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Sustainability Aspects of Rapid Prototyping and Frequent In-Orbit Demonstrations with CubeSats

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Abstract
The study focuses on examining the sustainability challenges associated with CubeSats' rapid prototyping and in-orbit demonstration (IOD). The topic is highly relevant nowadays, especially for university student associations working on CubeSat missions. Environmental, economic, and societal factors are all part of these sustainability concerns. Despite the lack of existing research, the rising demand for CubeSats necessitates addressing these issues. CubeSats are selected for investigation due to their popularity, compactness, and cost-effectiveness. The goal of this research is to establish criteria for sustainable prototyping and IOD practices, crucial for technological progress but requiring greater attention to sustainability. The authors propose an approach, highlighting the significance of well-planned IODs and improved end-of-life strategies for CubeSats to foster sustainability in the industry. The research includes a case study about the EPFL Spacecraft Team, which is an example of a student association working on IODs for their CubeSat.

1. Nomenclature

ADCS	Attitude Determination and Control System
ADR	Active Debris Removal
CHESS	Constella- tion of High-Performance Exospheric Science Satellites
COTS	Commercial off-the-shelf
EPFL	Ecole Polytechnique Federale de Lausanne
EPS	Electrical Power System
ESA	European Space Agency
ETHZ	Swiss Federal Institute of Technology in Zurich
FMEA	Failure Mode and Effects Analysis
GSTP	General Support Technology Program
IOD	In orbit demonstration
ISS	International Space Station
MEMS	Micro-Electro-Mechanical System
OBC	On-board computer
TRL	Technology Readiness Level

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2. Introduction

The growth of the space industry is accompanied by the pressing challenge of minimizing negative externalities and maximizing benefits for humanity, in other words, finding and maintaining the sustainable development track. This research aims to carry out an up-to-date analysis of sustainability issues associated with rapid prototyping and frequent in-orbit demonstration (IOD) with CubeSats, and, building on the results of this analysis, provide a set of guidelines for the said processes useful for student-led space missions. By sustainability issues the authors mean environmental (material waste, particulate pollution, greenhouse gasses emissions, etc.), economic (cost and value analysis, economic viability, contribution to economic development) and societal, educational (knowledge transfer) aspects. The sustainability problems concerning prototyping and flight-proving with CubeSats are legion with the existing body of research not offering clear and exhaustive solutions for fixing the entirety of them, yet, the demand for this format of a satellite is growing, which necessitates fixing the gap and explains the relevance of the research at hand.

The choice of the CubeSat format as the object of research for this paper stems from its compactness, relative cost-efficiency, simplicity and functionality. The characteristics listed above explain the format's popularity, which is expected to grow tremendously in the near future, potentially leading to the problem of drastically reduced orbit availability.

The subject of the research, which is the prototyping and IOD in the context of space sustainability, was chosen due to the fact that nowadays the space industry lacks clear and unambiguous criteria for the said actions concerning CubeSat missions carried out by non-commercial student associations. Moreover, the authors identified these particular stages, because they present vital importance and cannot be neglected. Fast prototyping allows for accelerated technological and economic growth, however it can come at a cost both literally (material expenses) and figuratively (possible impact on sustainable development). As for the IOD, it is particularly important when it comes to the development of new space technologies, as it allows for the testing of new systems in the harsh and demanding environment of space. Given the increasing demand, vital importance and high risks of IOD, the sustainability issues of this stage deserve significantly more attention from researchers and policy-makers than they currently are paid.

The authors of this article provide an overview of the trade-offs between the number of IODs and their associated costs, risks, benefits and externalities in the context of student-led CubeSat missions. Based on their findings, the authors present a balanced approach to determining the appropriate strategy for IODs, as well as practical recommendations for the prototyping phase to ensure the sustainability and success of CubeSat operations. The research includes a case study on the EPFL Spacecraft Team, a student association actively engaged in conducting in-orbit IODs as part of their preparation for the upcoming CHESS mission. This final 3U CubeSat mission, CHESS, aims to analyze the chemical composition of the exosphere.

3. Overview of IODs

3.1 Background and context of IODs

In-Orbit Demonstrations are critical for the development and validation of new space technologies and techniques. These demonstrations represent the highest level of Technology Readiness Level (TRL) scale used to assess the maturity of new technology. In other words, for a technology to be considered fully mature, it needs to be demonstrated in orbit, particularly when users require evidence of flight heritage or when there is a high risk associated with their use.[4][5]

The European Space Agencies' (ESA) In-Orbit Demonstration Element, which is part of its General Support Technology Program (GSTP), is responsible for finding flight opportunities for innovative technologies and demonstrating new research and operational techniques. These could include using reflected navigation signals or exploiting Automatic Identification System signals from global ship traffic. The program also supports the demonstration of in-orbit operational techniques, such as formation flying or re-entry, ans associated technologies and products. [4]

Another role of IODs is to gather data on spacecraft and space environments to prepare for the deployment of future innovations. For example, one such application is characterizing radiation effects to estimate the vulnerability of Micro-Electro-Mechanical Systems (MEMS). [4]

The IOD Element includes a series of technology demonstrator micro-satellites, namely the Proba missions, and also places technology experiments on carriers of opportunity, such as the ISS or ESA space missions that have capacity to host guest payloads. Broadening access to space in this manner is a means of building industrial skills and capacity, particularly for smaller companies and new member states. This also enhances industrial competitiveness and widens the portfolio of mature space technologies that operational ESA missions can utilize, thereby increasing their effectiveness.

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In terms of specific examples, the RemoveDEBRIS mission from Surrey Space Centre [6], which developed a net device to capture space debris, provides a good illustration of how in-orbit demonstrations are used. While ground tests of increasing complexity were conducted to verify the functions of the net device, they could not validate the full capture of a free-floating, non-cooperative target in space. Thus, an IOD was required to give full confidence in the design and reduce the risk associated with scaling up the technology for actual Active Debris Removal (ADR) missions to capture larger objects. As these missions show, ensuring the survivability and functionality of key subsystems through IOD is a vital step in the development and deployment of innovative space technologies, providing critical insights into the feasibility and reliability of these technologies in a real-world, space-based environment.

3.2 Relevance for Student Associations

Conducting CubeSat missions is very popular among student associations at universities because CubeSats are small, cost-effective satellites that provide an accessible entry point to space exploration. However, whole CubeSat missions are still complex projects and, since they are developed entirely by students, come with a large risk of failure. This is why a lot of student associations increasingly focus on conducting IODs of individual subsystems. With IODs, the tested subsystem is placed as a payload on a ride-share platform that is launched into space. By then gathering the data of the subsystem, the students can see whether the subsystem works successfully and thus increasing the reliability of the subsystem for the final mission.

Next to the advantages that IODs bring to the final missions' success, IODs provide invaluable hands-on learning experiences for students, allowing them to directly apply theoretical knowledge to real-world scenarios. By participating in the design, development, and deployment of subsystems, students gain practical skills and enhance their understanding of space engineering. Whole CubeSat missions often span multiple years, surpassing the duration of students' university studies. Whereas, IODs enable students to actively participate in all stages of a space system development.

Furthermore, IODs offer a unique opportunity for students to showcase their technical competence and innovative ideas, thereby boosting the visibility and reputation of their universities and student associations. This demonstration of technical expertise reduces the risk of the overall mission, making it more attractive to potential industry partnerships and sponsors.

4. Case Study: EPFL Spacecraft Team

The EPFL Spacecraft Team is a student association with over 40 members that was founded in 2019 at EPFL in Lausanne. With a bold ambition to make a mark in space exploration, the team strives to leave a lasting impact in this field. The team's primary mission is to provide students with an extraordinary opportunity to actively participate in space-related projects.

At the core of their approach, the EPFL Spacecraft Team focuses on the development of in-house subsystems for CubeSat missions that are designed to be independently launched into space. This unique strategy allows each student involved to work on a dedicated project that will ultimately find its way to the stars.

By developing their own subsystems, the team members gain hands-on experience and expertise in diverse areas, including satellite communication, power systems, instrumentation, system engineering and more. This approach empowers students to delve deep into their specific areas of interest and contribute to the overall mission of the team.

The ultimate goal of the EPFL Spacecraft Team is to launch a 3U CubeSat, with the so-called CHESS (Constellation of High-Performance Exospheric Science Satellites) mission. The primary science objective of this mission is to improve the understanding of the upper atmospheres of planets by in-situ measurements. The CubeSat is therefore equipped with an instrument to study the chemical composition of the terrestrial exosphere and its density in situ. The suite consists of a miniaturized time-of-flight mass spectrometer led by the University of Bern as the main payload and a high-precision multi-GNSS payload board with four receivers conceived by ETHZ. These payloads will provide unique, long-awaited data from Earth's upper atmosphere, namely the number density of species, altitude profiles of them, total electron content, ion population, and dynamics.

The space experiments, of the CHESS mission, will be hosted on a 3U CubeSat platform that is almost fully developed in-house by students of the EPFL Spacecraft Team. Since the students do not have experience with the direct development of space systems, the strategy of the EPFL Spacecraft Team is to launch different IODs of critical subsystems before the actual launch of the final CHESS mission. This will greatly reduce the risks of failure of the subsystems and therefore make the whole mission more reliable. [7]

A first IOD was already conducted in January 2023 utilizing a similar OBC intended for the CHESS mission, called Bunny (Figure 1, left). This demonstration took place aboard the ION SCV-009 orbital transfer vehicle from D-Orbit, which accommodated Bunny as a hosted payload. Bunny collects crucial data throughout the first half of 2023,

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specifically focused on the behavior and reliability of its constituent elements. Notably, Bunny employs commercial and consumer-grade components, effectively demonstrating their suitability for the demanding space environment. Encouragingly, all data collected from Bunny thus far has been nominal, affirming the success of the mission. [8]

In 2024, the team plans to perform another IOD specifically for the in-house developed X-Band module. The X-Band module is responsible for transmitting the science data gathered by the instruments back to the ground. Since this communication link is absolutely crucial for the success of the CHESS mission, the X-Band module is one of the most important subsystems. Conducting an IOD will therefore serve as a crucial step in mitigating this risk and enhancing its reliability.

Alongside the X-Band module a second iteration of the OBC, called Twocan, will be flown (Figure 1, right). The reason for this is that, the development and testing of Bunny revealed several limitations, particularly with regard to computational power. The primary goal of Twocan is to provide a more powerful and redundant on-board computer, replacing the unused parts of Bunny (the FPGA). This redundancy ensures that in the event of a computer failure, the other can take over, thereby increasing the reliability of the system.

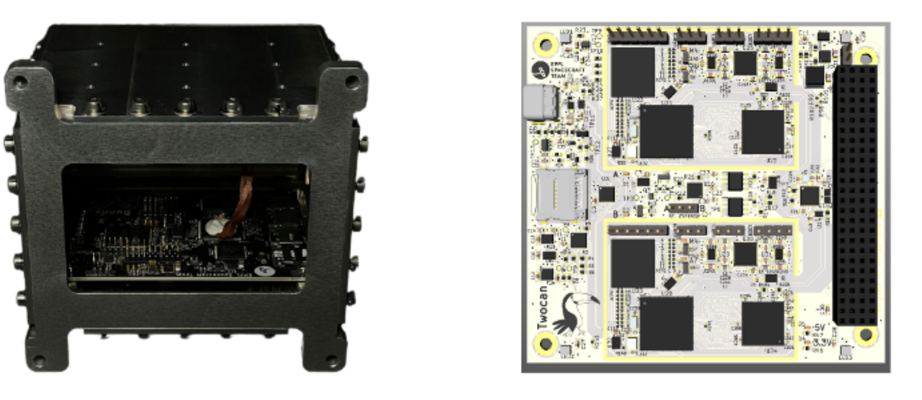

Figure 1: On-Board Comuter Bunny (left) and Twocan (right)

5. Technological considerations

5.1 Technological Advancements and Innovation

When looking from a technical standpoint, performing IODs of CubeSat subsystems brings several significant benefits and advancements.

Firstly, IODs enable the verification and validation of subsystem functionality in the actual space environment. While ground testing plays a vital role in subsystem development, it can never fully replicate the exact conditions and challenges present in the space environment. With IODs the performance, durability and reliability of the subsystems can be assessed, providing valuable insights into their behavior and identifying any potential issues that may arise only in space.

Furthermore, IODs offer an opportunity to gather valuable data and insights that can significantly enhance future design iterations and therefore improve the overall CubeSats mission success. The data collected during the IODs can be analyzed to improve models, validate simulations, and finally to validate the performance of the subsystems. This data-driven approach helps in understanding the actual behavior of the subsystems, enabling the refinement of designs for subsequent missions. By incorporating lessons learned from IODs the reliability and performance of subsystems can be improved.

IODs also serve as a platform for testing and evaluating novel technologies or techniques that may have practical implications for future space missions. IODs can for example be used to demonstrate new innovative solutions, novel materials or new communication protocols. This has the potential to greatly influence future missions and industry practices. The ability to showcase and validate these advancements in the real space environment enhances the credibility and practical applicability of the developed subsystems. [5]

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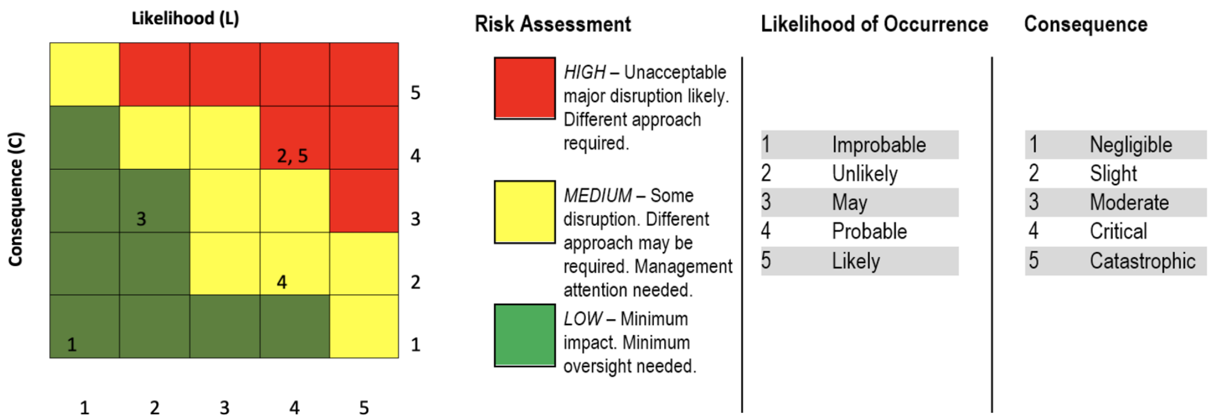
5.2 Risk assessment of different subsystems

In addition to the technical advantages discussed earlier, the primary reason for conducting IODs is to mitigate the overall risk of failure of the final CubeSat mission. While ground tests provide valuable insights into the potential success of subsystems, there is always a level of uncertainty. This risk becomes even more important for subsystems functions that cannot be fully replicated in ground tests to simulate in space conditions. But by conducting successful IODs, the risk of failure for the respective subsystem can be significantly reduced and therefore give more trust in the success of the final mission.

It is however important to note, that from a time and cost perspective it does not make sense to validate each individual subsystem of a CubeSat in orbit. Priority must be given to the subsystems that have a particular high risk. The following Table 1 applies a simplified version of the Failure Mode and Effects Analysis (FMEA) method, developed by NASA [13], to the most common subsystems of a CubeSat, to identify which subsystems have the highest associated risk. The subsystems considered are the structure, the telecom module, the power system, the attitude determination and control system (ADCS) and the on-board computer (OBC). For each subsystem, a risk mitigation strategy is provided.



Risk	L x C	Subsystem	Description	Mitigation strategy
1	1,1	Structure	The structure is not able to withstand the loads during launch.	Identification of the right materials and perform qualification in lab to model the highest loads from the launch vehicle.
2	4,4	Telecom	Platform cannot communicate with the ground station. Data cannot be downlinked. Commands cannot be uplinked and executed.	Use flight heritage subsystem. Redundancy of communication link (multiple frequency bands) and exhaustive testing (in lab and in orbit).
3	2,3	Power System	Not enough power is stored. Not enough power is delivered to the subsystems.	Redundancy Test exhaustively / manufacturer responsibility.
4	4,2	Attitude Control	ADCS is not providing the right pointing and maneuvering. ADCS cannot compute or control the satellite attitude.	Test sensors, test actuators, test power connections, test deployment of magnetometers. Use flight heritage subsystem.
5	4,4	OBC	Commands cannot be executed. OBC gathers wrong or no data.	Use flight heritage subsystem and in-orbit testing

Table 1: Risk analysis of common subsystems of a CubeSat

From the Table 1 it can be seen that the subsystems with the highest risk are the Telecom module, the ADCS and the OBC. However, from a technical perspective, performing an IOD of the ADCS can be challenging. This is primarily because, the subsystems undergoing IODs are payloads on other spacecrafts. As a result, the ADCS subsystem is not the primary spacecraft responsible for attitude control, and therefore cannot perform and test its own maneuvers. Conducting IODs of the Telecom module and the OBC is however very much feasible and according to the Risk analysis highly recommended.

In the Case Study of the EPFL Space Craft Team, it is evident that a similar approach was followed in selecting subsystems for IODs. The OBC Bunny was already tested successfully in orbit, and there are plans for an upcoming IOD of the X-Band telecom module. To mitigate risks, the team chose COTS solutions for the UHF module and ADCS system. This decision aims to minimize potential risks associated with these subsystems, ensuring high probability of success for the final mission.

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6. Environmental sustainability

6.1 CubeSats and the space debris problem

Space sustainability is a complex and multifaceted problem manifesting itself in many different ways, and every aspect of this problem is worthy of consideration by the scientific community, policymakers and space actors. While recognizing the significance of this comprehensive matter, the authors of this particular research focus exclusively on one aspect of space sustainability: space debris. It is widely acknowledged that space debris poses the most urgent challenge within the realm of space sustainability [1, p.7]; consequently, it is imperative that humanity acts upon it without further delay.

There are two different approaches to defining "space debris": one comprises both natural (dust and other "planetary construction material") and human-made debris in space; another one refers exclusively to artificial debris, brought into space by human activity. [1, p.10] While both types of space debris are dangerous, we will use the term "space debris" according to the second approach, for it is more relevant in the context of space sustainability.

According to NASA, there are over 100 million space debris currently orbiting the Earth [2], which implies the risk of at least 1 collision per year [1, p. 9]. On the face of it, a potential strategy to mitigate the proliferation of space debris would involve minimizing the frequency of launches for satellites deemed unnecessary. However, defining the term 'unnecessary' becomes a matter of contention. Some might argue that CubeSats employed for in-orbit demonstrations, as they serve no purpose beyond testing novel technologies, fall into this category. Nonetheless, it is crucial to conduct in-orbit demonstrations of new technologies, despite the transitory nature of CubeSats utilized for such purposes [3].

Overall, in the academic literature dedicated to space debris, we can outline three major strategies for mitigating the problem at hand:

- Identifying and tracking the 'space junk' in order to minimize collision risk.
- Development of strategies to prevent multiplication of space debris.
- Space debris removal.

6.2 Sustainability guidelines for student associations performing rapid prototyping and frequent IODs with CubeSats

Taking into consideration the previous paragraphs of this study, the first guideline to a sustainable approach to IODs with CubeSats can be derived. Student associations are thereby encouraged to use a similar strategy as provided in the previous section, to conduct the risk assessment of different subsystems and, based on this assessment, decide on the most critical technologies to be tested. It must also be mentioned that especially the subsystems with a true innovative component need such testing.

Student associations often have to conduct rapid prototyping for a variety of reasons, including:

- High members turnover due to a limited time spent at a university. Out of 3-4 years of Bachelor, only 1-2 years can be fruitfully spent at such a student association as the work is knowledge- and skill-intensive; for a Master student, the lifetime at a student association would normally be around 1 year.
- Financial considerations (see 7.2).
- Innovative student environment facilitating the growth of ideas and motivation for their quick implementation.

In the context of rapid prototyping, it is important to assign high priority to sustainability considerations. Here are some of the guidelines learned from the experience of the EPFL Spacecraft Team:

- Choice of partners. Space student associations have to rely heavily on their partnership network, therefore, it is important to choose responsibly, prioritize the companies and organizations that implement sustainable approaches.
- Regulatory compliance. It is key to be informed about up-to-date regulations and guidelines related to sustainability in space activities. Ensuring compliance with international space debris mitigation standards and any other relevant environmental regulations is a must, yet student associations should take a step even further, taking into account non-mandatory recommendations and sustainability guidelines.

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- End-of-life considerations. Responsible disposal of the IOD subsystems once they reach the end of their operational life is one of the crucial aspect of space sustainability when it comes to in-orbit demonstrations. The end-of-life strategy is thereby chosen by the ride-share platform provider. The most common strategy is to de-orbit the spacecraft, meaning to burn up in the Earth's atmosphere to prevent space debris. There is a range of commercially available technologies that allow for such disposal.
- Upgradability. It is worth designing CubeSats with modularity in mind, allowing for easy upgrades and replacements of specific components instead of replacing the entire satellite, in case a certain subsystem does not prove useful. This way, in case a novel technology fails during an in-orbit demonstration, there will be no need to redesign the entire mission and dispose of the components already purchased/developed/assembled.

Even though it is challenging to implement for a student association doing rapid prototyping and frequent in-orbit demonstrations with CubeSats, it would be immensely helpful to conduct a lifecycle assessment and potentially consider alternative materials to replace those that appear unsustainable.

7. Economic sustainability

7.1 The economic context of CubeSats' success

Due to its cost-effectiveness and scalability, the CubeSat format has gained enormous popularity in the space industry teetering on the brink of commercialization. C. Cappelletti et al., write: "CubeSats make excellent platforms for technology demonstrations and for proof-of-concept missions" [10]. They highlight that there is an abundance of factors supporting it, most notable of those being: widely accepted industry standards, design specifications, simplicity, and adaptability.
In fact, the growing popularity of the CubeSat (and SmallSat) format disrupted the entire space industry, facilitating the advance of new companies in the space supply chain and the evolution of the legacy ones [12]. G. Denis et al. identify four key trends in the modern market associated with CubeSats' increasing usability, and building on their conclusions, we suggest outlining six major trends:

- Minutiarization: Reduced size, weight, and power requirements decrease the cost barriers for companies to enter space and decrease the potential risk associated with space debris formation (smaller-sized would-be-space-junk, lower impact in case of collision, easier to de-orbit).
- Standardization: CubeSats enable more rapid development, higher agility, and scalability, as well as the accessibility of satellites. They require less material, have simpler designs, and can be manufactured using commercial off-the-shelf components (COTS).
- Specialization of the supplier's thanks to minutiarization and standardization. There appear more and more small businesses focusing on a certain aspect of a CubeSat and excelling almost exclusively in its development. For example, Thrust Me specialized in electric propulsion mechanisms for small-scale satellites.
- Vertical Integration: As small specialized startups become more renowned and established, they are likely to be "swallowed" by a space giant integrating its supply chain to make its operations more efficient. A classic example here is SpaceX.
- New manufacturing techniques, such as additive manufacturing, modular and scalable design, PCB integration, etc.
- Constellation of satellites: The trends outlined above fostered the deployment of not just single, but constellations of CubeSats. There are numerous benefits brought by this model, the most notable being redundancy and resilience to system failures (which would have been more expensive if not for the miniature and standardized model), more extensive coverage (for example, the CHESS mission will consist of two CubeSats placed in different orbits - circular and elliptical - to allow for a more exhaustive and comprehensive data collection).

Launch service providers, such as SpaceX, Rocket Lab, and SpaceFlight, thanks to economies of scale, launch and deploy secondary spacecraft at a reduced cost. The most impressive results in this domain have been achieved by SpaceX. Falcon 9 is the world's most widely used rocket for commercial rideshare programs [12]. The first IOD of the OBC developed by the EPFL Spacecraft Team was also carried out by Falcon 9 on January 31, 2023.

One of the most successful "business models" in the context of IODs with CubeSats are rideshare programs [11]. Rideshare programs, where multiple small satellites are launched together as secondary payloads on larger missions,

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have revolutionized access to space for startups, educational institutions, and research organizations. By capitalizing on the economies of scale, rideshare programs have facilitated the proliferation of CubeSats, driving innovation and expanding the boundaries of space exploration.

CubeSats are a relatively inexpensive "track to space" for novel technologies, and in case of mission failure, the losses would not be catastrophic. That explains why in the era of the new space economy in-orbit demonstrations with CubeSats will not only retain their importance, but also gain momentum, potentially aggravating the space debris problem. Even though most of the CubeSats will burn in the atmosphere within several years (we are taking into consideration CubeSats operating in LEO), the space debris problem still persists. The most evident risk is that as the number of CubeSats serving for in-orbit demonstrations grows, the risk of collision with other objects in the orbit grows as well, consequently, the more we launch, the higher are the chances that new satellites will crash and shatter into a myriad of new debris. Moreover, if we assign the label "space junk" to any spacecraft in the orbit that is not actively carrying out a mission, then a CubeSat becomes one immediately after it has "demonstrated" the technology it had brought. In other words, if it takes 2 months to run all the tests of a new on-board computer carried by a CubeSat, and the carrier will stay in orbit for 5 years, then it can be considered space debris right after those 2 months of tests have elapsed. Last but not least, the risk of the CubeSat not fulfilling its mission in orbit is never zero, in which case it can become a space junk immediately after it is ejected.

7.2 Student associations and IODs with CubeSats: sponsorship plans, academic funding and industry partnerships

The case of the EPFL Spacecraft Team, demonstrates how student associations can leverage CubeSat IODs for academic funding, sponsorship, and industry partnerships. In order to ensure economic sustainability of the project, that is to say, in order to obtain and maintain good financial standing throughout the lifetime of the association; the team has built a network of industrial and academic partners that it continues to expand in the due course of its main mission.

Given the high cost of space missions, even the affordable format of CubeSats can be beyond the budget of a usual student association. Table 2 shows the main challenges and opportunities that stem from the concept of a student-led CubeSat mission:

Challenges	Opportunities
No investment is possible due to the fact that student associations do not make a profit. A student association can promise no financial returns to its sponsors.	Sponsorship opportunities with non-financial returns for the sponsor: visibility, reputational gains, publications, etc.
Restrictions imposed by the regulatory landscape limit the scope of financing opportunities for a student association.	Student associations are in no direct competition with the companies operating on the said market because all the accumulated knowledge from a student project becomes open-source.
Maintaining long-term financial sustainability is challenging because most of the sponsorship deals are specific to a certain part of the project and regular funding is limited.	Collaboration with industry partners and alumni networks for ongoing financial support.
Limited access to grants and funding programs tailored specifically for student associations.	Engaging with the university administration and seeking their support for funding opportunities.
Limited awareness and networking opportunities with potential sponsors.	A broad range of opportunities to actively networking and participating in industry events and conferences to connect with potential sponsors.

Table 2: Challenges and Opportunities

7.3 Economic risk assessment of a CubeSat mission with in-orbit demonstrations

Technological malfunction is not the only threat faced by a space mission. Any in-orbit demonstration comes at a cost, and it is therefore essential to weigh up the costs and opportunities in order to ensure economic sustainability of the project and the longevity of the student association conducting it. (Table 3)

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The prices provided in column 'Market price' (Table 3) correspond to the overall market situation as of June 2023. It should be noted that many manufacturers communicate prices on their subsystems only upon request, therefore, the numbers provided might not be representative of the market as a whole. They serve to give an idea of the price range on the subsystems in question to allow for a valid comparison with costs of in-house development, and consequent analysis of financial risks for a student-led CubeSat space mission.

The costs indicated in the column 'Costs of in-house development' (Table 3) are based on the corresponding budget of the EPFL Spacecraft Team, where the lower bound is the best-case scenario and the upper bound is the worst-case scenario.

Subsystem	**Description of Risk**	**Market Price**	**Price of In-house Development**
Structure	The structure is not able to withstand the loads during launch.	$1,800-$3,000 (for 1U)	$2,000-$5,000
Telecom	Platform cannot communicate with the ground station. Data cannot be downlinked. Commands cannot be uplinked and executed.	$4,000-$8,800	$5,000-$10,000
Power System	Not enough power is stored. Not enough power is delivered to the subsystems.	$3,800	$4,100-$26,800
Altitude Control (ADCS)	ADCS is not providing the right pointing and maneuvering. ADCS cannot compute or control the satellite altitude.	$2,000-$23,500	$9,600-$20,000
On-Board Computer (OBC)	Commands cannot be executed. OBC gathers wrong or no data.	$4,300-$9,900	$7,500-$15,300

Table 3: Subsystem Risks and Costs

Even a cursory look at the Table 3 is enough to notice that, generally, the costs of in-house development are higher than those dictated by the market. There are several explanations to this:

- Research and Development (R&D): Designing and developing a subsystem from scratch requires significant investment in research and development, including expenses related to the design process, prototyping, testing, and iteration. A special attention should be paid to the fact that R&D poses additional challenges for a student association due to the lack of expertise and experience.

- Trial and Error: In the costs of in-house development, we always include the 'wiggle room' in case of failure. When it comes to established production, such risks are low, but when it comes to a student-led mission driven by innovation, these risks are substantial enough to be taken into account.

- Economies of Scale: Unlike an established manufacturer, a student association cannot profit from economies of scale.

- Time and Resources: In-house development is, undoubtedly, a resource-intensive process, requiring dedicated time, facilities, and equipment. Student associations often face resource constraints, making it challenging to allocate sufficient time and resources to complete the development within a given timeframe, especially given the fact that full-time often student struggle to allocate time for extracurricular activities.

- Opportunity Cost: Developing a subsystem in-house requires significant time and resources that could be allocated to other aspects of the project at hand. Consideration should be given to the opportunity cost of in-house development, weighing the benefits of customization and control against the potential trade-offs in terms of time, resources, and expertise.

Despite all the difficulties, it is worth developing subsystems in-house, for it enables students to incorporate innovative ideas, obtain invaluable experience and generate knowledge that can be transferred to academia and industry.

Coming back to Table 3, we can conclude that on top of the technological risk assessment, a sustainable approach to managing a student CubeSat mission demands careful cost consideration. The choice of subsystems to test in the orbit must stem not exclusively from the innovative components and risks of failure, but also from the comparison of market prices and the costs of in-house development.

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7.4 Economic sustainability guidelines for student associations performing IODs with CubeSats

Taking into consideration all the aforementioned technological, environmental and financial aspects, we suggest the following guidelines to ensure economic sustainability of student-led in-orbit demonstrations with CubeSats:

- An extensive and reliable network of academic and industrial partners is an inherent component of long-term financial sustainability for a student-led mission. Such a network should allow for financial support, expertise exchange and materials supply.

- When it comes to in-orbit demonstrations, an association is advised to take the following approach:
  1. Choose the subsystems to test based on their innovative potential, risks of technical failures and costs of in-house development versus market prices;
  2. Perform in-orbit demonstrations of the said subsystems, and in case of failure, replace the technologies developed in-house by those available on the market. This way the mission will hold even if one or several subsystems fail an IOD.

- When forming a budget, it is important to:
  1. Consider several possible scenarios, from the best outcome to the worst one. For instance: What is the budget if all IODs are successful? What is the budget if all IODs fail? What is the budget if the IOD of the OBC fails? etc.
  2. Short-term expenses and income should be in line with the long-term vision. Due to high members turnover that is characteristic of a student association, it is not uncommon that short-term planning moves the long-term vision away from the spotlight, whereas for economic sustainability of the project it is crucial to align these two aspects at all stages.

8. Social and Educational sustainability

CubeSat missions, especially the innovative component enabled by IODs, offer a unique, hands-on learning experience for students, combining theory and practice and accumulating valuable knowledge. In the due course of working on various stages of systems' design, development, and launch, students acquire knowledge about satellite engineering, space physics, electronics, software development, space economy, space logistics, legal aspects as well as a broad range of soft skills.

CubeSat projets inherently necessitate the understanding and application of a wide range of academic disciplines. The interdisciplinary approach promotes teamwork and collaboration, as students from different fields of study - such as physics, computer science, engineering, economics, environmental sciences, and management - must come together to complete the project. Such a collaborative effort requires a level of communication, cooperation, and management skills that are as valuable in the professional world no less than technical skills are.

The key aspect of educational sustainability in the context of student-led CubeSat missions is knowledge transfer. We can outline three dimensions of knowledge transfer:

- Knowledge transfer within the team must be ensured through proper documentation and continuity.

- Knowledge transfer in academia should be facilitated through scientific publications, participation in events and collaboration with students and researches.

- Knowledge transfer from a student association to the industry might be conducted through partnerships, joint projects, exchange of expertise and future employment of team members.

Furthermore, IODs can also promote sustainability in the academic community. CubeSat projects encourage students to grapple with the challenges presented by sustainability issues in the space industry. They get to study and apply concepts such as waste management, energy efficiency and end-of-life disposal, leading to a practical understanding of sustainability that extends beyond theoretical knowledge.

The potential for knowledge sharing and collaboration among and inside student associations is another significant benefit. As more student groups engage in CubeSat projects, there is a natural trend for inter-universities collaboration. They can share insights and findings, compare designs, exchange troubleshooting strategies, and improve their understanding of space and space technologies. This type of collaboration is a practical application of academic principles and it reflects the nature of international cooperation found in the space industry. And further down the road, these collaborations incentivize a culture of shared learning, creating an academic community that values cooperation over competition.

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In conclusion, CubeSat IODs present an unrivaled opportunity for student associations to foster technical skills, teamwork, and interdisciplinary collaboration, and promote a culture of sustainability and shared learning. By facing real-world challenges, students are not only preparing for their future careers in the space industry, but also contributing towards the improvement of the academic community and the general sustainable development of space technology.

9. Limitations and Opportunities

When consulting this research, the following limitations must be taken into consideration:

- Time constraints. The space industry is going through rapid transformations and is seeing drastic technological and economic changes, as well as raising sustainability awareness. This study is relevant as of 2023 and provides a reliable outlook for the near future, however, it cannot guarantee longevity; and in the decades to come might be consulted more as a study representative of its time of conduct.
- Access to information. As members of a student association, the authors of the research at hand have limited access to information sources and rely mostly on open-source data. For example, some of the market nuances might be known exclusively to commercial actors and be out of sight of a student association.
- Target audience. The recommendations developed in the due course of this study are useful for student associations carrying out IODs with CubeSats, which narrows down the scope of possible applications of our findings.
- Experience. The EPFL Spacecraft Team is a relatively young student association and there is still a long path ahead. The association has conducted one IOD so far, with more yet to come.

While some of the aforementioned limitations pose permanent and strict constraints, others open up opportunities for future research to build on the foundations of this study.

- Commercialization opportunities. The research can be expanded to include commercial prospects of student-led innovation as a part of the economic sustainability discussion.
- Access to information. As the team gains more experience and further expands its academic and industrial network, more information can be accessed and accumulated, which would allow for a more in-depth study of the problem at hand.
- Target audience. Having explored the commercialization prospects arising from student-led CubeSat missions, the team can broaden the target audience of the recommendations it develops and include space startups operating in the field.
- Life-cycle assessment. It would be valuable and insightful to conduct a thorough life-cycle assessment of the mission at hand. This is the opportunity that the team is planing to realise in the near future.

Overall, the research at hand opens many doors for future research in the field of sustainability aspects of rapid prototyping and frequent in-orbit demonstrations with CubeSats.

10. Conclusion

Summing up the findings obtained in the due course of the CubeSat mission of the EPFL Spacecraft Team and relevant to the sustainability aspects of rapid prototyping and frequent in-orbit demonstrations with CubeSats, we propose the following guidelines for student-led space associations embarking on a complicated journey of testing novel technologies with the help of in-orbit demonstrations with CubeSats:

- IODs do pose an additional risk of more space debris formation, yet they represent a crucial step on the way to realization of a space mission incorporating novel technologies; therefore, IODs must not be set aside but rather approached with a sense of responsibility and careful consideration.
- Risk assessment of different subsystems allows to gain understanding of the necessity to test some of them in orbit. This generally accepted technique is a reliable and standardized approach that would allow to determine the optimal number of IODs.

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- In order to ensure environmental sustainability of the project, a student association should pay special attention to choice of their partners, regulatory compliance, end-of-life strategies, upgradability and modularity. An additional and valuable step would be to conduct life-cycle assessment.
- Economic sustainability of a student-led CubeSat mission is built on the following pillars: an extensive and reliable network of academic and industrial partners; consideration of costs of in-house development and market prices of key subsystems; replacement strategy in case of a subsystem's failure; developing several variations of a budget depending on different scenarios; aligning short-term expenses with the long-term vision.
- In terms of social and educational sustainability, it is vital to ensure smooth knowledge transfer within the team, academic circles and industry. As student associations are non-commercial entities, their accumulated knowledge should become publicly available and, therefore, enable more research and technological advancements to be built on the foundation of their achievements.

The triple bottom line of the study at hand is that there are three key aspects to sustainability when it comes to student-led IODs with CubeSats: environmental, economic and social (educational). All these three pillar are built on the technological and innovative foundation.

11. Sources

1. B. M. Shustov. 'On fundamental research concerning the problem of space debris' - 2019. DOI: 10.21046/spacedebris2019-7-14 0
2. NASA. Space debris and human spacecraft. URL: https://www.nasa.gov/mission_pages/station/news/orbital_debris.html Accessed: 21.04.23
3. ESA. Technology CubeSats. URL: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_CubeSats Accessed: 30.04.23
4. ESA About In-Orbit Demonstrations URL: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/About_In-orbit_demonstrations Accessed: 24.06.23
5. In Orbit Demonstration. https://technology.esa.int/program/in-orbit-demonstration Accessed 22.06.23
6. RemoveDEBRIS: An in-orbit demonstration of technologies for the removal of space debris. https://www.cambridge.org/core/journals/aeronautical-journal/article/removedebris-an-inorbit-demonstration-of-technologies-for-the-removal-of-space-debris/88B966915E7A3BD6F0B047A38FF713D2 Accessed 21.06.23
7. EPFL Spacecraft Team. https://www.epfl.ch/education/educational-initiatives/discovery-learning-program-2/interdisciplinary-projects/chess/ Accessed 23.06.23
8. The EPFL Spacecraft Team is launching EPFL back into space. https://actu.epfl.ch/news/the-epfl-spacecraft-team-is-launching-epfl-back-in/ Accessed 24.06.23
9. SpaceX Mission Starfield. https://www.dorbit.space/starfield-january-2023 Accessed 22.06.23
10. CubeSat Handbook, Chantal Cappelletti, Simone Battistini, and Benjamin K. Malphrus, 2020
11. A. Toorian, K. Diaz, and S. Lee, "The CubeSat Approach to Space Access," 2008 IEEE Aerospace Conference, Big Sky, MT, USA, 2008, pp. 1-14, doi: 10.1109/AERO.2008.4526293.
12. G. Denis, D. Alary, X. Pasco, N. Pisot, D. Texier, S. Toulza, 'From new space to big space: How commercial space dream is becoming a reality", 2020, Acta Astronautica 166, pp. 431-443.
13. NASA. "Standard for Performing a Failure Mode and Effects Analysis (FMEA) and Establishing a Critical Items List (CIL) (DRAFT) Flight Assurance Procedure (FAP) - 322 - 209." URL:https://rsdo.gsfc.nasa.gov/documents/rapid-iii-documents/mar-reference/gsfc-fap-322-208-fmea-draft.pdf Accessed 05.052023.