-free graphene. One significant leap made in this regard was the development of a single-crystal graphene at a scale of 500mm × 50mm by researchers at Peking University [47]. With a tensile strength of 130GPa, single-crystalline graphene is the strongest material ever tested, which makes it ideal for use in the construction of a space elevator tether [44]. As the tether has been viewed as the main obstacle to the realisation of a space elevator, the discovery of single-crystal graphene marks a significant milestone in terms of the development of a viable project [33]. However, extensive research is needed to develop the capacity needed to produce the length of graphene needed for the full length of the space tether.

4.4.3.3 Economic viability of space elevators

The requirements of space travel for both people and payloads have thus far been fulfilled using rocket transportation. However, rockets have significant drawbacks as a means of transportation, including the high costs associated with getting people and payloads to space and safety issues due to explosion risks. Hence, for a space elevator to be a suitable means of transportation to space, it needs to be reliable and cost-effective [30]. Currently, the expectation is that rocket-based space travel incurs a cost of $25,000/kg for the launch of missions to orbit. Based on this figure, for Mars exploration, which is viewed as the next frontier in the space push, there would be a cost implication of $125 billion (5,000 tonnes × $25,000). Evidently, this is a costly estimate, and this has long been a concern for space agencies around the world, resulting in the term 'tyranny of the rocket equation' [4]. In addition, the danger of rockets exploding remains a significant concern for space travel projects.

Based on current estimates, the completion of a space elevator would significantly reduce the cost implications associated with launching missions to space. For instance, the cost of shipping 5,000 tonnes of material as has been estimated for missions to Mars would be roughly $500 million. This is a significant reduction on the costs using rockets, representing only 0.004 percent of the rocket-based estimates, largely because the space elevator represents an infrastructure project as opposed to the chemical fuels approach embodied by the use of rockets [4]. Table 3 below details the significant cost reductions in space travel that a space elevator would result in, especially for transporting payloads into space.

Table 3: Cost comparisons for space travel using rockets and a space elevator

	Cost Comparisons	
	Rocket Costs	**Space Elevator Costs**
Capacity (kg)	@ **$25,000/kg**	@**.005 (0.4%) $100/kg**
20,000	$500,000,000	$2,000,000
5,000	$125,000,000	$500,000
2,000	$50,000,000	$200,000
200	$5,000,000	$20,000
20	$500,000	$2,000

The noteworthy opportunities that exist beyond the low orbits of Earth have been universally acknowledged. However, getting there using the current rocket systems is a hazardous and costly undertaking. Thus, the development of an infrastructure that parallels significant projects such as the transcontinental railroad in the USA would effectively bring about new possibilities for space exploration [4]. It would also provide unique avenues for developing programmes designed to aid in the process of solving the problems that are currently facing humanity. The availability of routine access to space costing approximately 1 per cent of the current expense of launching missions to outer orbit would make it possible to launch missions more frequently, while also encouraging views of the future that are not hampered by the 'tyranny of the rocket equation' [4]. Due to its addressing the cost and safety challenges associated with the existing rocket transportation system to space, there is a case for the development of a space elevator from an economic standpoint.

4.4.3.4 Management risks associated with a space elevator megaproject

The pursuit of a megaproject on the scale of a space elevator calls for technical expertise, significant funding, political support and managerial skills. From a managerial perspective, one of the primary risks that would hamper the realisation of the project would be an inability to foster an inspiring vision among the various stakeholders. According to [4], one of the crucial components in the realisation of a megaproject is the ability to develop an exciting vision of how effective the project, once completed, will be in addressing the challenges for which it was envisioned. Creating a vision is integral to sustaining constant forward motion in the realisation of a project, and this should be accomplished early in the project development cycle, before establishing any hard project requirements [4]. For instance, in the USA in the mid-20th century, people dreamt of a good life for themselves and their children, and the fear of not realising that dream spurred many on to achieve the hitherto unthinkable. This extended even to space travel, where the success of the Apollo programme was largely due to fear of losing to the USSR, combined with the hope of what benefits space domination would bring for Americans. Hence, the vision of a megaproject is a key aspect of the project that the management needs to entrench promptly; failure to do so will result in opposition to the project, especially when challenges such as delays and cost overruns arise [4]. For a space elevator, the ease of access to Earth's outer orbit, the discoveries that would help realise, and the limitless horizons presented for bettering human life should form the foundation of the project's vision.

As a megaproject of monumental proportions, unlike any that has been attempted before, the space elevator will inevitably require the collaboration of multiple nations. Several factors will necessitate collaborative efforts, including the significant cost implications of the project, the extensive technical expertise needed to develop both the materials and technology needed to make the project a success, and the actual construction of the project [4]. Furthermore, the unique nature of the structure – especially the need to establish a base station at a suitable location along the equator – means that there will be a need to collaborate with the nations where such locations exist, which are mainly distanced from the Western powers expected to take the lead on a space elevator project. Hence, one of the most significant managerial risks that could derail the realisation of the space elevator megaproject is the lack of a consolidated effort towards the success of the project [4]. It could be argued that the research pertaining to the space elevator to date has largely been incoherent and seemingly chaotic. Consequently, one of the most daunting tasks for the project from a managerial perspective would be to obtain a concerted effort from different nations and various space agencies around the world with a view to developing the space elevator for the benefit of all humankind.

Over the years, megaprojects have been documented to be integral to both unlocking economic potential and significantly improving people's livelihoods in the regions within which they are constructed. As a result, extensive studies have been undertaken, especially within the past two decades, with a view to understanding the major factors that hamper the successful completion of megaprojects. One of the key managerial risks associated with megaprojects – those that cost in excess of $1 billion – is cost overruns. In fact, according to a study detailed by McKinsey and Company, close to 90 per cent of all megaprojects go over budget [46]. Crucially, considering that most megaprojects, which are often infrastructure projects, are approved with an expectation of a 20 per cent return on investment, cost overruns often leave the respective authorities to incur the additional costs. On top of cost overruns, time overruns are a perennial challenge associated with megaprojects, often resulting in the erosion of public support as people come to feel that a project is effectively unrealistic from an economic standpoint [46]. In the case of a space elevator, the risks of cost and time overruns are especially severe, as some of the challenges, e.g. material construction and unforeseen challenges in constructing up to outer orbit, threaten to bring up issues that will hamper the delivery of the project within scope and in line with the schedule.

4.4.3.5 Safety risks associated with the development of a space elevator

The nature of a space elevator, in that it is meant to operate in environments that are unlike what engineers are used to on Earth, inevitably brings about several safety concerns that need to be addressed conclusively for the concept to be accepted and adopted and for it to succeed. The major safety concerns in relation to a space elevator include the hazards ensuing from potential collisions between the elevator structures and other objects in the orbit such as orbital debris, active spacecrafts and meteoroids [29]. Orbital debris encompasses objects such as paint chips and dead satellites, which currently present significant threats to any spacecraft [8]. On this basis, there is acknowledgement among the leading researchers in the space elevator consortium that the clean-up of orbital debris is a high-priority undertaking that would be integral to ensuring the success of a space elevator from a safety standpoint [8]. In addition, active spacecraft have been identified as a potential threat to the safety of a space elevator, but there is a general consensus among the leading researchers in this field that future spacecraft systems could incorporate collision avoidance navigation systems to mitigate the risk of collisions between the space elevator and other spacecraft. Among the natural threats to the safety of a space elevator, meteoroids are one of the most significant risks, with the potential to hinder the effective maintainability of a space elevator.

Crucially, the first space elevator is likely to be built only after the current generation of existing space assets have been used up. This means that future space systems could be designed with a space elevator in mind, for example by incorporating automated collision avoidance systems on both satellites and the space elevator. These systems will be essential because all objects that orbit Earth cross the equator twice per orbit, hence presenting a real risk of collision with the structure of the space elevator [8]. Another challenge that poses a safety risk to the effectiveness of the space elevator is the potential of a catastrophic failure of the elevator structure itself. This could arise from different factors including fatigue due to triggers such as temperature variations and excessive vibrations throughout the entire structure. The repercussions resulting from such a failure cannot be overlooked since objects that come off the space elevator at an altitude of below 25,000km will likely fall back to Earth, while those that break off at altitudes of between 25,000km and 47,000km will likely escape the planet’s orbit. In the event that the structure were fully severed, a 3–4 km/sec acceleration capacity would be needed for the structure to either remain in orbit or have a soft re-entry [8]. As a result, several technical elements would need to be incorporated into the vehicles operating on the space elevator to ensure safety. This would include incorporating multiple backup modes so that, in the event of a system failure, it will be possible to ensure return capability. For example, this could feature a parachute deployment system in the event of an accident in lower altitudes. For failures above the Earth's atmosphere, a rocket propulsion system providing the requisite boost to arrive at a safe orbit would be the appropriate type of safety mechanism.

4.5 Discussion of Findings

The objectives of the study have been accomplished. The first objective was to determine the current managerial risks associated with the construction of a space elevator. The findings from the reviewed literature indicate that, from a managerial perspective, one of the primary risks associated with undertaking megaprojects is an inability to foster an exciting vision among the different stakeholders associated with the project. An exciting vision is a vital tool for maintaining goodwill towards the project even when certain aspects seem to be going against expectations, such as cost and time overruns [4]. Therefore, for a space elevator project, the inability of the management team to foster a suitable and exciting vision among the stakeholders could hamper its realisation, especially if issues such as materials development and costs threaten the completion of the project. Additionally, owing to the scale of a space elevator project, which makes it unlike any that has been attempted before, there will be a need for multi-national cooperation. As a result, one of the major managerial risks that could inhibit the realisation of such a project would be a lack of a consolidated effort towards its success [4].

Considering that the research pertaining to the space elevator to date has largely been incoherent and somewhat chaotic, there is a real risk of a lack of a concerted effort from different nations across the globe, effectively limiting any chances of the project’s success. Moreover, megaprojects have been documented over the years to accrue cost and time overruns, which often shift public perception against their development. For a space elevator, the risks associated with cost and time overruns are especially severe owing to the unique challenges faced by the project, including a lack of suitable materials for construction and unforeseen challenges in constructing a structure to outer orbit [4].

The second objective was to determine the financial risks associated with the construction of a space elevator. Regarding this objective, a study by McKinsey & Company on construction projects details that 90 per cent of all megaprojects undertaken tend to encounter significant cost overruns in the project implementation phase [46]. This means there is a serious risk that a space elevator project, similarly to other megaprojects that have been undertaken in the past, will encounter significant cost overruns. This issue is made particularly severe by several factors that remain vague, especially pertaining to construction in the outer zones of Earth’s orbit, i.e. >100,000km up in space. Issues that might arise during the project and significantly increase costs above those indicated in the project charter include additional safety reinforcements being required for both the elevator structure and the climbing vehicle to shield them from the perils associated with collisions with space debris.

At present, the most appropriate materials for the construction of the space elevator, especially the tether, are CNTs and graphene. The development of these materials is still in its formative stages, which makes it impossible to accurately predict the costs of the materials that would be required to construct a fully functional and safe elevator [44].

The third objective was to present conclusively the safety risks associated with the space elevator and to provide recommendations for the necessary remedies. The major hazard associated with a space elevator would be the possibility of collisions between the elevator structures and other objects in orbit, including orbital debris, spacecrafts and meteoroids [8]. In addition the risk of collisions, there is a possibility of the catastrophic failure of the space elevator structure due to factors such as temperature variations arising from orbital dynamics and excessive vibrations during use of the structure. Some of the plausible remedies to address these risks include incorporating several backup modes on the climbing vehicles, which would make it possible to get the occupants to safety irrespective of whether the vehicle was in lower orbit or outer orbit when it was ejected from the tether of the space elevator [8]. Furthermore, there would be a need for a concerted effort to clear out orbital debris, especially satellites that are out of service.

In addition, the design of the space elevator should feature provisions for mitigating collisions with natural objects including meteoroids [8]. This would involve the provision of an ongoing repair and maintenance schedule for the entire structure. There would also be a need to incorporate a collision avoidance system both on the space elevator and on other spacecrafts, to avert the risk of collision between these manmade objects. Radiation shielding remains a critical concern in the development of a suitable vehicle to use on the space elevator, as it will be needed to shield climbers from the extremely high levels of radiation in the outer atmosphere [28].

The final objective was to detail the financial viability of a space elevator project. From the reviewed literature, it is evident that the successful completion of a space elevator would promise to offer monumental benefits to space exploration endeavours, especially due to the significant cost savings that it would offer when undertaking space travel compared to the current rocket-based approach [30]. Based on current estimates, a mission to space using a space elevator would comprise just 0.004 per cent of the costs currently incurred using rockets [4]. This is because a space elevator would entrench an infrastructure-based approach to space travel instead of the chemical fuels approach embodied by the use of rockets. As such, a space elevator would provide a unique avenue for space exploration and for obtaining extensive insights into the resources that exist in outer space that might prove essential in improving life on Earth.

5. Conclusion and Recommendations

5.1 Conclusion

The study's objectives have all been met, and in the process, an in-depth understanding has been offered of the key factors that need to be considered in undertaking a space elevator project. In terms of the managerial risks that are likely to arise in delivery of the project, some of the identified factors include an inability to foster an exciting vision of the project among relevant stakeholders, which would result in limited buy-in for the project, thus hindering its realisation. Additionally, the scale of the project would necessitate multi-national cooperation for its realisation. Thus, one of the major risks is a lack of a consolidated effort towards the realisation of the project owing to clashes of opinions and perspectives between different nations. Moreover, there is an evident risk of cost and time overruns that are largely attributed to lack of alignment with the project scope in megaprojects. In this regard, the situation of the space elevator is especially severe considering multiple factors, especially those pertaining to construction of projects in the outer space of Earth's orbit, i.e. >100,000km up in space. Furthermore, the lack of a readily available material that would be appropriate for the construction of a space elevator gives rise to an evident financial risk, with a likelihood of cost overruns in the delivery of the project.

Alongside identifying the financial and managerial risks associated with a space elevator project, the third objective sought to determine the safety risks that would need to be considered. The main hazards would be the possibility of collision between the space elevator structure and other objects in orbit such as space debris, and potential failure of the space elevator structure due to factors such as temperature variations brought about by orbital dynamics and high levels of vibrations while the structure is in use. The possible solutions for addressing these risks include incorporating several backup modes on the climbing vehicles, which would make it possible to get the occupants to safety [8], and making a concerted effort to clear all existing orbital debris, especially equipment that is out of service.

There would also be a need to offer provisions for continual maintenance and repair of the entire structure. Despite the evident risks in terms of managerial, financial and safety considerations, there is a financial case for the development of a space elevator due to the significant cost reductions that the project would present in terms of undertaking space missions. This assertion is supported by estimates indicating that the cost of a mission to space using a space elevator would be about 0.004 per cent of the costs currently incurred using rocket propulsion systems [4]. This saving is mainly due to a space elevator representing an infrastructure-based approach to space travel, as opposed to the chemical fuel approach used for rockets in space travel.

5.2 Recommendations

Despite the evident benefits that would arise from the development of a space elevator and the commencement of its use, there are challenges that need to be addressed before the project becomes a reality. At present, the research on the space elevator concept is largely fragmented, which makes it unsuitable for providing a coherent idea on the state of research and development towards the realisation of the project. Consequently, there is a need for a more concerted effort to amalgamate the existing studies across diverse fields, such as materials science, laser propulsion, space policy and radiation policy, that are integral to the success of the space elevator project. Furthermore, considering that a space elevator project cannot be undertaken by one nation alone, there will be a need for extensive collaboration among nations with a view to making certain that the project becomes a reality and yields the benefits for which it is intended. Despite the researcher ensuring that the current study featured a wide range of resources, there is a possibility that more studies could have been incorporated in the review. Future research could apply software tools, especially algorithms to help search through more resources, to obtain more information and help expand the comprehension of the research topic.

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Appendix 1

Scoping review

Year	Country of Origin	Aim	Methodology	Key Findings	Research Gap
2000	USA	Present an analysis of the various aspects of the space elevator, and determine the challenges that the endeavour is likely to encounter, and possible solutions for the challenges using current and near-future technology.	Primary Research Article	The key challenge relates to the construction of the elevator cable, which will likely be addressed conclusively using carbon nanotubes. Other challenges including determining the optimal location on the equator to establish the earth's end of cable are not unsolvable using existing or near-future technology	More studies needed to determine additional challenges that might be encountered, to ensure they are addressed before the development of the space elevator.
2006	USA	Determine the feasibility of a space elevator in the context of the existing space exploration policy.	Review Article	The paper determines that all of the space elevator's components will need to be developed independently inorder to meet separate near-term objectives. The space elevator will need to be viewed as as one of the many possible applications for the developed technologies in the pursuit of the research and	More studies are needed to determine how existing technologies tally with the required components of a space elevator, so that the technologies and materials can be developed independently, with the hope that once mature, they can eventually

				development of the technology suited for space travel. Once the enabling technologies are mature enough, they may eventually be incorporated in the construction of a full-scale space elevator for Earth's surface to geosynchronous orbit and beyond.	be incorporated into the development of a full-scale space elevator.
2019	USA	To quantify, assess, compare, and suggest improvements to the potential environmental and financial performance of three proposed space elevator system designs, namely i.) One-Tether Initial Space Elevator (the base design) ii.) A Two-Tether Initial Space Elevator iii.) An Additional One-Tether Space Elevator	Research Article	Additional One-Tether Space Elevator scenario had the lowest environmental impact, while the Two-Tether Initial Space Elevator scenario had the lowest production cost per unit mass delivered to orbit. The analysis identified system elements for targeted impact reduction, e.g. operational impacts could be significantly reduced by improving the sustainability of terrestrial transportation delivery systems to the space elevator port. The proposed space elevator design was found to be an environmentally	Replication of the study for application of sustainability engineering and quantitative sustainability assessment methodologies to the spacecraft and orbital transportation systems and industries.

				and financially sustainable option for orbital transportation.		
2007	USA	Provide an overview of the radiation belts in terms relevant to space elevator studies. Compute the expected radiation doses, and evaluate the required level of shielding. Offer proposals for passive shielding, and active shielding using magnetic fields.	Research Article	Shielding the climber from the space radiation with aluminum would require approximately 18 × 103 kg of the material to shield a compartment about the size of the early space capsules. Shielding with a magnetic field would require an extremely large current which would be impossible with resistive materials such as copper. There appears to be no simple solution to the problem of shielding the radiation to levels routinely acceptable to human occupants, and providing a	Other more exotic shielding materials as well as magnetic shielding based on super-conducting materials, need to be investigated as possible solutions to the radiation problem, that would hamper the realisation of a space elevator.

				solution will impact the economics of the space elevator.	
2014	USA	Propose suitable design concepts for the first 40 kilometres of travel, to ensure the success of space elevators.	Research Article	High Stage One design is proposed for the realisation of space elevator, by simplifying the design of the tether and tether climbers by dealing with atmospheric hazards such as winds and ice independently and transmitting the forces down to the surface. It would use commonly available materials especially Kevlar. By relying on magnetic levitation which is a proven technology, there is a high likelihood for the success of the successful development of the space elevator.	The design research is still immature hence more studies will need to undergo a thorough prototyping and development schedule to make it ready for use as part of the space elevator.

2020	Turkey	Focus on the definition of space elevator, and its construction, and present a case for the suitability of the project, as a way of fostering sustainable and affordable space travel.	Review Article	Despite its complexity and greatness the development of a space elevator is not an impossibility Although it requires profound financial investment; its benefits will outweigh the initial financial costs once it is built. Space elevators will eventually lower the costs for asteroid mining, space logistics, space tourism, space travel and space colonization; all of which will be the mankind's basic needs to survive soon.	In the process of realising the space elevator megaproject, the questions that need to be addressed include how to protect the infrastructure from external threats.
2007	Czech Republic	The article focuses on addressing the issue of how the space elevator will avoid collisions with active satellites, space debris, and meteorites.	Research Article	Within the operational phase, a simple model of space elevator would feature a mass point at the end of a tether beyond the geostationary distance. The tethers and cables will need to be active and have to actively respond locally to any disturbances, whether as a requirement by nature, or as a way of improving performance.	More models and simulations of the space elevator tethers will need to be undertaken with a view to obtain an actual understanding of suitable design features that will need to be incorporated into the space elevator, to ensure that it is able to cope with disturbances such as space debris.

2009	Austria	Under the assumption that a proper material (carbon nanotubes) is available, making the connection possible technologically, the article seeks to address the question of existence and stability of the radial relative equilibrium of a tapered string on a circular geosynchronous trajectory around the Earth, reaching from the surface of the Earth far beyond the geostationary height.	Research Article	The article presents the result of the equation which outlines the radial relative equilibrium of a tapered string made from carbon nanotubes moving on a circular geostationary orbit and reaching from the surface of the Earth into space is orbitally unstable. The study also determines that the practically important result that for too soft strings the stabilization of the orbitally unstable relative equilibrium is not possible, because due to the large extension no stable relative equilibrium exists.	
2013	Italy	The article evaluates the strength of a nanotube bundle factoring in two possible failure mechanisms intrinsic fracture and sliding and posposes solutions for safeguarding its strength for the space elevator to work.	Research Article	The study determines the need for a smart strengthening technologies includign flaw tolerant design, and the nanotube self-collapse. The flaw tolerant design limits the required strength, whereas the self-collapse can increase the achievable strength. The ultimate desigh of a 35GPa strong	Additional studies need to be undertaken on both graphene bundles and composites for the realisation of the most-appropriate materials for use on tethers for use on space elevators.

				tether is proposed, thanks to the analysis of graphene bundles, and previous analysis by the author.	
2019	China	The paper analyses the dynamics and optimal stabilisation method of a partial space elevator system with multiple climbers	Research Article	Different climber moving patterns are found to have a significant impact on the dynamic behaviour of partial space elevators. To address the challenge, optimal control is proposed as a way of developing optimal operation modes to suppress the liberation of PSE with multiple climbers.	
2016	Japan	The article seeks to verify two basic technologies that would be essential for the success of a space elevator using microsatellites, the tether, deployment technology and the climber operation along the tether in space.	Research Article	The article presents the current progress in the development of two microsatellites to verify two basic technologies of the space elevator, in addition to obtaining data towards an improved future design. The STARS-C microsatellite is used to verify the tether(cable) deployment technology, while	

				the STARS-E is used to verify the operation of the climber along a tether in space.	
2019	Canada	"The paper develops a high-fidelity and high-accuracy dynamic model to The investigate libration suppression of partial space elevator caused by a moving climber through tether deployment and/or retrieval at main and subsatellites."	Research Article	A high-fidelity and high-accuracy model of Partial Space Elevator is developed based on the nodal position finite element method using the arbitrary Lagrangian–Eulerian description. The variable-length approach is used to describe the movement of climber along the tether and the deployment and/or retrieval of tether at the end satellites (main satellite and/or subsatellite). The proposed approach reveals the slack–taut phenomenon of tether happens as the climber starts to move, which is not shown in the rigid tether model. Therefore, for the safety operation of PSE, the trajectories of	

				climber should be optimized to avoid the tether slack–taut happening.	
2014	USA	The article explores classical and statistical mechanics of a novel dynamic system - the rotating space elevator.	Research Article	The study explores the classical and statistical mechanics of rotating space elevators (RSE) which are double rotating floppy strings reaching outer space. The main feature of the RSEs is that the objects sliding along the RSE string (sliding climbers) do not require internal engines or propulsion to be transported from the Earth's surface to extra-terrestrial locations. The developed RSE concept thus solves a major problem in space elevator science which is how to	Based on the special design developed, the RSE depicts persistent shape and enduring double rotating motion. That said, under certain conditions, the RSE could undergo a morphological transition to a chaotic state reminiscent of fluctuating directed polymers encountered in the statistical physics of strings and membranes. Future studies could thus address this

				supply energy to the climbers moving along space elevator strings.	shift to a chaotic state.
2016	USA	The paper considers the general theoretical problem of how to model the dynamics of objects sliding on moving strings. This study answers the question of; what is the general form of the equations governing string motion in the presence of objects sliding along discretized strings?	Research Article	The study describes in detail a subtle yet powerful algorithm that can be used to investigate motion of objects sliding along floppy strings. The algorithm was motivated by the fundamental physics of sliding climbers on a unique class of dynamical systems, rotating space elevators.	
2006	USA	The article details the physics of a space elevator considering the basic mechanical principles that underpin its	Research Article	The study conveys an understanding of the basic features of a space elevator, as well as some of its applications including the transfer of payloads to space, as well as	Thorough analysis of the space elevator would need to address the multiple threats it would face in space, and how

		construction, as well as its principle applications.		the launching of spacecrafts for voyages to other planets.	they would be addressed.

Country	**No of Articles**
China	1
Japan	1
Canada	1
Czech Republic	1
Italy	1
Austria	1
Turkey	1
USA	8
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