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Teams' boundary-spanning capacity at university: performance of technology projects in commercialization

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Abstract

Universities increasingly are taking on the commercialization of knowledge as their third mission. More recently, they appear to be challenged to go even beyond that mission and adopt more interactive relationships with user groups and society. A shift like this calls for a solid study on how well the knowledge commercialization has performed at university in recent years. Focussing on a European country, the Netherlands, this paper provides a characterization of that performance and the underlying factors, and in particular the boundary-spanning capacity of university teams. In an analysis of trends in commercialization, involving almost 370 university-driven technology projects, we observe that 22 percent of all older projects succeed in market access within ten years after start of the project. For younger projects, this is 15 percent of all projects within 5 years after start. In addition, a rough-set analysis of about 40 technology projects is carried out, pointing to the years of collaboration with a large firm/user organisation and an efficient use of resources as positive influences on commercialization, while affinity among project managers with the market also tends to be a key factor. Despite a general trend of more permeable university-industry boundaries, it deserves recommendation to further increase boundary-spanning activities, among other things through co-creation labs.

Key words: universities, technology projects, commercialization, collaboration, co-creation, boundary-spanning, the Netherlands.

1. A more prominent and engaged role of universities

1.1. Early engagement and third mission

It is widely recognized that developments in the 1990s and 2000s, both in the US and Europe, including measures that regulatentellectual property rights, increasing relevance of university research and its practical translation (industrial/societal problems), a larger availability of funding resources, etc., have led to a more direct involvement of universities in the business community (Mowery et al. 2004; Etzkowitz, 2008; Geuna and Muscio 2009; van Looy et al. 2011; Abreu and Grinevich 2013; Perkmann et al., 2013).

The first involvement of universities in knowledge commercialization (contract research) dates back to the beginning of the last century, with the establishment of John Hopkins university and hospital in the US (Feldman et al., 2014). This involvement continued during World War II, mainly through military applications, for example the development of the first nuclear weapons, the Manhattan project in 1940s, and the development of the first computers at Oxford (Copeland, 2006) and Manchester University in 1947 (Lavington, 1998). However, the systematic involvement of universities in contract research and other types of knowledge commercialization is a recent development, that started in the 1980s and continued in the 1990s (Rasmussen et al., 2006). As a result, nowadays, universities are not only seen as educational institutes and creators of new knowledge, but are involved in a wide set of activities of knowledge commercialization, denoted as their ‘third mission’, a mission that encompasses contract-research commissioned by the business sector, collaborative technology projects with business partners, the licensing of university patents and the creation and nurturing of spin-off firms (Shane 2004; D’Este and Patel 2007; Huggins and Johnston 2009; Loi and Di Guardo 2015).

In Europe, this new role of universities started to develop since the mid-1980s (Charles and Howells 1992), and included the establishment of science parks designed to attract existing technology firms for collaboration with universities, an initiative that was mainly originated externally (Rasmussen et al. 2006). Since the mid-1990s, initiatives typically became based on more internal drives at university, for instance the establishment of spin-off firms by graduates and staff, and patenting/licensing. As a result, today, a wide spectrum of motives and modes/channels of transfer and commercialization is part of the research policy of ‘entrepreneurial’ universities, and this activity is officially considered one of the tasks of universities (Etzkowitz 2008; Hussler et al. 2010; Rasmussen and Borch 2010; van Looy et al. 2011; Martin 2012). For example, in the Netherlands, the commercialization of knowledge was officially recognized as the ‘third mission’ in 2008, and it has been substantiated in a national policy program called the ‘Valorization program’ (Innovation Platform 2009). As a result, today, the main issue is to improve the performance of existing transfer structures and processes (Mustar et al. 2008; Geuna and Muscio 2009; Bruneel et al. 2010; Gilsing et al. 2011; van Geenhuizen 2013).

The term knowledge commercialization, as used in this paper, is the “process of creation of value from knowledge, by adapting it and/or making it available for economic and/or societal use, and transform it into competing products, services, processes and new economic activity” (Innovation Platform 2009, page 8). Knowledge commercialization is a stage-based process that starts with initial ideas about practical application and market introduction, sometimes in collaboration with a large firm, and about steps to realize that market introduction through various channels (Bekkers and Bodas Freitas 2008; D’Este and Patel, 2007). Essentially, knowledge commercialization at university requires the bridging of different ‘worlds’- science, business and eventually user groups - and accordingly it involves various boundary-spanning activities.

1.2. A more prominent engagement and ‘Open Science’

A new development is the more prominent position adopted by the public sector, citizens and civil society in university research, requiring a stronger social engagement on the part of universities (e.g. Breznitz and Feldman 2012). This development is part of an ongoing evolution in the way research is conducted and science is organized, that started with the development of the so-called science shops in The Netherlands in the 1970s. Science shops linked university researchers to civil society organizations in a broader attempt to democratize both science and society. Subsequently, science shops spread throughout Europe and now constitute a network of intermediaries between university and various societal groups (Schlierf and Meyer 2013).

‘Open Science’ (or ‘Science 2.0’) today is a holistic approach towards science-related processes, ranging from framing of problems, conceptualization of research ideas and data gathering and analysis, to the publication and use of scientific outcomes (EC 2014, 2015). The aim is to make research more open, global, collaborative, creative and closer to society, through the use of ICT tools, media and networks. Accordingly, citizens and society participate as contributors and direct beneficiaries of new knowledge. Citizens' engagement ranges from being better informed about research to participating in the scientific process itself, including observing, gathering and processing data, as well as funding research and developing ideas on innovation. Compared to the past, 'Open Science' encompasses a significant increase of scientific production, data-intensive science and an increase in the number of stakeholders in science, which enable interactive processes of co-creation and knowledge commercialization. This development is specifically important when it comes to finding solutions to persistent social (sustainability) problems in cities (Goddard and Valance 2013; Trencher et al. 2014), mainly in areas that are closely related to people's health and lifestyles, energy, daily living (environment), work, transport, etc. Note that various organizations in Europe were already involved before the label of 'Science 2.0' was launched. For example, the Frauenhofer Institute for Systems and Innovation Research (Germany) has been exploring user-centred innovation since 2010, including the co-development, co-testing and co-evaluation of sustainability and quality-of-life solutions (Living labs), while, in 2012, the University of Manchester (UK) launched the University Living Lab initiative to transform its campus into a site of applied teaching, research and experimentation (co-creation) with users in everyday circumstances (Evans et al. 2015; Voytenko et al. 2015).

Overall, it would appear that, with the introduction of 'Open Science', a set of weakly addressed and understood issues will arise, as already indicated by results from public consultation in Europe (EC 2015), and these are issues that also appeared in some earlier commercialization studies. They involve barriers at institutional level and individual level of scientists, including a limited awareness regarding 'Open Science', uncertainty about benefits and about quality assurance, etc., all reinforcing the need for boundary-spanning activity.

1.3 A focus on university-driven technology projects

Among the channels involved in knowledge commercialization, technology projects at universities have attracted relatively little attention in existing literature (D'Este and Patel 2007; Gilsing et al. 2011), with the exception of Barnes et al. (2002), who emphasize good practice in the management of university-industry collaborations, Fontana et al. (2006), Santoro and Bierly (2006) and Bruneel et al. (2010), who study the determinants of research collaboration or facilitators of knowledge transfer from the side of *firms*, while Bekkers and Bodas Freitas (2011) examine university-industry projects, with an emphasis on organizational structures affecting the outcomes of the collaboration. These studies suggest that collaboration experience, social connectedness and trust between university and industry, as well as a university's intellectual property policy and technological capability and relatedness, may reduce barriers and facilitate the transfer of knowledge. However, there is a lack of understanding as to how such factors at university influence projects reaching the market and the time involved (Perkmann and Walsh 2007). Very little is known about the timing of reaching the market among others under the influence of boundary-spanning capacity of research teams at university, for instance, the affinity of research managers with the market and their experience in collaboration. The relative lack of understanding of the performance of knowledge commercialization at universities (e.g. through contract research) may harm the future development of active co-creation models in a wider societal engagement. Accordingly, the current study limits the focus on universities and their research teams.

Given the knowledge gaps outlined above and given the changes universities need to make to go beyond the third mission, we address the following questions in this paper:

(1a) To what extent do technology-based projects at universities manage to reach the market (including societal use)? (1b) What are the time lines involved?

(2) What are the capacity factors at universities and what are the external factors that affect the outcomes of commercialization performance?

The Netherlands are studied as an example of a specific group of European Union countries that, in recent years, have been facing the so-called 'knowledge paradox' of a high R&D input and a low innovation output (or growth), a group that includes Norway, Sweden, Austria and parts of United Kingdom (Audretsch and Keilbach 2007; Bitard et al. 2008; ProInno Europe 2012). The paper is structured as follows. Model building, concerning factors that are expected to influence the commercialization outcomes, is discussed in Section 2. Section 3 deals with methodological and measurement-related issues. In Section 4, the empirical results are highlighted: 1) descriptive results on outcomes of commercialization lines (trends), 2) results on factors influencing commercialization outcomes (rough-set analysis), and 3) case studies. Section 5 provides the conclusions and recommendations for policy-making and future research.

2. Factors affecting knowledge commercialization

2.1. Introduction

Knowledge commercialization among universities, business world and user groups, cannot succeed without boundary-spanning activities in the organizations involved. Boundary-spanning has to do with crossing borders to build relationships, interconnections and interdependencies, in order to manage complex problems and collaboration (Williams 2002). Accordingly, at an individual level, partnerships are built to understand motives, roles and responsibilities, while, at an organizational level, strategic alliances and many other forms of collaborative activity, including learning, are formed across organizational boundaries. Within the context of innovation systems, boundary-spanning aims to facilitate a good flow of knowledge between different ‘worlds’, by actively building networks, partnerships and collaborative learning (Howells 2006; Maronne 2007; Meyer and Kearns 2013; Mørk et al. 2012).

Boundary-spanners may be located in-house at one of the organizations involved, for instance transfer offices (Comacchio et al. 2011) and R&D labs at universities (Mørk et al. 2012). Alternatively, they are located somewhere in-between two or more organizations, or they can be independent third parties (intermediaries). In this paper, research teams of technology projects at university are seen as key in-house organizational units with greater or lesser boundary-spanning intentions and capacities in their commercialization efforts (Williams 2002; Harvey et al. 2014).

In this section, a model of commercialization performance is designed, using factors that mainly derive from theory on (inter) organizational learning, empirical results from knowledge transfer studies and (spatial) innovation studies. The model is investigated in section 4.2.

2.2 Research team capacity

University research teams can be conceived as organizational units that depend on their internal resources and external resources that are accessed through networks (McEvily and Marcus 2005; Lavie 2006; Barney and Clark 2007). Internal resources include university finance and team (leader) experience. Organizational learning theory indicates that research teams have a certain capacity to recognize, acquire and assimilate external knowledge (absorptive capacity), and to make connections with large firms (Cohen and Levinthal 1990; Lane and Lubatkin 1998; Zahra and George 2002; Nooteboom 2009). These firms provide access to a wider pool of valuable resources, in the form of specific complementary technical and market-related knowledge, investment capital, and an improved reputation (D'Este and Perkmann 2011; Bozeman et al. 2013).

However, university-industry collaborations face many potential obstacles, caused by differences in attitudes and intellectual property (IP) strategies, although recently, there appears to be some convergence (e.g. Bjerregaard 2010; Bruneel et al. 2010; van Geenhuizen 2013). We mention different time horizons – which in most firms are shorter than they are in university research - while firms need to adapt quickly to changing circumstances, ending collaboration when a superior technology enters a firm or when reorganization dictates closure of a R&D department. In addition, university researchers are keen to publish information in journals quickly, while firms often prefer to keep new knowledge under wraps, e.g. for patent applications or to benefit from existing patents (Westness and Gjelsvik 2010). Overall, the different cultures need to be bridged, while diversity in the ability to do so among research teams may affect their actual learning and commercialization results (e.g. Datta 2011). In the remaining section, we discuss various general capacity factors (project embeddedness, seniority of managers, financial resources, project management efficiency) and various capacity factors connected to boundary-spanning (collaboration experience, affinity with the market and champion's capacities).

The capacity of a research team depends on its accumulated technical knowledge, which is included in the model in this paper, based on the embeddedness of projects in earlier and parallel projects. University-driven technology projects may start ‘from scratch’, or they can be based on previous research in a predecessor project (e.g. Bruneel et al. 2010; Fontana et al. 2006). The existence of predecessor projects increases the speed of commercialization, for example, because answers to more basic questions are already available. Also, the existence of parallel projects that are similar in subject matter may increase the speed of commercialization, due to economies of scale and synergies. Furthermore, the level of seniority of the manager - years active as a professor – appears to be important, as it indicates the degree of personal accumulation of knowledge and experience, both regarding subject matter and organizational routines. However, there may be a contradictory trend with more experience, which may include a relatively long experience with the old situation, in which knowledge commercialization was not required and did not belong to the routines. Also, having more financial resources available may speed up the commercialization process, because a larger research team can be established that includes additional technicians, and a larger team may work more efficiently in using advanced equipment. In this study, the projects were mainly supported in the form of a salary for one PhD student, but additional finance could come from the university and external sources. And, finally, an efficient project management, in terms of a team's ability to leverage team knowledge through specific inputs, may influence time-to-market. As main inputs to project management efficiency we consider various capacity factors, although not by themselves, but by their relation to ‘best practices’ with regard to commercialization outcomes (Taheri 2013).

From a boundary-spanning perspective, we first mention previous collaboration with a large firm as the most frequently identified factor in literature. The longer the collaboration, the more beneficial the routines that have developed, making the collaboration run more smoothly and more quickly based on the trust that has been created (Bruneel et al. 2010; Gilsing et al. 2011). However, there is also a danger here, namely, that after some time, the learning benefits with the same partner may decline, due to path dependency and locked-in situations that start to limit the search scope. This phenomenon has been addressed in the broader literature involving learning and open innovation (Laursen and Salter 2006; Dahlander and Gann 2010).

Furthermore, to bridge different ‘worlds’, project managers at university need to own what is defined in our study as ‘affinity’ with the market. This means they have to have a positive attitude or even emotional sympathy with bringing research results to the market, allowing them to act as boundary spanners. Key factors in this respect are social connectedness and trust in relations with firms, as observed by various researchers (Bruneel 2010; Santoro and Bierly 2006). Also, ‘entrepreneurial’ scientists, who pay attention to the economic value of teaching and research activity, are more likely to perform better when it comes to commercialization (Etzkowitz 1983). In recent literature, attention has been paid to the overall quality of researchers (PI - Principal Investigators) as key actors in their scientific field, but also with regard to the boundary-spanning role between science and business, shaping new horizons (Casati and Genet 2014; Mangematin et al. 2014). We can assume that being a ‘champion’ both in terms of science and ability to bridge science and business, as evidenced by a high profile in winning prizes and research grants, filing patents, publications in top peer-reviewed journals, and in managing or advising firms, makes a difference in the team’s capacity and commercialization results.

2.3 Invention and type of university

The market introduction of a new product or process also depends on the radical or incremental nature of the invention. Radical inventions require structural changes in infrastructures, like the fuel infrastructure in the case of electric cars, and in related social institutions, which is why radical inventions face more obstructions on their way to market (Utterback 1996; Geels 2004; Geels and Schot 2007). With regard to the character of a university, a distinction can be made between science-based learning, for instance in the case of life sciences and advanced nanotechnology, and problem-based and engineering types of learning that involve new applications or combinations of existing knowledge, for instance in the automotive industry (Asheim et al. 2007; Tidd et al. 2009). Problem-based learning provides a greater incentive for collaborative learning between (regional) partners and it may proceed more quickly and accelerate knowledge commercialization, whereas science-based learning takes more time (Jensen et al. 2007). Universities in Europe vary in the types of learning, with universities/institutes of technology or polytechnic universities placing a greater emphasis on applied, problem-based learning and, as such, on collaborative learning with firms, compared to science faculties of general universities. Furthermore, collaboration between different universities combining types of learning may provide synergy or other benefits.

2.4 External factors: market and regional business ecosystem

Differences in the performance of technology projects will arise when a mass market is foreseen, for instance a fuel cell technology replacing traditional batteries in all kind of electronic devices, compared to a limited market with few customers (Tidd et al. 2009). This factor is included in the model as envisaged market size. Also, markets may vary in the level of regulation. When there is a great deal of regulation, for instance in markets for new drugs and tissue-engineering, market introduction is a lengthy process, due to the testing and approval procedures involved, about 15 years longer compared to in markets with less regulation (Utterback 1996; Tidd et al. 2009).

And finally, the regional business ecosystem or cluster(s) where the university is located is also included in our model. First, there is a different sector specialization. Some of the universities in the Netherlands we studied are located within a large metropolitan area (Randstad), with highly developed clusters in commercial services and transport, alongside (petro-)chemical industry, food industry and upcoming clusters in life sciences, while other universities are located in regions adjacent to the Randstad, mostly in the Southeast of the country, with various advanced manufacturing clusters, for instance in micro-electronics, mechatronics, semiconductors and automotive industry. Secondly, there is a difference in the level of urbanization, with the Randstad area encompassing four relatively large cities and the Southeast encompassing medium-sized cities. Large cities are regarded as providing various agglomeration benefits (Audretsch and Feldman 1996), including labour market advantages (specialized professionals, a creative class), nearby test markets and launching customers, and easy access to the headquarters of multinational companies (e.g. Florida 2002; Sassen 2005).

3. Research methodology

3.1 Data

The unit of analysis used in this study is a technology project at universities, as one specific channel. We are aware of the many forms of knowledge (flow) and various channels that are partly related to the project level, including spin-off firms and patents licencing (Bruneel et al., 2010; Rossi and Rosli, 2015). For example, the development of spin-off firms occurs in 55 percent of the projects in this study. However, including such a channel in the analysis would significantly increase the actor complexity involved, including the entrepreneurial team starting the firm, the incubator and the support the incubator and university provide, etc., as well as the interrelations between the project and the spin-off firm that need to be disentangled, which is why we decided to adopt a narrow focus on projects in this stage.

The analysis consists of three steps: descriptive analysis of trends, rough-set analysis of factors influencing trends, and case study analysis. In the first, we explore the extent to which technology projects successfully reach the market and the timelines involved (related to the first research question). This descriptive analysis draws on 367 technology projects divided among two separate periods, with a take-off between 1995 to 1997 and between 2000 to 2002, derived from the project records of the Netherlands Technology Foundation (STW), which provides project grants. The two different periods are selected to prevent bias from the economic crisis of 2000 in one large sample. In addition, the projects are distributed among universities in the core metropolitan area (Randstad) and the Southeast of the Netherlands. In the second step, we use rough-set analysis to explore the factors that contribute to or hamper commercialization, to address the second research question. To that end, we use a *selected* sample of 42 technology projects drawn from the 367 projects, while focusing on differences in conditions along which the projects vary according to theory. This sampling provides insights that are representative in a theoretical sense, given the differently selected conditions of the projects, for instance the duration of collaboration with large firms, affinity of managers with the market, etc. With regard to generalization, this approach to sampling, combined with theory, leads to a so-called ‘typical material’ in view of broad segments of the population of projects (Mayring 2007). Next, the four case studies allow for a further exploration of the main factors, also including ‘a-typical material’, in order to confirm or critically check the results. This approach is part of iterative learning processes that are common in the framework of 'grounded theory' (Strauss and Corbin 1994). In addition, the sample was also composed to include several of the current Grand Challenges of the European Union (EU Horizon 2020), mainly technologies in the medical sector, sustainable energy, waste treatment and sustainable automotive. However, in the selection of projects, the emphasis has been on envisaged market size and level of regulation.

To provide data for the rough-set analysis, semi-structured face-to-face interviews were conducted in 2010/11 with technology project managers at universities. The interviews lasted 1.5 hour on average and focussed on factors that potentially enhance or prevent a quick commercialization, in particular the various team capacity characteristics, type of invention and a set of external circumstances.

3.2 Rough Set Analysis

Rough-set analysis is a fuzzy-based analysis with an explanatory power. It is used if the sample size is limited and the measurement level of data is low (categorical), and also if the data are somewhat fuzzy, all preventing us from using regression analysis (e.g. Pawlak 1991; for details, see Polkowski and Skowron 1998; for a new approach, see Klopotek et al. 2010). Unlike multiple regression analysis, no assumptions need to be made about the distribution of the data. In this study, rough-set analysis is applied, drawing on the 42 sampled projects, to identify factors that affect commercialization performance. As input for rough-set analysis, data from the interviews are coded and included in a so-called information table, where rows correspond to objects (technology projects) and columns correspond to attributes (variables). The software used – called ROSE (Rough Sets Data Explorer) – was developed mainly in the 1990s on the basis of rough set theory and rule discovery techniques, to analyse data stepwise using self-learning routines (Predki et al. 1998). The version used in our study is ROSE 2.2.

Data are entered in the information table in ROSE software. In the information table, objects are arranged on the basis of their condition (C) and decision attributes (D). These two types of attributes are analogous to the independent variables and the dependent variable used in regression analysis (an example of an information table for two objects is provided in Appendix 1). The basic procedure in rough-set analysis works through attribute reduction, i.e. finding smaller sets of attributes with the same or close classificatory power as the original set of attributes, called *reducts*. On the basis of a reduced information table, decision rules are composed. A decision rule is presented in an “IF condition(s) THEN decision” format, as an output of analysis by ROSE software. Two criteria commonly used in determining the importance of the decision rules in the best model are strength and coverage of rules. The strength of a decision rule indicates the share of all objects (technology projects) displaying the same combination of condition attributes as well as the same outcome on the decision attribute. The coverage is the absolute number of objects involved. The higher these outcomes, the better the rules describe part of the sample.

In greater detail, the most meaningful attributes, namely those in the intersection of all *reducts*, are called the *core*. The value of the core indicates the accuracy and quality of the rough-set approximation, given the data set. For example, if the value of the core is one (1.0), then the quality of classification for the decision attribute and the overall quality of the classification are at their maximum. Using a number of experiments, we intend to achieve the largest number of variables in the core and the value of 1.0, since this would support the relations we have defined in the conceptual model (Figure 1). The stepwise procedure is provided by the software (Appendix 2): the first variable is included in an empty rough-set model to reach the best core quality, after which the next variable is added to increase the number of variables in the core, the quality of the core (Appendix 2), and also the strength and coverage of the rules (e.g. Table 3). A check of borderlines between classes of the decision attribute is also part of the experiments.

Rough-set analysis is increasingly recognized in literature as a useful technique, particularly when it comes to analysing small samples and qualitative data, for example in comparing or in evaluating projects (urban revitalisation, university incubators), systems (transportation systems) and firm performance (e.g. Dimitras et al. 1999; Nijkamp et al. 2002; Soetanto and van Geenhuizen 2007; Peters and Skowron 2014). But first we turn to the description of broad trends in commercialization lines.

4. Commercialization performance

4.1 Trends in project commercialization lines

In the analysis of trends in the past 20 and 15 years, we discuss technology projects in terms of 'lines'. The reason is that the projects subsidized by Technology Foundation STW in the Netherlands are usually finished after four years, but this period is followed by various new initiatives and results in a line or path to market introduction. The results indicate that the share brought to market is 22 percent (older projects) 10 years after the project start, and 15 percent (younger projects) five years after the project start (Table 1). The smaller percentage involving younger projects may be a consequence of the economic crisis, making firms reluctant to be involved, and the shorter time-span available. However, the positive influence of a stronger awareness and efforts among project teams of younger projects could not compensate these negative impacts on the trend. In addition, failure, in the sense of a truncated line, tends to be already relatively high among young projects, namely 26 percent after five years, compared to the same share after 10 years for older projects.

Table 1. Outcomes of commercialization lines with take-off in different years

Type of outcome a)	**Take-off 1995-1997**	**Take-off 2000-2002**	**Additional information**
Market introduction (within 10 and 5 years respectively)	47 22%	23 15%	Including societal use (minor)
Failure (within 10 and 5 years respectively)	54 26%	41 26%	-
Stagnation or development unknown after 10 years	42 20%	Not applicable	Subcategories are difficult to identify
Continuation of commercialization line	66 32%	94 59%	Financed by a firm or new grant (STW)
Totals	209 100%	158 100%	

a) Older projects evaluated 10 years after project start and younger projects evaluated 5 years after project start (methodology by Foundation STW).

Source: Adapted from Van Geenhuizen (2013), drawing on data from Foundation STW.

When we focus on older projects, it appears that, in 32 percent of all cases, the commercialization line was continued, while 20 percent stagnated or had an unknown outcome. The trend of a large share of continuation after 10 years indicates that knowledge commercialization in technology areas takes a long time, which is confirmed for younger projects, where almost 60 percent of the commercialization lines are continued after five years. This also means that, after periods longer than 10 and five years, market introduction may be larger than the previously indicated shares.

Although the results of this trend analysis cannot be compared to the results in other countries, which makes it difficult to determine whether the share of projects leading to market introduction is high or low, the 22 percent suggests that a higher share could be possible after 10 years, similar to the 15 percent after five years. This justifies our selected sample exploration of influencing factors, in particular in view of an emerging pressure on universities to adopt more interactive types of research involving both industry and society.

4.2 Exploration of influencing factors: Rough Set Analysis

The selected sample used in the rough-set analysis is described in Table 2. Overall, the characteristics show a sufficient level of differentiation. Embedded-ness in projects is captured in three categories: 'absence of a related project', indicating started from scratch as a single project (21.5 percent), 'presence of a predecessor or parallel project' (50 percent), and both predecessor and parallel project apply (28.5 percent). Furthermore, seniority of the manager as professor of the faculty is captured using four categories of increasing experience, with shares of 28, 17, 31 and 24 percent. Financial resources is measured using two categories, a limited support (38 percent) and extended financial resources (62 percent), as asserted by the project manager. Next, project efficiency is grasped using data envelop analysis (DEA), derived from two output variables, while also including financial resources and various other resources as sets of input (Taheri 2013) (Note 2). Accordingly, three categories of increasing efficiency are identified, with shares of 40.5, 26 and 33 percent, respectively.

With regard to specific boundary-spanning capacities, experience in collaboration with a large firm is measured using duration in three categories that occur with almost the same frequency, namely, 36, 33 and 31 percent. Furthermore, affinity with commercialization/ markets is measured in three categories of increasing affinity, with shares of 21.5, 50 and 28.5 percent, respectively. In addition, being a champion/principle investigator is measured as being honoured in the recent past by at least one large national award and grant from the National Science Foundation (NWO), grants from programs of applied national/European research (including STW), while collaborating with various large firms. Accordingly, 39 percent of the project managers in the sample fit the profile of a champion. Furthermore, the nature of the invention, measured as radical or incremental according to the manager's view, displays shares of 38 and 62 percent, respectively. The type of university is measured as 'general', 'technical' and a combination, in the case of collaborative projects between the two types, with shares of 55, 33 and 12 percent, respectively. Next, envisaged market size is assessed by the manager and measured in three categories with increasing size, amounting to 36, 17 and 48 percent, respectively. The level of regulation is measured using three categories of increasing strength, for example with new diagnostics and bio-implants in a highly regulated situation. A high level of regulation occurs with a share of 28.5 percent, similar to medium regulation, while a low level of regulation occurs with a share of 43 percent. In addition, though not part of the analysis, the projects are mainly concerned with the Grand Challenges in EU, namely medical sector, sustainable energy (materials), waste treatment, and also sustainable automotive (Note 3). The type of business ecosystem in the Netherlands is measured in three classes, with projects in the core metropolitan area (52 percent), outside the core area (31 percent) and a combination following from collaboration between universities in these two ecosystems (17 percent). And finally, 'commercialization performance', as applied as the decision variable, is captured using the type of outcomes and the number of years of commercialization (duration). If a commercialization line ceases after a long time without any result, the project is assigned the lowest score, while a project that is launched to the market, especially within a short time frame, is assigned the highest score. This type of scaling, after robustness checks, produces the following picture: 11 projects (26 percent) show the best performance, eight projects (19 percent) the worst, and the remaining ones in-between: medium-low (38 percent) and medium-high (17 percent).

Table 2. Measurement and descriptive statistics in the rough-set model exploration

List of variables	**Measurement**	**Classification of projects**
Research team capacity factors		

Embedded-ness in projects	Presence of predecessor/ parallel projects in three categories	1: Absence: 21.5%; 2: Predecessor or parallel project: 50%; 3: Both: 28.5%
Experience of manager (seniority)	Time between starting the professorship and end of project/observation, in four classes	1: 0< X <= 5 years: 28.5% 2: 5< X<= 10 years: 17% 3: 10< X<= 20 years: 31% 4: X> 20 years: 24%
Financial resources	Amount in two classes	1: Limited financial resources: 38% 2: More financial resources: 62%
Project efficiency	Efficiency degree derived from Data Envelop Analysis in three classes	1: Low efficiency (0.2-0.4): 40.5% 2: Medium efficiency (0.5): 26% 3: Large efficiency (0.6-1): 33%
Specific: boundary spanning		
Collaboration with large firm	Time length relative to period of commercialization in three classes	1: no collaboration: 36% 2: 0 < X <=0.5: 33% 3: 0.5< X <=1.5: 31%
Manager's affinity with market	Degree in three classes	1: Small: 21.5%; 2: Somewhat large: 50% 3: Very large: 28.5%
Champion PI	Binary	1: Yes: 39%; 2: No: 61%
Invention and university type		
Nature of invention	Binary	1: Radical: 38%; 2: Incremental: 62%
Type of university	Three categories	1: Technical: 55%; 2: General: 33%; 3: Combination by collaboration: 12%
External		
Envisaged market size	Size in three classes	1: Small: 36%; 2: Medium: 17%; 3: Large: 48%
Regulation	Strength in three classes	1: Weak: 43%; 2: Medium: 28.5% 3: Strong: 28.5%
Business ecosystem of university's location	Three categories	1: Non-core: 31%; 2: Combination by collaboration between regions: 17%; 3: Core metropolitan: 52%
Decision variable		
Commercialization performance	Performance strength derived from reaching market introduction and time involved, in four classes	1: Low: 19%; 2: Medium low: 38%; 3: Medium high: 17%; 4: High: 26% (av. years): 7.2; s.d.: 4.3; min-max: 1-15

The outcomes of rough-set analysis are best if a model is reached with a quality of classification (attributes/attributes-in-the-core) of 1.0 (Appendix 2). Accordingly, six condition attributes as the optimal variable set, namely affinity of the project manager with commercialization, years of experience of the manager as a professor, (relative) duration of collaboration with large firms, project efficiency, envisaged market size and business ecosystem, are 'in the core', which specifies a reliable model.

The strongest rules in strength and coverage (Table 3) can be understood as follows:

- Rule 1 is by far the strongest rule, given a strength of 75 percent and a coverage of six projects. The rule, which is about *unfavourable* commercialization performance, indicates that, if the affinity of the project manager with commercialization is low and the period of collaboration with large firms is short (less than 0.5), performance will be poor.
- Rule 2, with a coverage of six projects but a strength of 37.5 percent, indicates that a longer period of collaboration with large firms (between 0.5 and 1.5) and a low level of project efficiency (less than 0.4) produce a medium level performance level.
- Rule 3, with a coverage of four projects and strength of 36 percent, has to do with *favourable* performance, while indicating that a longer period of collaboration with large firms (between 0.5 and 1.5), together with intermediate efficiency levels (a score of 0.5) produce the best results in terms of commercialization performance.
- Rule 4, with a coverage of five projects and a somewhat weak strength of 31 percent, is concerned with a somewhat *unfavourable* performance, while indicating a negative influence of a longer experience of the manager as a professor (10-20 years) and the lowest level of project efficiency.

Finally, there are two rules with a positive outcome (medium high) at a relatively weak strength, close to 30 percent, and small coverage (2 projects each):

- Rule 5 can be understood as a combination of a rather *favourable* influence of a medium-sized envisaged market and collaboration between two different business ecosystems, which may give rise to a high diversity of information, as input to commercialization, due to the economic specializations of diverse eco-systems.

- Rule 6 appears to be *contradictory* to some previous rules, in that a lack of affinity of the project manager with the market and absence of collaboration with a large firm may nevertheless produce a relatively favourable situation. The two 'a-typical' projects in question may indicate *new trends* of relatively quick commercialization.

Table 3. Strongest rules produced by the optimum variable set

No	Rules as a combination of condition attributes a)	Decision attribute (commercialization performance)	Strength (%)	Coverage (abs. nr. of projects)
1	CA=1 & DCF=2	Low	75	6
2	DCF=3 & Efficiency=1	Medium low	37.5	6
3	DCF=3 & Efficiency=2	High	36.4	4
4	DPR=3 & Efficiency =1	Medium low	31.3	5
5	MS=2 & BES=2	Medium high	28.6	2
6	CA=1 & DCF=1	Medium high/high	28.6	2

Selected condition attributes:

CA (commercialization affinity of project manager): 1: small; 2: large; 3: very large.

DCF (duration of collaboration with large firms relative to commercialization period): 1: no collaboration; 2 (short): 0< tc <=0.5; 3 (long): 0.5< tc <=1.5.

DPR (duration professorship): 1: 0< tpro <=5 yrs; 2: 5< tpro <=10 yrs; 3:10< tpro <=20 yrs; 4: tpro>20 yrs.

Efficiency: 1: low (between 0.2-0.4); 2: medium (0.5); 3: high (between 0.6-1)

MS (market size envisaged): 1: small; 2: medium; 3: large.

BES (business ecosystem): 1: non-core; 2: both core and non-core regions (collaboration); 3: core.

In the following step, the next best model is explored by excluding the condition attribute 'duration of collaboration with a large firm' from the model, to identify the other factors that emerge in strong rules. We include the following four condition attributes: affinity of the project managers with commercialization, their experience as a professor, efficiency of the project and envisaged market size. Under these conditions, the model reaches a quality of classification of the attributes/attributes-in-the-core of 0.70/0.70, which is clearly a weaker level than that of the previous model. The three strongest rules (Table 4) can be summarized as follows:

- Rule 1 is the strongest rule (37.5 percent) covering three projects. This rule indicates that a low affinity on the part of the manager with commercialization and a small envisaged market size yield the poorest performance. In other words, if a manager does not care about commercialization and the future market is small, chances are there that the product/process will not reach the market in a short time.
- Rule 2 shows the highest coverage, with five projects (at 31.3%), which indicates that more managerial experience as professor (between 10 and 20 years), together with a low level of project efficiency, yield a medium-low project performance. In order words, managers with longer experience as professors may find it difficult to engage in commercialization, due to existing (different) routines and a lower level of efficiency in project management.
- Rule 3, with a small strength of 18.8 percent (and three projects), indicates that a large envisaged market and a great deal of affinity on the part of the manager with commercialization, together with a low level of project efficiency keep the performance at a medium level. In other words, a low project efficiency may act as an obstacle to a very speedy commercialization.

Table 4. Relatively strong rules excluding collaboration with a large firm

No	Rules as a combination of condition attributes a)	Decision attribute (commercialization performance)	Strength (%)	Coverage (abs. nr. of projects)
1	CA=1 & MS=1	Low	37.5	3
2	DPR=3 & Efficiency=1	Medium low	31.3	5
3	MS=3 & CA=3 & Efficiency=1	Medium high	18.8	3

Selected condition attributes:

CA (commercialization affinity): 1: small; 2: large; 3: very large

DPR (duration of professorship): 1: 0< X <=5 yrs; 2: 5< X <=10 yrs; 3:10< X <=20 yrs; 4: X>20 yrs

Efficiency: 1: low (between 0.2-0.4); 2: medium (0.5); 3: high (between 0.6-1)

MS (market size envisaged): 1: small; 2: medium; 3: large.

The outcomes presented above regarding the strongest rules lead us to conclude that most of the attributes found to be important are related to the team’s capacity in, among other things, boundary-spanning. Negative influences on commercialization, as evident in delay, truncation of the commercialization line, etc., are likely to occur if project managers have little affinity with the market, particularly if they have little experience with collaboration (large firm) and the potential market in question is small. More experience in collaboration is likely to produce shorter time-lines to market, if it is coupled with a medium level project efficiency, however, a low level of project efficiency may block a quick commercialization. Furthermore, the business ecosystem plays a role, albeit a minor one, while there are also some contradictory influences. Obviously, the commercialization of technology projects is a highly complicated activity.

4.3 Case studies

We now explore the three overall strongest rules, plus the 'a-typical' rule of the optimal model estimation, by analysing four projects. The main results are summarized in Table 5.

Rule 1 on **low performance:** A project in the medical sector was inspired by the substance with which mussels cling to rocks. The aim of the project was to develop an adhesive for fixing human bones in vivo on the basis of physical chemistry and adhesive technology. The target market was the pharmaceutical industry, with hospitals as potential end-users. Primary bottlenecks were a low affinity on the part of the project manager with the (medical) market and his retirement, and modest experience working together with a large firm, all indicating a limited boundary-spanning capacity. After ten years, the commercialization line was truncated. Firstly, it was difficult to attract serious attention from a large pharmaceutical firm, because the development of the substance had not progressed sufficiently for clinical testing, and secondly, when a large firm became interested, it had different ideas regarding the application of the adhesive substance, namely as a component of coatings. However, the colour of the substance was considered problematic in the new application, which was why the firm pulled out after two/three years. It is noteworthy that, as a result of the truncated commercialization line at the project level, the main researcher established a spin-off firm to provide consulting services on the subject matter.

Rule 3 (project 1) on **high performance:** A project in medical technology aimed at the improvement of an instrument for minimal invasive surgery in hospitals, using robotics, precision mechatronics, optics, etc., with the medical instruments industry as the target market and hospitals as end-users. A primary enhancing factor was the long-standing collaboration with a fine instruments firm, a collaboration that existed before the project started and could be qualified as relatively interactive, involving both members of the project team at the university and hospital surgeons. Also, the university research team was used to interacting (co-developing) with surgeons to identify needs for improvement. Another enhancing factor was the satisfactory efficiency level in the way the project's resources were used, which can be seen as a proof of adequate project management. Although not part of the decision-making rule, many other factors were positive and in favour of commercialization, including a large envisaged market, embedded-ness of the project in earlier/parallel projects and a manager with a very high level of affinity with commercialization, and accordingly a large boundary-spanning capacity. Furthermore, there were no long-standing approval procedures involved, because the invention dealt with improvement of an already existing medical instrument. The commercialization started in 1999/2000 and the improved product was introduced to the market in 2008, thus covering eight/nine years.

Rule 3 (project 2) on **high performance:** A project in waste water treatment, using a new (anaerobic) bacterial process, aimed at a cheaper removal of nitrogen from industrial wastewater. Firms designing and constructing the installations were the main target market, with waste water treatment plants as end-users. In this case, there was a longstanding collaboration with an influential local firm (microbiology, yeast) in an often interactive manner for decades, which made it possible to explore new horizons. In one of the manufacturing processes of this firm, an unexpected loss of nitrogen was observed, which was addressed and taken up as new research at the university in 1992. Due to the research success, thinking about market introduction started in 1996/7. At the same time, another firm was involved, which was active in the construction of waste water treatment installations. The new firm acquired a world-wide licence on the new process in 1999 and it took six years before a full-scale plant using the new process could start operations in 2005. Furthermore, the need for a comprehensive fine-tuning of the treatment processes , all in all, produced a time-line of eight/nine years. Like the previously discussed high-performance project, this project also qualified as being efficient at a medium-level, benefitting from adequate project management. And similarly, many other factors were favourable, including a large envisaged market, embedded-ness in earlier/parallel projects and a project manager with a very high level of affinity with commercialization. However, the new process could have been marketed even more quickly, if no patent-related issues had arisen between the university and the construction firm.

Rule 6 on **medium high/high performance:** A project on faster regeneration of the skin of chronic wounds worked on a wound-healing substance in cultured skin products, with firms manufacturing medical skin care products as the main (intermediate) market, and hospitals as end-users. The technology included oral chemistry and tissue-engineering. In this case, the development reached the point where market introduction was considered in 2006, after which the manager decided to outsource the next stages of the development mainly at an existing spin-off firm at the university. A patent was applied for a few years later, in 2008. The product could be introduced to the market relatively early, without passing all the clinical tests. With sufficient proof of safety, it took six years to introduce the product to the market. 'A-typical' in the context of our sampled projects means that the inventor and project manager, with small personal interest/affinity and no willingness to put energy in boundary-spanning, were nevertheless successful, due to their decision to outsource most of the development to a spin-off firm that was culturally speaking close to the medical faculty. This move also implied that there was no need to involve a large firm. Another 'a-typical' element is that the relevant approving authorities (health sector) decided to allow a limited market entry relatively early, because of high demand for the product, preventing negative influence from regulation.

Overall, the relationship with a large firm (organization) calls for special attention because of the likeliness of a positive influence on the commercialization results.

Table 5 Case study analysis of projects selected based on involvement in strong rules

Optimal model rules	**Typical (relative) conditions in rules**	**Invention**	**Improvement**	**Performance outcome**
Rule 1	- Little affinity - Short collaboration with firm	Synthetic glue to fix human bones (similar to mussel adhesive)	Better fixation	Low (ceased after 10 years)
Rule 3 (1)	- Long collaboration with firm - Medium project efficiency	Product improvement of minimal invasive surgery tool	Larger precision and ease of use	High (introduced after 8/9 years)
Rule 3 (2)	- Long collaboration with firm - Medium project efficiency	New process of nitrogen removal from waste water	Smaller energy needs (less oxygen)	High (introduced after 8/9 years)
Rule 6 'a-typical'	- Little affinity - No collaboration	Using oral cells in wound healing cell cultures	Quicker healing process	(Medium) high ('restricted' use after 6 years)

Our analysis, including the previous case studies on waste water treatment and minimal invasive surgery tools, reveals the benefits of close collaboration between university and (relatively) large firms as users from the start of the project, including a joint formulation of the core problem, finding solutions and testing and evaluating of implemented solutions, in other words *co-creation*. Such close and interactive relationships are based on openness, trust and mutual respect, which can only be built over the years, although they can probably be accelerated with more attention from management (Bjerregaard 2010; Bruneel et al. 2010; Ramaswamy and Gouillart 2010).

Our results, however, also suggest that, even with a long-term collaboration and a high level of affinity on the part of the project manager with commercialization, there is a chance of failure. Although a low level of efficiency in project management may hinder commercialization, in most situations, failure is caused by *external* factors, including the introduction of new regulation at EU level (e.g. on diesel fuel for vehicles) making the invention superfluous; the acquisition of the collaborating firm by a larger firm, which forced the acquired firm to withdraw from R&D altogether, or to abandon the commercialization line; the emergence of a new and more competitive technology, making the collaboration and commercialization line redundant (e.g. advanced body scan system of heart rhythm monitoring versus the pace-maker that also has a correction function). What is apparently missing in these situations is a foresight and scanning of future developments and scenarios concerning markets and technology, in which university and firms can jointly anticipate upcoming trends and events, based on trust and openness.

The observations discussed above imply that the preliminary conceptual model presented earlier in the paper needs some extension with team capacity to understand business dynamics and technology foresight to adjust to new dynamics and needs. In addition, models of co-creation have to be included wherever that is relevant.

5. Conclusion and Recommendations

5.1 Discussion and conclusions

Large numbers of technology-driven projects at universities do not reach the market within a short time frame. In our empirical study involving such projects, only 22 percent of older projects and 15 percent of younger project manage to reach the market within ten and 5 year, respectively, while about 26 percent of each set of projects fail in their commercial efforts. If we had observed the projects over longer periods, the shares of market success could have been larger. A main outcome of the study as ‘typical results’ is that a long-lasting collaboration with a large firm/user organization and a medium level of efficiency in project management produce the highest likelihood of commercial success. By enabling large firms/users to participate in commercialization process from an early stage, research teams benefit from the creativity and innovative power of users, while at the same time being able to respond to their needs. Accordingly, an early participation of users tends to result in a quicker market introduction of the product/process. The emergence of ‘more permeable’ boundaries between university and industry, including awareness at universities that basic research may substantially benefit from research questions arisen in university-industry collaboration, tend to enhance these developments (Siegel et al. 2003; Bjerregaard 2010). On the other hand, commercial success is less likely when project managers have little affinity with the market, particularly if they have little experience working together (with a large firm) and the potential market is small.

A low level of market affinity, combined with a tendency to stick to old routines hampering commercialization, in part are caused by a weak reward structure or lack of incentives for university researchers who specialize and are successful in commercialization/societal application, e.g. there is no tenure track for them. However, universities of technology may be somewhat different (more rewarding) compared to general universities and their science departments. As a further explanation on the part of universities, variation in the size of future customer markets tends to originate from a certain 'randomness' of intentions at university to bring inventions to market, instead of the conscious design of a commercialization portfolio. Our analysis also identified a positive influence from a certain level of flexibility in commercialization at university by the use of alternative channels if necessary, for instance by transferring the commercialization to a spin-off firm, thereby accelerating the process.

With regard to the relationship between university teams and a large firm/user organization, our case studies reveal the crucial role of boundary-spanning activities in building trust and openness, which allow for interactivity (reciprocity), joint problem definition and problem solving, in other words co-creation. However, at the same time, there is a need to stay alert and develop foresight regarding new, external, developments, both in terms of technology and from an entrepreneurial perspective. Furthermore, long-standing 'intimate' relationships may suffer from path dependency and lock-in, decreasing the benefits after some years (e.g. Sydow et al. 2009). And, even with boundaries that are 'more permeable', the issue of intellectual property (IP) and upcoming issues of legal liability in collaboration need to be settled in advance, to prevent 'opportunistic' behaviour. Overall, given the results of this study, there is considerable room for improvement at universities in general at large and at the faculty/team level, as discussed below, in relation to emerging new university roles.

5.2 Recommendations

Recent developments and changes in the ways research is conducted and science is organized ('Open Science') tend to require a stronger engagement and commitment on the part of universities in solving societal problems, including energy sustainability, health care, and transport (EC 2014, 2015; Trencher et al. 2014; Goddard and Valence 2013). This calls for quicker and more substantial responses from universities. We foresee the following lines of improvement of commercialization of university-driven research addressed to universities to create better solutions there given the changing needs in the business world as well as society:

- Provide more places to meet and interact with business and citizens/civil society. This increases opportunities to span boundaries, including the creation of openness, trust and mutual respect.
- Provide training for university staff in boundary-spanning and commercialization activities, as well as foresight studies on dynamics and (sudden) shifts in technology and markets.
- Increase affinity with the market/practice among university staff, through human resource management, and in particular 1) improve the reward structure and create a (separate) tenure track for researchers who are successful in commercialization/societal application, 2) increase the number of part-time 'practice' professors maintaining their main job in business/practice, however, dual appointments are already common at various universities of technology in Europe, and 3) create a chair in each of the science faculties, specifically focussing on commercialization/practice.
- Enhance boundary spanning activities and joint collaboration with industry by establishing *co-creation labs* at university, in which universities and firms jointly develop solutions to problems. Some (technical) universities already practice this at a limited scale. However, this approach requires an additional organizational effort from universities, since time and manpower need to be made available for joint sessions. In addition, transparent decisions are required about the responsibilities/liabilities and intellectual property of joint findings. This also applies to so-called *living labs* that place end-consumers/users in the core in a real-life environment, aside from firms, public authorities, etc. (Almirall et al. 2012;

Yarime 2012; Van Geenhuizen 2013). An increasing number of universities create living labs on their campus, allowing them to jointly design solutions in sustainable energy, traffic, health and lifestyle, etc., and to have their students and staff conducting applied research and holistic learning in practical urban situations (e.g. Evans et al. 2015; Voytenko et al. 2015). However, due attention is needed to guarantee users' input from start of the project and to incorporate that input into next steps while respecting user values, and to have all stakeholders involved in an open and balanced management (Van Geenhuizen 2015).

- Support further investigation of external factors like size of the market and nature of the regional ecosystem because they tend to play a somewhat minor role in our results. There are indications of a positive influence from a medium-sized market while, when it comes to ecosystems, there appears to be a positive influence of collaboration between core and non-core region universities. Thus, differentiation between (the market size of) sectors needs to be taken into account and recommendations need to be further tailored to specific sectors, like the medical sector, sustainable energy, mechatronic systems, etc. In addition, advantages of collaboration between universities in different clusters and related boundary-spanning activities need to be further investigated. Furthermore, the influence of (changes in) regulations could be examined in greater detail, because of their drastic impact. For example, inventions could become obsolete and superfluous (for instance in transport fuel), or commercialization could become accelerating (versus time-consuming), if new regulations were to come into effect.
- Increase the success and credibility of commercialization at university through consciously creating a mixed commercialization portfolio. The portfolio needs to be balanced to include high risk projects that do not yet have or will never have appealing markets on the horizon, as well as low risk projects with sufficiently large envisaged markets. Flexibility needs to be a feature of the portfolio, for example, in the form of withdrawal from commercialization lines if there are no positive outcomes and shifting from one to another commercialization channel, particularly from a project to a spin-off firm context.
- Anticipate and participate in preparation for 'Science 2.0' or 'Open Science', using experience regarding barriers and boundary-spanning activities gained so far

in ‘third mission’ activities. This applies more to general universities than it does to universities of technology and institutes for applied science, which have already made steps towards open science. Additionally, fundamental science departments tend to be less involved in open science, unless there is an urgent need from applied research to solve more fundamental questions, for instance regarding material science and application of improved materials in renewable energy devices. As citizens and society at large participate as contributors and direct beneficiaries of new knowledge (EC 2014) their involvement could be supported, through the development of user-friendly platforms (jointly by universities and citizens), enabling their participation and sharing of feedback. In addition, new data collecting devices could be co-designed at universities to facilitate the collection of data by citizens concerning their environment in areas like medicine, safety, traffic and sustainable development, etc. Anticipation and participation are also needed on the institutional and regulatory side. An extended ICT and data infrastructure raise safety concerns. At universities, boundary-spanning experience could be used to develop solutions together with citizens and firms, to prevent problems of ownership of data, protection of privacy and protection against cybercrime.

Like most studies, this study has some (potential) limitations. Several data are not available at ratio level, for instance, precise data on financial investment and the size of research teams. Measuring financial resources is inherently difficult, as funding from a particular program is often accompanied by additional funding from other sources, while the size of a research team is often flexible, due to the use of temporary contracts and the simultaneous involvement in adjacent projects. As a second limitation, the study is partly an elaboration of data provided by Foundation STW in the Netherlands. Accordingly, the technology projects involved went through a selection procedure for grants from this foundation and, as a result, the projects included in the analysis of trends may not be entirely representative of the larger population. However, as indicated earlier, many of these projects have also obtained financial support from other sources, which increases their representativeness in the trend analysis. Furthermore, the rough-set analysis drew on a small number of selected technology projects, leading to preliminary ‘typical projects’.

This implies that generalizations can only be made in the sense of 'typical combinations of conditions' with which commercialization performance of projects likely vary (Mayring 2007). In the future, using larger randomly selected samples could help test our findings more rigorously, as well as identify differences between sectors. Such samples also make it possible to meet the requirements of statistical representativeness and apply stronger techniques to determine (non-linear) relationships.

Another point is that alpha and gamma university projects have been neglected in the study, but need to be included in future research to arrive at a more complete picture. The same applies to the countries involved. The Netherlands represent a group of Northwest EU countries that all face the 'knowledge paradox', meaning that we also need to include countries that do not face this specific situation, like Finland and Germany. And finally, we mention the narrow approach adopted in the study, focussing on projects while disregarding adjacent channels of commercialization, like spin-off firms. In future research, the scope could be broadened, while the increased complexity and interaction between different channels of commercialization could be handled at the same time, as suggested, for instance, by Bruneel et al. (2010) and Rossi and Rosli (2015).

Note 1

This is an extended and thoroughly modified version of a paper first presented at the High-Technology Small Firm Conference in Manchester (UK) in 2013.

Note 2

Data Envelop Analysis (DEA), applied in measuring project management efficiency in this study, is a non-parametric approach, using linear programming to build a piece-wise linear frontier (Cooper et al. 2000). DEA uses input and output data to compute the 'production possibility frontier'. The efficiency of each technology project is measured as a ratio of weighted output to weighted input, where the weights are calculated to reflect the unit at its most efficient *relative to* all others in the data set, including an estimation of the distance function (to this frontier) (Shepherd 1970; Coelli et al. 2005). Accordingly, DEA produces efficiency scores for each technology project by first determining the technology projects which exhibit 'best practice' with regard to commercialization outcomes. Thus, for each technology project in the sample, DEA determines whether it lies on the frontier (called efficient) and, if not, how 'far' from the frontier it lies. DEA as applied here, works stepwise in determining the relative efficiency of the technology projects (Cooper et al. 2000), taking various efficiency factors as input and performance results and satisfaction of the manager as output data (Taheri, 2013).

Note 3
Medical sector (49.5 percent), sustainable energy (materials) and waste treatment (33.5 percent) and sustainable automotive (9.5 percent), while the rest has no direct connection to the challenges.

Appendix 1 -

Information table with two projects (A-B), selected condition attributes and the decision attribute, Commercialization Performance.

	Financial resources	Embedded-ness in projects	Affinity of project manager	Project efficiency	Collaboration with a large firm	Nature of invention	Type of university	Envisaged market size	Regulation	Business ecosystem	**Commercia-lization performance**
A	1	1	Small	1	1	1	1	Medium	3	3	1
B	1	1	Large	3	3	2	1	Large	2	3	3

Appendix 2 - A summary of validity checks and results of rough-set analysis using ROSE2 software

Condition attribute	*Core variable*	*Quality of core*	*Number of rules*
1. Efficiency	Efficiency	0.14/0.14	8
2. Efficiency, DCF	Efficiency, DCF	0.47/0.47	16
3. Efficiency, DCF, DPR	Efficiency, DCF, DPR	0.69/0.69	23
4. Efficiency, DCF, DPR, CA	Efficiency, DCF, DPR, CA	0.85/0.85	24
5. Efficiency, DCF, DPR, CA, EP	Efficiency, DCF, DPR, CA, EP	0.90/0.90	23
6. Efficiency, DCF, DPR, CA, MS	Efficiency, DCF, DPR, CA, MS	0.95/0.95	20
7. Efficiency, DCF, DPR, CA, NI	Efficiency, DCF, CA , RI	0.95/0.95	22
8. Efficiency, DCF, DPR, CA, Regulation	Efficiency, DCF, DPR, CA, Regulation	0.90/0.90	22
9. Efficiency, DCF, DPR, CA, CPI	Efficiency, DCF, DPR, CA	0.85/0.85	21
10. Efficiency, DCF, DPR, CA, UT	Efficiency, DCF, DPR, CA, UT	0.90/0.90	22
11. Efficiency, DCF, DPR, CA, BES	Efficiency, DCF, DPR, CA, BES	0.95/0.95	20
12. Efficiency, DCF, DPR, CA, BES, MS	Efficiency, DCF, DPR, CA, BES, MS	1/1	21

DCF (relative duration of collaboration with large firms); DPR (experience of manager as a professor); CA (affinity of project manager with commercialization); EP (embedded-ness in projects); MS (envisaged market size); NI (nature of invention); CPI (champion PI); UT (type of university); BES (business ecosystem).

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