ARTICLE IN PRESS

Space Policy xxx (xxxx) xxx

Contents lists available at ScienceDirect

Space Policy

journal homepage: www.elsevier.com/locate/spacepol

Project and knowledge management at European public space agencies: The need for a three-dimensional project management office

Chiara Maria Cocchiara [a], Giovanna Lo Nigro [a], Paolo Roma [a], Antonio Ragusa [b,*]

[a] Department of Engineering, University of Palermo, Viale delle Scienze, 90128, Palermo, Italy

[b] Rome Business School, Space Economy Institute, Via Giuseppe Montanelli, 5 00195, Rome, Italy

ARTICLE INFO

Keywords:
Public space agencies
Space missions
Project management
Knowledge management
Case study

ABSTRACT

Space agencies are continuously developing new space missions, each of which undergoes a long development cycle, from the feasibility study to routine operations and disposal, as per the European Cooperation for Space Standardization (ECSS), the body responsible for developing and maintaining a set of standards for the space industry in Europe. Each mission is a stand-alone project, where the development cycle starts every time from scratch, with new resources, technologies, and requirements, applying the same (tailored) standards, but with limited usage of lessons learnt from earlier or parallel projects. In this article, we analyse typical project management and knowledge management approaches adopted by public space agencies, making use of a relevant case study in Europe. From the results of our case study analysis, we propose a three-dimensional Project Management Office (PMO) governance, explaining how this novel approach helps address limitations and challenges of the current approaches when dealing with multiple complex projects, such as space missions. With the PMO defined as an organisational body or entity assigned various responsibilities, the authors focus on three specific areas, namely, Strategy, Resources, and Knowledge, as three key drivers that can improve the current management of projects of the organization.

1. Introduction

With new needs and requirements from the scientific community, investors, and satellite data end users, space agencies in Europe keep increasing the number of Space Missions that they plan to launch in the next decade. Consequently, the space sector is experiencing a large expansion with more and more players being active in this sector, going from public space agencies (both national and intergovernmental), private industries, start-ups, and academia. By observing the top three public space agencies in Europe (ESA, EUMETSAT, and EUSPA), there is a clear understanding that satellite data are playing and will keep playing an important role in the near future. The European Space Agency (ESA), established in 1975, with the current participation of 22 member States, currently operates fifteen missions (twenty-two satellites) from the Operations Centre (ESOC) in Darmstadt, and other cooperative missions are operated elsewhere. ESA operates multiple types of missions, from earth observation to deep space, to human spaceflight. Future missions in preparation include nine new missions that will be launched in the next decade [1]. EUMETSAT, established in 1986, with the current participation of 30 member States, currently operates ten satellites, plus cooperative missions, all within the field of earth observation. The plan includes the launch of fifteen more satellites within the next decade [2]. EUSPA, established in 2021, is operating constellations of satellites and it provides safe and secure European satellite navigation services, advances the commercialization of Galileo, EGNOS, and Copernicus data and services, engages in secure satellite communications (GOVSATCOM & IRIS2), and operates the EUSST Front Desk [3]. The introduction of so many missions certainly brings an increased level of complexity for the internal processes and working practices of space agencies, especially in terms of Project Management (PM) and Knowledge Management (KM), with the need for new innovative approaches [4].

PM and KM are critical components within the operations of any organization, and space agencies are no exception. PM is responsible for the activities spanning from planning till execution of a project, ensuring it is completed within requirements, while KM focuses on the capturing, organization, and sharing of the organization knowledge. They are both input and output of each other: effective PM relies on access to relevant

* Corresponding author.

E-mail addresses: chiaramaria.cocchiara@unipa.it (C.M. Cocchiara), giovanna.lonigro@unipa.it (G. Lo Nigro), paolo.roma@unipa.it (P. Roma), ragusa@romebusinessschool.it (A. Ragusa).

https://doi.org/10.1016/j.spacepol.2024.101639

Received 2 August 2023; Received in revised form 17 May 2024; Accepted 6 June 2024

knowledge, provided in an organized manner by KM. On the other hand, successful projects contribute to the organizational knowledge collection. They work in cycle and keep improving each other. As space exploration and research continue to expand, the need for effective PM and KM becomes increasingly essential. Effective PM is demonstrated to bring benefits to the organization both in tangible (e.g., costs and schedule) and intangible ways (e.g., corporate culture and organizational efficiency) [5]. Space missions with their systems and subsystems are unique projects, undergoing long development cycles with complex procedures that include participation and contribution of the member States [6]. In this paper, a space mission shall be intended as the collection of all those activities, from requirements definition to preliminary design, development, launch, operations, and disposal of a satellite. It includes two segments, the Space Segment (satellite and all its subsystems) and the Ground Segment (all the technology supporting satellite operations from the ground). The analysis, design, and development of a space mission are intended as an iterative and recursive process. Numerous new missions are about to join the current portfolio, pushing the organizations to continuously refine the requirements and constraints, and improve processes and tools [7]. Each mission, as a stand-alone project, is developed following the ECSS (European Cooperation of Space Standardization) standards, with the ECSS being a set of guidelines in the fields of Space Project Management (SPM), Product Assurance (PA) and Engineering. While the main focus of this article is SPM, as the collection of those standards that indicate the guidelines to comply with when developing a new Space Programme [8], the standards are intertwined with each other, and certainly PA and Engineering standards play an important role within the numerous activities carried out as part of the SPM. Within each project, ECSS leads towards a complex development, implementation, and controlling of all major project parameters, including those typical of PM (cost, schedule, risk, and technology). However, while ECSS standards provide a good basis for addressing each individual project, they do not take the broader perspective of the entire organization with its portfolio of projects.

With the evolution of mission complexity as well as the introduction of a significant number of new missions, such a broader perspective that considers the synergies and interconnections of all missions within a space agency becomes more and more compelling for improving the efficacy and the efficiency of the mission management. Nevertheless, missions are still considered as stand-alone projects even by public space agencies who have attempted to develop SPM handbooks [9]. The need for the evolution of PM and KM working practices in space agencies is instead mainly pushed by the numerous new private players that keep entering the market. Traditionally, space was the domain of the public sector, while the contribution of the private sector is a more recent phenomenon. The two typologies of players travel at two different speeds, with the private players aiming at smoothening the processes, for example by skipping or combining reviews, to accelerate the fulfilment of the objectives. Their scope is more commercial compared to that of public space agencies, and accelerating processes would allow for a quicker economic return of investment, which instead is not a priority for the public space agencies. The creation of a Public-Private-Partnership (PPP) within the space industry is therefore a complex encounter of two opposite philosophies, where the public sector is still very much keen to applying a traditional approach (to procurement and operations), while the private industry pushes for commercial development. While the two approaches move towards a different direction, and the creation of a PPP could be seen as a procurement arrangement in the form of the conventional buyer-supplier relationship, in the space industry we witness the form of a partnership between the two sectors [10].

While the private component of the partnership needs to adopt, at least at some level, the ECSS Standards, to be able to work together with public agencies, when working with internal activities, private companies develop internal PM and KM policies that often result faster and more efficient than those adopted in the public sector [6]. It is clear that there are inner differences between the two players, such as the complexity of the public space agencies due to multiple member States cooperating and taking decisions together, that limit them in their capability of modernizing and improving their PM and KM processes. Nevertheless, the private sector is certainly pushing the public agencies to change and improve their PM and KM policies to become more efficient and faster, in the attempt to remain competitive in the global market and keep playing a key role in the space related PPPs. For instance, each new mission, as a stand-alone project, has a public budget allocated to each mission. The Member States funding the missions have accused the space agencies of duplication and pushed for the need to make savings [11]. Since then, some space agencies, such as ESA, have carried out multiple cost-benefit analyses. An example is the one about the Space Situational Awareness (SSA) program, which was carried out in 2016 [12]. Another example are the two independent cost-benefit studies of the Space Based Solar Power for terrestrial energy needs, carried out in 2022 by Frazer-Nash in the UK and Roland Berger in Germany [13].

Some progress has been made over the years, although the PM and KM approaches in public space agencies still show a scattered picture with single experiences, single missions, meaning single projects, that are not coordinated/harmonised among each other. Therefore, in this paper, we aim at identifying the gaps in PM and KM as applied today in European space agencies, and look for ways of improvement in their working practices. In our study, we focus on space missions conceived as big projects, exhibiting similar characteristics in terms of risk class and importance, and thus having high need of improvements in PM and KM practices.[1] Starting from the fact that each of these missions is a stand-alone project, we seek for ways of coordination and synergy among them, with the objective of finding in this a powerful tool for improving the PM and KM processes.

Our study starts with the analysis of PM and KM, encompassing an overview of the existing literature explaining the current working practices in space agencies, the application of ECSS standards, and the need for a Project Management Office (PMO) to complement the standards. This analysis will provide a theoretical foundation to our study and help understand the key concepts, principles, and best practices in the fields of PM and KM, highlighting the approach in terms of standards, efficiency, effectiveness, and adaptability to the unique challenges faced by space agencies. Key similarities, differences, strengths, and weaknesses of the above practices will be identified, forming the basis for further investigation.

The PMO, with its crucial role of providing centralized and standardized approach to PM, is identified as the most efficient tool to enhance the efficiency, consistency, and success of projects within the organization. The authors identify in the PMO the way to align project activities with the company's objectives and ensure that resources are effectively utilized, enabling better decision-making and improving the organization's ability to adapt to change (e.g., in the case of introducing new missions as new projects). To achieve the above, the authors identified three key areas of improvement: Strategy (to identify within multiple projects, happening in parallel, those autonomous activities that act in the same goal-directed manner), Resources (that translates strategy guidelines into allocation of human resources to multiple projects) and Knowledge (addressing the knowledge management and sharing across projects within the organization).

To gain a deeper understanding of PM and KM practices within space agencies, we employ a case study approach relying on a strict collaboration with a European public space agency. Information is collected by direct observations and document analysis. The case study explores the specific PM and KM practices, tools, and techniques employed by the

[1] Small projects are in the form of shared missions with other agencies, leading to different needs in terms of PM and KM, but this shall be addressed as separate study and is not the focus of this article.

considered space agency. The findings are then compared to the state-of-the-art practices identified in the literature review.

Afterwards, grounding on the analysis of the literature, comparative study, and case study findings, we draw the conclusions and recommendations for improving the working practices of space agencies with respect to PM and KM. The conclusions highlight the strengths and weaknesses of the current practices in space agencies and provide recommendations to address the identified gaps. The recommendations aim at enhancing the effectiveness and innovation of PM and KM practices in space agencies, encompassing changes in processes, tools, knowledge sharing mechanisms as well as organizational structures (including human resources management).

2. Literature review

For the purpose of this study, the literature review examines PM and KM with a focus on the space sector, encompassing agile and waterfall PM in space agencies, the role of ECSS standards, an analysis of risks, limitations, and challenges associated with PM and KM in space agencies. We then review the extant knowledge on the need for PMO in space agencies, as well as the interconnections between PM and KM. Before starting this literature overview, we provide a definition of PM and KM. According to the PMI (Project Management Institute), PM is defined as *"the practice of using knowledge, skills, tools, and techniques to complete a series of tasks to deliver value and achieve a desired outcome"* [14]. According to IBM company, KM is defined as *"the process of identifying, organizing, storing and disseminating information within an organization"* [15]. As we discuss later, the relationship between PM and KM is a key factor for the success of projects within an organization. The link between PM and KM is particularly relevant when the task of developing and implementing successful projects requires intensive knowledge activities [16].

2.1. PM at European public space agencies

The space agencies are responsible for the management of numerous and complex projects, related to research and space exploration, that involve multiple stakeholders, within the agencies, as well as external partners and contractors. Such a complexity and the involvement of thousands of people working across multiple disciplines generate the need of effective PM to ensure the success of individual projects (e.g., missions) and of the entire agency [17].

European space agencies are strongly dependent on the usage of standards. In particular, the ECSS standards are the most powerful tool to support their PM processes. Some agencies like the European Space Agency (ESA) have developed their own PM guidelines, based on the ECSS standards, to cover the main topics from project planning to risk management, quality management and reporting [18]. The PM approach in space agencies is based on the international standards, such as ISO 21500 [19] and PMBOK, which have both been tailored to the specific needs and requirements of space projects. In particular, standards and guidelines are applied to individual space missions, which are viewed as a stand-alone project, namely "a temporary organisation that is created for the purpose of delivering one or more business products according to a specified business case" [20].

ECSS are equally applied to all the projects across the space agencies, but certainly, each space mission has some specific requirements that impose a dedicated tailoring to suit the needs of individual projects [21]. Based on the ECSS Standards, the space agencies dealing with multiple projects break down the latter into smaller manageable phases, allowing multiple project teams to focus on dedicated aspects of a project at a time [22]. Projects are regularly reviewed and audited during the full mission lifecycle in compliance with the ECSS standards, where the project team prepares series of documentation to be carefully reviewed by peers and steering committees [23]. Dedicated project boards carry out reviews of the progress of the projects and are responsible for the identification of issues, challenges, and risks. These should be properly documented [24], following the ECSS guidelines.

2.1.1. Agile and waterfall PM in space agencies

Public space agencies normally apply a combination of waterfall and agile PM approaches to their projects. The classic waterfall approach is based on the importance of planning, execution, and expected results. They are based on the end-user requirements that have been established at the beginning of the project [25]. Space agencies' missions are commissioned by the Member States that express the requirements on the desired data collected by the satellites. Based on those, the projects are developed in a goal- and plan-oriented manner (work packages, roles and responsibilities, and deadlines in the form of reviews) in order to deliver the expected data, with expected timeliness to the end users [26]. Waterfall approach is highly supported by documentation, and is certainly a classic methodology that confers stability to the project.

Within the project lifetime, it is normal that missions undergo modifications through the project lifecycle, for which the agile method is applied: high-level requirements are defined at the beginning of the mission, but the implementation from an operational perspective could be challenging to be clearly defined during Phase 0 or Phase A, which are described below in support to the case study. In this situation, the agile approach is applied, where for example, at any point in time, a team manager may ask for a request for waiver (RFW), to include products/processes that in the first place were not taken into consideration, but that in a second moment were considered to be useful for the operational implementation. The agile approach allows for higher flexibility but cannot be used for long-term goals: it is rather implemented for small projects or individual tasks within a bigger project. This is for example the case for space agencies working with outsourced solutions, where external companies need to develop parts of their systems. In this case, agile methods, such as Scrum or Kanban are applied [27].

Agile and waterfall approaches in a hybrid combination are normally the preferred option used by space agencies: high level requirements and a mission lifecycle schedule is defined using a waterfall approach, while sub-projects are managed in an agile manner. This helps maximize the benefits from both methodologies [28].

2.2. KM in public space agencies

KM is a key element of business strategy, which may have an impact on the efficiency/success of product/process development in tech organizations [29], including space agencies. While KM is a key element, normally the associated strategies adopted by organizations are not sufficiently reliable [30]. Also, the literature examining the implementation of KM practices is still limited, especially in the public sector [31,32], thus suggesting the need for a focus on the improvement these practices.

To classify knowledge is quite a complex task in itself, and shall be divided into "explicit" and "implicit or tacit" knowledge [33]. The explicit knowledge is available through the usage of tools available in the organization, where documentation, lessons learnt, and other materials is collected and made available for the employees. The implicit or tacit knowledge instead is acquired by employees through work and years of experience. It is an intuitive knowledge, which is very difficult to transfer, not only because of its nature itself, being a natural knowledge acquisition of employees, but also because of the lack of willingness among employees to share knowledge [34].

KM covers an important role in public space agencies to ensure effective capture and share of knowledge to achieve mission objectives. KM shall ensure that knowledge and expertise are shared across departments, teams and projects within the space agency, and lessons learnt and practices shall be disseminated throughout the organization [35]. To these scopes, some agencies have developed some structures for managing and sharing knowledge, with the use of a centralized KM system, and the use of collaborative tools, such as wikis and online forums [36]. As an example, EUMETSAT has created a Document Management Tool (DM Tool) to facilitate knowledge sharing among members of dedicated teams, a tool that will be soon replaced by a more advanced software platform in the upcoming years [37]. Another example is ESA with its dedicated KM Portal, which has the objective of providing timely information about all activities related to KM, as well as to serve as a repository and sharing platform [38].

2.3. The relationship between PM and KM

In public space agencies PM and KM, and their interconnections, are vital elements for both short-term and long-term activities, and they are necessary for ensuring the success of the missions and the entire organization.

PM includes activities such as planning, executing, and controlling of a project. On the other hand, KM is responsible for the creation, capturing, sharing and, certainly, management of knowledge for a project or, in general, for the organization itself. They both represent a powerful tool for the success of space mission design, implementation, and operation. They are both input and output of each other: effective PM relies on access to relevant knowledge, provided in an organized manner by KM. On the other hand, successful projects contribute to the organizational knowledge collection. KM supports PM by providing the means to access the information, at any time, needed by the project teams. This includes documentation such as working practices, project documents, lessons learnt from other space missions, etc. Alavi and Leidner [39] suggest that "knowledge management is a critical enabler of project management, and project management is a vehicle for knowledge management". Project success depends on the proper and regular integration of KM into PM, through the full project lifecycle. In the case of a space mission, this becomes even more relevant, due to the regular handover of systems and knowledge from one team to another, in multiple departments, across the organization. As a good working practice, KM should be integrated in all processes and activities from project planning to team management, risk management, and project evaluation [40].

2.4. ECSS standards

ECSS provides the standards for space activities that are used in European space missions, encompassing three main groups of standards: SPM, product assurance, and engineering. For the scope of this article, we focus on the SPM branch, which collects the requirements for project planning, quality management, and risk management. The SPM branch of the ECSS standards is used to manage a mission effectively, while ensuring safety and reliability of the space systems. These standards are largely used in the European space framework for current and future missions and are equally applied across the European space agencies [41].

The project planning provides the top-level guidance on the management of a space mission, detailing aspects such as scheduling, risk management, quality management, and configuration management [42]. Some of these are then detailed under the ECSS-Q-ST-10C [43], which provides the know-how and tools related to quality management, and specifically quality assurance, quality planning, and control. The scheduling and controlling aspects are detailed under the ECSS-*M*-G-11 [44], while risk management is further detailed under the ECSS-*M*-G-20 [45].

2.5. Main risks, limitations, and challenges associated to PM and KM at European public space agencies

Space agencies currently deal with the management of large-scale complex projects, linked to space missions. Each of these missions requires a significant investment of resources, time, and money and involves very large teams, both staff across the organization, contractors, scientists, and other stakeholders. The management of such complex projects shows important limitations in current PM processes in space agencies [46]. Projects complexity often leads to delays and cost overruns, together with challenges associated to risk management and uncertainty, for which space agencies are not yet well prepared and need to improve their PM practices [47].

Another important limitation is linked to the knowledge sharing and communication processes. Public organizations deal with the issue of knowledge transfer and retention, sometimes also linked to large number of retirements that may lead to the loss of institutional knowledge. Currently space agencies are hiring numerous positions dedicated to the young generation to mitigate this issue for the future, as well as introducing new tools like mentoring and succession planning to transfer the knowledge [48]. Issues are linked also to the large number of people involved in each individual project, which makes the implementation of an efficient KM policy even more complex [46]. The biggest problem is also related to the structure of the human resources within public space agencies, which are divided into staff and contractors. The organization of resources between staff and contractors is a crucial aspect that ensures the successful execution of ambitious space exploration endeavours. Staff members, often consisting of skilled scientists, engineers, and administrative professionals, represent the core workforce of the agency, responsible for project planning, design, and execution. Concurrently, contractors, comprising external entities and specialized companies, bring additional skills, technologies, and resources to the organization, and deal more with the testing and technical support. Staff and contractors work closely with each other, as part of the same teams, and this dynamic resource allocation ensures that public space agencies can leverage a diverse skill set and optimize efficiency, ultimately advancing humanity's exploration of the cosmos. On the other hand, both staff and contractors often have limited duration contracts. In space agencies this translates normally into four or five years contracts, that sometimes are converted into permanent contract after two renovations, and in some other cases they are not. For contractors this is always the case, where permanent contracts for employees are normally guaranteed with their own external companies, but not with the space agencies. This limited duration contracts have a big impact on the knowledge transfer and communication of lessons learnt, as the turnover of people may result a bit higher than for a situation with a permanent contract.

As mentioned above space agencies have developed KM databases, but a big limitation is related to the fact that access to the information is normally restricted to the people working within a specific project. Limitations normally are imposed due to different reasons. First, certain information is confidential and as such must be restricted to a limited group of people. Second, it can also happen that, to simplify its search, documentation is classified and assigned to groups of people belonging to a dedicated project, making it easier for them to access the information. As a consequence, those that do not belong to that project (and normally their names do not belong to that project list) do not have visibility of that set of documents, even if no confidential information is listed. Therefore, in general, knowledge is not easily transferred from one project to another.

One last limitation on knowledge sharing is due to the lack of a common naming convention within the agency [38]. To bring an example from the Copernicus program, if we look at the Sentinel-3 Ground Segment, we find that the data acquisition and processing falls under the PDGS (Payload Data Ground Segment) while if we look at Sentinel-5, the data acquisition and processing falls under the PDAP (Payload Data Acquisition and Processing) [49]. This is just one of the numerous differences in the taxonomy in different missions.

2.6. Need for PMO in space agencies

In many large organizations, projects become integrated organizational structures, making these organizations project-based ones [50].

Among those, space agencies kept increasing their size over the last decade,[2] with the consequence that informal mechanisms of smaller organizations, such as centralistic decision-making approaches, are no longer effective. Space agencies are big project-based organizations, where a space project normally includes both a space segment and a ground segment, which are implemented in parallel, with a necessary interface with a launch segment. The space projects are born through a proposal typically raised by governments (alone or in cooperation), national space agencies (alone or in cooperation), scientific communities or commercial space players, and are considered unique projects, making the space agency a project-based organization.

Due to the large number of projects, we witness an important power decentralization, which, in return, leads to further complications for the alignment among projects, departments, and processes, also increasing the risk of failure [51].

With continuously new missions joining the current operational set of satellites, and the growth of the departments, human resources, services, and processes, the generation of a new entity established into the governance system is needed: the Project Management Office (PMO) [52]. According to the Project Management Institute (PMI), the PMO is: ''an organisational body or entity assigned various responsibilities related to the centralized and coordinated management of those projects under its domain. The responsibilities of the PMO can range from providing project management support functions to actually being responsible for the direct management of a project'' [25].

The need for the introduction of PMO into space agencies is supported by the analysis performed by Badewi [53]. He surveyed 130 firms, showing that transformation projects are more successful in organizations that have institutionalized their PM. PMO supports organization to solve inconsistencies in PM processes across different departments and projects, improving project outcomes and reducing duplication, which is one of the crucial issues in space agencies [11].

3. Case study

3.1. Case study description

The case study is a research strategy focusing on understanding the dynamics present within single settings [54]. In this paper, case study approach is used to analyse two real and similar space missions focusing on earth observation from the same European space agency. For reasons of confidentiality requested by the space agency, these missions are indicated respectively with Mission A and Mission B. The two missions have a launch date that is three years apart. At the time of this study, Mission A has recently been launched, while Mission B just suffered a further delay, leading to the three years expected separation. The characteristics of the two missions are illustrated in Table 1 to better visualize them.

We compare the two missions with a focus on the following three aspects.

- development of the operational scenario validation campaign (OSVC);
- development of tracking tools and associated methodologies for operational items;
- human resources issues.

Both missions followed the mission lifecycle, inclusive of all the reviews, as described in the ECSS Standards, going from Phase 0 to Phase F (see Fig. 1), [42], where.

[2] Space agencies can be national entities (e.g., ASI in Italy, DLR in Germany, etc) or intergovernmental (e.g., ESA; EUMETSAT; EUSPA). They all use typical outsourcing contractual terms to manage the relationships with external partners and contractors.

Table 1
Mission A and Mission B characteristics comparison.

Characteristic	Mission A	Mission B
Type of Mission	Earth Observation, specifically Geostationary (GEO).	Earth Observation, specifically Low Earth Orbit (LEO).
Mission Objectives	Deliver new data for advancing weather, climate, and Earth system research, as well as to enhance operational forecasting.	Deliver new data for advancing weather, climate, and Earth system research, as well as to enhance operational forecasting.
Number of Satellites per Mission	Six Satellites.	Six Satellites.
Number of Instruments on board the satellites (per pair of satellites)	Five instruments.	Ten instruments.
Measurement Domains	Five measurement domains: Atmosphere, Ocean, Land, Snow & Ice.	Five measurement domains: Atmosphere, Ocean, Land, Snow & Ice.
Copernicus participation	Yes.	Yes.
Financial approach	30% assumed by the space agency in question, while the rest shared among partner agencies, the European Commission, and other contributing stakeholders.	30% assumed by the space agency in question, while the rest if shared among partner agencies, the European Commission, and other contributing stakeholders.
Budget	Confidential information, but the two missions have a comparable budget.	Confidential information, but the two missions have a comparable budget.

- *Phase 0, Phase A and Phase B* include the set of activities necessary for **i.** Elaboration of system functional and technical requirements and identification of system concepts to comply with the mission statement, **ii.** Initial assessments of technical and programmatic risk, **iii.** Initiation of pre-development activities.
- *Phase C and Phase D* include the set of activities necessary for the development and qualification of the space and ground segments and their products.
- *Phase E* includes the set of activities necessary for the launch, commissioning, utilization, and maintaining of the orbital elements of the space segment and the utilization and maintaining of the associated ground segment.
- *Phase F* includes the set of activities necessary for the safe disposal of all products launched into space as well as ground segment.

Currently, Mission A is within Phase E, whereas Mission B is still within Phase D. The study focuses on the Phase D of the mission lifecycle for both the missions, and particularly between two key reviews: the SVVRR (System Verification and Validation Readiness Review) and the SVVR (System Verification and Validation Review). During this phase, the project team is preparing the operational scenario validation campaign (OSVC), developing the test specification (a document identifying the timeline, content, roles, and responsibilities of a dedicated campaign), and collecting test cases (steps of a validation) and test procedures (procedures to validate a dedicated step, and aiming at becoming operational procedures).

The OSVC includes a series of activities aiming at validating operational scenarios, addressing both nominal and contingency configurations. It makes use of ground-based tests and simulations to measure the satellite performance in multiple scenarios, with respect to pre-established operational requirements [55].

The OSVC aims at validating both the space segment and the ground segment of a mission, and in particular at developing the end-to-end system operations. This is necessary to simulate and prepare for the operations phase that will occur after launch. Due to the complex nature of a space mission, project teams of both Mission A and Mission B broke

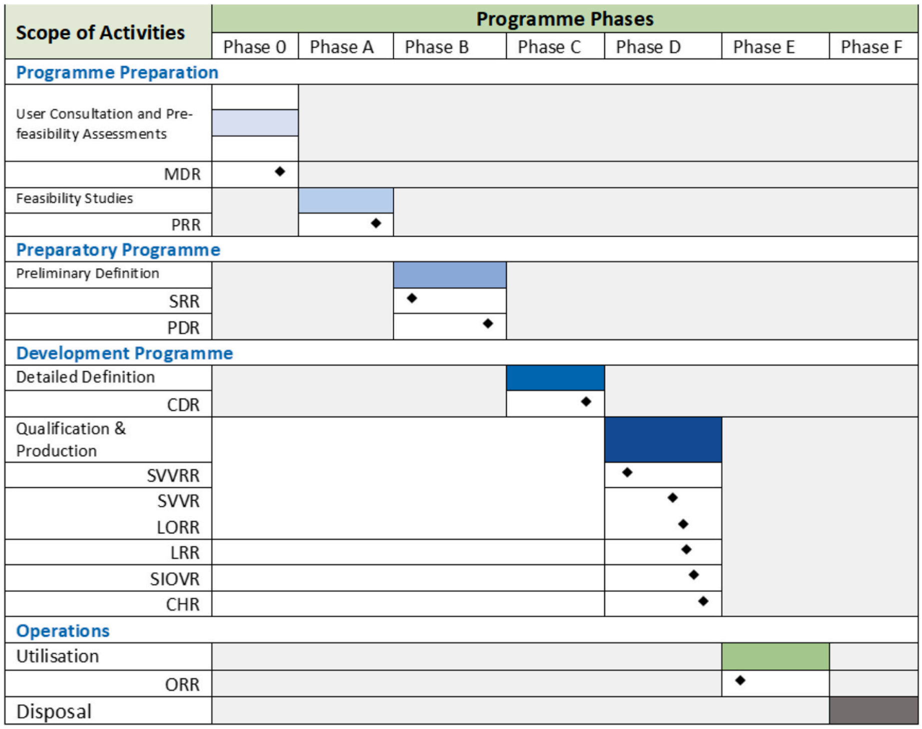

Fig. 1. Ecss project lifecycle.

down the testing activities into multiple sub-campaigns with different focuses. The two project teams, though, performed a different breaking down, but both with the common objective of validating the full set of operational scenarios, as defined in each respective Reference Operations Plan (ROP), which is a document describing operational activities of a specific mission.

The organization of the validation campaign of Mission A and Mission B has been developed independently and without, or just little, exchange between the two missions. Moreover, Mission A started the validation campaign closer to the satellite launch date (about two years before the launch date), while Mission B started the organization of the OSVC earlier, about four years before launch.

3.2. Development of the OSVC

Due to the development occurring relatively closer to the launch, Mission A took an "operational" approach from almost the very beginning. Systems from both the ground segment and the space segment needed to be tested together, in parallel where possible, with the objective of validating, almost from the beginning, a final configuration scenario. Test specification and test cases have been developed directly to simulate end-to-end scenarios, including the development of system procedures and system activities.

On the other hand, Mission B started the validation campaign with more margin from the launch date, with systems availability very much reduced. Therefore, while the final objective was to test end-to-end system scenarios, the Mission B's OSVC campaign started as a more "subsystem oriented" campaign, rather than "end-to-end scenario" oriented. The setup of the first validation campaign of Mission B included three separate campaigns, involving "satellite operations", "ground stations", "data processing", with no or very little interaction between subsystems. Only when closer to the launch, the Mission B′ s started to merge all the components and the individual campaigns in order to test the end-to-end scenarios.

As a result, Mission A became very efficient in the testing of the systems already in an "operational configuration", which was a positive approach showing immediately positive and negative systems behaviour. Nevertheless, it lacked testing for individual subsystems *per se*, and introduced numerous patches to "make the systems work", due to less individual testing of the subsystems.

On the other hand, for Mission B, a detailed testing of individual subsystems could be carried out before the testing of the end-to-end scenarios, but this led to investing more time and resources already at an earlier stage, continuously looking for "what can be tested", without the possibility of simulating real operational scenarios till a much later stage. A summary of the timeline for the two missions is shown in Fig. 2.

3.3. Tracking tool and associated methodology

At the time of a mission to be declared operational, numerous operational items, such as operational procedures, must be in place, to support real time operations, both in nominal and contingency configurations. The development of these operational items occurs during the OSVC conducted by the project team.

The project team is responsible for ensuring the adequate development and validation: a set of procedures is allocated to each test specification and test case. The project team is also responsible for ensuring that no procedure is missing to support real operations, and this is done with the usage of a dedicated tracking tool. To ensure this, each mission developed an independent methodology, including the tool aiming at tracking the development and validation process. Since in the space agency under consideration a standard approach and a dedicated tool were not available for this purpose, the two missions took two different ways.

While Mission A decided to allocate one human resource, for a period of about one year, to the development of a detailed and comprehensive tracking tool. The tool in the end was a complex combination and usage of three tools: the agency's KM tool integrated with two commercial software solutions.

On the other hand, Mission B took a simpler approach, giving the task (i.e., development of tracking tool) to a human resource who was also dealing with other activities, and for a period much shorter compared to the Mission A (only a few months). The output was a tool that was making use of the agency's KM tool and that was developed

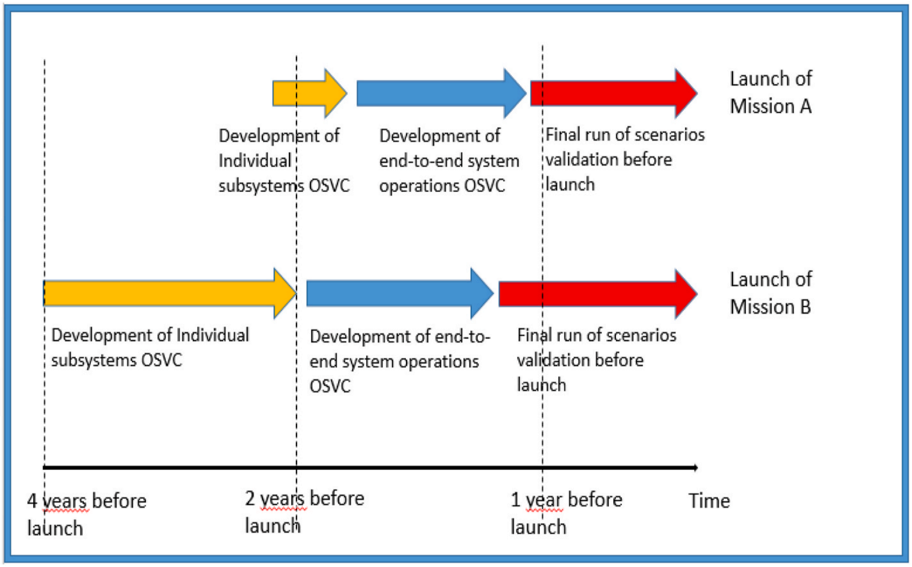

Fig. 2. Operational scenario validation campaign for mission a and for mission B.

with Excel.

As a result, Mission A invested a much bigger amount of time into the development of a complex tool and took the approach of allocating one resource almost entirely to this task. On the positive side, it was a very precise tool, able to deliver a picture of the tracking at any specific time, with multiple requests, in an immediate manner.

On the other hand, Mission B did not invest the same amount of time into the tracking tool development, which allowed for the resource allocated to this task to support other activities in parallel. However, the tool was not as precise as the one of Mission A, although still able to deliver the expected tracking and ensure operational readiness.

3.4. Human resources issues

Due to the lack of a shared project team between projects, a dedicated project team was allocated to the Mission A and a separate one to the Mission B. The preparatory phase of a space mission takes a long period of time, and within the Phase D, which was the focus of our case study, both teams happened to encounter difficulties due to lack of resources at a specific moment in time.

Lack of employees[3] was caused by various reasons: in some cases, members of the project team reached the retirement age and left the team, in some cases there were individual employee leave arrangements, or other reasons, or simply, team members left for a different job position. Lack of employees is the main cause for increased workload for the remaining team members, loss of expertise within the project and in some cases delay in the completion of dedicated tasks.

Moreover, during the Phase D, the project team underwent multiple reviews, with the need of defining, updating, and publishing documents addressing validation activities, verification activities as well as the design. In each mission, the resources invested a large amount of time to study and understand the documentation. Although they were different missions, many documents were similar. Therefore, the agency invested almost double effort to carry out project reviews.

Table 2 hereafter shows a summary of the above-discussed aspects used for this case study, compares the approaches of Missions A and B, and highlights the positive and negative aspects of each of them.

[3] Employees refer to both Staff Members (employed directly by the organization) and Contractors (employees provided by external companies to the organization).

While the two missions followed different approaches, and the unofficial work and workload was different, from an official point of view, the ECSS milestones and guidelines have been followed in terms of checkpoints, reviews, and milestones for both missions.

4. Analysis and proposal for an improved PMO solution for the public space agencies

4.1. The three-dimensional PMO framework

The case study brought up some limitations deriving from the application of individual project management at the Space Agencies.

From the case study, the two missions, both based on the ECSS standards, are expected to reach the final objective successfully. Results are in line with the expected requirements, but different resources, methodology, time, and tools have been used and changed over time to reach the same objectives. We are therefore not questioning the outcome of the project, but rather the working practices adopted at the space agencies. Was it possible to manage these projects more efficiently? How can SPM be improved for future missions?

With new missions joining the space agencies' portfolio, the latter are witnessing an increased presence of '*projectification*' (i.e., a proliferation of projects and sub-projects), leading to an increased need of sharing of project work [56]. It is also worth mentioning that projects complexity is increased by the outsourcing approach, which is today a normal working practice at space agencies, where the latter combine their expertise with that of other contractors, to deliver a solution in line with the mission requirements [57].

When examining the number of missions under development in the top public agencies, it is clear that agencies work on many parallel missions at the same time. In the case of EUMETSAT, they are all earth observation missions, at EUSPA they are all constellations of satellites for global navigation system (GNSS), and ESA shows the highest complexity with missions covering multiple areas, from earth observation to deep space or human spaceflight. While the variety and classification of the missions differ from one agency to another, they all face a similar issue of working in parallel projects, at the same time. Learning from the past is something that could be more easily implemented, using sequential projects strategically [58], but documentation from previous missions is not easily available, and would make this a project within a project, with the need of investing further resources. Therefore, knowledge sharing and learning need to be implemented between

Table 2
Case study key aspects and comparison between Mission A and Mission B.

Aspects	Mission A	Mission B	Comments
Development of operational scenarios	Direct development of end-to-end operational scenarios for validation campaign.	1st step: Development of broken operational scenarios addressing individual subsystems. 2nd step: merging of sub-system individual campaigns into end-to-end testing of operational scenarios.	**Mission A:** Positive: very efficient in the testing of the systems already in an "operational configuration" Negative: lacked testing for individual subsystems *per se*, and introduced numerous patches to "make the systems work", **Mission B**, Positive: detailed testing of individual subsystems. Negative: need for investing more time and resources already at an earlier stage, continuously looking for "what can be tested", without the possibility of simulating real operational scenarios till a much later stage.
Tracking of procedures and other operational items	Over one year for setting up a complex, tracking methodology.	Simpler tracking methodology developed in parallel with the testing campaign.	**Mission A:** Positive: it was a very precise tool, able to deliver a picture of the tracking at any specific time, with multiple requests, in an immediate way. The tool is capable of creating interconnected structures that represent the OSV, allowing to drill down to the Test Specification, Test Cases, Test Procedures and Operational Static Data associated with it, getting the latest status of a specific set of items (using filters) with a finger click. It is also possible to select all the details of interest in dedicated viewers in order to export them and use them for low detailed level of reporting. Negative: invested a much bigger amount of time into the development of a complex tool, allocated one resource almost entirely to this task, and long time was also required to populate the database once created. **Mission B**: Positive: required less time for the development, with resource allocated to this task also supporting other activities in parallel. The database is relatively easy to be used by all team members, also those not having a lot of experience with the tool. Negative: tool not as precise as the one of Mission A. The tool allows for tracking of operational static data with respect to a specific OSV, but it does not go down to the details of Test Cases. It provides a general picture in time of what has been run, when and in which campaign, but without too many insights about the exact test where they have been run. Therefore, only a general picture is available with the sole purpose to track validation of the items, providing a general report to management.
Human Resources issues	Lack of resources closer to the launch.	Lack of resources closer to the launch date.	**Mission A and Mission B:** Negative: lack of human resources is the main cause for increased workload for the remaining team members, loss of expertise within the project, and in some cases delay in the completion of dedicated tasks.

simultaneous projects, for missions undergoing similar phases at similar times, allowing for the possibility of technology and knowledge transfer during their implementation [59].

The three aspects addressed during the case study are for us the starting point to analyse and propose an improved approach based on a three-dimensional framework of PMO governance. The three-dimensional PMO aims at improving the PM and KM at space agencies, addressing the need for a centralized and coordinated management of the projects under three areas: *Strategy*, *Resources*, and *Knowledge*. Fig. 3 summarizes the three-dimensional PMO, which we discuss below.

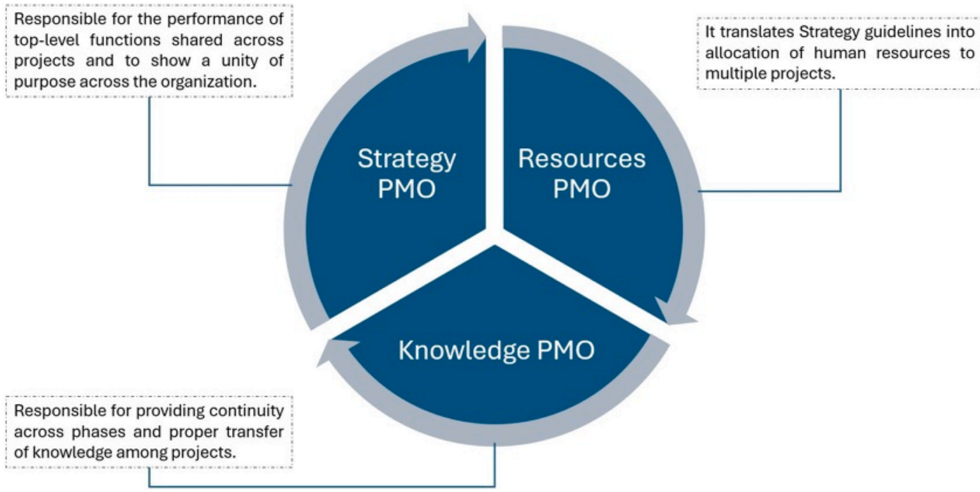

Fig. 3. The three-dimensional PMO.

4.2. Strategy PMO

The main objective of this area is to identify within multiple projects, happening in parallel, those autonomous activities that act in the same goal-directed manner [60]. A centralized governance must be implemented to manage multiple parallel projects, address their commonalities and differences. In other words, this area is responsible for the performance of top-level functions shared across projects, and that show a unity of purpose.

Strategy is one of the most challenging activities in a space agency, especially in the presence of numerous projects. PM is strictly linked to the organizational culture, as well as the size of the organization, the environment, and the context [61]. Managing a project is *per se* a difficult task, and shared management of multiple projects, with their needs and differences, could be even more challenging. In the case of space agencies, each mission is commissioned by the member States as a unique mission, with specific requirements, that makes sharing PM approaches more difficult [62]. The Strategy PMO is not responsible for a project from a technical point of view, but it should rather use the technical requirements, especially those that are repetitive and high level within multiple projects, and be responsible for the overall management and working practices that could be shared across missions and project teams [63]. The strategy PMO should be considered as place for centralization of all the agency's PM practices, enforcing further standardization and PM across the organization [64]. It should also be continuously improved bringing lessons learnt from other projects, collecting both success and failure perspectives [65]. The strategy area is expected to be responsible for tasks such as inter-organizational risk mitigation, replicated structures and responsibilities, and control mechanisms [66].

4.3. Resources PMO

The Resources PMO translates Strategy guidelines into allocation of human resources to multiple projects. The focus of this PMO is certainly on the technologies used within the projects, but also, in a space agency, the delivery of a mission is strictly linked to the human capital [67]. That is, the successful delivery of a project crucially depends on the human resources capability. The Resources PMO would have the objectives of standardizing human resource management practices and would be an integrated tool across multiple projects [68]. In this respect, the Resources PMO would represent a powerful tool to bridge the gaps that exist between multiple projects and within multiple phases of the same project, best achieved through continuity of deployed human capital [69].

This PMO would act as an overall management of all the resources and have visibility of them as well as the ability to deploy them into a dedicated project in a specific phase of the lifecycle. It would also need to ensure enough human resources to deliver, in a successful manner, the expected outputs based on the requirements for that specific mission and phase [70].

4.4. Knowledge PMO

Knowledge management and sharing is a key aspect of each project-based organization. Each project input and output need to be properly documented, and should serve as a basis for other projects. While this is a policy commonly understood at each organization, practically when it comes to multi-projects organization there are still many limitations and challenges linked to the application of an efficient KM policy [71]. Public space agencies have implemented KM systems, such as the document management (DM) tool implemented at EUMETSAT [37], but access rights are normally project specific. Therefore, only team members working on a dedicated project can access specific documents. This implies that sharing with other projects is very limited. We recall once again that each mission development till operations follows the lifecycle as described in the ECSS standards [40]. Along the lifecycle, there are six phases, and within each phase, a dedicated project team works on specific activities. At the end of each phase, we can identify gaps due for example to inconsistency in processes and methodologies, lack of knowledge transfer between one team working in a phase and the one working in the following phase, as well as poor general KM [69].

The KM PMO would be responsible for providing continuity across phases and proper transfer of knowledge among projects by enabling and facilitating detailed collection of lessons learnt, managerial and working practices, technological choices, key internal and outsourcing-related documents, etc. A lifecycle-based KM PMO becomes a powerful tool to improve the integration between other PM activities. KM PMO would extract from individual projects key common organizational knowledge, and put it at the service of every future mission. One of the main outputs, as will be described hereafter, is the definition of a common naming convention, as a first step for projects KM sharing and coordination.

4.5. Measuring PMOs' good practices

The three PMOs would need to oversee the overall PM and KM of the full organization. Here we try to identify the most powerful solutions to measure efficiently the application of good practices of the above PMOs. In particular, we link the three PMOs to the three aspects analysed as part of the case study (OSVC, development of tracking tool and associated methodology for operational items, and resources issues). Obviously, the three PMOs are viewed as strictly connected with each other, and the work of one PMO certainly affects and is affected by the work of a second PMO. Therefore, we identify three solutions whose responsibilities fall within more than one PMO and whose management needs to be shared among the responsibilities of the PMOs. This certainly highlights the complexity for the establishment of PMOs within an organization.

The three solutions that have been identified and that aim at improving the efficiency of space agencies' missions if guided by the PMOs are: sharing of human resources, sharing of technology, and common naming convention across projects.

4.5.1. *Sharing of human resources*

All the three PMO need an effective human resource management that could become one of the most powerful tools within the organization. The challenges linked to retain knowledge as well as the need of sharing with other projects is a key aspect within an organization and its projects. Human capital in a project requires time and other resources that need to be invested to train new people in multiple phases of the project. An effective solution is the introduction of a horizontal human resources approach into the vertical project approach, where a vertical approach follows the project lifecycle from Phase 0 to Phase F according to the ECSS standards. We suggest the sharing of human resources between multiple projects, where they are allocated to the same phase (e.g., Phase D in our case study) of multiple projects (horizontal approach). Human resources allocated to a specific phase and only to this one, become expert of the activities that must be carried out during that time of the mission lifecycle. The sharing among multiple projects allows them to learn from failures and successes of other missions and continuously improve the working practices and efficiency of that phase. In the case study, the sharing of resources is a powerful solution for multiple reasons. First, the expertise is shared across missions, improving the efficiency and the speed of the projects. As an example, during the project reviews, if a common team was allocated to both missions, it would have improved the efficiency of the project review (documents can use lessons learnt from the other missions and improve the quality of the review), as well as reduction of time, and thus costs. Moreover, a large team dedicated only to specific tasks across missions, would reduce the risks associated to loss of expertise, for example in the case of people leaving, permanently or temporarily. Experts allocated to each phase of the mission through this approach would improve the efficiency of the full mission as well as reduce risk and time. The approach also reduces risks associated to human error and human knowledge and experience, which is not the same for all projects, and provides greater flexibility for the agency. Sharing of resources results into an easier adjustment to changes in project priorities, needs, and other factors that could affect timeliness or project requirements.

4.5.2. *Sharing of technologies*

This solution is more specific for the Resources PMO, although certainly has an impact on the other two. Similar to human resources sharing, which improves efficiency and time while reducing risks of multiple projects, also sharing of technologies and tools leads to similar outcomes. Development, integration, and testing of a ground segment element require time and effort, and, of course, introduces risks. In addition, the development and tracking of operational items, as shown in the case study, could be challenging if each project adopts different strategies. Multi-mission technologies and tools represent a more robust solution, reduce direct PM dependency on a specific project and is a powerful tool for improving the quality of systems. A shared technology means to run the above cycle only once and apply to multiple missions. In addition, if a bug, a failure is identified in one project, it reduces the risk for it to be repeated into other projects. Sharing of technologies is certainly a powerful tool for a more effective PM, as well as increasing the sharing of KM across projects. In the case of Mission A and Mission B, they both have system elements that are outsourced, and in some cases by the same manufacturer. The sharing of resources would certainly benefit the agency that would procure a single set of systems and perform tailoring only to adapt them to Mission A and Mission B. This would certainly lead to a more robust system, where the lessons learnt from Mission A would be beneficial for Mission B and vice versa. Sharing of technologies would introduce a more standardized approach, where both missions could adopt same processes, as they are using the same systems. In terms of time and costs, a shared technology would be reviewed only once and then adopted by both missions. Moreover, in the long term, in the transition from Phase D to Phase E (operations), it would be much easier to operate a single system through a shared infrastructure and would be more beneficial in terms of maintenance activities.

4.5.3. *Common naming convention*

Effective PM and KM are highly challenged when projects do not speak the same language. Each project, with different human resources and (partially) different systems, leads for example to the definition of different acronyms. If the project terminology is not well understood by the parties involved, it becomes difficult to communicate, learn, and compare with other projects where products and processes are not well understood. The application of a common taxonomy ensures consistency in the way that information and knowledge are organized and categorized across multiple projects. Not only this is beneficial for projects running in similar phases at the same time, but also it makes it easier to find, retrieve, and use information from previous missions, reducing possible risks. A common naming convention is facilitated by the horizontal allocation of human resources to multiple projects, making it easier to apply the same language across projects, and consequently it becomes easier to organize and categorize information and knowledge. In the case of Mission A and Mission B, the project teams could have easily shared knowledge if they had talked the same language. During the reviews, this would have facilitated the sharing, understanding, and review of the documents. Common naming convention would improve the understanding of the mission as well as their future operability. During Phase D, in fact, multiple operational documents are created, and each of them is developed according to the naming convention of a specific mission. When handing over to the operational team, this is forcing into a lack of understanding between teams in the subsequent phase. While the case study focuses on Phase D, the earliest adoption of a common naming convention would be beneficial for all subsequent phases, including Phase D.

The introduction (or the improvement) of a documentation office is expected to be a powerful tool to improve this lack of consistency across the organization and would tackle issues of naming conventions, standardizing processes, and aggregating lessons learnt in a common information platform.

The establishment of a common naming convention within the organization improves what is currently part of the ECSS Standards, where for example one could find the names of the reviews (PDR, CDR, etc), but within the standards there is no indication on how to name parts of the systems, tools, practices, documents, etc., which apply to individual projects.

4.5.4. *Discussion*

According to Fernandes [72], organizations should implement a tailored PM, with associated tools and processes as a key for successful PM within the organization. The three-dimensional PMO and the three solutions identified, if applied to missions, such as Mission A and Mission B of the case study, can contribute to improving the quality and efficiency of the two missions, as well as reducing risks, time, and uncertainties linked to technologies, strategies, and resources. As an example, the sharing of human resources would likely bring a homogeneous approach for the management of the missions. It could also lead to a more efficient delivery of the outputs of Phase D. Lack of resources would not be strictly linked to a project, but instead, with a shared project team allocated to multiple projects, resources could better cover for each other and support different projects if needed. Sharing of human resources could be tricky and cause some friction between different management solutions/processes. Therefore, when developing a PMO, our proposal is to describe and detail, via standardized procedures, how the sharing of human resources should be managed to reduce the risk of frictions within and across projects. Sharing of resources could also lead to a better and more efficient sharing of technologies. The development of a tracking tool that needs to ensure efficient tracking of operational items would be a simplified and homogeneous choice applicable to all the missions. A well-established tool would be used by all the missions, without the need of investing resources in the analysis and development of new tools and strategies each time. Last, projects could easily talk to each other if the same naming convention is used, avoiding confusion, and improving efficiency. In the case of project reviews, for example, the review board would not need to understand every time what acronyms mean, but there would be a homogeneous understanding of systems, activities, etc., across all the projects within the organization.

5. Conclusions

Public space agencies deal with the introduction of new space missions that continuously enrich their portfolio. The activities of the organization are minutely regulated by the application of the ECSS standards, which are, however, applied to each single mission and each phase of the mission. Each space mission is considered as a stand-alone project, making space agencies project-based firms [73], with a clear need of introducing multi-project management. Moreover, space missions are large-scale, complex projects, each one requiring a big investment of resources, time, money, and people. The management of such complex projects shows important limitations in current PM processes in space agencies, starting with the natural project complexity, to challenges in knowledge management and sharing as well as communication processes.

The current approach of space agencies to PM is to implement a typical agile or waterfalls approach, often in a hybrid form. Nevertheless, these approaches are limited, especially when dealing with large organizations such as the space agencies, where projects are numerous, complex, and are integrated organizational structures. Under this scenario exhibiting many new and complex missions joining the current operational set of satellites, and the need to introduce new resources, we relied on an in-depth case study analysis to suggest a new PMO approach aimed at improving the efficiency of PM and KM in the agencies. Given the complexity and the number of projects, we suggest a three-dimensional framework of PMO governance, addressing the need for a centralized and coordinated management of the projects under three areas: *Strategy*, *Resources,* and *Knowledge*. The Strategy PMO is responsible for the overall governance of the organization and the projects with a focus on improving efficiency in tasks such as inter-organizational risk mitigation, replicated structures and responsibilities, and control mechanisms. The Resources PMO improves the resource planning and allocation to multiple projects. Lastly, the KM PMO aims at providing continuity across phases and proper transfer of knowledge among projects. The main outcomes from the application of the three PMOs are associated to the sharing of human resources, technologies, and the application of a common naming convention, which, as discussed above, help improve what is already provided by the ECSS standards. We argue that all together these elements can improve the quality and efficiency of projects within an agency, save time, and reduce risks associated to individual projects.

The three PMOs together aim at addressing commonalities among the missions and avoiding "re-inventing the wheel" every time a new project is brought into the organization. While the three PMOs have the objective to coordinate the projects across the organization, we acknowledge that, given that different space missions have different requirements and objectives, not all parts of the projects could be considered for coordination purposes, and some level of tailoring should always be put in place. Indeed, this complexity cannot be decoupled from a space project due to its own nature.

Finally, it is important to acknowledge the limitations associated with this study. First, due to the diverse nature of space agencies around the world, and the restricted access to internal practices, while still relevant, the case study findings may not be fully representative of all space agencies, thus providing useful indications only for the European context. Second, the rapidly evolving nature of PM and KM practices necessitates continuous monitoring and updating of the conclusions and recommendations provided in this study. Third, the sharing of technologies and other resources may challenge procurement, allocation of funds and participation of member States contributing to different missions. This shall be addressed as a separate study, addressing the economic/political distribution and decision power within the organization.

Finally, future areas of research are then suggested for the following points: 1) analyse and compare working practices in different geographical areas (e.g., space agencies in Europe vs. those in India, or space agencies in the US vs. those in Japan, etc); 2) monitor PM and PMO practices evolution in public agencies (within or outside the space sector), to address new advantages/limitations of new practices, or how to adopt practices from other public agencies into the space sector; 3) analyse the structure of the policy within the space agencies, such as how member States/cooperating States influence the funding allocation and sharing between projects, and how to improve this. One last topic that the authors suggest for future studies certainly relates to the introduction of new technologies, and in particular the growing importance of Artificial Intelligence (AI) and Machine Learning (ML). For instance, future studies could focus on the use of AI technologies such as NLP (Natural Language Processing) for PM and KM issues, as for example such technologies are already being experimented in some space agencies for the management of requirements.

CRediT authorship contribution statement

Chiara Maria Cocchiara: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Giovanna Lo Nigro:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Paolo Roma:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Antonio Ragusa:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that have been used are confidential.

Acknowledgements

The authors are grateful to the Editor and the two anonymous reviewers for their valuable comments and suggestions that helped improve the manuscript significantly.

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