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Forecasting the Development of RFID Technology

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Abstract
Industry 4.0 (I4) as a concept offers powerful opportunities for many businesses. The set of Industry 4.0 technologies is still discussed, and boundaries are not perfectly clear. However, implementation of Industry 4.0 concept becomes strategic principle, and necessary condition for succeeding on turbulent markets. Radio Frequency Identification (RFID) was used before I4 emerged. However, it should be treated as its important part and even enabler. The question arises how adoption of RFID was impacted by I4 paradigm. Therefore, to answer this question a set of technology management tools was selected and applied to forecast RFID potential development in forthcoming years. Moreover, case studies were conducted for technology management tools and their applications for RFID for qualitative discussion of its relevance. It aimed to prove that existing toolset should be applied for modern technologies related to I4. Tools were proven to be necessary and successful. However, some specific challenges were observed and discussed.

Keywords
Industry 4.0, technology management, technology audit, technology roadmap, S-curves, patents' analysis, RFID.

Introduction

Industry 4.0 concept became prominent and important approach in modern industries, especially in manufacturing, but not only there. Industry 4.0 is the term coined for the fourth industrial revolution, following the first revolution (introduction of steam machineries), the second revolution (electronic equipment), the third revolution (IT support in 1970s). Industry 4.0 focuses on synergistic utilization of automation, data processing and exchange, and manufacturing technologies. The term, which is especially popular in Europe, is in use since the German federal government announced "Industrie 4.0" in industrial trade fair Hanover Messe 2011 as one of the key initiatives of its high-tech strategy (Kagermann et al., 2011). There are many scientific and business conferences addressing I4 topic. However, when considering the concept itself, it is worth to notice, that in fact it is the evolution (nowadays technologically possible) of visions formulated few decades ago under umbrella the of computer integrated manufacturing and flexible manufacturing systems. Number of publications on Industry 4.0 is dynamically growing, what proves significant interest of academia, business and authorities in this concept (Öztemel and Gursev, 2020). Among them one can find papers oriented on technological and engineering aspects, but also on managerial issues and relations with concepts like lean management (Ejsmont et al., 2020a; Ejsmont and Gładysz, 2020) or sustainability (Ejsmont et al., 2020b). Therefore, the goal of this paper is to extend existing literature with case study of available technology management tools applied for a selected technology, namely the RFID, enabling the Industry 4.0 paradigm.

Research methods

Set of technology management (TM) tools related to each stage of technology management process was chosen. Single case study was applied to discuss phenomena of each of the selected TM tools in Industry 4.0 (I4) environment. The goal of the study is to answer, if (and eventually how) available TM tools are applicable considering one of modern technologies

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enabling I4 paradigm, i.e., Radio Frequency Identification. The case is defined herein both by selection of technology to be discussed and selection of technology management tools to be applied for this technology. If examples of such application are found (in the literature or in practice), the answer is positive. If positive answer would be obtained, then the supplemental goal of this research will be discussion of selected commonly used TM tools (Phaal et al., 2006) in the context of their application for specific selected technology enabling I4 paradigm. Therefore, the goal is qualitative description and exemplification of successful applications of selected basic TM tools for RFID as an example of technology enabler for I4.

Such a qualitative case might constitute inspiration for managers introducing I4 concepts in their organizations, as well as for researchers willing to compare different I4 technologies or TM tools. It will also serve as a base to find eventual shortcomings and to outline necessary developments of TM toolbox. Such comparison will be a foundation of complex research leading to definition of TM reference framework for I4.

It was assumed that the case study should cover available TM tools related to full TM process.

The logic of decisions related to research methods is presented in Fig. 1.

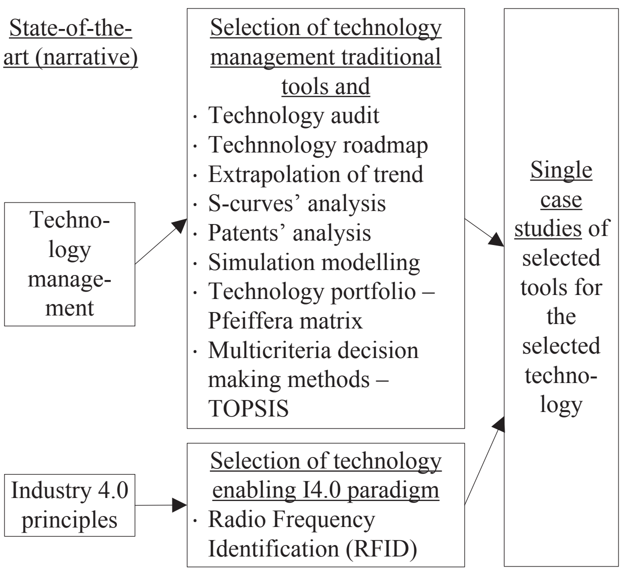

Fig. 1. Research procedure and methods

The technology chosen for the case study is RFID, because it is not new to many industries. Therefore, there is relatively large number of examples of TM applied for RFID projects to be considered. This technology was discussed widely from technological and engineering viewpoint, as well as considering its managerial implications (Gladysz et al., 2020; Gladysz and Kluczek, 2019; Gladysz and Buczacki, 2018). Moreover, RFID is commonly considered as the technology that existed before but benefited significantly from I4 advent. It is important part of a number of I4 initiatives. The reason is that its costs decreased last years, and it could automatically deliver data not only for transparency of objects' flows within factories and supply chains, but also for:

- objects' identification for machine to machine, human to machine communication, autonomous and collaborative robots as one of key technologies in IIoT (Industrial Internet of Things),
- large datasets for further proceeding in simulation modelling, big data and artificial intelligence.

Technology management toolset

Technology management process

A.M. Badawy (2009) formulated concise definition of technology management as a process of effective integration and utilization of innovation, and strategic, operational and market mission of a company to achieve competitive advantage. This definition directly implies crucial role of technology management in the context of Industry 4.0, where technologies are notably important, because they are core of the concept, they represent a wide range of potential utilization, and they are evolving dynamically.

Technology management should be considered from two perspectives, i.e. operational perspective (acquisition, implementation, exploitation, maintenance, renewal, modernization, exchange) and strategic perspectives (dynamic effective combining resources and process to achieve competitive advantage) (Cetindamar et al., 2009). Technology management covers then several phases:

- identification of technologies important to achieve strategic goals, and resolve operational problems – technology audit,
- forecasting technology development in order to make decisions – extrapolation of trends, S-curves' analysis, patents' analysis,
- selection of technology, assessment and decision making on technologies satisfying requirements of an organization – Pfeiffer matrix of technology portfolio, multicriteria decision making method i.e. TOPSIS,
- assessment and evaluation applied for acquisition, implementation, exploitation and integration of technologies – simulation modelling, TOPSIS.

Technology management toolset, therefore, includes wide range of methods related to above mentioned phases. Selected tools, commonly practiced in industries, are discussed in more details below.

Identification of technologies

Technology audit is basic tool in the identification stage. In general, audit is a tool supporting intraorganizational controlling, whose goal is to identify potential improvement actions. It may have institutional or functional character (Reichmann, 2006). Technology audit is a method of organization's evaluation considering technological potential, procedures in place, and existing technological needs in the context of strategic and operational goals (Gladysz et al., 2017). The goal of technology audit is defining technological gap, which is understood as a difference between current state and needs considering organization's capabilities and needs of main stakeholders (owners, shareholders, personnel, customers, government and self-government). The scope of assessment is the impact of possessed technologies on performance indicators, e.g. return rate, reliability, costs, unit and cycle times, energy and material consumption, emissions, noise, etc. Usually capabilities are not fully exploited, what can be eliminated through continuous improvement actions. Other option, necessary at some point, is modernization or exchange of a technology. However, there are situations, when achieving goals is impossible with available technologies. Such state is the driver for searching (and acquisition) of new technology, which are still in development, or utilized in other sectors. In general, the analysis of the technological gap (Fig. 2) may consider exploited capabilities and/or full capabilities of possessed and/or possible to acquire technology, strategy requirements, market and customers, perception, risk taking and innovativeness.

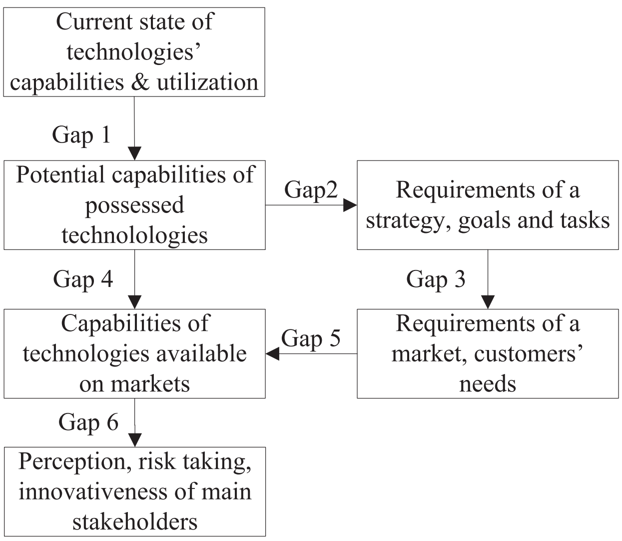

Fig. 2. Technology gaps based on (Gladysz et al., 2017)

Technology (development) map is a tool depicting existing and missing relations between technologies and both strategic and operational goal. Maps are basic tool for managing complex research and development programs leading to acquisition, development or transfer of technology considering the level of sector, branch, company, good, specific technology. Technology map is orderly, purposeful, long-term and continuous planning and decision-making methodology.

Forecasting technology development

Considering technologies, one of the most important issues that managers want to forecast is the dynamics of technological developments, including change of capabilities (development boundaries), development directions, technology exchange/substitution rate by newer technologies, scope of technology (market share). There are many advanced methods for technology forecasting (Roper, 2011), including research of experts (e.g. foresight), Delphi method, supporting methods of individual assessments synthesis – Concordet's law, Kemedy's median, Pareto principle, multicriteria decision making (MCDM) methods (e.g. AHP/ANP, ELECTRE, PROMETHEE, TOPSIS, VIKOR, multicriteria programming), scenario methods (often used with simulation modelling), monitoring methods (e.g. patents' analysis, bibliometrics, scientometrics, infometrics, webometrics, press and websites' clipping, S-curves analysis), normative methods (e.g. technology roadmaps), trend extrapolation.

Extrapolation of trend is a part of time series analysis, which include also simple methods like econometrics programming, regression and correlation analysis, moving averages, exponential smoothing, but also complex methods like Box-Jenkins method. Extrapolation of trend assumes that factors influencing process dynamics in the past, would influence the process in the future to the same extent. However, those methods are sensitive for any changes of factors, as they assume that factors are constant. In general, time series may include many characteristics including trend, seasonality and periodicity, random and situational fluctuations.

Least squares method can be applied to estimate also other simple prognostic functions, e.g., exponential and power (example is given in section Applications of selected technology management tools for RFID).

S-curves depict development of technologies (Fig. 3). The shape of oblate letter S illustrates evolution of technology capabilities (technical and exploitation parameters) in time. Identification of the stage on S-curve allows to identify characteristics of driving consumers (early adopters / emerging, early majority / pacing, late majority / key, laggards / base) and factors for technology (functionality / emerging, reliability / pacing, convenience / key, price / base). S-curves allow to identify the moment for technology exchange and substitution without risk of early development stage (shortcomings and development costs) and avoid costs of delayed (too late) decision of exchange (loosing competitive position or even advantage). Models of technology substitution assume that the substitution of technology by other technologies is the function of their market shares and in some cases time. There are also other models for S-curves, e.g., Fisher-Pry model, Gompertz model, logistics curves. When it comes to assess the level of maturity of one technology, Gartner hype-cycle is widely used. The difference is that S-curves depicts technology performance, and hype-cycle is oriented on expectations.

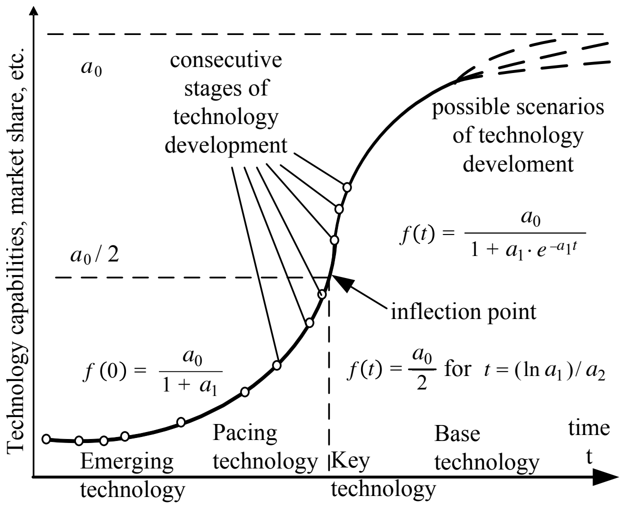

Fig. 3. S-curve – Pearl model based on (Gladysz et al., 2017)

Selection and assessment of technology

The clue of technology selection is deciding, which technologies will be exploited in a company. Decisions should be justified by a business strategy. If no technologies are available (ready to use) on the market, then selection may include definition of requirements for new technologies. Selection includes, in order, assessment, ranking, choosing (Klincewicz and Manikowski, 2013). Technology assessment (evaluation) is a multicriteria task. It considers identification of technology lifecycle stage (Fig. 3). Therefore, selection of technologies is oriented on finding those technologies, which are necessary for achievement of strategic goals considering both capabilities of a technology itself and capabilities of an organization (organizational, financial, human, assets, etc.). Klincewicz and Manikowski (Klincewicz and Manikowski, 2013) proposed a comprehensive list of criteria based on seven models (Hsu et al. model, Jolly's model, De Coster and Butler model, Chen et al. model, Łunarski's model, Lucheng and Wenguang model, Shen et al. model), guidelines for criteria selection considering decision-making situational characteristics (research planning, research execution, commercialization planning, implementation), and a list of questions with assessment guidelines for each criterion. Selection may be also supported by simulation modelling.

Complex assessment of technologies, considering technology attractiveness and organization's capabilities, is possible using portfolio matrices known from strategic analysis. Matrices are built of two dimensions: internal – dependent on organization's processes, external – dependent on surroundings. Well known matrices for technology portfolio management include ADL matrix, BAH matrix, McKinsey matrix, Pfeiffer's matrix (Phaal et al., 2006). Phaal et al. (2006) identified over 850 (!) technology portfolio matrices. Several questions, therefore, arise: how to find appropriate method?, how to assess its usability and quality of results?, how to apply chosen method in practice?, how to integrate chosen method with other managerial tools? However, very important, those issues are left out of the scope of presented article.

Shortcomings of discussed tools

Discussed tools are widely adopted and proven in practice to be effective in order to achieve technology management goals. However, application of those tools could be challenging, especially in early phases of technology development. This is due to the fact, that tools vastly need:

- historical data and/or
- quantifications for performed assessments.

This is great shortcoming, when considering new technologies, for which there are:

- only few historical data,
- lack of quantitative data and
- problems with experts proficient to deliver their opinions.

For example, S-curves could be exceptionally reliable when forecasting key or base technology development but may fail for earlier stages or may need careful consideration of forecasting scenarios development and considering wider range of scenarios (what makes forecasts more difficult to analyze and less useful).

One more problem could be that in I4 often several technologies have to be applied at the same time and with these models it is difficult to consider in the analysis the interdependencies among complementary technologies.

Applications of selected technology management tools for RFID

Industry 4.0 technologies

Technologies are the core of Industry 4.0 and the implementation of the I4 concept without them is impossible. Some of the I4 technologies are being actively introduced since some time (e.g. RFID), while some are still under intensive research and development phase. While technological toolset of Industry 4.0 is still being defined by many studies, there is consensus of the types of technologies to be included in I4. Those are autonomous and cognitive robots, cloud computing and big data, (Industrial) Internet of Things and Cyber Physical Systems, IT systems integration, simulations and digital twins, cybersecurity, virtual and augmented reality, additive manufacturing (Nascimento et al., 2019; Tarasov, 2018; BCG, 2020; Dalenogare et al., 2018).

Radio Frequency Identification – RFID

Radio Frequency Identification is defined here as any technology, where radio frequencies are employed to identify objects in supply chains (both, internal and external). Therefore, it is a wide range of technologies deploying different frequencies (low, high, ultrahigh, ultra-wide band) and standards (e.g., RAIN RFID, Wi-Fi, DASH7, MiFare, among others) and logic (passive, battery-assisted passive, active). In general, RFID technology enables remote identification (using readers, e.g., mobile handhelds, gates, etc.) of objects, which are tagged with RFID tags. RFID tags enable unique identification of every tagged object. Though RFID technology is not new, it can benefit out of the digital innovation brought by the fourth industrial revolution and its use is expected to increase in the future. RFID can be thus considered as one of key technologies in the concept of Internet of Things, and as such should be included also in the set of I4 technologies.

Defining technology gap for RFID seals

RFID seals will be used as an example of technology gap analysis conducted by a solution provider who delivers RFID systems to its customers. Solution provider discussed with its customer a system in which a seal equipped with RFID tag was considered. Such seals would be used to protect tanks' valves. Seals currently used by a customer are traditional ones (not equipped with any remote identification features) and they are hardly accessible for worker. This made checking process time-consuming, error prone, unsafe and not ergonomic. Elimination of checking tasks seemed to be possible using RFID to identify seals. RFID solution needed to be passive due to ATEX directives to protect employees from explosion risk in areas with an explosive atmosphere (Directive, 1999; Directive, 2014). Yet, RFID seals available on the market did not have a feature of identifying if a seal is broken, in case the seal is placed close to valve with no visible signs of a breakage and RFID tag is still operating. It was relatively easy to design a seal, which would not be read at all if broken, but then no read would mean missing seal (e.g., process mistake) or broken seal. In order to resolve discussed needs, the customer cooperated closely with RFID supplier, who designed seals with expected feature (remote identification of the seal status: broken or not broken). Prototypes and trial run were manufactured and tested in the field. Considering discussed case and types of technology gaps (Fig. 2), it should be classified that discussed gap is of fifth type. This case also illustrates how process improvement needs lead to define a technology gap and a way to eliminate the gap. Considering discussed case, the only way to bridge the gap, was the development of new technology and innovation of a seal that can be read after breakage with indication of a breakage. Concluding this case, findings from technology audit were used to formulate goals for research and development actions, which were performed in close cooperation by the customer and the supplier. Proposed actions were only possible in joint project of technology provider (who get the knowledge about user needs) and the customer (who was able to get tailored solution without launching fully internal R&D project, what would demand also acquiring knowledge). Presented case proved that gap analysis is useful to make strategic decisions of make or buy class, i.e., if to consider acquisition or own research and development actions.

Forecasting and planning RFID development and adoption – technology roadmap, patents' analysis, extrapolation of trend, S-curves

Fig. 4 depicts technology roadmap for discussed RFID seal. This map was developed from RFID supplier point of view, who considers new product development satisfying identified requirements of a specific customer as a chance to enter new markets with new product. Developed map covers a family of RFID-based final goods manufactured by the supplier.

Fig. 5 depicts patents for RFID tags and chips in Europe in years 1990–2020 and extrapolated trends. Linear trend was developed using least squares method to define a and b of a trend function $f(t)$ in time t: $f(t) = a \cdot t + b + \varepsilon$, where ε is the forecast error. Linear model is not appropriate for the case, what is visible for errors for forecasts in years 2010–2020 (Fig. 5 – left). It means that other model should be considered, and errors estimated (Fig. 6). Next analysis (Fig. 5 – right), include longer time series (forecasts for years 2021–2025 based on historical data in years 1990–2020). Data until 2011 could indicate that S-curve Gompertz model would fit (Fig. 7). However, after 2011 RFID started to play new role in Industrial Internet of Things and in I4. The I4 idea was introduced in 2011, but broader literature on it and real-life applications were slightly delayed in time and became significantly more popular since 2015 (Muhuri et al., 2013). Fig. 7 clearly shows that pure S-curve models are inappropriate. It is rather the case of second S-curve launched after 2011. Significant increase in the number of patents after 2011 could prove revolutionary character of I4, new role of RFID in I4, and next S-curve could be expected. However, in 2018–2020 there is unexpected decrease in number of patents. This means that none of well-known and widely used models of those discussed here are valid (Figs. 5–7). Such situation could again be explained by revolutionary character of I4 and high forecasting

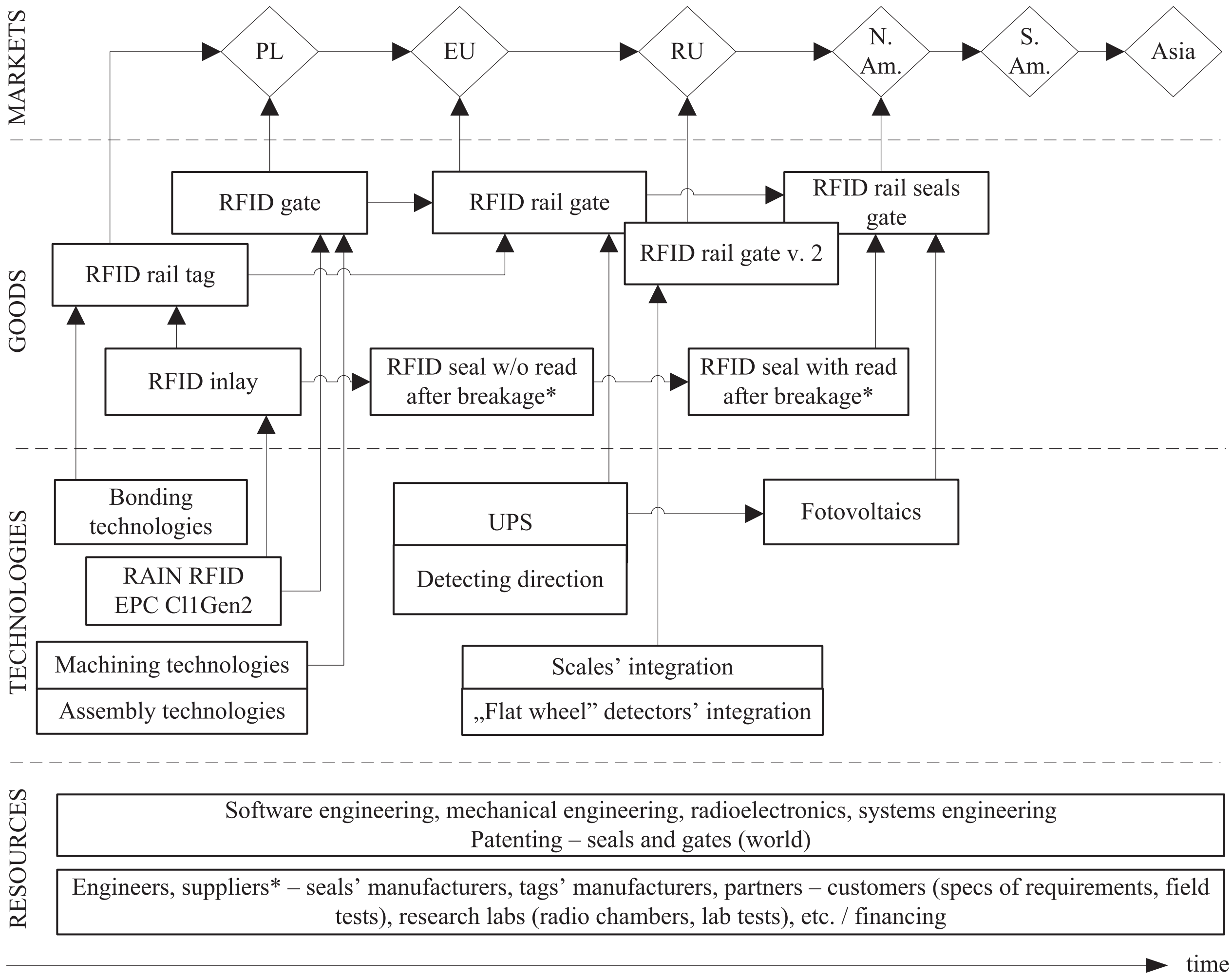

Fig. 4. Simple technology roadmap for RFID from RFID supplier perspective

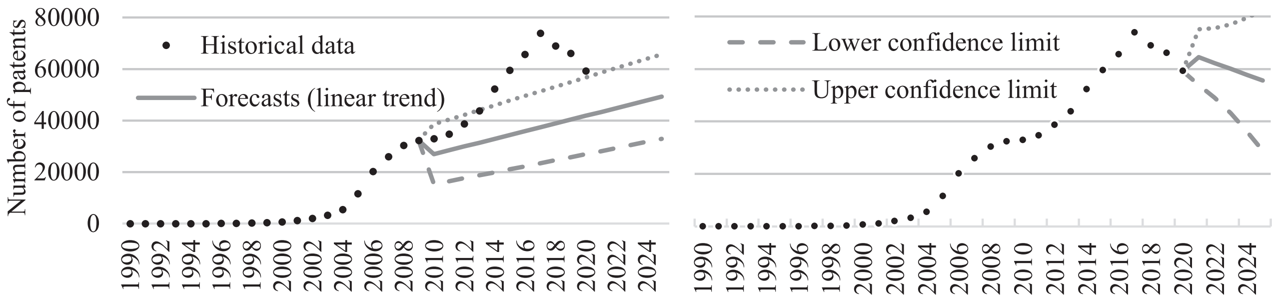

Fig. 5. Forecasts for RFID tags and chips patents (2010–2025 – left; 2021–2025 – right, linear trend, $\alpha = 0.95$) based on European Patents Office patent search engine (espacenet.com, 1.01.2021)

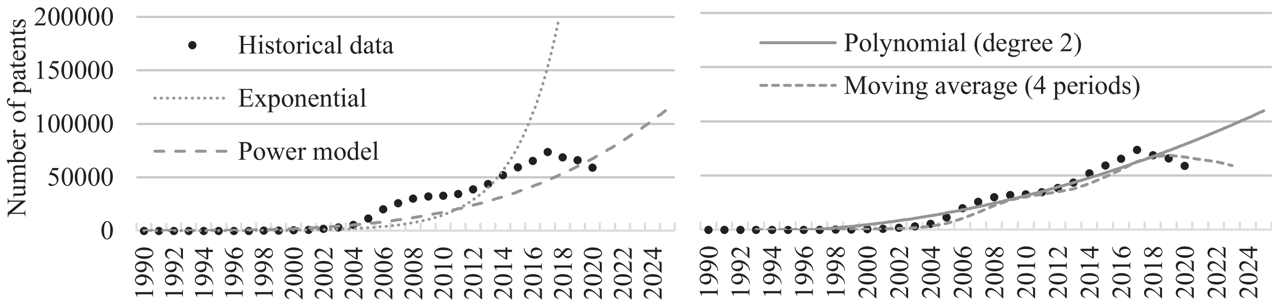

Fig. 6. Forecasts for RFID tags and chips patents (exponential, power, polynomial, moving average) based on European Patents Office patent search engine (espacenet.com, 1.01.2021)

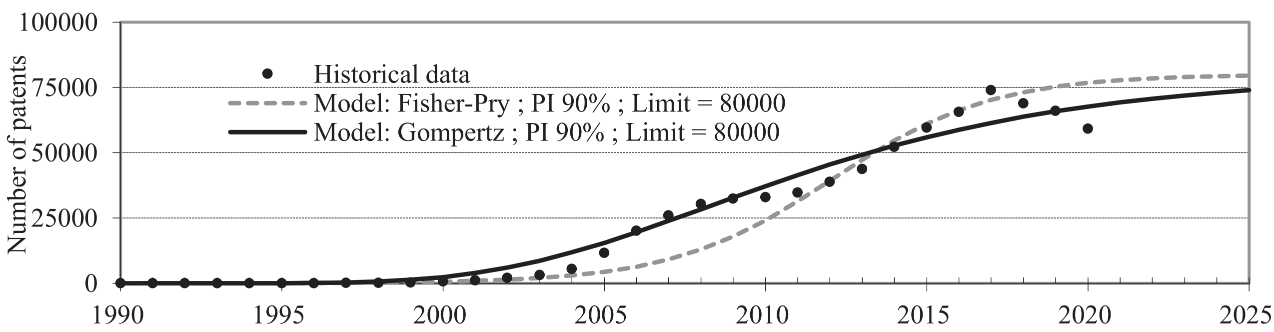

Fig. 7. S-curves for RFID patents based on data from European Patents Office (espacenet.com, 1.01.2021)

uncertainty. Presented forecasts showed that new and more sophisticated models are needed for forecasting. Especially, those models should not be based just on historical data, but consider also fluctuations of economic situation. Fig. 7 presents forecast of global RFID market prepared using most popular models of S-curves years 2018–2020 based on data from years 2009–2017. According to the analysis (Fig. 7), RFID should be considered as a pacing technology, which still has not reached inflection point (Fig. 3). Therefore, it is not a key technology yet. However, forecasts show expected rapid growth in forthcoming years and its soon recategorization as a key technology. This means that strategically, technology providers and solution integrators should now focus on grounding their market position and increase market share, to gain benefits when RFID becomes key technology. Interestingly, moving average delivered least differences of forecasts and real data. This is due to the fact that other models have not considered economic situation changing rapidly with I4 adoption.

Computer simulation modelling could be applied to consider scenarios for technology adoption. E.g. Bass model (Bass, 1969) for diffusion of innovative solutions could be exploited. An example of system dynamics model for RTLS (Real Time Locating Systems) in Polish logistics parks is presented in Fig. 8. Bass model may also be presented as simple agent-

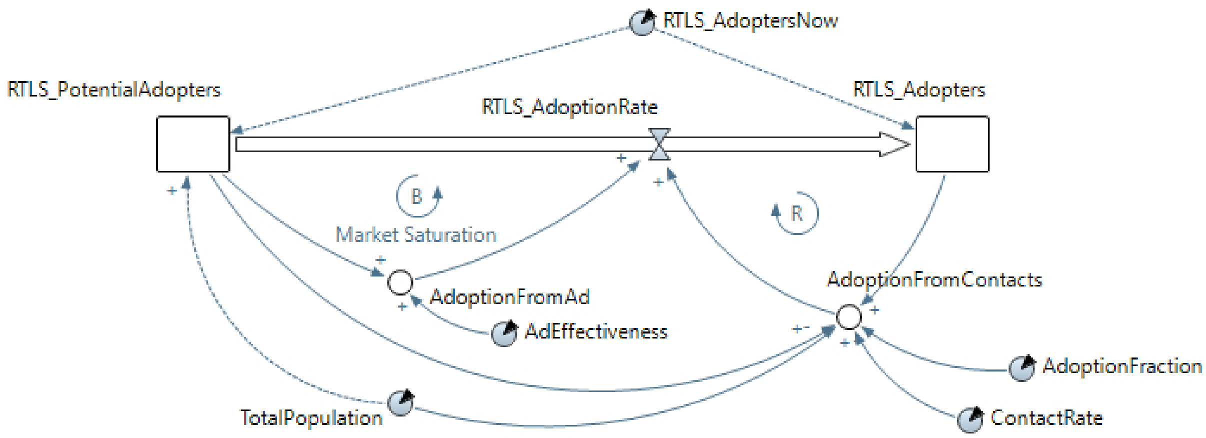

Fig. 8. Bass diffusion model for RTLS in Polish logistics parks using system dynamics (Anylogic software)

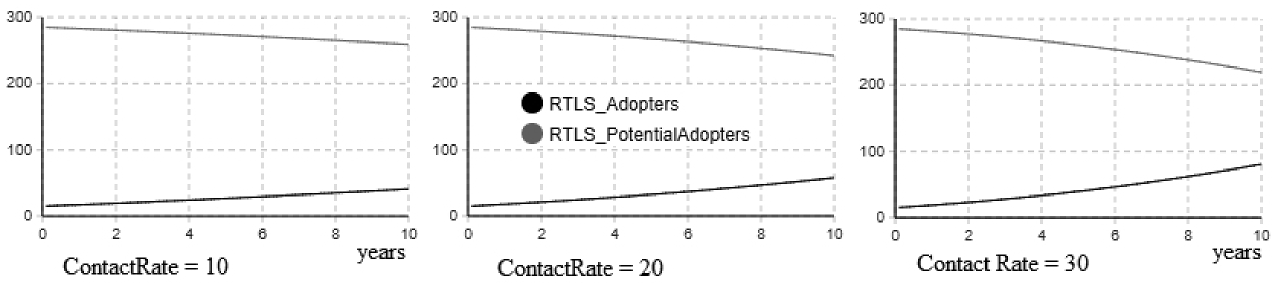

Fig. 9. Simulated scenarios for RTLS diffusion in logistics parks in Poland (Anylogic software)

based model, where customer is an agent with two states (current user, potential buyer). First scenario was executed for diffusion in years 2021–2031 for assumed model parameters:

- *Total Population* = 300 (Cushman and Wakefield, 2020); total number of logistics parks in Poland
- *RTLS_ AdoptersNow* = 30; RTLS current adopters at the beginning of a simulated period; 10% of population as assessed by interviewed experts from logistics association;
- *ContactRate* = 20; This sector is characterized by frequent contact during numerous industrial events, seminars, fairs, etc.);
- *AdoptionFraction* = 0.005; Relatively low as other technologies are in place and are not depreciated yet, and RTLS is relatively capital intensive investment;
- *AdEffectiveness* = 0.005; Relatively low as advertising is not the main adoption driver for this sector (business to business sale) and relatively high awareness of buying decision makers.

Due to fuzzy nature of experts' assessments used to estimate model parameters further scenarios were executed to check results' sensitivity for changes of *ContactRate* (Fig. 9).

Discussed case shows how simulation modelling could be applied for forecasting technology diffusion. Such simulation results may constitute essential data not only for decision makers, who base their decision on forecasted behavior of other players on the market (here represented by adoption of RFID technology), but even for governmental and self-governmental units deciding on schemes, sources and addressing financing. The model allows to simulate the number of RFID users among logistic parks and, therefore, estimate the needed growth of RFID solution providers. Simulation for Polish logistics parks showed significant forecasted growth of RFID users (relative to current users). Therefore, solution providers should make preparation for this situation in terms of its own necessary growth (human resources, assets, facilities, etc.).

Assessment, ranking and selection of RFID technology

There are also many other examples of simulation modelling in the context of technology management and assessment of implementation results (both positive and negative, financial, environmental, social), e.g. application of Business Process Model and Notation for assessment RFID implementation impact on technical and organizational indicators for internal logistics (Gladysz, 2015).

Gładysz and Santarek (2017) presented multicriteria decision making method (i.e., TOPSIS) application for ranking and selection from alternative RFID technologies for real time locating system in warehousing.

Another example of application of traditional technology management tool in the context of RFID technology is an application of Pfeiffer portfolio matrix for assessment of strategic potential of RFID implementation (Santarek and Gladysz, 2014) and TOPSIS for selection of the scope of implementation (Gladysz and Santarek, 2014).

Summary

Available technology management tools may find applications for modern Industry 4.0 technologies, what was proven by discussion of case studies depicting the use of several tools for RFID technology. Considering specific characteristics of Industry 4.0 technologies and their dynamic development, technology management should play crucial role for Industry 4.0 technologies and implementation initiatives. Selection of appropriate tools may be challenging, e.g., design of precise forecasting models is time-consuming and complex task due to numerous variables. Different models should be employed for strategic decision making (if to transfer or develop technology) than models employed for operational decisions on exploitation of possessed technologies.

One important factor to be analyzed and incorporated into existing tools is a framework to consider results of government-driven (also EU-driven) initiatives and their impact on technology adoption. Such framework should also enable concurrent analysis of numerous technologies and their correlations. For example, it is the case of RFID. That technology was known before Industry 4.0 was launched. However, it should be discussed as important enabler for Industry 4.0 paradigms and its adoption significantly increased together with a spread of Industry 4.0 ideas like big data (for which RFID could deliver datasets) and Industrial Internet of Things (for which RFID constitute technological basis for low-cost identification of objects).

Examples were given to prove that available toolset may be used for technology management considering new reality of Industry 4.0 paradigm. Available technology management tools are necessary and should be applied. However, it is not sure if they are sufficient and this should be further studied. Therefore, reference framework linking existing technology management tools and Industry 4.0 technologies with indication of gaps and insufficiencies of existing toolset should be developed.

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