The international post-graduate Master programme for space exploration, SEEDS: education and training from a System Engineering perspective

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Abstract. *The SEEDS (SpacE Exploration and Development Systems) initiative was initially conceived and promoted by Politecnico di Torino and Thales Alenia Space-Italy in 2005. It aimed at establishing a post-graduate International Master Program in space exploration to offer an opportunity to young engineers to get prepared for the future of Europe in space and specifically in human space exploration. ISAE-Supaero in France and University of Leicester in UK participate to SEEDS together with Politecnico di Torino (Italy). Turin, Toulouse and Leicester have a long common tradition of space activities at both the industrial and academic level and within the SEEDS initiative they represent three poles of European cooperation in space programs. The Master course comprises two different steps in sequence: an initial learning phase and a Project Work phase. Both phases pursue a multidisciplinary approach, where all specialized disciplines are integrated to make the students able to acquire the system view and then to accomplish the conceptual design of a selected case-study. The distinguishing feature of SEEDS is the Project Work activity, performed by all students together under the supervision of academic and industrial tutors. Main objective of the Project Work is to train the students on the basic principles of the system engineering design, through their application to a well-defined project related to a specific human space exploration mission. The Project Work includes the Preparatory Work, during which the students identify the complete architecture and overall scenario of the mission, and the conceptual design activities, performed in the three European sites to develop a limited number of building blocks. Seven academic years of activities have passed and seven project works have been successfully completed, dealing with various space exploration themes. The eighth edition is about to be completed with the aim of designing a "Transit and return habitable Mars orbital port". The paper focuses on the description of the Master Program, both from the point of view of its contents, structure and multidisciplinary design methodologies, and on the main results achieved in terms of Project Work activities. The use of Concurrent Design in support of the Master activities and as experienced by the students is also presented in the paper. The positive experience of almost eight years of SEEDS is brought to evidence and the lessons learned are discussed.*

1 INTRODUCTION

SEEDS (SpacE Exploration and Development Systems) initiative was conceived and promoted by Politecnico di Torino and Thales Alenia Space Italy in 2005. It aimed at establishing a Post-Graduate International Master Program in Space Exploration and Development Systems, to offer an opportunity to young engineers to get prepared for the future of Europe in space. SEEDS project was originally shared with Supaero Toulouse in France and University in Bremen (together with ZARM) in Germany [1] [2] [3] [4] [5] [6]. Once the first phase of SEEDS was over, the second phase started in 2013 and is currently in process. Supaero Toulouse in France and University of Leicester in UK participate to the second phase of SEEDS together with Politecnico di Torino. Turin, Toulouse and Leicester have a long common tradition of space activities at both the industrial and academic level and within the SEEDS initiative they represent the three poles of European cooperation in space programs. SEEDS master course starts in November and lasts about 11 months. Students may be recruited from all sites, i.e. Turin, Toulouse and Leicester. They spend few months separately at the beginning attending courses in their original site and eventually they join as an integrated team to accomplish the Project Work, which lasts about six months (two months per each location). Students apply to SEEDS through a Master of Science Program in France and UK, whereas they apply to a Post-Graduate Master in Italy at Politecnico di Torino. Consequently, enrolment conditions are slightly different in the three sites. The maximum number of available places is 15 in Turin and entry requirements are Master of Science (MSc), or 4-year Bachelor of Science (BSc or equivalent) in Aerospace, Mechanical, Thermal, Nuclear, Electrical, Electronic and Telecommunications Engineering, in Information and Communications Technologies or in Physical Sciences. SEEDS Master is funded and supported by aerospace companies, space agencies and students' tuition fees. A remarkable in-kind support, in terms of teaching hours, tutoring and funding comes from one of the major European Space Companies, Thales Alenia Space in Italy, France and UK. SEEDS Master is supported and promoted by the European Space Agency, ESA, which every year hosts at ESTEC in the Netherlands the final event of the Master. In order to meet the demand for skilled personnel in space related subjects, the number of post-graduate education programs on space topics is continuously growing, particularly in Europe [7]. Existing programs differ widely in scope and characteristics, coverage and focus, quality and organization, as well as entry qualifications and required time effort. Unlike all other post-graduate programs, SEEDS course focuses on human space exploration and puts major emphasis on a large project work to be sequentially performed through three successive internships in three different European locations under the supervision of companies and universities personnel. The paper aims at presenting the second phase of SEEDS Master course. It focuses first on SEEDS structure, methods and students' team organization (section two), then on the results obtained in terms of project work activities and on the use of Concurrent Design (section three and four respectively). The achievements in terms of development of future space workforce are also presented (section five). Eventually, lessons learned are discussed and main conclusions are drawn.

2 SEEDS MASTER COURSE: STRUCTURE, METHODS AND STUDENTS TEAM ORGANIZATION

SEEDS master course lasts about 11 months during which full-time students attend lecture modules separately in Turin, Toulouse and Leicester, and then work at their Project Work first in Turin, then in Toulouse, and eventually again in Leicester. The written and spoken language during the entire program is English. Figure 1 illustrates the main structure of SEEDS Master course in terms of phases, activities, time frame and locations. The master course comprises two different steps in sequence: an initial Learning Phase and a Project Work Phase. The Learning Phase lasts about five months, during which students attend courses and perform exercises with the aim of understanding space basic concepts and learning fundamentals of space systems engineering design and specific space disciplines. The Project Work Phase lasts about six months, during which students accomplish the Conceptual Design (Pre-Phase A/Phase A) of a human space exploration mission. Both the Learning and the Project Work Phase pursue a multidisciplinary approach, where all specialized disciplines are blended together and integrated to make students able to acquire the system view and then to accomplish the conceptual design of a selected case-study, applying Systems Engineering tools, methods and processes. At the beginning the basic design techniques and criteria pertaining to various engineering disciplines are introduced; later on the acquired knowledge is focused on the development of an integrated system level design concept, where the attention is mainly oriented to ensure adequacy and coherence of proposed solutions. Students are therefore supported along a technical education path where individual capabilities are progressively incremented through acquisition of new information and methods and then enhanced and tested through intensive team working sessions. System level sensitivity towards design objectives is developed and engineering best practices are eventually applied to a selected case-study. The distinguishing feature of SEEDS is without any doubt the Project Work, performed by all students together under the supervision of academic and industrial tutors. Main objective of the Project Work is to train students on basic principles of System Engineering design, through their application on a well-defined project, which every year is oriented towards a different case-study related to a specific space exploration mission. The Project Work includes the Preparatory Work and the Conceptual Design activities, whose main features are reported hereafter:

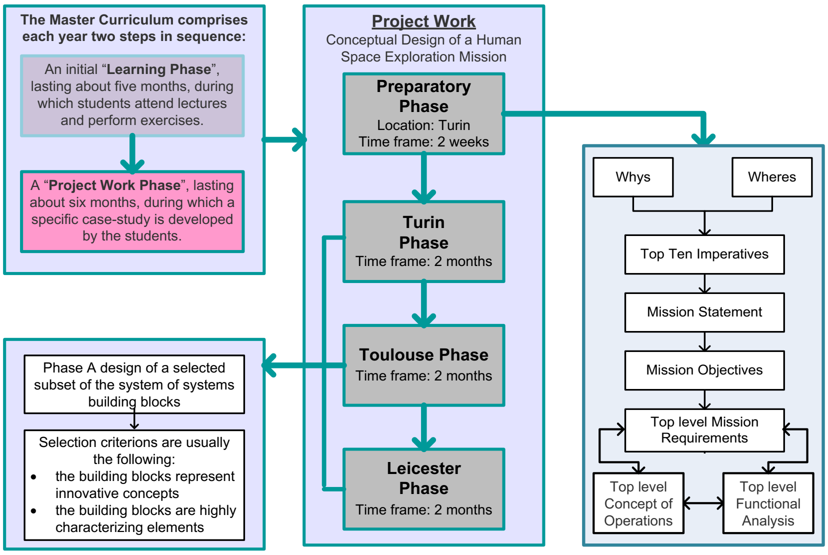

Figure 1. SEEDS master course: structure

1. Preparatory Work. During the Preparatory Work the students focus on the investigation of whys and wheres of space exploration, on the definition of mission statement, mission objectives, and top level system requirements through the accomplishment of top level Functional Analysis and top level Concept of Operations (top level refers to System of Systems level). Major functions at system of systems level are thus allocated onto various categories of composing building blocks and the final result of the work is the identification of the complete architecture of the system of systems (i.e. the collection of single systems that pool their resources and capabilities together to create a more complex system, which offers more functionality and performance than simply the sum of the constituent systems).
2. Conceptual Design activities, carried out by the students in the three European sites (Turin, Toulouse and Leicester), in order to further develop the design of a selected subset of aforementioned building blocks. Selection criteria are usually the followings:

- building blocks shall represent innovative concepts, both in terms of functions performed and technological challenges;
- building blocks shall be highly characterizing elements, which constitute an added value for the whole system of systems.

Every space system is developed through a process with phases and reviews. In Pre-Phase A the system engineering approach is used to develop initial concepts, as well as a preliminary/draft set of key high-level requirements; to realize these concepts through modelling, mockups, simulation, or other means; and to verify and validate that these concepts and products meet the key high-level requirements. During Phase A, the iterative and recursive use of the system engineering approach is continued, this time taking the concepts and draft key requirements that were developed and validated during Pre-Phase A and fleshing them out to become the set of baseline system requirements and Concept of Operations (ConOps). During this phase, key areas of high risk might be simulated or prototyped to ensure that the concepts and requirements being developed are good ones and to identify verification and validation tools and techniques that will be needed in later phases [8]. Starting from system requirements, which stem from mission statement and mission objectives, the conceptual design methodology evolves through system architecture definition and mission definition. In particular, after the list of systems requirements has been completed, the Functional Analysis begins. Results of this analysis are first the functional tree and then the physical (or product) tree: the former identifies the basic functions, which the system has to be able to perform to match requirements, while the latter maps system functions onto products able to carry out those functions. In other words, these products are the subsystems and equipment which generate the system. Once the Functional Analysis has been accomplished and the elements of the product tree have been identified, it is possible to think of how all these elements are connected to form the system. It is thus possible to draw the functional/physical block diagram of each subsystem and eventually of the whole system. In order to complete the system definition, the system budgets (mass, electric and thermal power budgets, etc.) have to be carried out, but, before being able to do so, system modes of operation have to be established. However, it has to be remembered that this task can be fulfilled only after subsystems and their relative equipment have been identified. The definition of the system modes of operation is a crucial activity that, together with the Concept of Operations, helps accomplish the definition of the Mission.

Typical analyses contained in ConOps include evaluations of mission phases, operation timelines, operational scenarios, end-to-end communications strategy, command and data architecture, operational facilities, integrated logistic support and critical events [8] [9].
Once both the mission and the system have been preliminary defined, before proceeding any further with the system design synthesis, it is important to verify whether or not all system requirements have been satisfied. Being the design activity typically a process of successive refinements, various iterations may be necessary before being able to perform the system design synthesis, thus freezing the system configuration.

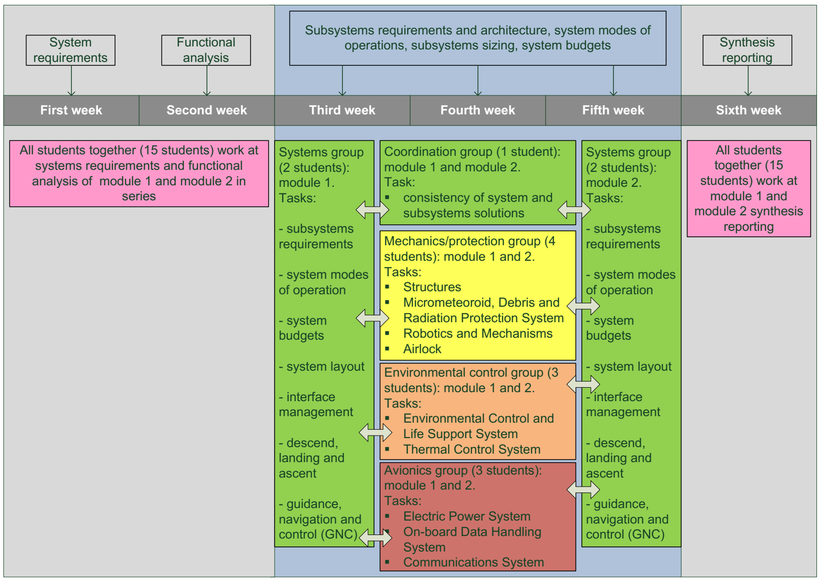

Figure 2. SEEDS master course: methods, tasks and students team organization

Typically, each conceptual design activity lasts about six weeks. Figure 2 sums up an example of schedule of tasks and students team organization (based on a team of 15 students) during the six weeks of conceptual design activity, which can be subdivided into three different phases:

1. First Phase (that lasts about two weeks): all students work together at the definition of system requirements and at the accomplishment of system functional analysis. The total number of students may generally range between 15 and 30. In Figure 2 the total number of students that constitute the team has been assumed equal to 15. During each conceptual design activity in the three different European sites either one or more than one building blocks can be designed by the students, depending on the proposed system of systems (case-study of the Project Work) and on the systems' complexity. The example shown in Figure 2 considers the design of two building blocks (named respectively module 1 and module 2) during the conceptual design activity. Throughout the first phase all students work at the two building blocks in series, in order to enhance consistency of results.
2. Second Phase (that lasts about three weeks): the students are split into smaller groups to deal separately but in a highly integrated way with the definition of subsystems requirements and subsystems architecture at main equipment level and with the identification of system modes of operation, subsystems sizing and system budgets for the two building blocks in parallel, in order to shorten design times. In particular, as illustrated in Figure 2, two systems groups, of two students each, have been envisaged to deal respectively with module 1 and module 2 at system level, as well as one coordination group, consisting of one single student, to verify the consistency of system and subsystems solutions. Apart from the systems and the coordination groups, there are other three groups that have been envisaged to focus on specialized disciplines: the mechanics/protection group, consisting of four students, the environmental control group, consisting of three students and the avionics group, consisting of three students.
3. Third Phase (that lasts about one week): all students work together to finalize final reporting.

3 PROJECT WORK ACTIVITIES

As far as the Project Work activities are concerned, the new phase of SEEDS envisages five academic years dedicated to missions and expeditions to Mars, as part of a rational and thorough long-term vision of Mars exploration. This vision is intended to trace, in a preliminary way, the steps that would be needed to get one day to the conquest by humans of the Planet Mars. The proposed overall strategy for the conquest by humans of Mars in five steps is at the basis of the Project Work activities of the first five years of second phase of the SEEDS Master and is structured as follows:

1. Step one: Exploration of Mars from its Proximity.
2. Step two: Exploration of the Mars Surface
3. Step three: Exploitation of Mars Resources ISRU
4. Step four: Development of Mars Permanent Outpost
5. Step five: Development of Mars Independent Base.

The SEEDS Master gives high prioirity to the opportunity for its students to work on projects that could provide them the instruments for an immediate integration into the work environment. For this reason, is not excluded a priori the interruption for one or two years of the sequence of steps for a specific phase, should an interesting and urgent project work theme be proposed by an Agency or another major player. Flexibility of approach is considered mandatory and the Master management dedicates great attention to the identification of concrete study themes, as well as effective interactions with the responsibles for current and future Exploration Programs, in order to constantly keep up-to-date the contents and objectives of SEEDS. The sixth edition of the Project Work of the SEEDS Master (SEEDS VI Project Work) has covered the first step of the overall strategy of the current phase, and is centered on "A Journey from the Earth to Planet Mars", which has been named ORPHEUS, Orbital Reconnaissance and PHobos Exploration by hUmanS. Orpheus mission statement is reported hereafter: "To perform human exploration of Mars from its proximity; to execute a manned landing on Phobos, including a sample return; to develop and validate techniques to lay the framework for future manned exploration and exploitation of Mars" [10].

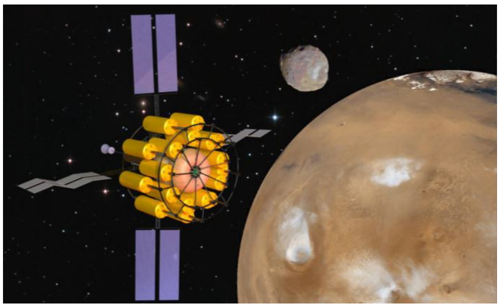

Figure 3. An artist's impression of the CIV

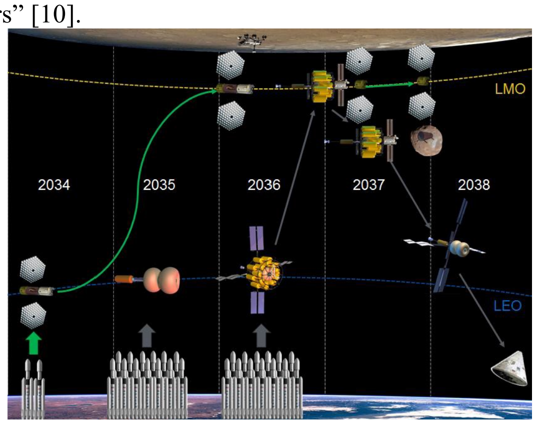

Figure 4. Overview of the mission concept

Table 1. Main data of Orpheus design reference mission

Mission Orpheus	
Summary	Specifications
CIV Launch date	May 2036
MATV Launch date	2034
Overall duration of the CIV mission	602 days
Mars vicinity duration of the CIV	35 days
Total crew size	6
Landing crew size	2
Aerocapturing	No
CIV trajectory profile	Venus fly by for approach of Mars Lambert transfer for return
MATV trajectory profile	Continuous low thrust trajectory
CIV departure mass	4000t
MATV departure mass	120t
Phobos landing mission duration	2 landings of 3 days

A mission to Mars leads to major mass budgets due to the high ΔV requirements; furthermore the level of safety implies additional mass for redundancy. Hence, the mission concept of Orpheus was designed to reduce the initial spacecraft masses by sharing the payload between two. The smallest of both is unmanned and its payload mass has been maximized in order to send payloads not linked with human activity or human safety to Mars: its name is the Mars Automatic Transfer Vehicle (MATV). Its payload consists of the following elements: the scientific landing packages to be deployed on the surface of Mars; the Phobos Lander (PhL); the Laboratory (LAB). The latter two systems are used by the crew once in Mars proximity, in order to land on Phobos and to analyse regolith samples. The manned spacecraft has all the subsystems necessary for sustaining humans for the entire mission duration, the required habitable volume and all the necessary spacecraft's propellant. The manned spacecraft is called the Crew Interplanetary Vehicle (CIV, see Figure 3). The advantage of using an unmanned transport spacecraft is the use of a high-efficient, low-thrust propulsion system; in particular solar-electric propulsion. On the CIV however, due to human presence, strong transfer time constraints are imposed. Hence, the CIV will have short trajectories with a less efficient propulsion system. The docking manoeuvre in Mars orbit will be necessary for the exchange of modules between the two spacecraft. In case of failure of docking, the scientific mission fails, as the crew cannot access the PhL; this is an acceptable risk due to fault tolerance. However, the risk of loss of the crew in this case is not acceptable. This risk imposes the requirement to equip the CIV with all the necessary propellant for the entire manned mission, rather than the MATV carrying fuel for the CIV's return trip. This decision is less effective from the mass point of view, as the CIV propellant is carried by the CIV itself, which has a propulsion system with lower efficiency. Orpheus mission is a short stay mission. Figure 4 schematically shows Orpheus design reference mission, whereas Table 1 reports its main data.

4 THE USE OF CONCURRENT DESIGN IN SUPPORT OF THE PROJECT WORK

Concurrent Engineering is a powerful instrument for Conceptual and first Phases of space projects (design, technology and operation selection, review work). Even if the access to concurrent engineering tools and facilities might be limited for students, it is important that they are introduced and trained to the related methodologies, having possibly the opportunity to compare the outcome of their work with results deriving from the use of concurrent engineering instruments. As part of its effort for continuous improvement, the Master SEEDS strives to offer to its students also the fundamentals to Concurrent Engineering and to give them the opportunity to apply them in some practical situations.

The exposure of the SEEDS students to concurrent engineering methodologies and tools is currently implemented in different moments of the Master schedule, contributing to a better understanding of their potential:

i. Introduction to Concurrent Engineering for Space Mission Design during the "Learning Phase". This task is carried out through dedicated lectures by academic and industrial experts.
ii. In advance to the start of the "Project Work Phase", presentation by videoconference of the Concurrent Design Facility (CDF) of the European Space Agency (at ESA/ESTEC) and provision of openly available tools for concurrent design, that the students might use to support their work.
iii. Discretional use by the students during the "Project Work Phase" of the basics and tools acquired in Concurrent Engineering for the development and verification of their project.
iv. Use of the ESA/ESTEC CDF (in Noordwijk, NL) [11] in conclusion of the Project Work Phase, to perform two main tasks:
    a. Critical review of some of the sub-elements of the architecture studied (technologies, subsystems, operations) in a concurrent session with ESA experts (over 2 days)
    b. Final presentation of the project work results at the CDF to an audience of technical and programmatic experts in space exploration, including Q&A (1 day).

Through the presented approach, the SEEDS students are exposed in a nutshell to the potential of using modern design and verification tools, such as Concurrent Engineering, to carry out their work and to present it for criticism and improvement to reviewers and customers. This, associated to the opportunity to visit and use advanced facilities, is considered an attractive feature of SEEDS and has been so far highly appreciated by its participants.

5 FUTURE SPACE WORKFORCE

The results of six editions of SEEDS Master course may be expressed both in terms of number and nationality of enrolled students and in terms of current employment status of the students themselves. Since the first SEEDS edition in 2005 each year the number of students' applications in Turin location ranged from about 30 to 50 for a maximum number of 15 places. A smaller number of participants were also selected at ISAE (Institut Supérieur de l'Aéronautique et de l'Espace)-Supaero in Toulouse (French, Spanish, Italian and German students) to join the team recruited in Italy during the Project Work phase. Since the sixth edition a considerable number of students from the University of Leicester has also joined the team to accomplish the Project Work. It is worth underlying that unlike in Turin where, only MSc or 4-year BSc (or equivalent) in Engineering Disciplines or in Physical Sciences students are eligible to admission, both in Toulouse and Leicester students attending the MSc can choose SEEDS Master as internship during the last semester of their academic career. In Turin the recruitment follows a selection mainly based on the applicant's curriculum vitae. Relevant working experience is considered, albeit not strictly required. Generally, about 20% of applicants are female. At least 50% of the applicants are usually not admitted. If 20% of the applicants are female, this share reduces to 10% on average among the enrolled students. Even though the percentage of female applicants and then of female enrolled students is considerably poor, no special measures have been taken so far to improve the balance of gender ratio. Up to the fifth edition the policy of SEEDS Master course was in fact more focused on the increase of the proportion of foreign (in particular from ESA countries) students, as the percentage of applicants at Politecnico di Torino coming from outside Italy never exceeded 15%. However, since the sixth edition, thanks to the considerable number of students recruited in Leicester, at least half of the students during the Project Wok activity have been foreign students. Applicants' average age ranges between 24 and 28 with few exceptions. Taking into account the first sixth editions of the SEEDS Master course, sixty-six students have attended SEEDS. As far as students' nationality is concerned, as already mentioned, the vast majority of students was Italian with contributions from other European countries, specifically UK, France, Germany, Spain and Rumania, and also from non-European countries, like Argentina, Uganda and Venezuela (see Figure 5). Three main reasons may be the cause of this students' composition:

1. the recruitment in the original three locations, i.e. Turin, Toulouse and Bremen for the first five editions of the SEEDS Master, was originally supposed to gather students of different nationality and to make them work all together as an integrated design team during the Project Work. This ideal situation rarely occurred in the past as a part from few students coming from Toulouse, no students ever came from Bremen, although the local team always provided SEEDS students with the opportunity for the Project Work Phase in Bremen. Since the sixth edition, students have been recruited both from Toulouse and from Leicester, thus improving the percentage of not Italian students;

3. different strategies of post-graduate studies in various European countries. In some European countries it may be in fact more likely that MSc or 4-year BSc graduate students look for jobs rather than for another post-graduate master course. This situation happened particularly in Germany and seriously affected the results of students' recruitment in Bremen, where the limited number of applications and the required high tuition fees prevented the University of Bremen from succeeding in including SEEDS master course in the frame of its institutional offer of MSc programs.

Eventually, as far as the current employment status of former SEEDS students is concerned (see Figure 6), it is worth highlighting that almost 70% of the students have been employed in aerospace industries just few months after the end of SEEDS. This stunning result testifies the success of SEEDS initiative. The remaining 30% of the SEEDS students have been partly employed in other fields, in space agencies or have applied at universities for PhD or researcher positions. This last option actually represents a very small percentage but it is worth mentioning it because it is a very interesting case of perfect mixture between industry and aerospace, according to SEEDS approach, as, for instance one PhD fellowship has been sponsored by an aerospace industry.

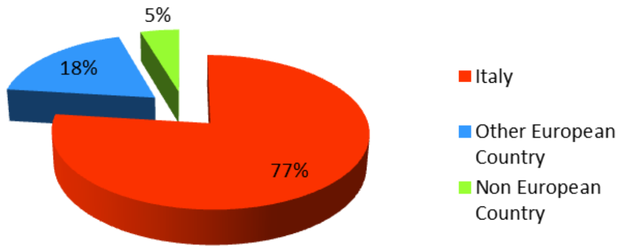

Figure 5. Six years SEEDS students' nationality

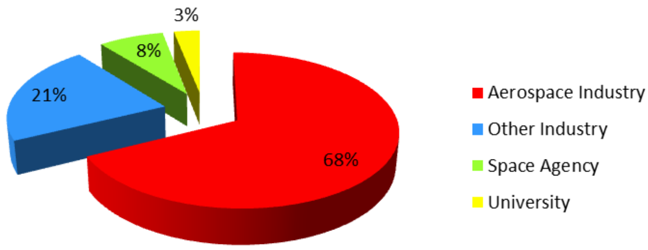

Figure 6. Current employment situation overview of five years SEEDS students

6 CONCLUSIONS AND LESSONS LEARNT

The first year of activity of SEEDS master course started in November 2005, with a Plenary Opening, which took place at the European Space Technology Centre (ESTEC) of the European Space Agency- in, Noordwijk (NL), with the full support of ESA. Seven years of activities have passed since then and seven Project Works have been successfully completed, dealing with various space exploration themes. The positive experience of seven years of SEEDS, in terms of Project Work activities and development of future space workforce, has been brought to evidence. Eventually a few important lessons have been learned, as reported hereafter:

- the Project Work, where the students play the role of systems engineer or system specialist, is a fundamental step of the program, as it helps student develop their skills through the accomplishment of specific design activities;
- the enhancement of students' team working capabilities through dedicated lessons and practical applications during the Project Work is very precious to prepare students for the future real aerospace industrial world;
- blending together industrial experience on real case-studies and academic approach of university is an essential feature of the program, as it allows students acquire both the knowledge coming from real design cases and the tools and methodologies to face them;
- exposure of the students to the use of modern tools, such as Concurrent Engineering, allows them to be

confronted to practical situations and to reduce the gap between academia and future working environment;

- multidisciplinary teams of students are highly recommended to improve the quality of systems engineering works, even though communications between team members may be difficult at least at the beginning because of the different educational background of students, which, for instance, may be more theoretical in some cases or more practical in others. On the other hand, this diversity of background and approaches represents a good simulation of real-life situations and therefore anticipates the exposure of the students to their future working environment, educating them to benefit from all the advantages which might derive from composite teams. Lectures during the Learning Phase, dealing with technical topics as well as with personal skills development and team building, turn out to be particularly useful from this point of view, as they help students share common language and common understanding of space systems;
- the international background of both tutors and students has to be strongly enhanced to foster the exchange of knowledge, educational methods and design solutions
- the opportunity for the SEEDS students to visit as part of the Master programme different university sites, as well as industry and agency facilities (including the visit of engineering labs and the test centre at ESA/ESTEC), is highly appreciated by them and facilitates their subsequent introduction to the professional world in the space field.
- a good and well maintained contact and interaction between the SEEDS Master management and industrial and agency references has been so far an essential instrument to guarantee the effectiveness of the education provided, the responsiveness of the Master's content to realistic and up-to-date professional needs, the access to facilities and instruments for the students, great opportunities for visits and contacts, in anticipation to the start of their future professional careers.

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