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Article

Strengthening Urban Resilience: Understanding the Interdependencies of Outer Space and Strategic Planning for Sustainable Smart Environments

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Abstract: The conventional approach to urban planning has predominantly focused on horizontal dimensions, disregarding the potential risks originating from outer space. This paper aims to initiate a discourse on the vertical dimension of cities, which is influenced by outer space, as an essential element of strategic urban planning. Through an examination of a highly disruptive incident in outer space involving a collision between the Iridium 33 and Cosmos 2251 satellites, this article elucidates the intricate interdependencies between urban areas and outer space infrastructure and services. Leveraging the principles of critical infrastructure protection, which bridge the urban and outer space domains, and employing simulation methods and software, this study articulates the intricate governance complexities of urban security and presents viable solutions for its enhancement. Consequently, the study contributes to the ongoing deliberations regarding the spatial integration of security practices by providing scholarly discourse on urban governance with potential strategies for cultivating sustainable smart cities. In essence, the intrinsic resilience of urban areas heavily relies on the interconnections between cities and outer space, necessitating urban strategists to acknowledge and comprehend these intricate interdependencies. To ensure sustainable urban development, it is imperative to fortify smart cities' resilience against space debris through the implementation of more stringent regulations.

Keywords: strategic urban planning; smart city; ICT advancements; critical outer space infrastructure; governance of security; complex systems

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1. Introduction: Strategic Urban Planning and Development

Have we passed the "point of no return" regarding the development of our (smart) cities? Damocles sword is increasingly hanging over humanity, underscored not just by accelerating urbanization and environmental degradation but, as this paper argues, also by vulnerabilities originating from outer space. While information and communication technology (ICT) advancements have transformed urban landscapes, they have also created a web of dependencies tied to outer space infrastructure, such as satellites. These space assets are vulnerable to natural and human-made disturbances, from solar storms to satellite collisions, which can have cascading effects on essential services on Earth, such as communication, transportation, and even national security.

The necessity to integrate outer space considerations into strategic urban planning is no longer optional; it is imperative. Failing to address this vertical dimension can put at risk the sustainable and smart development that urban planners aim to achieve. This paper argues that understanding the intricate interdependencies between Earth-bound urban environments and outer space elements is critical for shaping resilient and sustainable smart cities.

As technological advancements continue to progress, the emergence of “smart cities” and the transition towards more efficient and sustainable urban living have become evident. Yet, distinguishing between today’s cities and their historical predecessors is essential. How has the notion of a “smart city” evolved over the course of history, and what factors have contributed to its evolution? Additionally, how do present-day cities compare to ancient cities in terms of their infrastructure, technology, and urban design?

Throughout history, the significance of well-thought-out urban planning has been evident, reaching as far back as ancient civilizations. Numerous age-old metropolises featured painstakingly planned architecture, focusing on spatial layout, essential infrastructure, and effective governance. The primary goal for such historic urban planning was to meet community needs, with aspects such as livability, safety, and protection valued more than aesthetic design principles. Consequently, the evolution of ancient urban centers was often directed by environmental factors such as their proximity to clean water, food provisions, and important trade routes. However, even in those distant times, individuals emerged who displayed remarkable foresight and ingenuity in the realm of urban planning.

The concept of organized street grids can be traced back to antiquity, with notable examples having been documented by *The Economist* [1] (p. 21). Cities such as Mohenjo-daro in Pakistan, dating back to 2600 BC, and the visionary plans of Hippodamus of Miletus in the 5th century BC exemplify early instances of grid-planned urban development. These designs featured square blocks arranged in a rectangular grid surrounding a fortified core, which offered defensive capabilities and facilitated orderly urban life. Greek and Roman cities, including Athens, also showcased systematic street networks and public spaces, emphasizing the importance of functional and sustainable urban environments. Similarly, other ancient civilizations, such as the Mayans, Egyptians, and Mesopotamians, embraced strategic urban planning, placing a high value on thoughtful design.

During the Middle Ages, European urban planners adopted radial city designs characterized by roads spreading out from central plazas and fortifications of solid walls and towers. Filarete, a Florentine architect and urban planner from the 15th century, is renowned for his design of an ideal fortress city with a star-shaped layout, converging roads leading to a central square dominated by a church, and fortified walls [2]. These symmetrical and orderly designs incorporated central plazas, wide avenues, and grand public buildings.

In more modern times, urban grid designs have seen a resurgence, primarily driven by economic considerations [1] (p. 21). This revival can be traced back to historical factors such as the Law of the Indies [3], which mandated grid-based planning resembling European models in Spanish colonies across South America and Asia. Shortly after, in North America, Thomas Jefferson’s land ordinance of 1785 further influenced the development of new American cities, advocating for structured grids in unexplored western lands. The grid pattern was not only effective for efficient land parcel sales, thereby helping to generate government revenue, but also advantageous for transportation. Specifically, the design facilitated the implementation of tram networks, enabling swift movement between emerging developments and the city center with just two tram lines running on orthogonal axes [1] (pp. 21–22). Grid designs also offer benefits such as effective traffic segregation [4], allowing for the separation of pedestrians and vehicles, and accommodating varying speeds and traffic volumes, thereby improving traffic flow and reducing pollution.

However, a debate between grid and radial city designs emerged in the 20th century. Advocates such as Ebenezer Howard [5] proposed the concept of small radial “garden cities” with curved streets and a clear separation between industrial and residential areas. Renowned architects such as Le Corbusier [6] applied these principles in the design of new cities, exemplified by, for instance, Chandigarh, India. Cul-de-sacs became prevalent in many new settlements worldwide, offering the advantage of limiting through traffic but in turn disadvantaging non-residents [7,8]. This debate exposes the larger issue faced by urban planners: the trade-off between comfort and cost, or quality of life and economic considerations, which is ultimately a false dilemma, as quality of life always comes at a price.

Urban areas have also experienced significant population growth, not only in developed countries but also in less urbanized regions such as African countries [9]. Critics such as Jane Jacobs [10] argue that outdated city infrastructure, including street grids, poses limitations, with short blocks and narrow roads contributing to congestion. Building a new city from scratch, as seen in the case of Brasilia, Brazil's capital inaugurated in 1960 and designed by architect Oscar Niemeyer, presents an opportunity to explore alternative strategic approaches to urban planning that go beyond traditional grid or radial designs. Cul-de-sacs alone are insufficient for effective city planning and strategy development [11], prompting the need for innovative thinking and design in shaping the cities of the future.

Addressing the Gap, Strengthening Urban Resilience

The notion of urban resilience is a multifaceted subject that has garnered significant scholarly interest, often concentrated on terrestrial factors such as climatic fluctuations, extreme meteorological occurrences, and issues of cybersecurity [12–21]. Nevertheless, the field has generally overlooked the intricate dimensions of extraterrestrial vulnerabilities, specifically those related to space debris collisions, that bear upon smart cities [22].

Existing investigations into urban resilience provide limited insights into the cascading effects within urban infrastructure and services [23,24], especially the second- and third-order repercussions. This study aims to rectify this shortcoming by creating an interdisciplinary dialogue between research into the sustainability of extraterrestrial activities and the resilience and operational efficacy of technologically advanced urban settings.

The concept of resilience is gaining increasing relevance in the discourse on smart cities [25,26], particularly concerning urban systems' capacity to recover from both intentional and inadvertent types of disruptions. This manuscript aims to augment the existing corpus by introducing an under-explored facet: the role of space-based technological networks. Specifically, we scrutinize smart cities, interlinked through space technologies and services, as highly complex and adaptive entities susceptible to extraterrestrial disturbances such as space debris collisions.

Building on extant scholarship [27,28], we propose a nuanced definition of urban resilience that is tailored to smart cities under threat from space debris and satellite mishaps. Here, urban resilience refers to the adaptability of a smart city's socio-technical and orbital networks in maintaining or swiftly recuperating optimal functionality when faced with disruptions emanating from space. This expanded conceptualization allows for the incorporation of multiple adaptive strategies, such as contingency planning and system redundancy. It also underscores the complex interplay between urban centers and orbital activities, advocating for resilient governance structures involving various stakeholders, ranging from urban planners to space agencies.

As for policy implications, much of the existing research [29,30] falls short of addressing the unique challenges that extraterrestrial threats pose to smart cities. Although emerging studies have started to shed light on the significance of space debris as a factor in urban planning [22,28], comprehensive assessments detailing their precise impacts on smart cities are still lacking. This study aims to bridge this academic void by investigating the effects of space debris, whether resulting from satellite collisions or other means, on the resilience and efficient operation of smart cities.

2. ICT Advancements and Smart Cities

The rapid growth of information and communication technology (ICT) infrastructure has provided new ways to manage the challenges of urbanization, particularly in developing countries. As cities transform into more efficient and livable spaces, ICT will continue to play a crucial role. Artificial intelligence and complex algorithms are now used to optimize networks for transportation, communication, services, and utilities. These technologies specifically address issues such as improper waste management, water and sewage problems, pollution, poor traffic control, and energy grid failures—all issues that are exacerbated by the world's rising population. Consequently, city-level decision making has become increasingly guided by key performance indicators that focus on these technological interconnections [31,32].

On the other hand, emergent concepts such as "sustainable development" and "smart growth" have gained momentum in the international arena, with governments needing to adhere to sets of rules aimed at finding localized solutions for eco-friendly urban places. In 1987, the Brundtland Report defined "sustainable development" as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" [33]. The study promoted the idea of "sustainable development" and helped mainstream "sustainability" in policy discourse. These two concepts have been used interchangeably ever since; nevertheless, to distinguish between them, UNESCO formulated a distinction as follows [33,34]: "Sustainability is often thought of as a long-term goal. . . while sustainable development refers to the many processes and pathways to achieve it". Later, Agenda 21 claimed that the economic, social, and environmental dimensions are inseparable when discussing sustainability [34]. Finally, the 2030 Agenda for Sustainable Development put forth a list of 17 goals and 169 targets to balance "the three dimensions of sustainable development, the economic, social and environmental" [34]. Regardless, strategic thinking in these areas is enriched with concepts and methods based on agility, flexibility, and the integration of various technologies, such as artificial intelligence, machine learning, and other algorithmic ways of reducing uncertainty and calculating managerial efficiency.

From this, it is clear that a sustainable smart city is one that is designed to address its social, environmental, and economic impacts through urban planning and city management, incorporating in the process various forms of ICT [35]. However, whereas the literature on smart cities focuses, on the one hand, on framing dimensions (i.e., smart mobility, smart environments, smart people, smart living, smart governance, and smart economies [36]) and, on the other hand, on parameters of technological intelligence, the domain of outer space and its connection with smart cities has been left untouched. Moreover, the implications of such a novel manner of thinking have not at all been considered.

While there has been some scholarly attention on the role of extensive data analytics in ensuring the effective governance of smart urban cities [37], the literature has, overall, neglected to consider the connections between events originating in outer space and the performance metrics of tech-savvy municipalities. However, a few recent studies are notable exceptions [22,28]. Furthermore, the influence of outer space disruptive events on the technological scaffolding that modern smart cities rely upon is an area that is virtually untouched in the current literature. This manuscript aims to contribute towards filling this void by emphasizing the vital importance of outer space sustainability due to its direct repercussions on earth-bound activities, and particularly within the context of smart cities. By employing an analytical lens that starts by focusing on distinct, space-born disruptions, this investigation aims to forge an integrative dialogue between technology and sustainability, offering nuanced insights into strategic urban planning.

2.1. Related Work on Technology and Urbanization

The transition from traditional cities to smart cities involves the integration of technology and data to enhance the efficiency, sustainability, and quality of life in urban areas. This transition is driven by the need to address the challenges facing modern cities, such as urbanization, climate change, and resource depletion, as well as to improve the delivery of public services and infrastructure.

In recent scholarly discourse, the evolution from conventional urban centers to technology-enabled smart cities has been a focal point of investigation. A recurrent theme in academic debates centers on the pivotal role of community involvement and civic participation in shaping the trajectory of smart urban initiatives. As articulated in Anthony M. Townsend's groundbreaking work [38], the journey towards smart urbanism is not solely reliant on technological advancements; it also demands the reconfiguration of governance structures, civic responsibilities, and planning methodologies. His work underscores the capability of smart urban environments to democratize citizen agency, thereby encouraging a more interactive form of democratic engagement. Some scholars [39–41] contend that participatory funding methods, such as civic crowdfunding, can serve as robust mechanisms for actively involving the populace in both the financing and practical execution of smart city ventures. Their studies elucidate the capacity of civic crowdfunding to foster transparent, accountable, and community-driven processes.

In the field of smart cities, numerous authors have made seminal contributions that span various dimensions of this evolving paradigm. For instance, urban planner Carlo Ratti has been instrumental in advocating for citizen-centric smart city models [42,43] and has contributed to significant initiatives, such as MIT's Sensable City Lab.

The existing literature offers profound insights into the role technology can play in elevating urban efficiency and sustainability. Researchers such as Zanella [44] have studied a range of technologies, including, but not limited to, wireless sensing technologies, cloud infrastructure, and big data analytics. Such authors have underlined these technologies' ability to optimize public services, curb energy usage, and heighten civic participation.

Governance and policy frameworks also form a crucial axis of discussion in existing research. Various scholars [45–49] have dissected the governance structures involved in smart city initiatives, stressing the need for multi-stakeholder collaboration, explicit policy directives, and definitive regulatory guidelines.

Additional key figures in this field include Martin Dodge and Rob Kitchin, who have focused on the intersections between technology, data, and the urban environment [50,51]. Further, sociologist Saskia Sassen [52] has offered nuanced views on the interplay between globalization, urbanization, and how smart cities could mitigate socio-economic disparities. Adam Greenfield [53] has highlighted the potential pitfalls and ethical considerations surrounding smart cities, particularly regarding data privacy and surveillance issues. Geographer Jennifer Clark [54] has explored the nexus between innovation, urbanization, and economic stimulation, while sociologist Manuel Castells [55] has investigated the broader societal impacts of global digital transformations on urban ecosystems.

The transition to intelligent urban ecosystems represents a complex and multi-layered endeavor that requires the proactive engagement of a broad variety of participants—ranging from governmental agencies and industrial actors to community members and civic organizations. Achieving the promise of smart cities mandates an integrative methodology, blending expertise from fields as varied as urban development, engineering, informatics, and social sciences. Current scholarly contributions to the study of smart cities indicate a rising fascination with technology's capacity to enhance urban sustainability, invigorate civic participation, and reframe governance structures. This heightened focus highlights the pivotal role technology will play in guiding the urban future towards more adaptive and efficient landscapes.

Nonetheless, this emphasis also flags the necessity for a meticulous scrutiny of the socio-economic and political ramifications of technologically driven urban initiatives. A critical gap in the extant literature is an examination of smart cities' relationship with outer space—a theme this article aims to address.

Beyond conventional urban challenges such as traffic management, earthquake resilience, energy-efficient architecture, intelligent power distribution, eco-friendly infrastructure, and reducing carbon footprints, it is vital to consider an often-overlooked facet: the spatial component of urban design. This element transcends the act of merely building taller edifices for residential, commercial, or public functions, and necessitates a transition from a planar to a volumetric framework, facilitated by geospatial tools such as Geographic Information Systems (GIS) [56,57].

The third spatial dimension of smart cities will also incorporate new aerial vehicles, such as drones, airborne taxis, and even flying automobiles, each assigned specific operational altitudes [54]. This integration will further elevate the significance of geospatial instruments in the conceptualization of future smart cities, synergizing with technologies such as Building Information Modelling (BIM) and three-dimensional city planning. This naturally extends our attention to outer space—a realm already facing issues of congestion. A critical question thus emerges: Does the cosmos exert any measurable influence on terrestrial urban living? If it does, what are the implications of this?

This study aims to furnish nuanced answers to these queries by examining the symbiotic interactions between urban and extra-atmospheric domains, seeking in turn to illuminate the prospective impacts of this interplay.

2.2. Sustainable Smart Cities and Outer Space Technologies

Outer space begins right in our cities. Physically, every place or individual on Earth is just 100 km away from it. Operationally, space technology significantly enhances the facets of our lives, with about 5500 operational satellites [58] providing a wide range of services that augment our environment in a variety of ways—from the GPS systems in our automobiles to daily weather predictions. In the event of an unintentional or natural interruption, these critical services, or rather the lack thereof, also serve as a representation of our collective fragility. Thus, how do we reconcile technological progress with technological stagnation? More importantly, how should we strategically address and integrate this dichotomy into city design?

Cities can benefit greatly from space technologies during this transformation from analogue to digital (e.g., the monitoring of water and air quality, planning, traffic management, green areas mapping, et cetera). One example is the EU's Galileo system, a European Space Agency (ESA) satellite constellation that supports services such as public transportation optimization, smart parking, autonomous electric transportation, emergency tracking, and more. Space-related technologies that have terrestrial uses provide a different kind of contribution to cities. By using their digital infrastructure to integrate space assets both on Earth and in space, as well as to connect with user segments in the cloud, digital giants such as Amazon, Microsoft, and Google have recently joined the space business. The space sector is embracing new business models such as Ground-Station-as-a-Service and Satellite-as-a-Service, which adhere to the pay-as-you-go paradigm and allow users to only pay for the services they utilize.

Outer space activities and phenomena, such as satellite launches, space exploration, and space debris, can have a significant impact on urban management. Interruptions in satellite services can affect a wide range of industries, including telecommunications, transportation, and emergency services. Meanwhile, satellite imagery and remote sensing provide valuable data for urban planning and management. For example, satellite data can be used to monitor land-use changes, urban sprawl, and environmental conditions, which can inform decisions on urban development, disaster management, and climate change adaptation.

Moreover, the increasing amount of space debris resulting from decades of space activity poses a threat to urban areas. As this debris re-enters Earth, it can cause damage to urban infrastructure and pose a risk to human safety. Urban managers must consider the potential impacts of space debris and ensure that their cities are resilient to such impacts. In the event of a natural disaster or other emergency, outer space activities can play a critical role in urban management. Satellites can provide real-time information on the extent of damage and help emergency responders to plan and execute their response efforts.

These elements represent an exponentially growing market that comes with great benefits but also with uncertainties, turbulence, instabilities, and potential errors. If urban sustainability as a desirable process can be enhanced with the help of outer space technologies, this implies that urban decision making should first be kept in mind and then integrate events in outer space into urban management at all scales.

In summary, outer space activities have a significant impact on urban management, and urban managers must consider their potential impact. By understanding the risks and opportunities of space activities, urban managers can ensure that their cities remain resilient and adaptable to the changing landscape of space activities.

2.3. Sustainable Outer Space and Smart Cities: Definitions and Scope

To provide clarity and context, several key terms and areas of focus need to be defined:

In the context of this paper, "outer space technology" refers to any technology designed to function in the extraterrestrial environment, such as satellites, space stations, and lunar habitats, which can have both direct and indirect effects on sustainability in smart cities. By adhering to these boundaries, we aim to elucidate the tangible links between sustainable smart cities and sustainable outer space activities.

By "influence of outer space on smart cities", this paper refers to the direct and indirect impacts of outer space activities on the sustainable development and functioning of smart cities, and in turn to their impacts on human activities such as communication, navigation, positioning and timing, and others.

While acknowledging catastrophic space-related events such as planetary collisions, the study's primary focus is on the intersection of technologies and policies that influence both smart cities and outer space sustainability. Specifically, this includes the use of space-based services such as satellite imagery and GNSS in smart cities, the adaptation of sustainable technologies such as renewable energy in both domains, and the policy frameworks that govern these activities. While catastrophic events such as planetary collisions are a consideration in space sustainability, they are not the focus of this paper unless they have direct implications for current space-based services such as early warning systems.

The concepts of sustainable outer space and smart cities encompass the utilization of advanced technologies to foster sustainable development both on Earth and in space. There are several interconnected ways in which these concepts can be linked:

1. Space-based services for sustainable cities: Smart cities can leverage space-based services, including satellite imagery, remote sensing, and global navigation satellite systems (GNSS), to monitor environmental conditions and inform decisions that promote sustainable development. For instance, satellite imagery enables the monitoring of land-use changes, facilitating informed urban planning choices aimed at sustainable growth.
2. Smart cities as a testing ground for space technologies: Earth's smart cities can function as testing grounds for sustainable technologies that may eventually find applications in outer space. Renewable energy sources such as solar and wind power can be tested and refined in smart cities before their deployment in space habitats.
3. The sustainable development of space infrastructure: The development of space infrastructure, such as space stations and lunar habitats, necessitates sustainability considerations to prevent resource depletion on celestial bodies. The long-term sustainability of space exploration efforts can be promoted by implementing sustainable practices during the design and construction of space infrastructure.
4. Space debris management: As previously mentioned, space debris poses a threat to both space infrastructure and urban areas on Earth. Implementing sustainable practices is imperative for managing space debris and minimizing the risk of collisions.
5. The remote monitoring and management of space infrastructure: Advanced technologies such as artificial intelligence and robotics enable the remote monitoring and management of space infrastructure. These technologies reduce the need for human intervention in space, thereby promoting sustainability by minimizing the resource requirements for supporting human presence.

While the sustainability of outer space has garnered attention from political decision makers, the focus of this attention tends to align with international affairs rather than local urban management. Given its direct association with peaceful uses of outer space, space sustainability represents a focal point of global politics, with governments actively involved in decision making in this domain. In this context, there is limited intersectionality with urban settlements, particularly concerning the broad notion of "quality of life". Furthermore, within the framework of the United Nations' sustainable development concept, the operationalization of sustainability in global space politics has relied on documents serving as moral guidelines rather than legally binding directives. The notion of sustainability in outer space usage aims to secure socioeconomic benefits in the present and in the long-term future. Nevertheless, these guiding documents play a crucial role in facilitating long-term strategic thinking in decision-making processes.

In more recent times, there has been a growing realization that Earth's orbital space environment is a limited resource that is being utilized by an increasing number of space actors. Consequently, the need for effective measures to protect this environment has become urgent. States, commercial entities, and other non-governmental organizations contribute to the proliferation of orbital debris through the deployment of spacecraft, which poses risks to space operations by elevating the probability of collisions and interference with satellite functionality. These threats, particularly space congestion, have a global scope and necessitate global resolutions in forums such as the United Nations system.

In 2019, the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) endorsed a set of 21 voluntary guidelines, known as the UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities [15,16]. These guidelines are categorized into four sets: policy and regulatory measures, safety in space operations, international cooperation and capacity building, and scientific and technical aspects. While the guidelines do not explicitly reference urban settlements, they broadly address the overarching objective of enhancing the quality of life of current and future generations.

Furthermore, the UN's comprehensive definition of long-term sustainability (LTS) as "the ability to sustain space activities indefinitely in a manner that ensures equitable access to the benefits of outer space exploration and utilization for peaceful purposes, meeting the needs of present generations while preserving the outer space environment for future generations" [58] encompasses the technologies and services that constitute smart cities. Activities related to the sustainability of outer space include collisions between debris and active satellites, human impacts on the space environment, and radio frequency interference originating from satellites, space weather, or terrestrial systems.

The extent to which these perceptions of space sustainability align with the principles of sustainability in smart cities remains a matter of debate.

2.4. Sustainable Smart Cities and Outer Space Sustainability: Bridging the Gap

Sustainable urban development is generally concerned with the mindful use of finite resources for the development of urban settlements for residential, commercial, or recreational purposes [59]. One important link between this and space sustainability is the concept of resource depletion. Just as cities on Earth must grapple with the challenge of resource depletion and the need to manage their resources sustainably, space-faring societies must also be mindful of the limited resources available in space. This includes everything from the resources needed to sustain human life in space to the materials needed to construct spacecraft and infrastructure.

Further, a pivotal nexus between the two realms emerges through the concept of systems thinking. Both domains embody intricate systems that demand a meticulous contemplation of the intricate interplay among diverse components. Within the context of smart cities, deliberations regarding transportation infrastructure hold the potential to reverberate throughout the urban fabric, engendering repercussions for energy consumption, air quality, and public health. Likewise, in the realm of outer space, choices concerning resource allocation and waste management bear profound ramifications for astronaut well-being, the durability of space-based infrastructure, and the overarching sustenance of extraterrestrial domains.

As our case study will later highlight, it is impossible to think about sustainable urban activities without considering outer space. An accidental collision in outer space will trigger, at the minimum, the failure of vital services and, at the maximum, the cascading collapse of the urban structures that form the current lifestyle framework.

Finally, there is the issue of innovation. Both outer space and smart cities require innovative thinking and technological advancements to address the challenges they face. In a smart city, this may involve the development of new technologies for energy generation or waste management, while in outer space, it may involve the development of new propulsion systems or life support technologies.

Overall, while the challenges of outer space sustainability and smart city sustainability may be different in nature, they share several key connections in terms of the need to manage resources sustainably, implement systems thinking, and innovate to address complex challenges. Therefore, if urban strategic decision making ignores those risks originating in outer space, smart cities will be susceptible to disruptions and failures. Thus, achieving sustainability in both cities and outer space calls for harmonized strategic approaches.

3. Materials and Methods

This study carried out a simulation of a specific catastrophic event in outer space to investigate its impact on the functioning of smart cities. The goal was to explore the interconnectedness between smart cities and disruptive space events. Understanding outer space conditions can offer valuable insights for strategic urban planning, making it possible to integrate built-in resilience into city infrastructure. In other words, an awareness of potential space disruptions can help city decision makers avoid or mitigate breakdowns in the systems that make up a sustainable urban environment. Simulation software, often used in space operation centers globally, can be valuable for both space agencies and urban planners. By predicting collision risks and taking preventative actions, operational officers in both domains can utilize the same set of data.

Using a forensic research approach, we examined a specific past event—the collision between Iridium 33 and Cosmos 2251—to assess its impact on the essential infrastructure and services in smart cities. We supplemented our understanding of this event with information from academic, operational, and news sources. Subsequently, we collected satellite orbital coordinates, known as Two-Line Element Sets (TLEs), from databases such as SOCRATES and space-track.org. Commercial software such as STK (Systems Tool Kit) could not accurately represent the outer space environment at the time of the event, so an updated simulation environment was created. Additionally, we used the open-source platform CelesTrak to search for potential satellite conjunctions over the following week by comparing a comprehensive list of satellite payloads to objects already in orbit. Determining which payloads are active versus inactive is challenging due to limited public information. We based our scenarios on data from both CelesTrak and STK (version 11.2), using STK's SGP4 propagator and STK/CAT (Conjunction Analysis Tools) to provide the minimum distances and collision probabilities when conjunctions were within 5 km. Given the computational demands and the need for additional software components to create a realistic environment, we favored CelesTrak whenever feasible.

The simulation model was developed using STK Software, with a variety of input variables considered, such as orbital altitude, velocity, mass of objects, and probability distributions for collision scenarios from platforms such as CelesTrak.org and Spacetrack.org. These variables were derived from historical collision data and publicly available datasets from agencies such as the European Space Agency and SOCRATES.

To emulate a realistic outer space environment, we incorporated factors such as gravitational pulls, drag forces, and the Earth's oblateness. The focus of the simulation was to estimate the volume, velocity, and trajectories of debris resulting from satellite collisions and their potential cascading effects on services in smart cities.

The simulation underwent a validation process using historical collision case studies, such as the Iridium 33 and Cosmos 2251 encounter, to ensure that the model's outputs were aligned with actual event outcomes.

We recognize that our focus solely on collision scenarios might have narrowed the scope of our simulation. However, collision events offer tangible and readily quantifiable examples of outer space activities that can have a significant impact on smart city infrastructure.

After compiling a list of potential collisions from Space-track.org, every payload within the ESA satellite catalogue was examined. Certain payloads identified as large debris fragments were excluded from the analysis. However, for satellites active during the analyzed events, various databases related to smart city projects were consulted. We also looked at applications that used services from potentially affected satellites to identify possible service disruptions. Due to the significance of the analyzed events and the numerous fragments still in Earth's orbit, the unavailability of comprehensive access prompted an additional analysis: we conducted a thorough assessment of objects that have remained in orbit over a period spanning several years (February 2009 to June 2022). This analysis serves as a valuable inventory of objects that have persisted in orbit for a significant duration.

Although the broader scope of this paper explored a variety of challenges and considerations concerning human-made space debris and its impact on smart cities, it is worth noting that the simulation analysis specifically focused on the collision scenario between satellites. This choice was deliberate: collisions offer a poignant and readily quantifiable example of the cascading effects outer space activities can have on urban services and infrastructure. Nevertheless, we acknowledge that space debris poses other forms of risks, such as uncontrolled satellite re-entry and fragmentation events. This article is, however, the result of a broader doctoral research project that has also tackled fragmentation and satellite re-entry events and the impact of such events on the well-functioning of urbanized areas. Future research will seek to broaden this study's simulation analysis by incorporating these and other scenarios to provide a more comprehensive assessment of the subject area.

4. Results

The collision between the military communications satellite Cosmos 2251 and the communications satellite Iridium 33, which occurred on 10 February 2009, at 11:56 a.m. Eastern Standard Time over Siberia, holds significant historical significance as the first complete payload collision. The collision resulted in the creation of tens of thousands of smaller fragments and approximately 2000 objects with a minimum diameter of 10 cm [60]. These remnants, which will persist in orbit for extended periods, pose a high risk of collision with other objects in low Earth orbit, as depicted in Figure 1. The collision transpired at a speed equivalent to 26 times the speed of sound, with Iridium 33 weighing 600 kg and Cosmos 2251 weighing 900 kg [60,61].

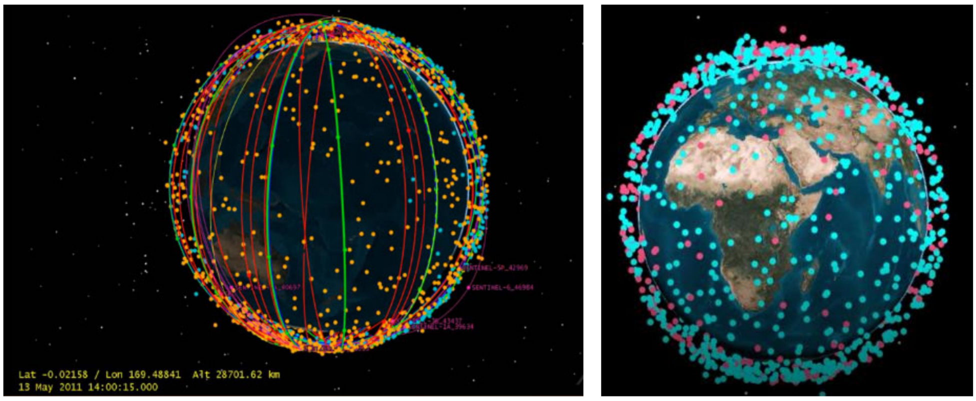

Figure 1. Fragments still in orbit on 13 May 2011, rendered with the main satellites' orbits (**left**) and fragments still in space on 24 June 2022 (**right**) (©STK).

This accidental collision between Iridium 33 and Cosmos 2251 produced the second-largest space debris event in satellite fragmentation history [62]. The immediate observations after the collision recorded 1603 fragments from Cosmos 2251 and 598 fragments from Iridium 33 [63]. Although numerous fragments from Iridium 33 were already dispersed in orbit by 10 February 2009, at 18:26:10 h, only 153 debris pieces were plotted within 35 min of the impact. The initial predictions estimated that half of the tracked debris would re-enter the Earth's atmosphere within five years; however, by 1 October 2009, fewer than 60 catalogued fragments had re-entered, leaving most newly produced debris in orbit [64]. This suggests that only 4% of the existing low Earth orbit (LEO) objects have been discovered [65].

This collision serves as a poignant example of the potential consequences when the near-Earth space environment lacks protection. Aside from the loss of one operational communications satellite, the collision generated hundreds of debris pieces larger than 1 cm, significantly increasing the long-term risk of danger to future communications and Earth resource satellites occupying similar orbits. NASA has asserted that accidental collisions between catalogued objects currently occur every one to five years, with the likelihood of such incidents predicted to increase in the future [66]. While the 66-satellite Iridium constellation experienced minimal losses, with its regular service being promptly restored [66], the damage caused by the collision in the orbital region may have been more severe. Approximately 1000 fragments from the collision have persisted in orbit for extended periods, posing a threat to other functioning satellites, including the remaining viable Iridium payloads.

As of June 2022, there were still 1485 large fragments from Cosmos 2251 and 533 large fragments from Iridium 33 in orbit that could have potentially collided with other orbiting objects, as illustrated in Figure 2. Furthermore, the remaining fragments of Cosmos 2251 in orbit could have collided with an additional 1685 debris pieces, 69 active satellites, and 61 rocket bodies. Similarly, fragments from Iridium 33 could potentially have collided with approximately 531 debris pieces, 25 active satellites, and 30 rocket bodies.

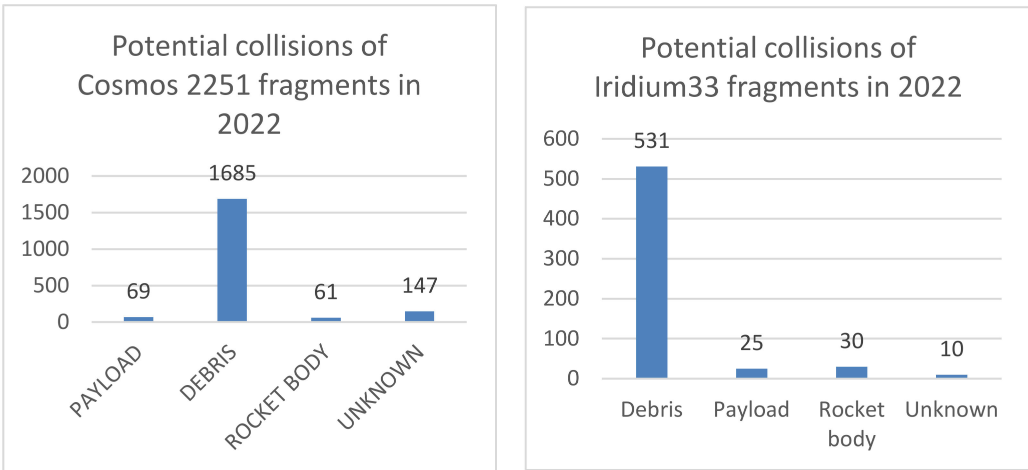

Figure 2. Potential collisions of debris caused by the collision between Iridium 33 and Cosmos 2251 with other pieces of payloads, debris, or rocket bodies in June 2022 (processed data from space-track.org).

All the catalogued fragments resulting from the 2009 collision event that are still present in orbit were accurately located and processed using the U.S. Space Track open-source database ((www.space-track.org (accessed on 24 August 2023)). The entries underwent two rounds of verification using SATCAT, a text file containing information about all the human-made objects orbiting the Earth since 1957. The analyzed data suggests that the collision between Iridium 33 and Cosmos 2251 may have impacted crucial services, as depicted in Table 1. These services include food and water management, localization services, disaster response capabilities, and research efforts.

Table 1. List of satellites that could have been potentially impacted by debris caused by the Iridium 33 and Cosmos 2251 collision in June 2022.

Collision Probability	Name 1	Name 2	Type of Satellite	Type of Service Potentially Affected
0.000274496	IRIDIUM 33 DEB	EXPLORER 7	EO and space exploration	N/A, the satellite was decommissioned at the time of research
0.001121804	IRIDIUM 33 DEB	STEX	Reconnaissance/ intelligence gathering	N/A, the satellite was decommissioned at the time of research
0.000198616	IRIDIUM 33 DEB	LANDSAT 5	EO and space exploration	▪ Food and water management ▪ Water management ▪ Climate change ▪ Ability to respond to disasters ▪ Ecosystem studies ▪ Energy sector ▪ Ability to detect forest fires ▪ Human health management ▪ Urban management ▪ Water management
0.000252395 0.000398829 0.000492121 0.001309433	IRIDIUM 33 DEB	COSMOS 1375	ASAT target—it was a target for Cosmos 1379 on 18 June 1982 Debris is still in orbit	N/A, the satellite was decommissioned at the time of research
0.002249103 0.001138301 0.000991591 0.000116312	IRIDIUM 33 DEB	DEMETER	EO (observation of geophysical parameters of the terrestrial environment)	▪ GNSS—especially localization services ▪ Earth observation ▪ Research
0.000134388	IRIDIUM 33 DEB	COSMOS 1626	ELINT (Electronic and Signals Intelligence) satellite, a military space-based system; replaced Cosmos 1408	N/A, the satellite was decommissioned at the time of research

Source: authors' calculations.

Collisions in outer space can lead to the release of debris and other materials that pose a threat to food and water storage facilities, potentially resulting in the loss of supplies. Damage to equipment used for food production or water generation due to space collisions can have significant ramifications for society's ability to sustain itself. It is imperative to establish backup systems to ensure the uninterrupted production of food and water, even in the event of a collision.

Moreover, large-scale collisions in outer space can have indirect effects on the Earth's climate due to the substantial amount of dust and debris they can introduce into the atmosphere. This debris can block the sun's rays, causing a global cooling effect. Additionally, collisions can release substantial quantities of carbon dioxide and other greenhouse gases into the atmosphere, potentially contributing to long-term climate change.

Further, collisions occurring in the vast expanse of outer space can have notable repercussions for global navigation satellite system (GNSS) services, which heavily rely on an intricate network of satellites to provide users on Earth with precise location and timing information. The presence of debris or its colliding with other satellites can cause damage to or even destroy satellites in the Earth's orbit. This inevitably leads to a reduction in coverage and a concomitant decline in accuracy in GNSS services, negatively impacting the provision of such services. Moreover, collisions can create debris fields within the Earth's orbit, thereby serving as an imminent risk to other satellites and spacecraft and critically compromising an array of indispensable services that support smart cities across the globe.

In addition, it is worth highlighting that numerous technologies harnessed in disaster response and smart city domains critically depend on satellite communications, encompassing GNSS services, satellite imaging, and satellite internet. These technologies operate as indispensable sources of vital information for emergency responders, enabling them to execute their duties promptly and effectively. At the same time, they empower city managers to make data-driven decisions aimed at improving urban infrastructure and services. If collisions in outer space inflict damage upon satellites or result in their outright destruction, the ensuing disruptions to satellite communications will consequently yield delays and curtailed functionality for disaster response and smart city technologies. For instance, the loss of GNSS services precipitates heightened challenges for emergency responders in terms of navigating and locating individuals requiring assistance. Furthermore, the proper functioning of smart city technologies, including but not limited to traffic management systems, energy grids, and public safety systems, hinges on the receipt of real-time data. Consequently, any disturbances stemming from disrupted satellite imaging or other data sources arising from collisions in outer space undeniably give rise to inefficiencies and impeded performance within these systems.

In conclusion, it is crucial to acknowledge that collisions transpiring within the realm of outer space engender indirect ramifications that impede smart cities' capacity to respond effectively to disasters and impair their optimal functioning, chiefly by disrupting satellite communications and jeopardizing essential data sources. Consequently, it becomes imperative to adopt preventive measures aimed at averting collisions altogether, coupled with the formulation of comprehensive contingency plans in the case of disruptive collisions that are designed to ensure the uninterrupted provision of vital services.

Figure 3 provides an examination of the impact of the Iridium 33 and Cosmos 2251 collision event on different categories of satellites. Our analysis of data gathered from various databases underscores the pronounced repercussions suffered by Earth Observation (EO) satellites because of this collision incident. Communication satellites also experienced a notable impact, although to a lesser extent. It is noteworthy that the least impact was observed in the case of constellation-based communication satellites, where service continuity was maintained despite the collision.

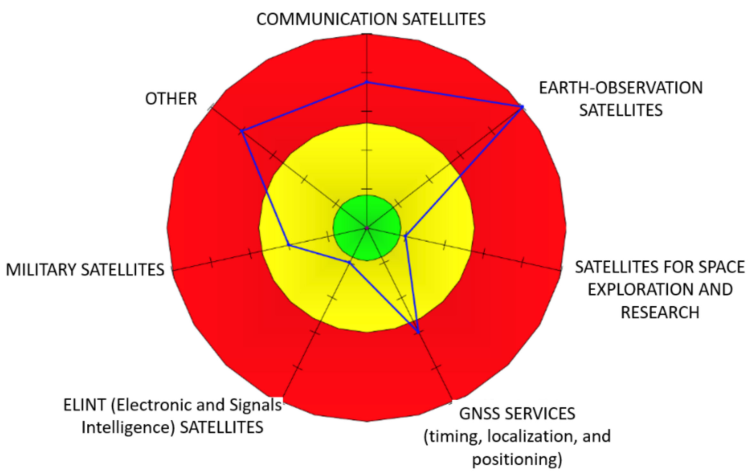

Figure 3. The effect of the collision of Iridium 33 and Cosmos 2251 on various typologies of satellites.

The collision between Iridium 33 and Cosmos 2251 had far-reaching consequences, extending beyond the destruction of a communication satellite associated with Motorola, which led to a temporary disruption of satellite telecommunication services. Thirteen years after the event, its aftermath still had the potential to compromise the continuity of critical infrastructure sectors in several smart cities, including Landsat, Demeter, and Iridium, as depicted in Figure 4.

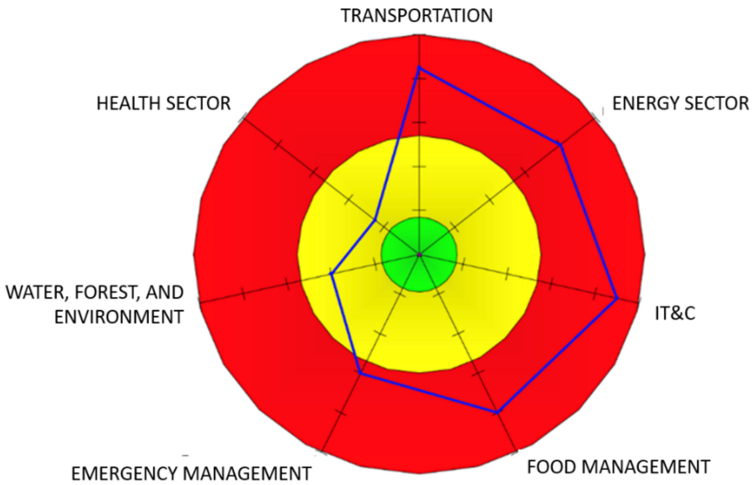

Figure 4. Critical infrastructure sectors were affected by the collision of Iridium 33 and Cosmos 2251.

In the event of additional collisions, the transportation, information, and communication technology (ICT) and energy sectors would be at risk of experiencing significant repercussions. Conversely, the health sector, particularly the emergency services, would likely face a relatively lesser impact, owing to the existing redundancies incorporated within this sector.

Our simulations indicate that space debris originating from satellite collisions has the potential to disrupt key smart city functions such as navigation, telecommunications, and even emergency services. A single collision in outer space can create a cascade of debris, with a broader impact potentially being felt across multiple city services, highlighting the need for redundant systems and contingency planning.

5. Discussion

The presence of generic space debris in outer space poses a significant threat to satellite operations, emphasizing the need for vigilant monitoring by satellite operators. This research highlights that satellite operators, including the public conjunction assessment service SOCRATES, use screening capabilities to generate close approach predictions for satellite payloads. However, as the production of debris increases, these services will face greater demands. City-level decision makers should be aware of these monitoring tools to foster a common understanding of the risks posed by outer space and their potential cascading effects on smart city technologies.

The effects of collisions in outer space extend beyond just their initial impact, as debris from such collisions poses risks to other objects in orbit. For instance, the encounter between Cosmos and Iridium produced a substantial number of visible fragments from both satellites. While efforts are being made to monitor and track such debris, observing and accounting for all potential objects remains impossible. Additionally, the mechanisms behind satellite disintegration are not fully understood, although it is acknowledged that debris fragmentation produces various fragment sizes and masses. The issue of debris in space cannot be disregarded as it does not naturally degrade into dust.

Addressing these challenges is crucial for carrying out a comprehensive analysis of the effects of orbiting debris, the identification of genuine threats, and effective communication with the public and relevant stakeholders. However, political and scientific obstacles impede progress in these areas. The scientific challenges lie in our limited knowledge regarding the scale of the issue, while the political dilemmas arise from the prolonged timeframes required for mitigating potentially harmful occurrences.

It is crucial to discuss the likelihood thresholds for satellite collision events that warrant significant attention. Currently, a collision probability of higher than 1 in 10,000 is generally considered to be of high concern and would typically trigger avoidance maneuvers if possible. Given the current technological and economic constraints, it may be justifiable to consider ignoring collision probabilities that fall below a certain threshold, such as 1 in 100,000, as the costs and efforts required to take corrective action in these cases may not be justified.

However, this is not a recommendation to dismiss low-probability events entirely but rather a suggestion to weigh them against the other pressing concerns faced by smart cities, such as immediate threats to infrastructure or public health. In terms of prioritization, decision makers should focus first on high-probability, high-impact events that can significantly disrupt urban services, while scenarios with lower collision probabilities and less immediate impacts may be accorded a lesser priority but should nevertheless not be entirely ignored.

We acknowledge that as technology improves and the costs associated with monitoring and prevention decrease, these probability thresholds should be revisited. The balancing act between economic feasibility and risk mitigation is an evolving landscape that requires ongoing assessment.

Smart cities are regarded as a solution to numerous global challenges, such as increasing energy consumption, air pollution, and urban traffic and the declining food production caused by population growth. However, cities face a multitude of issues and risks, some of which originate in space and impact vital systems and services encompassing the transportation, water, electricity, communications, healthcare, and social services sectors. To monitor service losses in real-time, a stronger link between smart cities and space infrastructure is necessary. This study proposes the establishment of an intermediate level "governing entity" that bridges small-scale urban governance structures and national security councils focused on nuclear and missile deterrence.

Specifically concerning ICT, space debris poses a latent threat to services such as navigation, telecommunications, and even weather forecasting—all of which are vital for the efficient functioning of smart cities. While outer space collisions are isolated incidents, we can still imagine the scale of impact that space debris could exert on urban services; more comprehensive measures for resilience in this regard are therefore needed.

The governing body proposed above should be responsible for building the tools required, including financial mechanisms, to ensure the deployment and delivery of operational space situational awareness (SSA) services to smart cities, as well as their ongoing monitoring. This governing entity must ensure the availability and continuity of relevant data and services, as well as their long-term sustainability. Moreover, fostering structured and mutually reinforcing relationships among stakeholders along the value chain is essential for aligning activities with the governing organization's primary objectives.

On a broader level, our research exemplifies the importance of comprehensive information for strategic smart city planning. The vulnerability of advanced technological systems, which form the backbone of smart cities, due to a lack of awareness about the risks posed by outer space underscores the direct connection between the continuity and cost of operations. Furthermore, this research establishes a direct link between the sustainability of outer space and the sustainability of smart cities, emphasizing that to avoid any disruption to ground services, outer space technologies should be leveraged responsibly for the benefit of future generations.

Within the larger context of urban resilience, the study's consideration of space debris marks a novel approach [22]. This research builds upon the primary author's earlier investigations, which initially studied the potential influence of space activities on urban amenities, by specifically exploring their potential repercussions for the functioning of smart cities.

6. Recommendations and Limitations

Collisions in outer space can have direct and indirect effects on the proper functioning of smart cities on Earth, as well as on the ability to respond to disasters and safeguard human activities in general. Urban development strategies should incorporate considerations of the potential impact of collisions in outer space and include measures to mitigate the risks they pose to the normal functioning of city services. To address these challenges, the following recommendations are proposed for urban development strategies regarding collisions in outer space.

Firstly, developing redundant communication systems is crucial. Cities should consider establishing alternative communication systems that are not solely reliant on satellite communications. Potentially involving the development of terrestrial networks or alternative satellite systems, these could ensure the continuity of communication services in cases of outer space collisions.

Secondly, cities should plan for emergency responses in the event of disruptions to satellite services. It is essential to have contingency plans in place, including alternative methods for navigation and locating individuals in need of assistance.

Thirdly, implementing resilient infrastructure is vital to withstand the potential impact of debris from collisions in outer space. Cities should reinforce buildings and critical infrastructure to reduce the risk of damage caused by falling debris.

Furthermore, collaboration with satellite operators and space agencies to monitor space debris is essential. By tracking the movement of debris and taking proactive steps to avoid collisions between debris and satellites, cities can actively contribute to reducing the risk of collisions.

Additionally, promoting sustainable practices can help mitigate the risk of collisions in outer space. Cities should encourage sustainable practices such as reducing carbon emissions and minimizing waste in order to reduce the number of debris in orbit and decrease the likelihood of collisions.

Regarding the study topic's limitations and areas for further research, several aspects require attention. Firstly, the lack of data on the impact of collisions in outer space on smart cities necessitates further research to better understand the potential impact of such collisions and to develop effective mitigation strategies regarding them.

The cost associated with the development and implementation of smart city technologies, redundant communication systems, and resilient infrastructure is a significant concern. However, research on the impact of collisions on smart technologies might prove less costly than repairing the damage caused by such disasters.

The lack of governance and regulation surrounding outer space activities, particularly regarding debris mitigation and collision avoidance, has created uncertainty for cities and satellite operators. Establishing clear governance frameworks is crucial for effectively managing the risks associated with collisions in outer space.

The integration of outer space activities with smart city technologies is still in its early stages. Further research is needed to better understand how these technologies can be integrated and how they can best support urban development goals.

Lastly, the potential inequitable distribution of benefits from smart city technologies and outer space activities needs consideration. Research should explore how these technologies can be used to address urban inequalities and promote social and environmental justice.

In conclusion, while smart city technologies and outer space activities hold significant potential to support urban development, addressing their limitations and areas for further research is essential to ensuring their responsible and equitable use. Urban development strategies should prioritize resilience and preparedness in the face of disruptions to satellite services caused by collisions in outer space. By taking proactive measures to mitigate risks, cities can minimize the potential disruptions to city services and ensure the safety and well-being of their residents.

7. Conclusions

This study explored the concept of sustainability regarding the governance of two distinct realms: outer space and smart cities. Sustainability in outer space pertains to the various means and methods by which space is dedicated to societal benefits. Conversely, sustainability in smart cities relates to the preservation of vital services and infrastructure, under any circumstances, without resource depletion. This paper identified a connection between maintaining a debris-free outer space and ensuring functional and resilient urban services.

Further, the study analyzed the accidental collision between the Iridium 33 and Cosmos 2251 satellites and its potential impact on critical services in smart cities. The findings demonstrate that this collision indirectly affected essential infrastructure such as energy grids, transportation systems, and information and communication technologies (ICT). Beyond the loss of a satellite and the temporary disruption of the associated communication network, the long-term consequences of this collision could have led to substantial disruptions across multiple critical services.

These findings establish a direct correlation between collisions in outer space and the vital services that underpin contemporary smart cities. The sustainability of outer space and the ground-level core of our cities are intricately intertwined, which necessitates the strategic engagement of urban decision-making entities with outer space sustainability, at least at an awareness level and ideally through an active engagement via intermediate governing bodies.

Consequently, urban development strategies must consider the potential hazards of space debris and ensure that urban infrastructure is resilient to its potential impacts. This may require the implementation of stricter regulations on satellite launches and the mitigation of orbital debris to safeguard the long-term sustainability of space operations.

In the context of the sustainability and smartness of cities, a temporary inverse progression has been observed [67], whereby the greater the technological interconnectedness of our urban settlements, the more technologies are placed in Earth's operational orbits. As a result, the increased presence of objects in orbit elevates the risks of collisions and compromises the time-sustainability of our lifestyles. This thought-provoking antithesis underscores the potential danger to smart cities' strategic planning posed by the lack of sustainability in outer space.

While the history of space activities is marked by a relatively low rate of incidents directly impacting ICT and other urban services, the stakes of such incidents are elevated in the context of smart cities whose infrastructural and service interdependencies are high. As the volume of space activities continues to increase, the statistical likelihood of disruptive incidents will also rise, necessitating a proactive approach to urban resilience that accounts for both terrestrial and cosmic threats.

In summary, this study emphasized the interdependence of sustainability in outer space and the effective functioning of smart cities. By recognizing this interconnectedness, urban decision making should actively include considerations of activities governed by intermediate entities. Strategic urban development planning must address the hazards posed by space debris and prioritize resilient infrastructure while advocating for stricter regulations on satellite launches and debris mitigation to ensure the long-term sustainability of space operations. Recognizing the occasional tension between the sustainability and smartness of cities underscores the need to address the risks tied to the unsustainable use of outer space when safeguarding the strategic planning of smart cities.

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Abbreviations

ASAT	Anti-satellite weapon
BIM	Building Information Modelling
CityGML	City Geography Markup Language—an open-source 3D city modelling format
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
ELINT	Electronic and Signals Intelligence
EO	Earth-Observation
ESA	European Space Agency
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICT	Information and Communication Technology
LEO	Low-Earth Orbit
LTS	Long-Term Sustainability
NORAD (ID)	North American Aerospace Defense (Catalog Number)
SATCAT	Satellite Catalog Number
SOCRATES	Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space
SST	Space Surveillance and Tracking
STK	System Tool-Kit
STK/CAT	STK's Conjunction Analysis Tool (CAT)
TLE	Two-Line Element
UNESCO	United Nations Educational, Scientific, and Cultural Organization

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