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Building Polish space sector – from small islands of excellence to a national innovation ecosystem

Bogdan Wiszniewski *

* Polish Space Agency (POLSA), Gdansk, Poland (e-mail: bogdan.wiszniewski@polsa.gov.pl).

Abstract: In the paper a national potential of Poland to build its space industry after joining the European Space Agency (ESA) in 2012 is assessed, based on the series of survey reports published annually by POLSA since 2016. Their methodology was based on the ESA technology tree, classifying all the space-related technical knowhow and allowed identification of the most promising strengths to exploit and shortages to challenge by policymakers implementing up to the 2030 horizon the Polish Space Strategy adopted by the Polish Council of Ministers in 2017.

Keywords: Space industry, ESA technology domains, high-growth firms, space policy rules.

1. INTRODUCTION

The establishment of POLSA in 2014 through a parliamentary act constituted an important milestone on the way of Poland to benefit from the access to space and created a legal framework for coordinating activities to build up the national space sector. This act was a natural consequence of Poland joining ESA in 2012, after which the next step was the adoption of the Polish Space Strategy (PSS) by the council of ministers in 2017. PSS covers the 2017-2030 horizon and is an element of the wider Strategy for Responsible Development (SRD), adopted by the government to drive growth of the Polish economy through innovative capacity spurred by knowledge and new technologies. PSS is aimed at: increasing competitiveness of the Polish space sector and in its share in the turnover of the European space sector (1); developing satellite applications as a contribution to the process of building the digital economy (2); strengthening capabilities in the area of security and defense by using space technologies and satellite applications (3); creating favorable conditions for the development of the space sector in Poland (4); building human resources for the Polish space sector (5). Reaching these goals, as part of the more general goals of SRD, will require creating in Poland in the foreseeable future foundations of an *innovation state*. It in turn will require investments in space related science and technology to create a potential for that, as well as legal and administrative adjustments to build the appropriate structure supporting creation and growth of new firms of the space sector.

Etzkowitz (2018) indicates the government, academia and business as three interdependent players in the innovation state and argue that they all should adopt a relatively equal status in order to achieve an equilibrium between the statist regime of bureaucratic government control over the activities of the university and industry and the laissez-faire regime with the minimal state intervention in the economy. He argues that except such core national security spheres as defense, health and agriculture, bureaucratic government control can rather be an impediment than a stimulus to the introduction of inventions to the market. However, elimination of government control over economic processes cannot guarantee success of the postulated innovation state either.

For each of the goals of PSS listed before the forms of cooperation of the aforementioned players should certainly be diversified, due to the delicate balance between them. For example, the equilibrium for Goal 2 of PSS will lie much closer to the laissez-faire regime, unlike the equilibrium for Goal 3, as developing satellite applications for the digital market will certainly involve more individualism and self-interest of independent firms than delivering a turnkey solution for national security and defense by a state-owned or private firm. In either case, however, the role of governments would be crucial to initiating and encouraging systematic innovation in a sector focused on achieving these goals.

The key aspect to be considered is growth. According to Mason and Brown (2014), policy makers across the OECD have been promoting high growth firms (HGFs), since by operating on the cutting edge of new (disruptive) technology and being active in the early phases of a new industry they are widely believed to boost productivity and create new employment. One emerging approach to that is based on the concept of an *ecosystem*, where HGFs can interact with multiple actors at the specific geographical location. The location should have an established base of knowledge organizations capable of supplying scientists and engineers, such as research universities and institutes. They should be able to generate scientific discoveries and technological advances to lay the ground for new businesses and attract talented individuals from outside the region to boost further the technological capacity of the place. In the paper we will refer to such a dynamic system of actors, resources and their complex relationships as the *innovation ecosystem*. Its principal functional goal is to enable technology development and innovation. Indis-

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pensable elements of the innovation ecosystem, as emphasized by Oh et al. (2016), are universities and research institutes, high-tech firms, centers of excellence, economic development funding agencies and active policy makers, as well as locally available material resources, such as funds, infrastructure and human capital.

In the light of the above the focus of this paper is on the prospect of building the *national space innovation ecosystem* in Poland. Although several Polish research entities have already been able to cooperate with their leading European counterparts and to actively participate as subcontractors in the global technological race in several specific domains, we will argue that although the potential for space research and exploitation in Poland exists, building the aforementioned national ecosystem would require well coordinated and long-lasting effort of government, business and academia. In Section 3 major findings on that potential are presented, based on analytical reports published annually by POLSA. They exploited a standard conceptual classification of the space-related technical know-how provided by the ESA technology tree, as specified in Westman (2013). The tree specifies all related technology domains, subdomains and technology groups related to procuring and exploiting space systems; they are briefly characterized in Section 2, alongside the broader view on the space economy segments represented by OECD. The analyzed data concerned projects performed by universities and research institutes in the period of the last five years, including basic research funded by the National Science Center (NSC), applied research funded by the National Center for Research and Development (NCRD), products developed by commercial firms associated in the Polish Space Industry Association (SpacePL) and in the framework of ESA tenders (ESA Industry Portal). Alternative scenarios for building the Polish space ecosystem are discussed in Section 4 based on a brief survey of the literature concerning various knowledge economy and innovation concepts in the light of findings reported in Section 2. Conclusion of the paper indicates several desired areas of intervention to be considered by the state based on the analyses reported in Section 3 and political considerations in Section 4.

2. SPACE ECONOMY

The use of satellite technology has given rise to a whole new stream of applications, which in turn are creating a new downstream users and markets. It is a real industry, where the disruptive technology creates a new sector of the national and global economy – with its own production systems, consumption patterns and lifestyles. In fact society has always profited from disruptive technologies, from the telephone to the automobile, the computer or the World Wide Web. There is no reason to expect that satellite and space technology in the 21st century would be different – expectations of the society in that regard are rising, especially for the downstream segment. The space sector will constantly attract more and more attention worldwide, as public and private investors will look for new sources of economic growth and innovation and consider space economy as the relevant domain for high-tech innovation.

The prospective innovations would come at a cost, however. The related technological challenges would include in the near future for example: the need to develop more efficient electrical power generation and energy storage technologies than the ones used today – especially in the context of IoT and ubiquitous computing, ensuring integrity of satellite navigation services despite of signal degradation in urban areas – especially in the context of autonomous vehicles, fusion of data from incompatible sources – given the constantly growing inflow of data from numerous sources, and space debris mitigation – due to the excessive amount of human made objects on low orbits around the Earth.

The space economy comprises two complementary economies, the *commercial economy* driven by the marketplace, and the *research economy* driven by basic and applied research in various technology domains. The former one is tied to the exchange of goods, services and labor activities that have a well defined monetary value, whereas the latter involves intangible assets such as scientific knowledge, trade secrets and intellectual expertise that has a potential to yield profits if used properly. As proposed by Oh et al. (2016), the tension that exists between these two economies may be exploited as drivers behind the innovation ecosystem. Throughout the rest of this section basic features of these two economies will be characterized with regard to the specificity of the space market.

2.1 Segments of the commercial space economy

The space sector is traditionally divided into five main domains: *communications*, *Earth observation*, *navigation*, *launchers* and *science activities in space*. The last estimate of the global space market in 2018 is close to G€250, with the stable annual average growth rate of 2-3% according to the Satellite Industry Association (SIA) reports.

The communications segment is the largest one and relatively established, but changing due to expectations of private and public users, risen by the development of innovative ICT solutions and related new business models. Its share in the global space market reached nearly 40% in 2017, from upstream involving manufacturing of communication satellites to the variety of downstream satellite services, such as television, radio, broadband, mobile telephony and fixed management services and transponder agreements – with over 80% share of revenues of this segment generated in downstream only, according to SIA.

Earth observation (EO) had a share of 2.3% in the global space market in 2017, and has been growing fast since 2014 – at the average annual growth rate over 10%. Prospects for further development of this sector should be seen in the growing interest of public administration and enterprises in the use of satellite data in order to improve the efficiency of the economy, comfort of citizens' lives and their safety. Examples include precision farming, homeland security, exploration of natural energy resources, meteorology and urban monitoring, among others.

One of the most widely used space assets today are navigation satellites, contributing over 20% to the global space market in 2017. It is expected that the demand from its constantly expanding user base will be growing in the com-ing years, especially for precise and internal positioning services needed for autonomous vehicles. Only for downstream – including stand-alone navigation devices and GNSS chipsets supporting location-based services in mobile devices, traffic information systems, aircraft avionics, maritime, surveying, and rail – the average annual growth rate of the navigation segment was about 8-10% since 2014. The existing upstream infrastructure is constantly improving owing to the parallel deployment of several independent navigation systems, with fully operational GNSSs of the United States' GPS, Russia's GLONASS and China's BeiDou (BDS) and the European Union's Galileo scheduled to be fully operational by 2020.

The share of launch services in the global space market was slightly above 2% in 2017. Spacefaring nations support their domestic launch sector to guarantee independent access to space, but since more and more launches use less expensive launch vehicle types, the share indicator dropped recently by -7%.

Finally science activities in space including human spaceflight contributed over 33% to the global space market in 2017. The vast majority of that were the development, assembly and running costs of the International Space Station (ISS), with only a minor amount spent on scientific satellite missions (less then 5% of the population of all satellites orbiting the Earth in 2018), interplanetary probes and resupply vehicles. The rate of growth of the latter has been oscillating around zero by less than 1% since 2014.

A more restrictive view on space economy disregards consumer services related to the exploitation of space systems and narrows to products and services directly involved in the space industry supply chain. Then, while maintaining a broader global context of the planned development of the Polish space sector as part of the SRD activities, such a focused view would be more appropriate to assess the potential and the current standing of Polish entities aspiring to participate in that process. In particular, Eurospace, the trade association of member companies representing today 90% of the total turnover of the European Space Industry, has identified four main space product segments: *launcher systems*, *satellite systems*, *scientific systems*, and *ground systems and services*. Throughout the rest of this subsection basic characteristics of the European space product market and its four segments, based on the data reported by Eurospace (2017) are presented.

The current estimate of the European space product market is close to the amount of G€8.3 and exhibits the stable year-to-year growth at the rate of 6-7%. The structure of the European market is specific, since ESA, as the main implementor of European space programmes, is the prime customer with the 41% share of that amount. Other institutional customers of the 18% share are European governments implementing their various national programmes, including both civil and military projects. The remaining commercial share of the product market is split between commercial launchers (over 27%) and commercial satellites (less than 14%). It is also worth noting that for the last decade the ESA's share alone has been steadily growing at the average annual rate of 16%; the reason for that has been two flagship EC programmes: Galileo for satellite navigation and Copernicus for Earth observation.

The launcher systems' segment contributes to the European space product market at the stable year-to-year level of 20-21% and the growth rate of 8%. This market includes two complementary activites of approximately the same scale: operational launcher systems for Arianespace, the European principal launch services operator, and development activities aimed at introducing new or improved launcher systems for future use.

The satellite systems' segment of the space product market includes three categories of products: *telecommunication systems*, *Earth observation systems* and *navigation systems*, constituting jointly almost half of the European space product market, with the average 46-51% year-to-year share and its steady growth rate of 3%. Majority of telecommunication systems' products are acquired by private customers, whose total share in the satellite systems segment reached 35% in 2017, whereas the two remaining categories of this segment are dominated by public customers, with the respective 7% share of institutional customers acquiring Earth observation systems' products, and 4% acquiring navigation systems' products. These last two figures are related to the fact that massive deployment of Earth observation and navigation systems still remains a strategic domain of the state and private customers, who have not yet achieved the adequate investment capability, whereas telecommunications systems exhibit already a relatively high commercial maturity.

Majority of the scientific systems' segment of the space products market is entirely in the domain of governmental programmes. It involves three categories of products: *science and exploration products*, including the design, development and production of spacecraft systems, *human spaceflight* programmes including ISS, and products related to *microgravity experiments* and tests. The average year-to-year share of this segment in the space product market has been 17% in 2017, and in that 64% of science and exploration products, 33% of human spaceflight products and 3% of microgravity products. The growth rate of the last two categories – the human spaceflight and microgravity categories are practically nil, whereas the science and exploration category exhibits the steady annual growth of 10% throughout the entire last decade.

Finally, the share of the ground systems' segment in the European product market remained at an average level of 15%, and after the moderate growth of 4% over the past decade has increased sharply by 18-37% in the last few years. According to Eurospace (2017), the reasons of this phenomenon can be attributed to the Galileo programme, which provided significant business opportunities for this market segment. The segment involves three broad categories of products: the electric and mechanical ground support equipment (EGSE/MGSE) used to assemble, integrate and test spacecraft systems, subsystems and instruments, the ground infrastructure required to operate launchers during launch and spacecraft during operational lifetime, and professional technical services for the manufacturing industry as well as management services for the space agencies implementing their programmes. Products of these categories have their respective share in the ground systems' market segment equal to 8%, 51% and 42%, respectively. Over 88% of these products are acquired by public customers (mostly ESA), with the respective share of each category 5%, 47% and 35%.

2.2 Technology domains of the knowledge space economy

The ESA technological tree provides a three-level classification system for all space-related technical knowhow. The tree addresses both basic research issues, undertaken to gain new knowledge about the fundamentals of phenomena and observable facts and applied research issues, aimed at improving or developing new devices, processes and technologies used in space exploration. It combines topics from various fields of science and engineering into domains, subdomains and groups, which enable systematic, well structured and objective identification of competences of individuals and organizations aspiring to participate or already involved in space industry. For brevity only ESA technology domain identifiers and names are listed below; a detailed specification of their characteristic keywords may be found in Westman (2013):

TD1 - Onboard data systems.
TD2 - Space system software.
TD3 - Spacecraft electrical power.
TD4 - Spacecraft environments and effects.
TD5 - Space system control.
TD6 - RF systems, payloads and technologies.
TD7 - Electromagnetic technologies and techniques.
TD8 - System design and verification.
TD9 - Mission operation and ground data systems.
TD10 - Flight dynamics and GNSS.
TD11 - Space debris.
TD12 - Ground station system and networks.
TD13 - Automation, telepresence and robotics.
TD14 - Life and physical sciences.
TD15 - Mechanisms.
TD16 - Optics.
TD17 - Optoelectronics.
TD18 - Aerothermodynamics.
TD19 - Propulsion.
TD20 - Structures.
TD21 - Thermal.
TD22 - Environmental Control Life Support (ECLS) and In Situ Resource Utilization (ISRU).
TD23 - Electric, electromechanical and electronic (EEE) components and quality.
TD24 - Materials and processes.
TD25 - Quality, dependability and safety.

In the next section we present the main results of several in-depth surveys on the achievements of Polish universities, research institutes and companies, which POLSA has been conducting annually since 2016.Their goal was to identify and monitor the existing national potential from the point of view of creating conditions for the systematic growth of the Polish space sector.

3. PSS – HOW LONG THE WAY TO GO?

Given the financial figures quoted in Section 2.1 it is clear that Poland has yet a long way to go to fully benefit from the global market of space-based data and services as its active player, and whose activity in the European space industry supply chain could be statistically noticeable. This statement can additionally be supported by analyzing employment in the European space industry, surveyed by Eurospace (2017). Over 90% of the total of nearly 41 thousand employees of the European space industry work in the six major ESA member states: France, Germany, Italy, United Kingdom, Spain and Belgium. There are four large industrial groups, which employ via their dedicated business units and joint ventures over half of the total European space industry workforce: Airbus 26.96%, Thales 17.72%, the Ariane Group 10.21%, and Leonardo 5.56%. Two other noticeable employers include OHB 4.59% and RUAG 1.92%. Within the remaining 33.05% of the total employment the proportion of SMEs is estimated in the aforementioned survey between 6% and 21%. Such a low percentage of SME employees results, according to the Authors, from the fact that the key European space industry groups tend to extend control in the space supply chain by absorbing their suppliers and potential competitors to secure the supply of critical equipment. Thus the European space sector counts a large number of small space units, but a rather limited number of independent SMEs. In that context it is interesting to see if there is any growth potential in Poland for these types of units.

The engineering complexity of space programs requires workers in the space industry, most of whom can identify themselves with a high level of skills, confirmed by a PhD or MSc university diplomas in science or engineering. In that regard the Polish higher education system is quite productive. In Poland there are 18 public and five non-public universities educating over 300000 students in practically all fields of science and engineering, according to the OECD (2007) classification. In that number 14 are universities of technology, i.e. having the right to confer doctoral degrees in at least ten disciplines, including at least six qualifications in engineering. According to the Polish Graduate Tracking System (PGTS) in 2016 alone nearly 4000 students got their MSc in science and respectively over 28500 in engineering in over 900 various graduate level study programs. These universities are the main source of qualified personnel for the Polish industry, making it largely self-sufficient in terms of the engineering staff supply. These universities are also effective in supplying national scientific units with researchers, employed by academia, state research institutes, and more recently also research centers directly supported by private businesses. According to the Polish Science database (OPI) there are over 51000 scientists in Poland, who got their PhD degrees or higher in science or engineering from Polish institutions and acted as research leaders or served as management in various scientific entities.

A question to be raised would be whether such a human capital can be effectively exploited in reaching the objectives of PSS and building space industry in Poland. Given the specific structure of the European space industry and the current size of its market it would be reasonable to focus on just a few carefully selected technology niches that could guarantee the fastest growth of several entrepreneurs, acting as drivers of the national ecosystem. In the long run such an ecosystem could be seamlessly assimilated in the European space industry ecosystem as a whole. For otherwise small Polish entities competing in isolation with their European counterparts on the delivery of minor components and sub-assemblies to the key players of the European or global space industry market, will always fall in the middle income and average product traps, as warned against in SRD.

Only a few Polish entities are suppliers of components ordered by major institutional players on the global space market, such as ESA or NASA. One example is the ESA space probe Rosetta mission to the 67P/Czuriumow-Gierasimienko comet, completed successfully in 2016 and for which the Space Research Center of the Polish Academy of Science codesigned the penetrator of the comet lander Philae. Another is the less successful NASA robotic lander InSide mission landed in 2018 on Mars and designed to study the deep interior of the planet. The Polish company Astronika designed the tractor mole component of the self-penetrating heat flow probe, provided to NASA by the German Aerospace Center (DLR), which was intended to penetrate as deep as 5m below the Martian surface while trailing a tether with embedded heat sensors to measure how efficiently heat flows through Mars' core. Unfortunately the mole had made a little progress into the ground, probably because of hitting a rock. However impressive, such achievements have negligible impact on fostering competitiveness and economic growth of the Polish space industry.

Throughout of the rest of this section major findings on niches for growing the Polish space ecosystem are summarized, based on the analytical reports published by POLSA. These include both academia and research institutes, financed by the state and constituting the main national R&D capacity, and private companies, mostly SMEs, with limited investment capability and supported mainly from public funds in the form of grants. In its reports POLSA has been focusing only on identifying the technological competences of the Polish R&D entities, with no attempt to analyze their economic condition, estimate their target market volume nor growth indicators. By using the ESA technology tree as the reference point several islands of excellence were identified; they have a potential to be expanded in the growth oriented entrepreneurial ecosystem, if only institutional alignment of priorities could be properly set and peer-based interactions between entrepreneurial actors, legally fostered by the central and regional economy policymakers.

3.1 Domestic R&D activity

Data on the current R&D activity in Poland have been collected by POLSA from the following sources:

(1) Publication records and questionaries of universities, research institutes of the Polish Academy of Sciences and state industrial research institutes, which according to the periodic parametric evaluation by the Ministry of Science and Higher Education got the A/A+ (excellent) category.
(2) The lists of basic research projects funded by the National Science Center (NSC) completed in between 2015-2018.

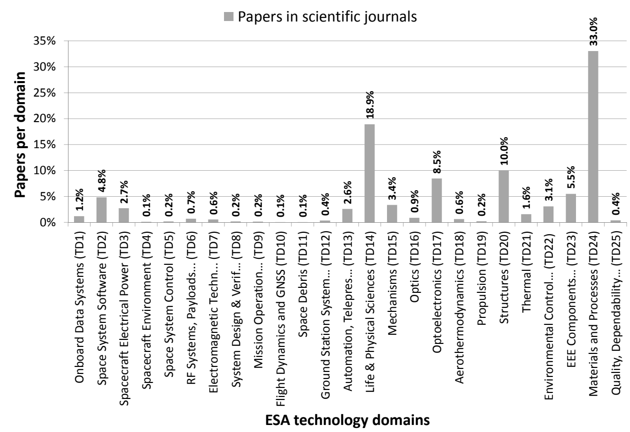

Fig. 1. Top journal papers on topics of the ESA tree

(3) The list of applied research projects funded by the National Center for Research and Development (NCRD) completed in between 2015-2018.
(4) Questionaries returned by SMEs associated in the Polish Space Industry Association (SpacePL).

Universities and research institutes Out of 993 categorized entities, 148 research units (university departments and institutes) got the A/A+ category and were identified by POLSA as performing R&D activities in science and engineering domains defined in the ESA tree. In that number 19 entities received the top A+ category.

According to the Polish Scientific Bibliography database (PBN) in the period of 2016-2017, all A/A+ entities published a total of 20 235 publications in highly ranked international scientific journals. Their respective bibliographic records, available in the database, were filtered for the affiliation of their authors to the 148 research units mentioned before, to finally extract 5938 records of publications on various topics identified in the ESA technology tree. Results of their analysis are summarized in Figure 1. It was found that out of 148 research units 17 of them had their respective publication records exceeding 100 papers, which may be considered a noticeable contribution to the total number of publications on the topics specified by the ESA tree procured by Polish authors. The top five domains, with the highest share of conformant papers were respectively: "TD24 - Materials and processes" 33%, "TD14 - Life and physical sciences" 18.9%, "TD20 - Structures" 10.0%, "TD17 - Optoelectronics" 8.5%, "TD23 - Electric, electromechanical and electronic (EEE) components and quality" 5.5% and "TD2 - Space system software" 4,8%.

All 148 entities were also asked by POLSA to indicate in a special questionnaire the most important results of R&D projects completed by them in the last 5 years (regardless of the funding sources) and the lab infrastructure created or exploited in connection to each reported project. Over 80 entities responded to the inquiry, in that 43 entities declared specific achievements in various technology domains specified by in the ESA tree. Their geographical distribution is outlined in Figure 2. The successive columns in each voivodship's histogram correspond to the respective domains of the ESA tree, and the hight of each of them is proportional to the number of entities declaring research

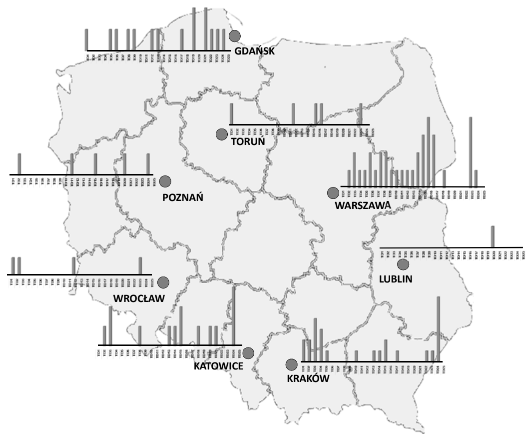

Fig. 2. Geographical distribution of R&D competences on topics of the ESA tree

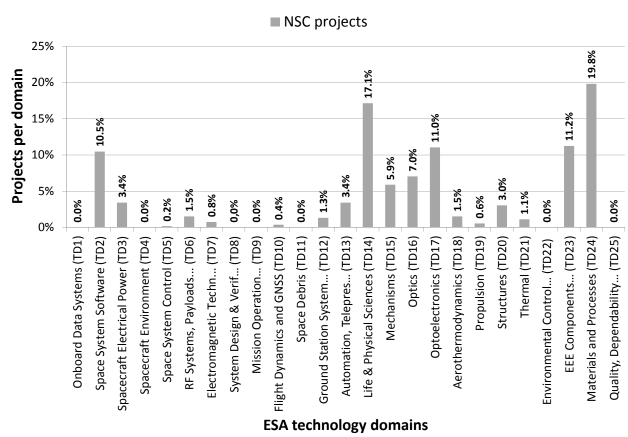

Fig. 3. Basic research projects on topics of the ESA tree

activity in the appropriate domain. The top four regions in that regard are: Masovia (20 domains, 13 units), Lesser Poland (13 domains, 10 units), Pomerania (13 domains, 3 units) and Upper Silesia (10 domains, 5 units).

Basic research funded by NSC Periodic calls for basic research projects issued by NSC allows for free definition of research topics by the applicants themselves – universities or research institutes. Specific issues addressed in the submitted project proposals are subject to only general classification into ten domain panels in basic science and engineering. In the years 2015-2016, a total of 1236 basic research NSC projects were completed, of which 525 addressed various topics listed in the ESA technology tree. Ranking of their research profiles based on that analysis is presented in Figure 3.

The largest 19.8% share of the analyzed projects addressed topics from the "TD24 - Materials and processes" domain. Second to that 17.1% share of projects on "TD14 - Life and physical sciences" domain can be explained by the basic character of the performed research, related mostly to physics and biology. The next group of domains, with a much weaker representation, were domains "TD23 - Electric, electromechanical and electronic (EEE) components and quality" with the 11.2% share, "TD17 - Optoelectronics" witch the 11.0% share and "TD2 - Space system software" with the 10.5% share, followed by "TD16 - Optics" with the 7.0% share and "TD15 - Mechanisms" with the 5.9% share. Surprisingly, the entire range of technology domains did not enjoy any noticeable interest from the basic research units, among them "TD8 - System design and verification" and "TD25 - Quality, dependability and safety", which topics, after all, cover much wider problem areas than just space applications.

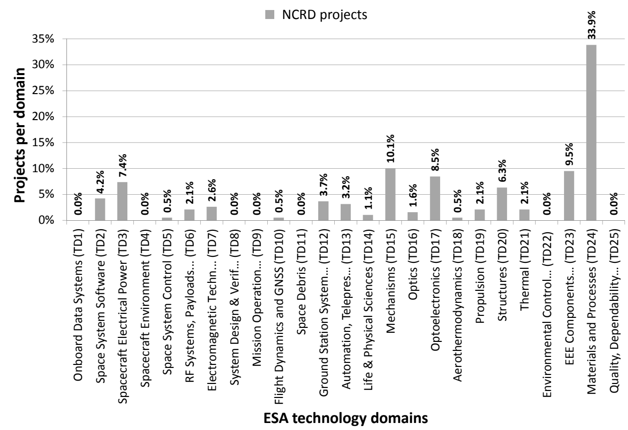

Fig. 4. Applied research projects on topics of the ESA tree

The group of 17 units indicated in the previous subsection to have publication records exceeding 100 per unit had a 74.1% share in the total number of the 525 NSC projects surveyed.

Applied research funded by NCRD Periodic calls for applied research projects published by NCRD are dedicated to specific subjects and expected to end in prototypes of devices or implemented new processes or services. Most often, projects of this type are performed by consortia lead by enterprises, who are responsible for the implementation of the project' final products in their business activity. For the purposes of this study 3513 projects were analyzed, completed or still in the implementation phase by the end of 2016, of which 190 addressed specific topics included in the ESA technology tree. Results of this analysis are shown in Figure 4. As in the case of basic research projects, the largest 33.9% share of applied research projects addressed topics of the "TD24 - Materials and processes" domain. Other topics of the ESA technology tree were represented much less often in the survey. For the group of projects exceeding the 5% threshold of the total of projects addressing one domain the same domains as in the case of NSC basic research projects can be observed: domains "TD15 - Mechanisms" with the 10.1% share, "TD23 - Electric, electromechanical and electronic (EEE) components and quality" with the 9.5% share and "TD17 - Optoelectronics" with the 8.5% share. Additionally two more domains less represented in the NSC basic research projects exceeded that threshold for the NCRD projects: "TD3 - Spacecraft electrical power" with the 7.4% share and "TD20 - Structures" with the 6.3% share. It is also worth noting that, as in the case of basic research projects, technology domains "TD8 - System design and verification" and "TD25 - Quality, dependability and safety" were also poorly represented in the applied research projects.

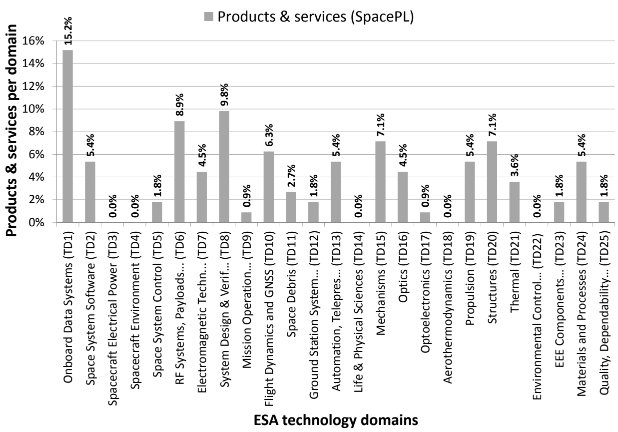

Fig. 5. Products and services of the SpacePL SMEs

Polish space SMEs For the purpose of this study POLSA surveyed activities of all 49 SMEs of the SpacePL association, asking them to indicate the most important products or services in their current market offer along with the thematic classification according to the ESA technology tree, and the number of engineering and technical staff directly involved in R&D activities. 33 companies responded to the survey and reported 31 products and 20 services, each one addressing topics from more than one technology domain. Summary of their share in all addressed topics is presented in Figure 5. The declared employment of these companies exceeded by the end of 2018 the total of 650 engineers and technicians, which in comparison with 213 employees reported by Eurospace (2017) for the entire Polish space industry sector represents a threefold increase.

It may be seen that the largest 15.2% share of topics of all reported products' or services' fell in the "TD1 - Onboard Data Systems" domain, as declared by 18 surveyed SMEs. Additionally, the 5.4% share of the respective topics declared by 14 SMEs fell in the "TD2 - Space System Software" domain. Their joint dominance in the results of this survey is probably related to the fact that most of the reported products were dedicated software solutions, supplied as components of larger systems to external integrators. That, of course, required suppliers to adopt rigorous space industry standards for product assurance; that is why the relatively high 9.8% share of topics from the "TD8 - System Design and Verification" technology domain was observed, as declared by 11 SMEs. Other categories of the components supplied by the surveyed SMEs can be characterized by the 8.9% share of topics from the "TD6 - RF Systems, Payloads and Technologies" domain declared by 10 SMEs, and the 7.1% share of topics in the "TD15 - Mechanisms" and "TD20 - Structures" alike, each one declared by eight SMEs. Six SMEs reported their products or services in the "TD10 - Flight Dynamics and GNSS" domain (6.3% share), and "TD13 - Automation, Telepresence and Robotics", "TD19 - Propulsion" and "TD24 - Materials and Processes" domains, all of the 5.4% share. Note that compared to Figures 3-4, topics of the "TD25 - Quality, Dependability and Safety" domain were finally represented in commercial products or services, with the respective share of 1.8% (according to declarations of just two surveyed SMEs), contrary to their absence in the basic and applied research projects analyzed before.

ESA tenders On the basis of an agreement between the Polish Government and ESA, national entities can participate in the Polish Industry Incentive Scheme (PLIIS) program until the end of 2019. Under this program, ESA publishes tenders for proposals in which only Polish entities can participate.

During the program, out of 442 Polish entities registered in the ESA-STAR system, 145 entities submitted 451 proposals, of which 67 ended with signing contracts. Most entities were involved in projects related to the "TD2 - Space system software" technology domain. Other often represented technology domains, however with a particularly large share of domestic daughter companies of the international space industry companies, were "TD3 - Spacecraft electrical power", "TD8 - System Design and Verification", "TD9 - Mission operation and ground data systems", "TD15 - Mechanisms", and "TD19 - Propulsion".

In the case of several other technology domains, a noticeable inactivity could mean not so much a deficit of relevant competences in Poland, but rather lesser interest of domestic companies in developing cooperation with international space sector institutions. This might be the case of such technology domains as "TD14 - Life and physical sciences", "TD17 - Optoelectronics", "TD23 - Electric, electromechanical and electronic (EEE) components and quality", quite well represented in the NCRD projects summarized in Figure 4, and "TD25 - Quality, Dependability and Safety" reported in Figure 5 by two SMEs.

4. TOWARD THE POLISH SPACE ECOSYSTEM

One key issue is to find a construction that would lend a representative legitimacy of the social interests set out in the SRD document to the initiative of building a national space industry. An interesting approach to handle such an issue by politicians was proposed by Hoerber (2018), who applied framing theory to analyze the European space policy. The framing theory, used widely in the social sciences to analyze how individuals, and societies, can perceive and communicate about reality, has become more and more popular in recent European studies. In particular it can provide techniques that can be used to reduce the ambiguity of intangible topics by contextualizing the information in such a way that the general public can connect to what it already knows. In other words, politicians can frame their vision effectively so that the public can understand its significance and accept it. Moreover, although several different frames reflecting different preferences of different actors may exist at the same time they may coexist and help to define even complex political realities. One example of that at the international level could be the process of building the European space sector. Hoerber (2016) indicated three different frames of the "big three": France, Britain and Germany, whose efforts finally crowned that process by the creation of ESA in 1975. France advocated for independence in space technologies, what lead to the development of the Ariane launcher, Britain was mainly concerned with budgetary constraints and the quick commercialization of space services, such as telecommunication satellites, whereas Germany expressed interest in fundamental space research and exploration with a concrete commitment to the Spacelab science laboratory for use on Space Shuttle flights. In addition, smaller EU member states were able to catch up – Belgium in the sector of space hardware and the Netherlands in the sector of services providing mass satellite data to end users. Other frames have been introduced in the meantime that are widely used across EU since then and are reflected in the two flagship EU satellite programs. One is the Copernicus program, promising the universal access to Earth observation data allowing for the supervision of environmental standards and to modernize the European agricultural industry. Another is the Galileo program, which is civilian but could be used for defense purposes. The latter "dual-use" frame is particularly interesting to governments, as it allows for the access of military funding into civilian space programmes.

In the light of the above, it is worth asking what frame for Polish space policy should be adopted for the period up to the horizon of 2030 set up in the the PSS document, so that reaching of the goals 1-5 listed at the beginning of the paper could be fully justified from the point of view of the social interests of the Polish taxpayer. When doing that many unsubstantiated beliefs of academics and politicians alike that pervade the space advocacy rhetoric and function as popular myths often reproduced by media should be avoided.

Several fundamental myths of that kind were already analyzed and criticized in the literature. For example, the myth that mankind has innate drive to explore or to migrate into space was criticized by Schwartz (2017a) in all three commonly used interpretations: "mystical" (destiny of humans to explore and migrate into space), "cultural" (exploration and migration as universal features of human cultures) and "biological" (a psychological or genetic basis for exploration or migration). Schwartz (2017b) also criticized the myth that settling the space "frontier" is necessary for avoiding societal stagnation. Whereas the two aforementioned myths reach far behind the 2030 horizon of PSS, the third category of myths criticized by Schwartz (2018) requires a closer look when considering the frame for the current Polish space policy. On the basis of a variety of survey analyses the Author has shown that while there is some indication that being scientifically literate makes a person more likely to support spaceflight, there is no clear indication that the extent of spaceflight activities (or the extent of funding for spaceflight) makes people more likely to be scientifically literate or to be supportive of spaceflight (at least in the United States). In other words, he found no clear evidence that spaceflight spending could be uniquely inspirational for science, technology, engineering, and mathematics (STEM) education.

Before considering the best frame for justifying specific policy rules and approaches to building the innovative space ecosystem in Poland let us first summarize the results of analyzes of the activities of Polish research units and SMEs in various ESA technology domains presented in Section 3 to assess complementarity of their potential, i.e. whether they could implement the full space product cycle - from research, through development work to manufacturing of the qualified product having a commercial value.

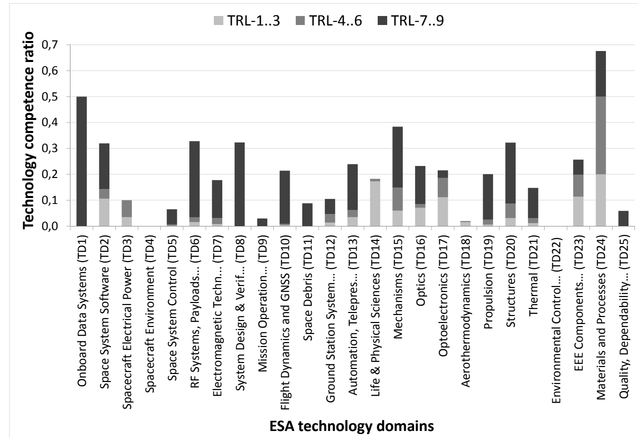

Fig. 6. Technology competences across ESA domains

4.1 Complementarity of the domestic potential

One may assume that in general results of the NSC projects depicted in Figure 3 concerned basic research on a new technology, aimed at proving its feasibility at the most, so their results would never exceed the Technology Readiness Level (TRL) higher than TRL-3. Consequently, NCRD projects analyzed in Figure 4 concerned mostly technology demonstration, thus their results would reach probably not higher than TRL-6. Contrary to that, the SMEs data presented in Figure 5 concerned products and services qualified by the ordering party for integration into a larger system so reaching at least TRL-7.

Consider a metric, which for all projects and products analyzed within the same ESA technology domain, would aggregate all three share indicators presented in Figures 3-5 in a manner that takes into account TRL indicators corresponding to particular categories of the results reported in this survey. Let's define the technology competence ratio CTR_i as

$$CTR_i = w_B \cdot S_B(i) + w_A \cdot S_A(i) + w_P \cdot S_P(i), \qquad (1)$$

where $i \in \{TD1, ..., TD25\}$, $S_B(i)$, $S_A(i)$ and $S_P(i)$ denote the respective share values for the ith technology domain for basic research, applied research and products/services, and w_B, w_A and w_P denote respective weights for each range of TRL indicators mentioned before. By assuming $w_B = 0.2$, $w_A = 0.3$ and $w_P = 0.5$, proportional to the respective TRL levels, and combining share values for each domain we get the stacked column chart in Figure 6. Each column of that chart indicates whether for the corresponding technology domain complementary competences in research, development and manufacturing existed in the surveyed entities, in what proportion and to what extent.

Note that for two domains, "TD4 - Spacecraft environments and effects" and "TD22 - Environmental Control Life Support (ECLS) and In Situ Resource Utilization (ISRU)" no competences existed. Moreover, for three domains "TD3 - Spacecraft electrical power", "TD14 - Life and physical sciences" and "TD18 - Aerothermodynamics" only R&D competences were identified, whereas for seven more domains, e.g. "TD1 - Onboard data systems" or "TD8 - System design and verification", only manufacturing competences were reported. The latter indicate that probably no SME of the surveyed group was able to built yet manufacturing competences for products which could be invented by domestic R&D entities. On the other hand, such a large representation of SMEs capable of producing specific products of the space industry, despite the lack of domestic R&D support indicates that they are probably only subcontractors to external entities, who order products for specific users and design specifications developed elsewhere.

However, for about the half of technology domains specified by the ESA tree all three categories of the required competences existed. With such a potential some prospective niches for growing the Polish space ecosystem could certainly be identified.

4.2 Policy rules and approaches

As in the natural ecosystem, entities of the innovative ecosystem compete with each other for various resources as part of very complex interactions. However, development of the latter in a manner consistent with the social interest defined by the underlying frame requires legislators to adopt appropriate regulations that will allow competing entities to cooperate for its development to achieve growth. This in turn depends on the social perspective for successful creation of demand for new services based on disruptive technologies. The opening digital market with the significant space component, involving 5G wireless systems, IoT, ubiquitous and everywhere access to the Internet, intelligent transport including unmanned, autonomous vehicles, precision agriculture using farming robots, are just a few examples of the new market opportunities for entrepreneurs to start businesses. Clearly, one underlying frame for that in Poland could be adoption of satellite technologies to increase the comfort of citizens' lives. This would require Polish entities to have unlimited access to satellite data and on the other hand to maintain the R&D potential to develop innovative products. Whereas satellite data can be acquired or shared in the framework of international cooperation, as for example in the Copernicus and Galileo programmes, the products built on them should be competitive and stimulating other entrepreneurs to develop new, even better ones. The later could often be future entrepreneurs, fostered as spin-offs by various incubator organizations.

Mason and Brown (2014) have defined six general principles to implement policies that could foster creation of the space innovation ecosystem postulated in this paper: pre-existing assets, which as summarized in Figure 6 already exist in Poland (1); forms of state intervention related to the maturity of the ecosystem, gradually evolving from the start-up process towards internationalization support and access to growth capital (2); customization to local circumstances and capabilities (3); holistic implementation of the policy, as isolated initiatives would be ineffective (4); a blend of "top-down" approaches, such as IPR and tax legal regulations, and "bottom-up" approaches, such as engaging larger firms in the ecosystem to reduce government involvement (5); fostering the "entrepreneur policy", which requires supporting businesses with high growth potential (6).

When considering local circumstances and capabilities (principle 3) policymakers should take into account that successful ecosystems have been emerging in places that already have an established knowledge base in specific technology domains and employ significant numbers of scientists and engineers capable of generating technological advances forming the base for the creation of new businesses. Lawton Smith (1996) indicated that on the other hand, most universities and government research laboratories alone are ineffective incubators, for their lack of exposure to markets and research output of a relatively low TRL. Indeed, a spin-off process is started by people, who after leaving their original organizations launch their own businesses. Mason and Brown (2014) argue that once started such a process can often develop a momentum of its own, setting in motion a self-reinforcing process that leads to the creation of an ecosystem that can support further entrepreneurial activity in the area. Authors indicate that equally significant for that is the process of *entrepreneurial recycling* – when entrepreneurs leave their businesses and put their expertise and capital to work as serial entrepreneurs, venture capitalists or mentors to new entrepreneurs and institution builders. According to Mason and Harrison (2006) of particular significance in driving this process of growth are "blockbuster entrepreneurs" who can reinvest their substantial wealth and experience to create more entrepreneurial activity. Mason and Harrison (2006) also indicate that "top down" approaches (principle 5) should provide both corporate and individual taxation policies that would reward risk-taking and encourage reinvestment. If possible, grants and subsidies should be avoided as they may distort entrepreneurial behavior. In the same spirit, Shane (2009) spoke against supporting by the state the unlimited multiplication of start-ups, for their short survival and high failure rates, and provided arguments that "small business policy" is the "bad public policy" (principle 6).

5. CONCLUSION

A distinctive characteristic of the innovative ecosystem is that it forms to achieve something together that lies beyond the effective scope and capabilities of any individual player. Certainly, diversity of all actors involved, with their collective ability to learn, adapt, and most important to innovate together, are key determinants of their longer-term success. No less important for that success is the implementation of policy rules with the strong focus on promoting entrepreneurs who can drive productivity growth of the entire ecosystem, as found in numerous case studies reported by OECD (2010). Given the global, European and domestic space industry data summarized in this survey the final question to be asked is how to prepare Polish economy for the increasing role of space in the future and reap the benefits of space now? Based on the arguments of many authors cited before the answer to this question is two-fold. One is to implement policies that can ensure growth of enterprises capable of developing disruptive solutions, and another is to base the latter on technology domains for which there already exists a substantial identified intellectual potential in the country.

Detailed considerations of all relevant aspects of the implementation of policies for reaching the objectives described in the SRD document in line with the policy rules advised by Mason and Brown (2014) is well beyond the scope of the paper. However, identification of the most promising technology domains where disruptive solutions may be sought based on the existing domestic potential summarized in Figure 6 is possible, depending on the actual frame adopted. For example, if the selected frame is just active participation of Polish entities in international space research programmes the "TD14 - Life and physical sciences" domain is a good candidate – Polish entities are equally active in the related basic and applied research. But because of its very elitist character and limited impact on the national economy it may not be attractive to the public. On the contrary, state support for disruptive solutions in technology domains for which according to Figure 6 competences existing in Poland are complete – will certainly meet with a much wider social acceptance, if only properly framed as contributing to the improvement of everybody comfort of life. One example is the "TD2 - Space system software" domain, which covers both archiving systems and analytical processing of space data and creation of higher-level information products and services. Another is "TD13 - Automation, telepresence and robotics", addressing the range of issues from novel exploration robots, through methods that allow robot systems to understand of the operating environment, up to immersive and haptic systems that allow users to interact with robotics systems in the teleoperation fashion. The latter frame could further be enforced by extending the "dual-use" one mentioned before to "multiple-use", as developing robots capable of exploring hostile environments opens up to numerous fields of applications, from strictly military, through rescue and disaster management to Earth and planetary research.

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