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Robotics in the Context of Industry 4.0: Patenting Activities in Poland and Their Comparison with Global Developments

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The article analyses patenting in the field of robotics in Poland as the key technological area supporting the Industry 4.0 transformation. The article answers six detailed research questions that unveil various aspects of robotics inventions in Poland and compare the situation in Poland with global trends in robotics patenting. The research is based on bibliometric techniques and the use of datasets regarding patent applications from the Polish Patent Office and the Derwent Innovation Index databases. The extent of robotic patenting in Poland is discussed, with distinctive tendencies observed among businesses, higher education institutes, individual inventors and public research organisations, as well as the phenomenon of inter-sectoral collaboration, geographical distribution and thematic diversity of patenting activities. Inter-sectoral and international comparisons are based on themes that coincide with the sub-classes of the International Patent Classification. The analysis reveals gaps in the adoption and development of robotics in Poland, the marginal popularity of the field, limited inflow of locally developed, innovative solutions and a small number of companies engaged in patenting activities. The present, unsatisfactory progress towards the Industry 4.0 model opens up opportunities for future developments, motivating private and public actors in the innovation system to mobilize intellectual and inventive resources and follow global trends in order to bridge gaps in the development and adoption of these important technologies.

Keywords: Industry 4.0, patents, inventions, bibliometrics, robotics, industrial robots, innovation system.

Robotyka dla Przemysłu 4.0: aktywność patentowa w Polsce i jej porównanie z tendencjami światowymi

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Artykuł analizuje polską aktywność patentową w zakresie robotyki, która jest kluczowym obszarem technologicznym, wspierającym transformację w kierunku Przemysłu 4.0. Artykuł udziela odpowiedzi na 6 szczegółowych pytań badawczych, które prezentują różnorodne aspekty polskiej wynalazczości w obszarze robotyki i porównują sytuację Polski z globalnymi tendencjami w zakresie patentowania w robotyce. Badania opierają się na technikach bibliometrycznych, wykorzystują zbiory zgłoszeń patentowych pobrane z baz Urzędu Patentowego RP oraz Derwent Innovation Index. Artykuł omawia skalę aktywności patentowej w obszarze robotyki w Polsce, ze specyficznymi tendencjami dotyczącymi przedsiębiorstw,

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uczelni wyższych, indywidualnych wynalazków i instytutów badawczych, jak również bada występowanie współpracy międzysektorowej, geograficzną dystrybucję i zróżnicowanie tematyczne aktywności patentowej. Porównania międzysektorowe i międzynarodowe są oparte na obszarach zidentyfikowanych poprzez analizę podklas Międzynarodowej Klasyfikacji Patentowej. Analiza ujawnia luki w adopcji i rozwoju robotyki w Polsce, przy niewielkiej popularności tego obszaru, ograniczonym dopływie tworzonych lokalnie, innowacyjnych rozwiązań i małej liczbie firm zaangażowanych w aktywność patentową. Obecna, niesatysfakcjonująca transformacja w kierunku modelu Przemysłu 4.0 stwarza okazje do dalszego rozwoju, motywując aktorów sektora prywatnego i publicznego w ramach systemu innowacji do mobilizacji zasobów intelektualnych i wynalazczych oraz naśladowania globalnych trendów w celu wypełnienia luk w rozwoju i adopcji tych istotnych technologii.

Słowa kluczowe: Przemysł 4.0, patenty, wynalazki, bibliometria, robotyka, roboty przemysłowe, system innowacji.

JEL: O33

1. Introduction

Robotics is an emerging technological field of vital importance for the industrial transformation of modern economies, and it remains particularly relevant for companies in Poland. The article documents analyses of patenting activities in the field of robotics in Poland, discussing research results in the context of Industry 4.0, which has recently inspired policy makers and industrial companies throughout the world. Patent applications filed with the Polish Patent Office 2006–2015 were analysed to reveal the state of the nascent sectoral innovation system in robotics. Bibliometric techniques were applied in the research, analysing counts of patent applications and granted patents. The article aims at addressing five detailed research hypotheses regarding various aspects of the Polish patenting activities, and, subsequently, at comparing the situation in Poland with robotics patenting on a global scale and in selected countries or regions (the United States, China, Japan and the European Patent Office). The article discusses the extent of robotics patenting activities in Poland, patenting patterns in four sectors (business enterprises, higher education institutes, individual inventors and public research organisations), the phenomenon of inter-sectoral collaboration, as well as the geographical distribution and thematic diversity of patenting activities. International comparisons have been based on the sub-classes of the International Patent Classification, which revealed a certain diversity of thematic focus, "white spots" in certain countries, and areas of relatively higher or lower level of patenting activity of Polish inventors.

The article begins with a review of literature on Industry 4.0 and robotics, which is followed by data on robotics in Poland and a summary of the existing studies on patents in robotics. Next, research methods are presented, including procedures applied to identify patent applications in the field of robotics. Research results organised into 6 research hypotheses

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are subsequently discussed. The final section presents conclusions outlining the main findings of the study and their relevance for researchers and practitioners. Analytical results may be useful for companies and scientific organisations conducting research in robotics, innovation policy makers and researchers interested in the economics of innovation or in technology and innovation management.

2. Literature review – Industry 4.0 and robotics

Industry 4.0, or the fourth industrial revolution, combining industrial automation and data exchange is becoming an increasingly popular concept. The term was coined in Germany, no more than several years ago; at present, it fuels the imagination of policy makers, consultants, industrial managers and academics throughout the world. With the important, agenda-setting role of governments and the relative fuzziness of the concept, Reinschauer (2018) sees the Industry 4.0 movement as "*policy-driven innovation discourse in manufacturing*" or as "*broader communicative action that mobilizes actors to innovate collaboratively and that is driven yet not determined by politics*" (Reinschauer, 2018, p. 26). This view of Industry 4.0 as policy discourse or communicative action rather than a mere set of technologies or artefacts corresponds to the model of organising visions proposed by Swanson and Ramiller (1997), with managerial ideas contributing to a shared vision of a technology-enabled future, mobilizing stakeholders, helping them make sense of the available technological options and their possible applications in business enterprises.

It is expected that the impact of Industry 4.0 initiatives will be comparable to the industrial transformations brought about in the 1980s by the diffusion of several Japanese approaches to operations management, such as *kanban*, *Just-in-Time* and the Toyota Production System (Moeuf et al., 2018). Not only does Industry 4.0 have the potential to spur new, technology-enabled companies and industries, but also to transform industrial incumbents and revitalize more traditional industries (Brusoni and Sgalari, 2006). The combination of advanced software and hardware on the factory floor creates the so-called cyber-physical systems, automating the industrial processes (Lee et al., 2015). New technologies such as 3D printing (additive manufacturing enabled by the use of digital technologies) support distributed manufacturing and low-cost customisation, contributing to the disruption of existing business models (Berman, 2012; Rayna and Striukova, 2016). Furthermore, new technological opportunities emerge thanks to the processing of big data (Tien, 2013) and the use of digital labour intermediated by online platforms, not requiring physical presence in one location and thus dramatically changing the nature of work and industrial processes (Fuchs and Sevignani, 2013). Key impacts of Industry 4.0 are related to increased digitalisation and automation within factories, with the upgrade of technological platforms and upskilling of managers and machine operators (Lasi et al., 2014). Owing to the wide range of relevant technologies and their possible applications, as well as its potential for industrial transformation, Industry 4.0 appears similar to other concepts, which have been defined in an equally non-deterministic manner, such as: "*ubiquitous manufacturing*", "*intelligent manufacturing*", "*cloud manufacturing*" and "*cyber-physical production systems*" (Wang, Ong and Nee, 2018, p. 605), as well as "*smart manufacturing*" (Kang et al., 2016), introduced by publications in multiple linguistic variants, which involve the combination of terms: "*smart*", "*intelligent*", "*real-time*", "*ubiquitous*" and the designation of business practices, such as "*factory*", "*manufacturing*" or "*enterprise*" (Strozzi et al., 2017, p. 6574). Attempts to delineate these intertwined concepts go beyond the scope of the present article, and Industry 4.0 still awaits more precise definitions and distinctions from alternative approaches, or – alternatively – decisions to blur conceptual boundaries in order to propose an all-encompassing concept of a future-oriented, technology-enabled and intelligence-based enterprise. For example, Liao et al. (2017) made an early attempt to understand how the term Industry 4.0 is understood by researchers, analysts and policy makers, by analysing the contents of Industry 4.0-related publications with a view to tracking the co-occurrence of specialist terms and exploring divergent approaches to which the same thematic label might be attached. Industry 4.0 still remains a relatively vague concept, lacking definite delineations and overlapping with alternatives known from previous studies (Yin, Stecke and Li, 2018), but it has also become increasingly popular due to the significant endorsement of governments in major economies, with specific references to Industry 4.0 in various initiatives and support programmes. Given that the concept has been introduced relatively recently to the academic discourse, empirical studies or country-level analyses related to Industry 4.0 remain scarce, with analyses of government initiatives and reactions of business enterprises available for Germany (Sommer, 2015; Kang et al., 2016; Li, 2018), China (Li, 2018), South Korea (Sung, 2018; Kang et al., 2016) and the Czech Republic (Basl, 2017). In parallel, Industry 4.0 is gradually being superseded in popular business discourse by the notion of the 5th industrial revolution, not yet described in scientific publications, with developments of artificial intelligence and ubiquitous mobile networks (5G) expected to further transform the global industry. In particular, this might increase the diffusion of *cobots*, collaborative robots interacting with humans, having increased autonomy owing to the developments of artificial intelligence (Cherubini et al., 2016).

The present article focuses on robotics as one of enabling technologies for Industry 4.0. Robots are machines that replace human effort, with a certain degree of autonomy in decision making or adjustments to conditions in the external environment, and robotic technologies have multiple applications in manufacturing, construction, healthcare, education and households, going beyond the popular view of humanoid robots known e.g. from science-fiction

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movies (Keisner, Raffo and Wunsch-Vincent, 2016, p. 8). Robotic devices could be remotely controlled by human users, operate as semi-autonomous, or even fully autonomous devices, owing to the use of artificial intelligence that supports human-like decisions (Keisner, Raffo and Wunsch-Vincent, 2016, p. 8-9). ISO 8373:2012 standard defines a robot as "*actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment to perform intended tasks*" (ISO, 2012) and an industrial robot as "*an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*" (ISO, 2012). Popular applications of industrial robots include: picking and placing, assembly and disassembly, machine feeding, material handling, handling for metal casting, wafers or plastic moulding, grinding and cutting, welding and soldering, painting and enamelling, polishing, sealing, application of adhesive materials, packaging and cleanroom operations (IFR, 2018, p. 35-41).

Technologies and solutions used by robotics have significantly improved in the 20th century, with a distinctive focus on components responsible for the physical contact between the robots and items that were subject to transformations enabled by robotics (driven by the development of mechatronic engineering). The seminal study by Kumaresan and Miyazaki (1999) tracked the developments of robotics innovation systems until the 1990s, analysing activities related to scientific research, technology development (patenting) and product sales (market data). In the past, robotic inventions coming from the academia or publicly supported research were frequent sources of commercially successful solutions (see e.g.: MacBryde, 1997). At present, more emphasis is put on the development of software, including software relying on artificial intelligence, which enables complex decision-making by robots and increases their independence (Keisner, Raffo and Wunsch-Vincent, 2016, p. 10). Moreover, the observed emergence of new technologies affects product portfolios and R&D strategies of incumbent companies, as approaches based on artificial intelligence have the potential to disrupt specific market segments and render older generations of robots less appealing to industrial customers (Roy and Sarkar, 2016). Not surprisingly, robotics is viewed as one of core technologies that could fuel the industrial transformation envisaged by the concept of Industry 4.0, next to the Internet of things and the use of big data. Lu (2017) offered an overview of technologies that could form the basis of Industry 4.0 initiatives, including the digitalisation of industry, inter-connectivity or organisations, human-machine interaction and automation owing to the industrial use of the Internet of things. As Kang et al. (2016) suggest, complex frameworks and a multitude of technologies are needed for Industry 4.0 or smart manufacturing, among them also robotics. In particular, collaborative robots and machine-to-machine communication offer significant development potential as part of the Industry 4.0 approach (Moeuf et al., 2018, p. 1121).

The use of industrial robots seems an obvious candidate for the automation of enterprise operations in line with the imperatives of Industry 4.0, and is featured prominently in the strategies of German and Chinese governments (Li, 2018). However, interestingly and contrary to researchers' expectations, a systematic review of publications related to the complementary concept of smart factory found that robotics was not among key research topics identified by bibliometric analyses (Strozzi et al., 2017). Similarly, a comprehensive analysis of documented case studies of industrial practices aligned with Industry 4.0, carried out by Moeuf et al. (2018), revealed numerous examples of using specific technologies to support industrial transformations, but its authors admitted that they were not able to identify any relevant examples of the industrial use of robotics that would directly correspond to the premises of the Industry 4.0 approach (Moeuf et al., 2018, p. 1129). At the same time, there appear to be numerous examples of robotics applications in business enterprises, with clear economic benefits, but not necessarily labelled as contributing towards Industry 4.0. For example, Polish case studies of innovative robotic technology implementations by dairy company *Okręgowa Spółdzielnia Mleczarska w Piątnicy*, automotive components producer *GEDIA Poland Assembly*, mining company *PAK Kopalnia Węgla Brunatnego Konin* and the manufacturer of construction materials *Megaron* were documented by Łapiński, Peterlik and Wyżnikiewicz (2013), and a complex case study of the use of robotics to rejuvenate arc welding companies was examined by Chen and Lv (2014).

Apart from industrial robots, robots can also have relevant, economically beneficial applications in various other sectors or types of activities, for example, support surgeries by increasing the precision and reducing the occurrence and impact of human errors (Compagni, Mele and Ravasi, 2015), to care for elderly or disabled citizens, ensuring full availability and immediate reactions (Goeldner, Herstatt and Tietze, 2015), or to provide sexual services (Yeoman and Mars, 2012). The emerging categories of medical and care robots complement the already well-developed segment of industrial robots and, not surprisingly, their developments are actively pursued in countries with aging populations, high labour costs and limited availability of personnel. Popular types of personal/domestic service robots include: vacuuming, lawn moving, cleaning of floors, pools and windows, home security and surveillance, entertainment (toys, multimedia and education), robotized wheelchairs, personal aids and assistive devices (IFR, 2018, p. 44), while professional service robots can be used for field-work (agriculture, milking, livestock farming, mining, space), professional cleaning (floors, windows, walls, tanks, tubes and pipes, hulls of aircrafts and vehicles), inspection and maintenance (of facilities, plants, tanks, tubes, pipes and sewers), construction and demolition, logistics (with autonomous guided vehicles), medicine (with diagnostic, surgical, therapeutic and rehabilitation applications), rescue and security (among others for fires and disasters), defence (demining, bomb

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fighting, unmanned aerial vehicles or unmanned ground-based vehicles), underwater systems, exoskeletons (external skeletons supporting the body to facilitate human or animal operations) as well as robot joy rides, mobile guidance, telepresence and information (IFR, 2018, p. 45).

Robotics is one of important technologies, laying foundations for the implementation of Industry 4.0, even though the industrial use of robots remains marginal in Poland, particularly in comparison to more developed economies. Tab. 1 presents the density of robotics, measured by the International Federation of Robotics as the number of industrial robots per 10,000 employees. Poland has only 36 robots per 10,000 employees and is outperformed in this respect by its neighbours from Central and Eastern Europe, let alone more advanced, Western European or Asian countries. According to IFR estimates, by the end of 2017, Polish companies were using approximately 11,400 industrial robots.

Country	**Density of robotics**
South Korea	710
Singapore	658
Germany	322
Japan	308
Sweden	240
Denmark	230
United States	200
Taiwan	197
Belgium	192
Italy	190
Netherlands	172
Austria	167
Canada	161
Spain	157
Slovakia	151
Slovenia	144
Finland	139
France	137
Switzerland	129
Czechia	119
Europe	**106**
China	97
World	**85**
Hungary	78
Poland	36
Romania	18
Russia	4

Tab. 1. Density of industrial robotics in 2017, measured as the number of industrial robots per 10,000 employees. Source: IFR (2018).

Tab. 2 presents the density of robotics in the automotive industry, which remains the most active user of robots, accounting for the majority of relevant investments. In this highly automated industry, Poland stands even further apart from technologically-oriented nations, with only 165 robots per 10,000 employees. Density data reveals also that intensive investments in industrial robots have taken place not only in countries with highest labour costs, but also in lower-income countries, such as Hungary, Slovakia or Thailand.

Country	Density of robotics in automotive sector
Canada	1,354
United States	1,200
Germany	1,162
Japan	1,158
France	1,156
Austria	1,083
Slovenia	1,075
Spain	990
Thailand	974
Taiwan	940
Poland	165

Tab. 2. Density of industrial robotics in automotive sector in 2017, measured as the number of industrial robots per 10,000 employees. Source: IFR (2018).

The limited diffusion of robotic technologies among businesses in Poland is also confirmed by a recent local study by Piątek (2018), which suggests an increased interest of companies and peaking technology sales confirmed by robotics suppliers. Econometric modelling of the labour market in European countries confirmed a high probability of the elimination of jobs through automation owing to the diffusion of robotics, with a particularly high share of jobs at risk due to automation in Spain, Portugal, Slovakia, the Czechia, Hungary, Italy, Estonia, Cyprus and Poland (Bitner, Starościk and Szczerba, 2014, p. 18). In Poland, as many as 36.1% jobs are endangered by robotics, 35.9% are moderately endangered, and 28.0% remain safe (Bitner, Starościk and Szczerba, 2014, p. 26). Further increases in the use of industrial robots in Poland can be expected, particularly given the popularity of Industry 4.0 and strong support for industrial renewal in government strategies, including a prominent report on the future of robotics published by the Industrial Development Agency (Michałowski, Jarzynowski and Pacek, 2018).

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3. Literature review – patents in robotics

Patent analyses offer insights into an important dimension of sectoral innovation system, related to the development of innovations and R&D activities. Tracking patent applications helps reveal creative interests of social actors and their inventive activities. Bibliometric analyses of patent applications and granted patents support the profiling of countries, regions, organisations and research teams, with differentiated intensity of inventive activities, various thematic interests, as well as inter- or intra-sectoral collaboration patterns. Bibliometric studies tend to be descriptive, focusing on the illustration of trends, rankings of R&D performers and exploration of thematic diversity. It should be remembered that patent data present a relatively limited perspective on innovation systems, focusing on creative activities yielding inventive results that could be filed for patent protection, and thus disregarding important aspects related to the diffusion of innovations within markets and organisations. The issue of diffusion remains particularly relevant for discussing the use of robotics in the context of Industry 4.0 initiatives, as many companies will derive significant economic benefits from upgrading their technology stock through the implementation of robotic solutions, which would not be developed by the user companies themselves, but rather acquired in the market from specialist technology suppliers.

There is no overarching theoretical framework pertaining to robotics patenting, and relevant publications remain scarce. Existing studies of robotic patents include: a comprehensive analysis of the patenting landscape in robotics in the 20th century (Kumaresan and Miyazaki, 1999), as well as more recent studies based on the Derwent Innovation Index platform, 2004–2013 (Intellectual Property Office, 2014) and the PATSTAT database maintained by the European Patent Office, which aggregated patent data from over 40 patent authorities worldwide, 1995–2012 (Keisner, Raffo and Wunsch-Vincent, 2016). These three studies focused on summarizing counts of patents filed by applicants from individual countries or types of organisations to illustrate technological developments. Studies focusing on selected subsets of patent data were also carried out for Chinese robotics inventions (Kong et al., 2017), Japanese science-industry collaborations unveiled by patenting practices (Lechevalier, Ikeda and Nishimura, 2011), and complementary research was conducted by applying patent-like analytical approaches to a database of R&D projects co-funded by the government of South-Korea (Lee and Jeong, 2008). None of the previous studies analysed robotic patents in Poland, and relevant patenting activities in Poland were disregarded in these studies due to relatively low counts of patent applications and granted patents in comparison with other countries. Moreover, analytical frameworks used in previous studies of patents in robotics were descriptive in nature, tracking tendencies and ranking positions, without advanced quantitative analyses, such as econometric modelling.

Keisner, Raffo and Wunsch-Vincent (2016) identified in their study key players and top patent applicants, highlighting the importance of a small number of leading technology-oriented countries in the global protection of robotics-related intellectual property. After 2000, three countries – China, South Korea and Australia – significantly increased their patenting activities and, consequently, joined the group of market leaders including Japan, the US, Germany and France (Keisner, Raffo and Wunsch-Vincent, 2016, p. 13). Organisations from high-income countries are motivated to develop robotic technologies as a manoeuvre that prevents the relocation of manufacturing to offshore locations and preserves their competitive edge despite comparatively higher costs of personnel, as the use of industrial robots offers productivity increases, quality improvements, reduction of production costs and opportunities to pursue novel business models (Keisner, Raffo and Wunsch-Vincent, 2016, p. 11). Also China is found to invest heavily in robotics and into the development of relevant innovations, as the rise of labour costs is expected to gradually erode the Chinese competitive edge in global manufacturing, while local companies turn to technological support in order to maintain their position as industrial cost leaders. Analyses of patenting activities revealed the predominance of the public science sector as a source of inventions in China, with a particularly strong role of public research institutes registered also in South Korea, Taiwan, Germany and Russia, and universities as leading robotics applicants in China (Keisner, Raffo and Wunsch-Vincent, 2016, p. 13); business enterprises play a prominent role among patent applicants in Japan, Germany, France and South Korea (Keisner, Raffo and Wunsch-Vincent, 2016, p. 14). Between 1995 and 2012, ten companies had accumulated portfolios of 1,000 or more patent applications in robotics; as many as eight of them were Japanene (Toyota, Honda, Nissan, Denso, Hitachi, Panasonic-Matsushita, Yaskawa and Sony), one company was South Korean (Samsung) and one German (Bosch) (Keisner, Raffo and Wunsch-Vincent, 2016, p. 20). In turn, all of the top ten patent applicants from the science sector (universities and public research institutes) were Chinese or South Korean (Keisner, Raffo and Wunsch-Vincent, 2016, p. 21). The role of individual inventors as patent applicants was limited in comparison to institutional applicants, i.e. companies or scientific institutions (Keisner, Raffo and Wunsch-Vincent, 2016, p. 14). Importantly, the group of the most active applicant companies included not only robotics specialists, offering robots and related technologies for sale, but also organisations from other industrial fields, which use robots to improve their internal operations, without the primary intent of selling them to third parties (Keisner, Raffo and Wunsch-Vincent, 2016, p. 15).

An important caveat of patent-based analyses of robotics is the importance of software-derived innovations, which do not necessarily find their representation in patenting activities, as the patentability of software algorithms and computer-enabled inventions is heavily impaired in the

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majority of patenting regimes. Moreover, robotic developers make an increasing use of open source software (Keisner, Raffo and Wunsch-Vincent, 2016), whose developers might intentionally refrain from seeking patent protection to ensure their wide diffusion that benefits society.

Patents and inventions play an important role in sectoral innovation systems, but other activities might be equally relevant for the successful development and diffusion of innovations. Patenting is focused on the legal protection of tangible results of R&D (development of innovations), while innovation systems also require the comprehension of innovations (through education, training, presentations and testing), adaptation of innovations (through local-scale R&D and adjustments, customisations), adoption of innovations (through their implementations bringing about process and organisational innovations), as well as the financing and organisation of innovative activities. Therefore, the present article and other patenting studies present only one aspect of complex innovation systems, even though all the remaining elements are also necessary in order to promote the development and diffusion of novel technologies.

4. Research methods

The research was based on quantitative analyses of patent applications (bibliometric techniques). The main advantage of bibliometrics as an approach to quantitative analyses lies in the specialist and knowledge-based process of data selection, cleaning and classification, enabling the mapping of scientific or technological activities in a given field, which could subsequently be used as input data for other analyses (Porter and Cunningham, 2005).

Patent documents were sourced in August 2018 from the database of the Polish Patent Office, based on search criteria corresponding to the field of robotics. The documents were downloaded using a custom-built data crawler, since the Polish Patent Office database does not offer analytical or exporting functionalities. Their contents were transformed into a standardized data structure, used for the subsequent quantitative analyses. Patent queries relied on the following sub-classes of the International Patent Classification (IPC), used also in previous studies of robotics (Intellectual Property Office, 2014; Keisner, Raffo and Wunsch-Vincent, 2016):

- B25J* (“manipulators, chambers provided with manipulation devices”),
- B60W* (“conjoint control of vehicle sub-units of different type or different function; control systems specially adapted for hybrid vehicles; road vehicle drive control systems for purposes not related to the control of a particular sub-unit”),
- G05D* (“systems for controlling or regulating non-electric variables”),
- G08G1/16 (“anti-collision systems”).

The queries identified all priority applications matching the selected IPC sub-classes that were filed with the Polish Patent Office between

1 January 2006 and 31 December 2015. The subset of documents included both applications with granted patents, as well as patent applications under examination and those that had been rejected. The reliance on patent applications rather than granted patents is common in bibliometric analyses. The analyses presented in the article illustrate technological activities between 2006 and 2015, but do not assess the levels of innovativeness of the concerned patent applications (some of the rejected patent applications might not demonstrate the necessary inventive steps, represent previously known or sometimes even trivial ideas).

It should be highlighted that patent applications are only publicly disclosed (i.e. listed in patent databases) 18 months after the date of priority application, so empirical analyses need to take into account the publication delay and cannot track most recent developments. Robotics patenting between January 2016 and September 2017 (i.e. the latest month for which data were available at the moment of finalizing this article) involved 50 further patent applications, including 19 patents in the B28J* sub-class, 7 in B60W*, 25 in G05D* (with 3 co-assigned also to B25J*) and 2 in G08G1/16. No acceleration or concentration of robotics patenting was observed in Poland after 2015.

The patent dataset was cleaned (including the standardisation of names of organisations-applicants and cities), transformed through data coding (by assigning applicants to specific sectors and regions of Poland), and processed using descriptive statistical techniques. The subsequent analyses were focused on addressing the following research hypotheses, which will be discussed in more detail in the following section of this article:

- H1. Patenting of robotics in Poland in 2006–2015 was dominated by activities of scientific organisations (including higher education institutes and public research organisations) rather than business enterprises or individual investors.
- H2. Patent applications in robotics filed in Poland by representatives of different sectors (business enterprises, higher education institutes, public research organisations and individuals) between 2006 and 2015 reveal divergent sectoral tendencies measured by:
  - H2a. patent success rates,
  - H2b. patent discontinuance rates,
  - H2c. patent failure rates,
  - H2d. counts of co-inventors jointly developing an invention filed for patent protection,
  - H2e. counts of co-applicants filing joint patent applications.
- H3. The extent of inter-sectoral collaboration in robotics, measured by counts of joint patent applications filed in Poland between 2006 and 2015, was insignificant.
- H4. Robotics patenting activities are highly concentrated in selected regions of Poland.

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- H5. In 2006-2015, the thematic diversity of patents in robotics applied for in Poland does not reveal the critical mass created by patent applicants from specific sectors in any specialised field of technology.
- H6. The thematic focus of patent applications in the field of robotics filed in Poland differs from thematic interests of applicants in leading international patent systems of the United States, the European Patent Office, Japan and China.

In order to analyse current tendencies in international robotics patenting that could be compared with the Polish data (H6), Derwent Innovation Index from the Web of Science database was used with the most recent available timeframe of 2010–2017, and the same list of IPC sub-classes as in the case of queries used to derive data from the Polish Patent Office.

5. Research results

Empirical analyses presented in this article are aimed at addressing 5 detailed research hypotheses, which offer an overview of patenting activities related to robotics in Poland, and H6, which compares Polish robotic inventions to parallel developments in other countries.

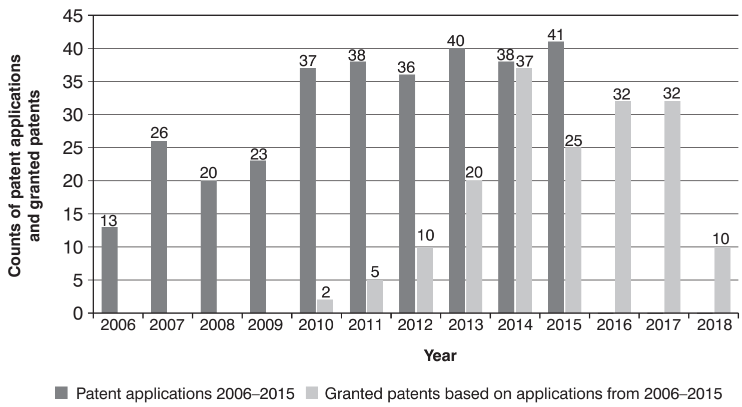

Fig. 1. Counts of robotics patent applications and granted patents in Poland. Source of data: Polish Patent Office database.

The analysis of patent dataset offered insights into the scale of patenting activity in robotics in Poland, including annual counts of patent applications and granted patents. Data derived from the Polish Patent Office database revealed that between 2006 and 2015, 312 patent applications were filed in the field of robotics, and these applications yielded altogether 173 patents granted in 2010–2018 (55.4% of filed applications), with 13 further patents granted but expired, as applicants failed to pay the compulsory patent maintenance fees, 27 patent applications rejected, 2 applications invalid as their conditional decisions expired, patent granting procedures for 2 applications discontinued for other reasons, and 95 patent applications subject to ongoing procedures.

Fig. 1 presents the annual counts of patent applications and granted patents based on the subset of applications from 2006–2015, with a notable increase in 2010, when average annual counts of patents nearly doubled.

This initial patent overview set the stage for the verification of hypothesis 1:

H1. Patenting of robotics in Poland in 2006–2015 was dominated by activities of scientific organisations (including higher education institutes and public research organisations) rather than business enterprises or individual investors.

Sectors of the Polish innovation system had diversified propensity to patent their innovations in the field of robotics, as evidenced by Tab. 3. Universities and other higher education institutes (HEI) had 81 applications and 59 granted patents. Public research organisations including the institutes of the Polish Academy of Sciences and government-funded research institutes turned out to be the most active actor, with 119 submitted applications and 73 granted patents. The sector of business enterprises (BES), including companies and non-public entities, such as foundations or private healthcare establishments, submitted 92 patent applications and were granted 35 patents. Individual inventors filing for patent protection played a relatively minor role in the field of robotics, with 31 submitted applications and only 14 granted patents. Altogether, HEIs and PROs accounted for 64.1% of all patent applications filed in Poland between 2006 and 2015, and 76.3% of granted patents in the field of robotics.

Differences in patenting approaches by individual sectors can be further analysed in relation to the following hypothesis:

H2. Patent applications in robotics filed in Poland by representatives of different sectors (business enterprises, higher education institutes, public research organisations and individuals) between 2006 and 2015 reveal divergent sectoral tendencies measured by:

- **H2a. patent success rates,**
- **H2b. patent discontinuance rates,**
- **H2c. patent failure rates,**
- **H2d. counts of co-inventors jointly developing an invention filed for patent protection,**
- **H2e. counts of co-applicants filing joint patent applications.**

Sectoral **success rates**, described by H2b, denote shares of patents granted among patent applications. These rates varied among sectors: 38.0% for BES, 72.8% for HEI, 45.2% for IND and 61.3% for PRO, compared with the average rate of 55.4% for all sectors forming the innovation system. Particularly notable is the difference between scientific organisations (HEI,

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PRO) and the private sector (BES, IND), confirming higher probability of success for patent applications in the field of robotics submitted by universities or research institutes.

Decision / sector	BES	HEI	IND	PRO	Total
Patent applications	92	81	31	119	312
Patent granted	35	59	14	73	173
Patent expired (unpaid maintenance fees)	0	7	2	4	13
Conditional decision expired	2	0	0	0	2
Application rejected	15	4	6	2	27
Procedure discontinued	1	0	0	1	2
Decision pending	39	11	9	39	95
Success rate [patents granted / patent applications]	*38.0%*	*72.8%*	*45.2%*	*61.3%*	*55.4%*
Discontinuance rate [patents expired / (patents granted + patents expired)]	*0.0%*	*10.6%*	*12.5%*	*5.2%*	*7.0%*
Failure rate [(applications rejected + procedure discontinued) / patent applications]	*17.4%*	*4.9%*	*19.4%*	*2.5%*	*9.3%*
Number of applicants	75	21	35	17	148
Number of applicants with 3+ patent applications	7	11	0	4	22
Number of applicants with 2+ patent applications	10	16	0	9	35

Abbreviations: BES = business enterprises, HEI = higher education institutes, IND = individual inventors, PRO = public research organisations.

Tab. 3. Key patenting statistics for sectors of the Polish innovation system. Source of data: Polish Patent Office database.

H2b refers to the counts of patents that were granted but expired due to unpaid patent maintenance fees (patent discontinuance rates). Such cases usually correspond to inventions that are intentionally discarded by their owners, who no longer believe in their commercial potential or technological viability. Counts of such discontinued, expired patents were generally low, with no expired patents of BES, 7 patents of HEI, 2 of IND and 4 of PRO. **Patent discontinuance rates**, comparing the counts of expired patents with the number of granted patents, either maintained or expired, turned out to be high for IND (12.5%) and HEI (10.6%), but relatively lower for PRO (5.2%).

Patent failure rates, covered by H2c, compare counts of applications rejected or abandoned due to discontinued procedures with the overall numbers of patent applications. Overall counts of patent applications include granted patents (see: patent success rates, H2a), applications rejected (H2c) and pending applications awaiting the decision of patent examiners. Failure rates for patents turned out to be particularly unfavourable in the case of IND (19.4%) and BES (17.4%), while public science organisation had proportionally fewer applications rejected (HEI: 4.9%, PRO: 2.5%). This indicates inter-sectoral differences and suggests better patent drafting skills and greater selectivity in the process of applying for patent protection among scientific organisations (HEI, PRO).

In order to provide further illustration of the diverging inter-sectoral patenting activities, Tab. 4, Tab. 5 and Tab. 6 list the most prolific applicant organisations representing, respectively, business enterprises, higher education and public research organisations. Altogether, 148 applicants filed patent applications in the field of robotics, including 75 BES, 21 HEI, 35 IND and 17 PRO. Only a small subgroup of 22 applicants had 3 or more patent applications (7 BES, 11 HEI, 4 PRO), and further 13 applicants had 2 patent applications each. The most active applicants were: PIAP (pl. *Przemysłowy Instytut Automatyki i Pomiarów*, Industrial Institute of Automatics and Measurements in Warsaw) with 83 patent applications, AGH (pl. *Akademia Górniczo-Hutnicza w Krakowie*, AGH University of Science and Technology in Krakow) with 19 applications and ITEE (pl. *Instytut Technologii Eksploatacji*, Institute for Sustainable Technologies in Radom) with 15 applications.

No.	Name of organisation	Applications
1	Joy MM Delaware, Inc.	5
2	ELOKON Polska Sp. z o.o.	4
3	Fundacja Rozwoju Kardiochirurgii im. prof. Zbigniewa Religi	5
4	Miejskie Przedsiębiorstwo Wodociągów i Kanalizacji Wodociągi Puławskie Sp. z o.o.	3
5	Proagria – Ria Watech Sp. z o.o.	3
6	Robotics Inventions Sp. z o.o.	3
7	Wikpol Sp. z o.o.	3
8	Linter S.A.	2
9	Markon Sp. z o.o.	2
10	RRM-Technic Sp. z o.o.	2
	Σ 75 organisations, including 10 with 2 or more patent applications	

Tab. 4. Business enterprises with highest counts of patent applications in the field of robotics. Source of data: Polish Patent Office database.

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No.	Name of organisation	Applications
1	Akademia Górniczo-Hutnicza w Krakowie	19
2	Politechnika Wrocławska	9
3	Politechnika Śląska	8
4	Politechnika Lubelska	5
5	Politechnika Rzeszowska	5
6	Politechnika Świętokrzyska	4
7	Politechnika Koszalińska	3
8	Politechnika Łódzka	3
9	Politechnika Poznańska	3
10	Politechnika Radomska	3
11	Politechnika Warszawska	3
12	Uniwersytet Technologiczno-Przyrodniczy w Bydgoszczy	3
	Σ 20 organisations, including 12 with 3 or more patent applications	

Tab. 5. Higher education institutes with highest counts of patent applications in the field of robotics. Source of data: Polish Patent Office database.

No.	Name of organisation	Applications
1	Przemysłowy Instytut Automatyki i Pomiarów PIAP	83
2	Instytut Technologii Eksploatacji ITEE	15
3	Narodowe Centrum Badań Jądrowych	3
4	Przemysłowy Instytut Motoryzacji	3
5	Centralny Instytut Ochrony Pracy	2
6	Centrum Badań Kosmicznych Polskiej Akademii Nauk	2
7	Instytut Technologiczno-Przyrodniczy w Puławach	2
9	Wojskowy Instytut Medycyny Lotniczej	2
	Σ 17 organisations, including 9 with 2 or more patent applications	

Tab. 6. Public research organisations with highest counts of patent applications in the field of robotics. Source of data: Polish Patent Office database.

Tab. 7 presents the outcomes of patenting procedures, ranking organisations based on the number of granted patents and revealing their patenting success rates (shares of patent applications in the field of robotics in 2006–2015 that became successfully granted patents), reaffirming the leading positions of PIAP, AGH and ITEE.

No.	Name of organisation	Patents granted	Applications	Success rate
1	Przemysłowy Instytut Automatyki i Pomiarów PIAP	50	83	60.2%
2	Akademia Górniczo-Hutnicza w Krakowie	15	19	78.9%
3	Instytut Technologii Eksploatacji ITEE	12	15	80.0%
4	Politechnika Wrocławska	8	9	88.9%
5	Fundacja Rozwoju Kardiochirurgii im. prof. Zbigniewa Religi	5	5	100.0%
6	Politechnika Lubelska	5	5	100.0%
7	Politechnika Śląska	5	8	62.5%
9	Politechnika Rzeszowska	4	5	80.0%
10	Miejskie Przedsiębiorstwo Wodociągów i Kanalizacji Wodociągi Puławskie Sp. z o.o.	3	3	100.0%
11	Narodowe Centrum Badań Jądrowych	3	3	100.0%
12	Politechnika Koszalińska	3	3	100.0%
13	Politechnika Łódzka	3	3	100.0%
14	Politechnika Poznańska	3	3	100.0%
15	Proagria – Ria Watech Sp. z o.o.	3	3	100.0%
16	Wikpol Sp. z o.o.	3	3	100.0%
17	Uniwersytet Technologiczno-Przyrodniczy w Bydgoszczy	3	3	100.0%
18	Politechnika Białostocka	2	2	100.0%
19	Politechnika Świętokrzyska	2	4	50.0%
	Σ 70 organisations, including 18 with 2 or more patent applications			

Tab. 7. Organisations with highest counts of granted patents in the field of robotics. Source of data: Polish Patent Office database.

H2d referred to structural differences between sectors in their patenting activities, represented by the individual or collective dimension of the inventive processes. **Counts of co-inventors** stand for the size of the collaborating team of R&D experts, who jointly contributed towards the

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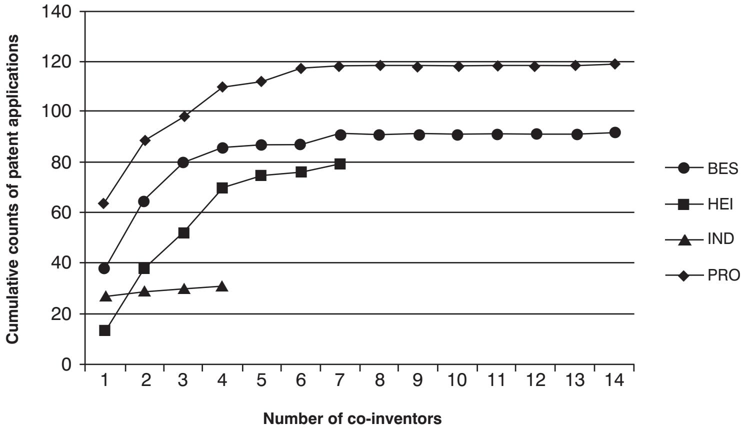
development of a given innovation and their contributions were recognized by the organisation filing for patent protection. This sectoral diversity is visible in Fig. 2, which represents cumulative counts of patent applications with a specific number of co-inventors. For IND, the majority of patent applications documented the work of individual inventors, with few applications listing 2, 3 or 4 co-inventors. Applications of HEI testified to more collective inclinations, with the maximum number of 7 co-inventors, while the applications of BES and PRO indicated the contribution of up to 14 co-inventors, although the majority of applications had 1-3 co-inventors.



Abbreviations: BES = business enterprises, HEI = higher education institutes, IND = individual inventors, PRO = public research organisations.

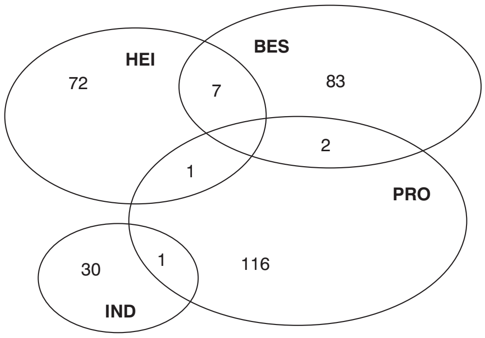
Fig. 2. Cumulative counts of patent applications with specific numbers of co-inventors. Source of data: Polish Patent Office database.

Quantitative verification of H2d was further offered by the one-way analysis of variance (ANOVA), used to determine whether any statistically significant differences can be observed between the means of the two groups. ANOVA procedure was carried out for the variable denoting the count of (co-)inventors listed on a given patent application, with observations divided into four groups based on their sectoral origin (BES – mean: 2.26, SD: 1.89; HEI – mean: 3.02; SD: 1.67; IND – mean: 1.19, SD: 0.65; PRO – mean: 2.10, SD: 1.81). F-test statistics amounted to 9.60 ($p<0.001$), thus indicating a statistically significant difference between sectors and supporting H2d.

H2e refers to collective aspects of patent ownership, i.e. the occurrence of joint patent applications submitted by more than one organisation, and tracing inter-sectoral differences (**counts of co-applicants**). Out of 312 patent applications, the majority (297) were submitted by single applicants (95.2%), with only 10 having two co-applicants, 4 listing three co-applicants and 1 with four co-applicants. ANOVA, with a dependent variable denoting the count of (co-)applicants decomposed into four sectors (BES – mean: 1.16, SD: 0.50; HEI – mean: 1.12, SD: 0.37; IND – mean: 1.16, SD: 0.52; PRO – mean: 1.11, SD: 0.42), did not yield any conclusive results, with F-test of 1.50, p=0.216, due to very small numbers of co-owned patent applications included in the analysis.

The findings of analyses related to hypotheses H2a, H2b, H2c, H2d and H2e were further extended by the discussion of hypothesis 3:

H3. The extent of inter-sectoral collaboration in robotics, measured by counts of joint patent applications filed in Poland between 2006 and 2015, was insignificant.



Abbreviations: BES = business enterprises, HEI = higher education institutes, IND = individual inventors, PRO = public research organisations.

Fig. 3. Counts of joint cross-sectoral patent applications in the field of robotics. Source of data: Polish Patent Office database.

Fig. 3 plots the ellipses representing stocks of patent applications submitted by applicants from each sector, with intersections representing joint inter-sectoral applications. Their counts are indeed marginal, thus supporting H3. Only 7 applications were jointly submitted by BES and HEI, 2 by BES and PRO, 1 by HEI and PRO and 1 by PRO and IND. This demonstrates relative immaturity of the sectoral innovation system, where collaboration and open innovations remain underdeveloped. Nevertheless, it should also be mentioned that these counts have varying relevance for applicants representing each sector, accounting for specific shares of patent applications filed jointly with other sectors: 9.9% for HEI (8 inter-sectoral applications with the involvement of higher education institutes), 9.8% for BES (9 applications filed by companies with other sectors), 3.4% for PRO (4 cross-sectoral applications) and 3.2% for IND (1 application filed jointly by an individual applicant and research institute). Fig. 4 offers a graphical representation of this small and fragmented network of co-patenting entities, developed using the Social Network Analysis tool *NodeXL*.

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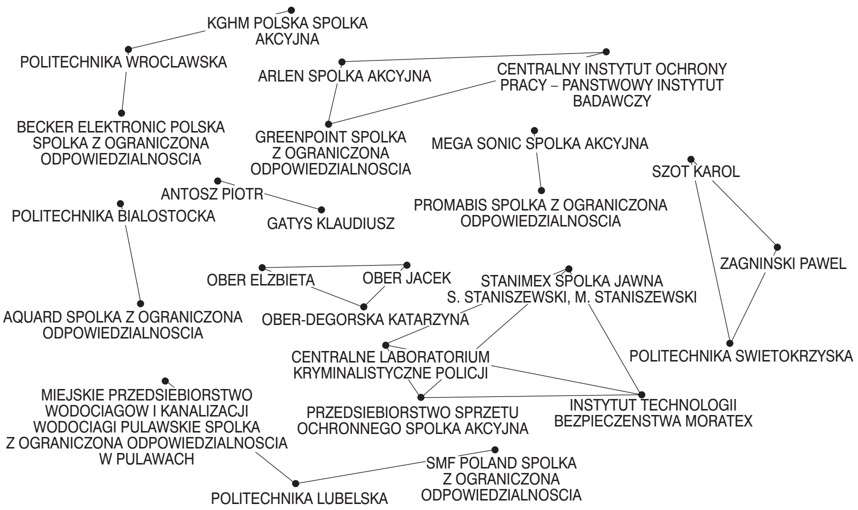

Fig. 4. Network of organisations and individuals with joint cross-sectoral patent applications in the field of robotics. Source of data: Polish Patent Office database.

H4. Robotics patenting activities are highly concentrated in selected regions of Poland.

Fig. 5. Counts of patent applications in the field of robotics filed by applicants from Polish regions. Source of data: Polish Patent Office database.

In order to verify H4, each affiliation of a patent applicant was assigned to one of 16 regions of Poland (voivodeships, pl. *województwa*) based on addresses listed in patent applications in order to analyse the geographical distribution of patenting activities. Results of the analysis are presented in Fig. 5 and they confirm the high geographical concentration of patent applications in the field of robotics in a small subset of regions (H4).

The central region of Masovia (pl. *Mazowieckie*), including the country's capital Warsaw, turned out to dominate the robotics scene, with almost half of all robotics patent applications (142 applications). Other regions were notably less prolific, with Silesia (pl. *Śląskie*) having 31 applications, Lesser Poland (pl. *Małopolskie*) 29, Lower Silesia (pl. *Dolnośląskie*) 21, and Greater Poland (pl. *Wielkopolskie*) 18 applications.

Tab. 8 lists regional counts of patent applications divided into sectors, revealing the dominance of BES in *Mazowieckie* and *Śląskie*, HEI in *Małopolskie*, IND in *Wielkopolskie* and PRO in *Mazowieckie*. Tab. 9 presents a list of cities where applicants are located, with Warsaw as the leader (116 applications), followed by Krakow (25 applications), Radom (19 applications) and Wroclaw (16 applications).

The concentration measure used to verify H5 was the Herfindahl-Hirschman Index, HHI, calculated based on the following formula:

$$HHI = \sum_{i=1}^{n} p_i^2,$$

where: pi denotes the count of patent applications originated in the region i, and n is the total number of regions. HHI assumes values between 0 and 1, with higher values representing higher concentrations. For all patent applications filed in the field of robotics in Polish regions, HHI was 0.2414, thus indicating the centralisation of inventions in a small subset of regions. The HHI for applicant sectors differed, with less concentration observed in BES (0.1254), HEI (0.1230) and IND (0.1308), but very high index value for PRO (0.8763), as the majority of patent applications were filed by research institutes registered in Masovia.

Region	**BES**	**HEI**	**IND**	**PRO**	**ALL**
Dolnośląskie (Lower Silesia)	7	9	7	0	**21**
Kujawsko-Pomorskie (Kujawy-Pomerania)	1	3	2	0	**6**
Łódzkie (Lodz)	6	4	2	2	**12**
Lubelskie (Lublin)	9	5	0	2	**11**
Lubuskie (Lubusz)	0	0	0	0	**0**
Małopolskie (Lesser Poland)	6	21	2	1	**29**

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continued Table 8

Region	BES	HEI	IND	PRO	ALL
Mazowieckie (Masovia)	19	11	0	116	**142**
Opolskie (Opole)	2	0	0	0	**2**
Podkarpackie (Subcarpathian)	4	6	2	0	**11**
Podlaskie	3	2	1	0	**5**
Pomorskie (Pomeranian)	3	1	2	0	**6**
Śląskie (Silesia)	18	9	3	3	**31**
Świętokrzyskie	1	4	1	0	**5**
Warmińsko-Mazurskie (Warmia-Masuria)	1	0	1	0	**2**
Wielkopolskie (Greater Poland)	8	3	7	0	**18**
Zachodniopomorskie (Western Pomeranian)	1	7	2	0	**10**
Abroad	9	0	1	0	10

Abbreviations: BES = business enterprises, HEI = higher education institutes, IND = individual inventors, PRO = public research organisations.

Tab. 8. Counts of patent applications in the field of robotics filed by applicants from Polish regions and from abroad. Source of data: Polish Patent Office database.

City	Applications
Warsaw	116
Krakow	25
Radom	19
Wroclaw	16
Gliwice	10
Poznan	10
Lodz	8
Rzeszow	7
Zabrze	7
Lublin	6
Szczecin	6
Bydgoszcz	5
Kielce	5

Tab. 9. Counts of patent applications in the field of robotics filed by applicants from Polish cities. Source of data: Polish Patent Office database.

H5. In 2006-2015, the thematic diversity of patents in robotics applied for in Poland does not reveal the critical mass created by patent applicants from specific sectors in any specialised field of technology.

H5 offers an opportunity to explore the patent dataset with a view to identifying the thematic diversity of patent applications, and repetitiveness in applying for patent protection of inventions in similar technological fields. Patent applications are assigned to specific (sub)classes of the International Patent Classification (IPC), representing distinctive types of technologies. The use of IPC in patent studies helps identify the thematic focus of patenting activities, sectoral differences, areas of concentration and "white spots", disregarded by the majority of applicants.

Tab. 10 and Tab. 11 include lists of the most frequent patent (sub-) classes, with higher- and lower-level decomposition of the IPC hierarchy. Tables present total counts of patent applications in each (sub-)class, accompanied by counts of applications filed by each sector, the importance of each (sub-)class for a given sector (as share of all sectoral patent applications in robotics) and the description of the IPC code, derived from the original classification developed by the World Intellectual Property Organisation.

The analysis indicates distinctive thematic interests of patent applicants from specific sectors. As per Tab. 10, outlining high-level IPC hierarchy (not suitable for the identification of specialist fields of technology, but rather presenting the overall thematic focus), public science organisations (HEI and PRO) tend to pursue inventive activities falling into the IPC class B25 ("Hand tools, portable power-driven tools, handles for hand implements, workshop equipment or manipulators"), while private sector entities (BES and IND) focus rather on IPC class G05 ("Controlling, regulating"). BES are also interested in robotics for vehicles (B60), measuring and testing (G01), engineering elements or units (F16), and signalling (G08). HEI pursue measuring and testing (G01), engineering elements or units (F16), robotics for medical or veterinary science (A61), land vehicles (B62) and machine tools (B23). IND excel in vehicles (B60), engineering elements or units (F16), earth or rock drilling and mining (E21), heating and ventilating (F24) and electric techniques (H05). PRO engage in inventive activities related to robotics for vehicles and land vehicles (B60, B62), measuring and testing (G01) and medical or veterinary science (A61). These findings reveal the diversity of thematic interests of patent applicants from each sector but, on the aggregate level of IPC hierarchy, do not yet allow to identify any distinctive technological specialisations.

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Tab. 11 presents more granular data, using lower-level decomposition of IPC sub-classes. Sub-classes B25J, B60W and G05D were used as the basis for the identification of relevant robotics patents and due to their broad character, they could not represent technological specialisations. BES are particularly active in H05B (electric heating or lighting), E21C (mining or quarrying), as well as G01C (measuring distances, levels or bearings, surveying or navigating). HEI also focus on G05B (general control or regulating systems) and A61B (diagnosis, surgery or identification). IND are strongly involved in the patenting of inventions related to sub-classes B60W (control systems for vehicles), G08G (traffic control systems) and H05B (electric heating or lighting). PRO have distinctive competencies in G01N (investigating or analysing materials by determining their chemical or physical properties), F15B (systems acting by means of fluids), B60R (vehicle fittings or parts) and G01H (measurement of mechanical vibrations or ultrasonic, sonic or infrasonic waves). Despite these differing technological interests of representatives of the four above-discussed sectors, no single field of technology (denoted by an IPC sub-class) attracted a sizeable number of patent applications that could indicate the existence of a distinctive technological specialisation. In particular, applications filed by business enterprises do not reveal thematic concentrations, with no field accumulating 10% or more applications and, among other sectors, only one IPC sub-class (B62D: motor vehicles, trailers) was represented by more than 10% of patent applications from PRO (12.6%), with robotics patent applications thematically scattered among various specialist fields of technology.

The lack of thematic concentration was further confirmed by the measure of Herfindahl-Hirschman Index (HHI), applied to data for 24 IPC sub-classes presented in Tab. 11 (excluding B25J, G05D, B60W as sub-classes used to select robotics patent data, and thus listed in all documents delineated in the patent dataset). HHI calculated for all patent applications and 24 IPC sub-classes amounted to 0.0251, thus indicating the absence of concentration and diversified distribution of patent applications among various IPC sub-classes. Applications from individual sectors also had low HHI values (BES: 0.0383; HEI: 0.0248; IND: 0.0353; PRO: 0.0411).

IPC class	No. of applications	Description of the IPC class	Number of applications				Share of all robotics applications from the sector			
			BES	HEI	IND	PRO	BES	HEI	IND	PRO
B25	172	HAND TOOLS; PORTABLE POWER-DRIVEN TOOLS; HANDLES FOR HAND IMPLEMENTS; WORKSHOP EQUIPMENT; MANIPULATORS	26	46	8	95	28.3%	56.8%	25.8%	79.8%
G05	121	CONTROLLING; REGULATING	55	32	18	24	59.8%	39.5%	58.1%	20.2%
B60	43	VEHICLES IN GENERAL	13	8	3	19	14.1%	9.9%	9.7%	16.0%
G01	43	MEASURING; TESTING	17	11	2	19	18.5%	13.6%	6.5%	16.0%
F16	29	ENGINEERING ELEMENTS OR UNITS; GENERAL MEASURES FOR PRODUCING AND MAINTAINING EFFECTIVE FUNCTIONING OF MACHINES OR INSTALLATIONS; THERMAL INSULATION IN GENERAL	8	11	3	9	8.7%	13.6%	9.7%	7.6%
A61	25	MEDICAL OR VETERINARY SCIENCE; HYGIENE	4	6	0	16	4.3%	7.4%	0.0%	13.4%
B62	25	LAND VEHICLES FOR TRAVELLING OTHERWISE THAN ON RAILS	6	9	0	10	6.5%	11.1%	0.0%	8.4%
B23	15	MACHINE TOOLS; METAL-WORKING NOT OTHERWISE PROVIDED FOR	1	7	2	5	1.1%	8.6%	6.5%	4.2%
E21	14	EARTH OR ROCK DRILLING; MINING	6	1	3	4	6.5%	1.2%	9.7%	3.4%
G08	14	SIGNALLING	10	5	0	0	10.9%	6.2%	0.0%	0.0%
F15	13	FLUID-PRESSURE ACTUATORS; HYDRAULICS OR PNEUMATICS IN GENERAL	3	4	0	6	3.3%	4.9%	0.0%	5.0%
F24	10	HEATING; RANGES; VENTILATING	5	1	4	0	5.4%	1.2%	12.9%	0.0%
H05	10	ELECTRIC TECHNIQUES NOT OTHERWISE PROVIDED FOR	7	0	3	1	7.6%	0.0%	9.7%	0.8%
B65	9	CONVEYING; PACKING; STORING; HANDLING THIN OR FILAMENTARY MATERIAL	3	0	0	6	3.3%	0.0%	0.0%	5.0%
B66	9	HOISTING; LIFTING; HAULING	4	1	1	3	4.3%	1.2%	3.2%	2.5%
G06	6	COMPUTING; CALCULATING; COUNTING	3	2	0	1	3.3%	2.5%	0.0%	0.8%
H01	6	BASIC ELECTRIC ELEMENTS	1	0	0	5	1.1%	0.0%	0.0%	4.2%
E03	5	WATER SUPPLY; SEWERAGE	3	3	1	1	3.3%	3.7%	3.2%	0.8%

Tab. 10. IPC patent classes most frequently occurring in robotics patent applications. Source of data: Polish Patent Office database.

IPC sub-class	No. of applications	Description of the IPC sub-class	Number of applications				Share of all robotics patent applications from the sector			
			BES	HEI	IND	PRO	BES	HEI	IND	PRO
B25J	172	MANIPULATORS; CHAMBERS PROVIDED WITH MANIPULATION DEVICES	26	46	8	95	28.3%	56.8%	25.8%	79.8%
G05D	115	SYSTEMS FOR CONTROLLING OR REGULATING NON-ELECTRIC VARIABLES	54	29	18	22	58.7%	35.8%	58.1%	18.5%
B60W	23	CONJOINT CONTROL OF VEHICLE SUB-UNITS OF DIFFERENT TYPE OR DIFFERENT FUNCTION; CONTROL SYSTEMS SPECIALLY ADAPTED FOR HYBRID VEHICLES; ROAD VEHICLE DRIVE CONTROL SYSTEMS FOR PURPOSES NOT RELATED TO THE CONTROL OF A PARTICULAR SUB-UNIT	9	7	3	4	9.8%	8.6%	9.7%	3.4%
B62D	24	MOTOR VEHICLES; TRAILERS	3	6	0	15	3.3%	7.4%	0.0%	12.6%
G05B	17	CONTROL OR REGULATING SYSTEMS IN GENERAL; FUNCTIONAL ELEMENTS OF SUCH SYSTEMS; MONITORING OR TESTING ARRANGEMENTS FOR SUCH SYSTEMS OR ELEMENTS	6	5	2	4	6.5%	6.2%	6.5%	3.4%
A61B	16	DIAGNOSIS; SURGERY; IDENTIFICATION	6	5	0	5	6.5%	6.2%	0.0%	4.2%
G01N	14	INVESTIGATING OR ANALYSING MATERIALS BY DETERMINING THEIR CHEMICAL OR PHYSICAL PROPERTIES	5	3	0	9	5.4%	3.7%	0.0%	7.6%
G08G	14	TRAFFIC CONTROL SYSTEMS	6	1	3	4	6.5%	1.2%	9.7%	3.4%
B60K	10	ARRANGEMENT OR MOUNTING OF PROPULSION UNITS OR OF TRANSMISSIONS IN VEHICLES; ARRANGEMENT OR MOUNTING OF PLURAL DIVERSE PRIME-MOVERS IN VEHICLES; AUXILIARY DRIVES FOR VEHICLES; INSTRUMENTATION OR DASHBOARDS FOR VEHICLES; ARRANGEMENTS IN CONNECTION WITH COOLING, AIR INTAKE, GAS EXHAUST OR FUEL SUPPLY OF PROPULSION UNITS IN VEHICLES	3	1	2	4	3.3%	1.2%	6.5%	3.4%
H05B	10	ELECTRIC HEATING; ELECTRIC LIGHTING NOT OTHERWISE PROVIDED FOR	7	0	3	1	7.6%	0.0%	9.7%	0.8%
E21C	9	MINING OR QUARRYING	7	3	0	0	7.6%	3.7%	0.0%	0.0%
F15B	9	SYSTEMS ACTING BY MEANS OF FLUIDS IN GENERAL; FLUID-PRESSURE ACTUATORS, e.g. SERVOMOTORS; DETAILS OF FLUID-PRESSURE SYSTEMS, NOT OTHERWISE PROVIDED FOR	1	2	0	6	1.1%	2.5%	0.0%	5.0%

IPC sub-class	No. of applications	Description of the IPC sub-class	Number of applications				Share of all robotics patent applications from the sector			
			BES	HEI	IND	PRO	BES	HEI	IND	PRO
B23Q	8	DETAILS, COMPONENTS, OR ACCESSORIES FOR MACHINE TOOLS, e.g. ARRANGEMENTS FOR COPYING OR CONTROLLING; MACHINE TOOLS IN GENERAL, CHARACTERISED BY THE CONSTRUCTION OF PARTICULAR DETAILS OR COMPONENTS; COMBINATIONS OR ASSOCIATIONS OF METAL-WORKING MACHINES, NOT DIRECTED TO A PARTICULAR RESULT	1	3	1	3	1.1%	3.7%	3.2%	2.5%
B60S	8	SERVICING, CLEANING, REPAIRING, SUPPORTING, LIFTING, OR MANOEUVRING OF VEHICLES, NOT OTHERWISE PROVIDED FOR	2	1	0	5	2.2%	1.2%	0.0%	4.2%
B66C	8	CRANES; LOAD-ENGAGING ELEMENTS OR DEVICES FOR CRANES, CAPSTANS, WINCHES, OR TACKLES	4	1	1	2	4.3%	1.2%	3.2%	1.7%
F16C	7	SHAFTS; FLEXIBLE SHAFTS; MECHANICAL MEANS FOR TRANSMITTING MOVEMENT IN A FLEXIBLE SHEATHING; ELEMENTS OF CRANKSHAFT MECHANISMS; PIVOTS; PIVOTAL CONNECTIONS; ROTARY ENGINEERING ELEMENTS OTHER THAN GEARING, COUPLING, CLUTCH OR BRAKE ELEMENTS; BEARINGS	1	4	0	2	1.1%	4.9%	0.0%	1.7%
F16K	7	VALVES; TAPS; COCKS; ACTUATING-FLOATS; DEVICES FOR VENTING OR AERATING	2	3	2	1	2.2%	3.7%	6.5%	0.8%
B60L	6	PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES; SUPPLYING ELECTRIC POWER FOR AUXILIARY EQUIPMENT OF ELECTRICALLY-PROPELLED VEHICLES; ELECTRODYNAMIC BRAKE SYSTEMS FOR VEHICLES IN GENERAL; MAGNETIC SUSPENSION OR LEVITATION FOR VEHICLES; MONITORING OPERATING VARIABLES OF ELECTRICALLY-PROPELLED VEHICLES; ELECTRIC SAFETY DEVICES FOR ELECTRICALLY-PROPELLED VEHICLES	2	0	0	4	2.2%	0.0%	0.0%	3.4%
B60R	6	VEHICLES, VEHICLE FITTINGS, OR VEHICLE PARTS, NOT OTHERWISE PROVIDED FOR	0	0	0	6	0.0%	0.0%	0.0%	5.0%

IPC sub-class	No. of applications	Description of the IPC sub-class	Number of applications				Share of all robotics patent applications from the sector			
			BES	HEI	IND	PRO	BES	HEI	IND	PRO
G01H	6	MEASUREMENT OF MECHANICAL VIBRATIONS OR ULTRASONIC, SONIC OR INFRASONIC WAVES	0	0	0	6	0.0%	0.0%	0.0%	5.0%
A61H	5	PHYSICAL THERAPY APPARATUS, e.g. DEVICES FOR LOCATING OR STIMULATING REFLEX POINTS IN THE BODY; ARTIFICIAL RESPIRATION; MASSAGE; BATHING DEVICES FOR SPECIAL THERAPEUTIC OR HYGIENIC PURPOSES OR SPECIFIC PARTS OF THE BODY	0	2	0	3	0.0%	2.5%	0.0%	2.5%
B60P	5	VEHICLES ADAPTED FOR LOAD TRANSPORTATION OR TO TRANSPORT, TO CARRY, OR TO COMPRISE SPECIAL LOADS OR OBJECTS	1	0	0	4	1.1%	0.0%	0.0%	3.4%
B60T	5	VEHICLE BRAKE CONTROL SYSTEMS OR PARTS THEREOF; BRAKE CONTROL SYSTEMS OR PARTS THEREOF, IN GENERAL; ARRANGEMENT OF BRAKING ELEMENTS ON VEHICLES IN GENERAL; PORTABLE DEVICES FOR PREVENTING UNWANTED MOVEMENT OF VEHICLES; VEHICLE MODIFICATIONS TO FACILITATE COOLING OF BRAKES	1	2	1	1	1.1%	2.5%	3.2%	0.8%
B65G	5	TRANSPORT OR STORAGE DEVICES, e.g. CONVEYORS FOR LOADING OR TIPPING, SHOP CONVEYOR SYSTEMS OR PNEUMATIC TUBE CONVEYORS	2	0	0	3	2.2%	0.0%	0.0%	2.5%
E21D	5	SHAFTS; TUNNELS; GALLERIES; LARGE UNDERGROUND CHAMBERS	3	2	0	0	3.3%	2.5%	0.0%	0.0%
G01B	5	MEASURING LENGTH, THICKNESS OR SIMILAR LINEAR DIMENSIONS; MEASURING ANGLES; MEASURING AREAS; MEASURING IRREGULARITIES OF SURFACES OR CONTOURS	2	2	1	0	2.2%	2.5%	3.2%	0.0%
G01C	5	MEASURING DISTANCES, LEVELS OR BEARINGS; SURVEYING; NAVIGATION; GYROSCOPIC INSTRUMENTS; PHOTOGRAMMETRY OR VIDEOGRAMMETRY	5	1	0	0	5.4%	1.2%	0.0%	0.0%

Tab. 11. IPC patent sub-classes most frequently occurring in robotics patent applications. Source of data: Polish Patent Office database.

IPC sub-class	Description of the IPC sub-class	All countries	US	EP	JP	CN	PL
A61B-017/94	Endoscopic surgical instruments	**0.00%**	0.00%	0.00%	0.00%	0.00%	2.56%
B25J-001/00	Manipulators positioned in space by hand	**0.00%**	0.00%	0.00%	0.00%	0.00%	2.24%
B25J-005/00	Manipulators mounted on wheels or on carriages	**2.97%**	3.09%	3.11%	3.03%	3.08%	**9.29%**
B25J-005/02	Manipulators mounted on wheels or on carriages • travelling along a guideway	**0.00%**	0.00%	0.00%	0.00%	0.00%	2.88%
B25J-007/00	Micromanipulators	**0.00%**	0.00%	0.00%	0.00%	0.00%	2.24%
B25J-009/00	Programme-controlled manipulators	**4.60%**	4.79%	4.83%	4.70%	4.78%	1.28%
B25J-009/02	Programme-controlled manipulators • characterised by movement of the arms, e.g. cartesian co-ordinate type	**0.96%**	1.00%	1.01%	0.98%	1.00%	2.24%
B25J-009/06	Programme-controlled manipulators • characterised by multi-articulated arms	**1.01%**	1.06%	1.06%	1.03%	1.05%	3.21%
B25J-009/08	Programme-controlled manipulators • characterised by modular constructions	**1.92%**	2.00%	2.01%	1.96%	1.99%	3.53%
B25J-009/10	Programme-controlled manipulators • characterised by positioning means for manipulator elements	**1.93%**	2.01%	2.02%	1.97%	2.01%	3.85%
B25J-009/14	Programme-controlled manipulators • characterised by positioning means for manipulator elements • • fluid	**0.81%**	0.84%	0.84%	0.82%	0.84%	2.56%
B25J-009/16	Programme-controlled manipulators • Programme controls	**5.08%**	5.29%	5.32%	5.18%	5.27%	0.96%
B25J-011/00	Manipulators not otherwise provided for	**5.69%**	5.92%	5.97%	5.81%	5.91%	4.49%
B25J-013/00	Controls for manipulators	**1.95%**	2.03%	2.05%	1.99%	2.03%	2.56%
B25J-013/08	Controls for manipulators • by means of sensing devices, e.g. viewing or touching devices	**2.81%**	2.93%	2.95%	2.87%	2.92%	1.60%
B25J-015/00	Gripping heads	**2.57%**	2.68%	2.70%	2.62%	2.67%	3.53%
B25J-015/06	Gripping heads • with vacuum or magnetic holding means	**2.22%**	2.31%	2.32%	2.26%	2.30%	1.92%
B25J-015/08	Gripping heads • having finger members	**2.39%**	2.49%	2.51%	2.44%	2.48%	0.64%
B25J-017/00	Joints	**1.53%**	1.59%	1.61%	1.56%	1.59%	2.56%
B25J-018/00	Arms	**1.21%**	1.26%	1.27%	1.23%	1.26%	2.88%
B25J-018/04	Arms • rotatable	**0.00%**	0.00%	0.00%	0.00%	0.00%	2.88%
B25J-019/00	Accessories fitted to manipulators, e.g. for monitoring, for viewing; Safety devices combined with or specially adapted for use in connection with manipulators	**4.09%**	4.25%	4.28%	4.17%	4.24%	7.05%
B60L-011/14	Electric propulsion with power supplied within the vehicle • with provision for direct mechanical propulsion	**2.73%**	2.84%	2.86%	2.78%	2.83%	0.00%
B60W-010/02	Conjoint control of vehicle sub-units of different type or different function • including control of driveline clutches	**2.37%**	2.46%	2.48%	2.41%	2.46%	0.00%
B60W-010/04	Conjoint control of vehicle sub-units of different type or different function • including control of propulsion units	**2.19%**	2.28%	2.30%	2.24%	2.28%	0.00%

IPC sub-class	Description of the IPC sub-class	All countries	US	EP	JP	CN	PL
B60W-010/06	Conjoint control of vehicle sub-units of different type or different function • including control of combustion engines	**5.39%**	5.62%	5.66%	5.50%	5.60%	0.00%
B60W-010/08	Conjoint control of vehicle sub-units of different type or different function • including control of electric propulsion units, e.g. motors or generators	**4.92%**	5.12%	5.16%	5.02%	5.11%	0.32%
B60W-010/10	Conjoint control of vehicle sub-units of different type or different function • including control of change-speed gearings	**2.05%**	2.14%	2.15%	2.09%	2.13%	0.00%
B60W-010/18	Conjoint control of vehicle sub-units of different type or different function • including control of braking systems	**2.12%**	2.21%	2.22%	2.16%	2.20%	0.32%
B60W-020/00	Control systems specially adapted for hybrid vehicles	**6.33%**	6.59%	6.63%	6.46%	6.57%	0.32%
B60W-030/18	Purposes of road vehicle drive control systems not related to the control of a particular sub-unit, e.g. of systems using conjoint control of vehicle sub-units • Propelling the vehicle	**2.48%**	2.58%	2.60%	2.53%	2.57%	0.00%
B60W-050/14	Details of control systems for road vehicle drive control not related to the control of a particular sub-unit • Means for informing the driver, warning the driver or prompting a driver intervention	**2.48%**	2.58%	2.60%	2.53%	2.57%	0.00%
G05D-001/00	Control of position, course, altitude, or attitude of land, water, air, or space vehicles, e.g. automatic pilot	**4.53%**	4.71%	4.75%	4.62%	4.70%	3.21%
G05D-001/02	Control of position, course, altitude, or attitude of land, water, air, or space vehicles, e.g. automatic pilot • Control of position or course in two dimensions	**7.95%**	8.27%	8.33%	8.11%	8.25%	4.49%
G05D-001/10	Control of position, course, altitude, or attitude of land, water, air, or space vehicles, e.g. automatic pilot • Simultaneous control of position or course in three dimensions	**2.78%**	2.90%	2.92%	2.84%	2.89%	0.00%
G05D-003/00	Control of position or direction	**1.65%**	1.72%	1.73%	1.68%	1.71%	3.53%
G05D-003/12	Control of position or direction • using feedback	**3.16%**	3.29%	3.32%	3.23%	3.28%	0.32%
G05D-007/00	Control of flow	**0.00%**	1.10%	0.68%	0.00%	0.00%	3.85%
G05D-023/19	Control of temperature • characterised by the use of electric means	**3.22%**	3.36%	3.38%	3.29%	3.35%	2.56%
G05D-023/20	Control of temperature • with sensing elements having variation of electric or magnetic properties with change of temperature	**1.91%**	1.99%	2.00%	1.95%	1.98%	2.88%
G05D-025/00	Control of light, e.g. intensity, colour, phase	**0.00%**	0.00%	0.00%	0.00%	0.00%	2.56%
G05D-027/02	Simultaneous control of variables covered by two or more of main groups G05D 1/00-G05D 25/00 • characterised by the use of electric means	**3.41%**	3.55%	3.58%	3.48%	3.54%	0.32%
G08G-001/16	Traffic control systems for road vehicles • Anti-collision systems	**8.47%**	4.70%	4.02%	6.62%	4.96%	3.53%

Abbreviations: US = United States, EP = European Patent Office, JP = Japan, CN = China, PL = Poland.

Tab. 12. Frequency of occurrence of top IPC patent sub-classes in robotics patent applications worldwide and in selected countries. Sources of data: Derwent Innovation Index and Polish Patent Office databases.

H6. The thematic focus of patent applications in the field of robotics filed in Poland differs from thematic interests of applicants in leading international patent systems of the United States, European Patent Office, Japan and China.

H6 verifies the technological themes of patent applications in Poland and selected other patenting systems, represented by IPC sub-classes. Polish patenting activities were contrasted with the themes of patent applications in other countries, based on data derived from the Derwent Innovation Index database, included in the Web of Science platform by Clarivate Analytics. International patent datasets were derived from Derwent using the same search criteria of IPC sub-classes as the Polish dataset. Patent database was subsequently queried to identify: (1) all relevant patent applications worldwide, (2) applications filed with the United States Patent and Trademark Office (US), (3) applications filed with the European Patent Office (EP), (4) applications filed in Japan (JP) and (5) applications filed in China (CN), as these distinctive geographical areas were hypothesized to represent diverging innovation systems with respect to robotics, with different thematic focus of inventive activities, facilitating direct comparisons with activities in Poland.

Tab. 12 presents a detailed comparison of technological focus areas of robotics patenting activities worldwide, in US, EP, JP, CN and PL. It helps identify technological differences that might be interpreted as gaps in the adoption or exploration of specific technologies in Poland compared to global tendencies, measured by the frequency of occurrences of individual IPC sub-classes. These comparisons reveal diverging focus of inventive activities, areas disregarded or insufficiently explored by Polish applicants and potential "white spots" that are yet to be filled by inventors. In Poland, a relatively greater intensity of robotics patenting is observed in IPC sub-classes B25J-005/00 ("manipulators mounted on wheels or on carriages") and B25J-019/00 ("accessories fitted to manipulators, e.g. for monitoring, for viewing; safety devices combined with or specially adapted for use in connection with manipulators"). Notable weaknesses of Polish robotics inventors (i.e. fields popular abroad, but hardly explored by Polish inventors) lie in several fields that are highly popular among international applicants, including: B25J-009/16 ("programme controls"), B60W-010/06 and B60W-010/08 ("conjoint control of vehicle sub-units of different type or different function – including control of combustion engines and control of electric propulsion units, e.g. motors or generators") and B60W-020/00 ("control systems specially adapted for hybrid vehicles").

Quantitative verification of H6 was enabled by the calculation of the Jaccard Index, based on the following formula:

$$J(PL,CO) = \frac{|PL \cap CO|}{|PL \cup CO|},$$

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where: PL denotes the number of patent applications from Poland assigned to specific IPC sub-classes, CO is the number of patent applications from other countries, and the Jaccard Index divides the number of items in both sets by the number of items occurring in either of the sets. Its value ranges between 0 and 100%, representing the share of overlapping items (thematic technological fields or IPC sub-classes in the case of the present analysis). For thematic fields to which robotics patent applications were assigned, the Jaccard Index comparing Polish and international patenting amounts to 65.1%, thus confirming a notable thematic divergence (with as many as 15 technological fields not covered by both patent document sets).

6. Conclusions

The empirical research documented in this article revealed a rather limited scale of inventive activities in robotics in Poland, with only 312 patent applications filed between 2006 and 2015, and 173 patents granted based on these applications. The dominance of public science (research institutes and universities) can be observed, which confirms H1. However, these organisations do not seem to actively pursue the commercialisation of many inventions, and have relatively high discontinuance rates i.e. successfully granted patents might no longer be perceived as commercially valuable and, consequently, their owners stop paying patent maintenance fees. Disproportional patenting activities of HEI and PRO can be ascribed to Polish scientific organisations's general propensity to patent. Organisations have been incentivized by the government to file for patent protection regardless of the commercial relevance of the inventions, as counts of granted patents have been included alongside scientific publications in institutional evaluations; these, in turn, influence the level of government funding for R&D allocated to each institution. Universities and research institutes have proven skilled in acquiring patents (see: success rates compared in H2a and failure rates in H2c), but had low motivation to pay the subsequent maintenance fees for granted patents (H2b). Business enterprises accounted for 92 out of 312 patent applications in robotics, with means that their success rate is much lower compared to public science organisations (i.e. lower shares of granted patents, as verified by H2a and H2c). Regardless of these overall counts of patent applications originating from each sector, the landscape remains fragmented: single organisations only have small numbers of applications, without visible critical mass in the private sector. Two public research institutes and one public university have accumulated relatively large counts of applications, but the remaining inventions are scattered among a large number of applicants, without patent portfolios in robotics or examples of consistent inventive activities within a single organisation. Inter-sectoral collaboration is also marginal (H3), with only 15 applications out of 312 jointly submitted by co-applicants.

This limited count of joint applications offers no compelling evidence for the importance of open innovations or science-industry technology transfer in the field of robotics in Poland. Analyses were inconclusive with regard to the verification of statistically significant differences between patenting sectors and the dependent variable of patent co-applicants count (H2e). For counts of co-inventors, representing the collective character of inventions described in the patenting applications of various sectors, differences were confirmed by means of ANOVA (H2d).

Geographically, patenting in robotics is heavily concentrated in the central region of Masovia, or more precisely in the city of Warsaw, with relatively small numbers of patent applications from other parts of Poland. The value of Herfindahl-Hirschman Index for regional concentration proved high, both for all patent applications in robotics and for applications filed by individual sectors (H4). Scientific research concerning robotics that yields inventions and patent applications is concentrated in Warsaw (with several key R&D performers from this city), while scientific organisations from other regions tend to focus rather on the adoption, adaptation and diffusion of existing robotics technologies than on the development of novel solutions or applications. This might not necessarily be problematic, as further diffusion of advanced robotics technologies still requires concerted efforts of various stakeholders in Poland, and the academia could play an important role in educating, adjusting and popularizing technical solutions for the industrial sector, not only through developing disruptive technologies.

Thematically, distinctive interests of private and public sector organisations can be inferred from the themes of patent applications: public science focuses rather on robotic tools (IPC class B25) while companies and individual inventors tend to be more interested in controlling and regulating mechanisms (IPC class G05). Companies have also been working on the use of robotics in electric heating or lighting (IPC sub-class H05B), mining or quarrying (IPC sub-class E21C), as well as the measurement of distances, levels or bearings, including navigation (IPC sub-class G01C); these topics did not attract comparable interest of public science organisations. Nevertheless, no critical mass was observed among specialist fields of technology included among the IPC sub-classes, and values of Herfindahl-Hirschman Index analysing a possible thematic concentration were notably low (H5). Comparisons between patenting activities in Poland and worldwide reveal further differences. For example, Polish inventors seem interested in manipulators mounted on wheels or on carriages and accessories fitted to manipulators, but their activities related to programme controls or specific types of control systems for vehicles, which were particularly prolific themes of patent applications in other countries, remained limited. Thematic differences between Poland and other countries were quantified by means of the Jaccard Index, which confirmed a large share of thematic

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niches that were either not addressed by Polish inventors, or explored in Poland but disregarded elsewhere (H6).

The analysis reveals significant gaps in the adoption and development of robotics as part of the Industry 4.0 movement in Poland, with persistent needs for further creative efforts to support the revitalisation of the Polish industry. Patenting data presented in the article confirm the marginal popularity of robotics in Poland and very limited inflow of locally developed, innovative solutions in robotics. Moreover, the field is dominated by scientific patenting, which might have limited commercial relevance for industrial companies, or low potential for spin-off ventures. Poland falls behind other developed nations and the majority of Central and Eastern European countries in terms of the adoption of robotic technologies. Robotics in Poland suffers from a limited interest of inventors, as well as a relatively small number of companies working on the development of novel robotic solutions. At the same time, the country has a significant improvement potential, both in terms of the diffusion of industrial robots and opportunities for locally developed innovations. While the present transformation of the Polish economy towards the model of Industry 4.0 remains unsatisfactory, this under-performance opens up opportunities for future leapfrogging, provided that intensified efforts of social actors within the innovation system are coupled with stronger public support. The Polish innovation system related to robotics is plagued by the dominance of the public science sector, limited technology transfer efforts and lack of a nation-wide mobilization of intellectual and inventive resources. The thmes of patent applications and the interests of inventors differ to some extent from those observed in other countries, with several white spots that could be covered by further R&D activities. Even though the article has painted a rather pessimistic picture of Industry 4.0 in Poland (focusing on robotics as a representative example of technologies that lay the foundations for Industry 4.0 implementations), it has focused on patent applications as part of the innovation system. However, Industry 4.0 requires also other technologies beyond robotics. Moreover, other types of activities supplement the processes of invention and protection of intellectual property and remain relevant for the successful transformation of Polish industry towards smart manufacturing and cyber-physical production systems.

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