Product Lifecycle Management and Open Innovation in the Deep Tech Start-Ups Development

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Abstract. Deep tech start-ups are enterprises established on cutting-edge and radical technologies based on scientific discoveries (deep technologies), like advanced manufacturing and robotics, blockchain, agrotech and artificial intelligence. They start in university laboratories without a specific application and evolve from fundamental research to commercial application slower than start-ups based on offline to on-line business model. With the increasing information exchange, complexity, and uncertainty among actors of innovation ecosystems and the world scientific community, it is required an approach that aims beyond the product development, covering the product lifecycle and understand the information flow among innovation ecosystem actors, i.e., how open innovation works across the boundaries of deep tech start-ups. This work performs a systematic literature review and proposes a conceptual model to understand how Product Lifecycle Management and Open Innovation support deep-tech start-ups in their development, seeking to encourage innovation ecosystems and members of the academic community towards the application of their research into disruptive solutions to complex issues.

Keywords: University spin-offs · Disruptive innovation · Science-based enterprises · Knowledge-based enterprises · Product innovation

1 Introduction

Product Lifecycle Management (PLM) represent a product centric lifecycle-oriented business model, supported by ICT, in which product data are shared among actors, processes and organisations in the distinct phases of the product lifecycle for achieving desired performances and sustainability for the product and related services [1]. As a technological solution, PLM establishes a set of tools and technologies that provide a shared platform for collaboration between product stakeholders and streamlines the flow of information throughout all stages of the product's life cycle [2].

As global competition intensifies and innovation becomes more risky, expensive, and necessary for survival, the concept of Open Innovation (OI) emerges as a novel strategy.

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According to Chesbrough & Bogers [3], OI is an innovation process distributed based on knowledge flows purposely managed across organisational boundaries, using monetary and non-monetary mechanisms in line with the business model of each organisation. These knowledge flows can involve knowledge flows to the focal organization (wing-leveraging external knowledge sources through internal processes), knowledge outputs from a focal organisation (leveraging internal knowledge through external marketing processes) or both (engaging external sources of knowledge and marketing activities).

As the innovation activity intensifies, Small and Medium-Sized Enterprises (SMEs) that generate innovation are being created worldwide exponentially, and the number is growing every day. In this universe, Start-ups play an essential role in the economy, differentiating themselves from other SMEs. Start-ups are companies created to evaluate business models developed around innovative ideas, typically proposed by several co-founders or members of the team [4]. Nevertheless, while the entire start-up market is growing, some parts are growing faster than others [5], the so-called Deep-tech start-ups (DTS), which are enterprises based on Deep-Technologies (Deep-techs).

Deep technology was sparked by Swati Chaturvedi, CEO of Propel(x) [6]. Deep techs are cutting-edge and disruptive technologies based on scientific discoveries and offer the potential to reinvent businesses for the better, maximizing impact, scale, profit, and social welfare [7]. Deep-techs usually originate in university laboratories, e.g., university spin-offs, which means that the technology itself is new and very sophisticated, it was necessarily undesigned with a concrete application or a specific market need [8], i.e., the business strategy of DTS is built round unique, differentiated, protected or difficult to reproduce, technological or scientific advances. Unlike software-based projects, where standard methods can be employed at any stage to rapidly develop a product, Deep-tech projects require frequently more time and specific knowledge. In addition, the core technology on which the start-up is based is extremely sophisticated and developed after years of fundamental research [8].

Start-ups concentrate efforts on product development [9]. A DTS, however, is slower and more ex-pensive than a digital start-up, for several reasons: 1) Strong research base: product development depends on fundamental research and/or advanced R&D, which requires support from a robust set of sophisticated skills, knowledge and infrastructure, in addition to prolonging the time to market products; 2) Heavy industrialization process: in addition to be supported by ICTs, most products in this field are hardware—typically based on advanced materials and resources—requiring highly developed industrial skills to acquire, manufacture and scale. These products are much more difficult to scale than products associated with the Internet and mobile technologies are used to; 4) Great investment needs: the infrastructure, skills and resources needed for a DTS require substantial financing capacity over an extended period; 5) Commercial application yet to be defined: the specifications of the final product can be undefined in the process. Blockchain developed as a specific technological solution for Bitcoin, for example, opened the door to an emerging financial market that its developers did not foresee. According to the Global Start-up Ecosystem report [5], the top four fastest growing sub-sectors of start-ups are: advanced manufacturing and robotics, blockchain, agrotech and new foods, and artificial intelligence, big data and analytics, that is, they depend completely on technological advances and tangible IP.

Most of this knowledge is generated by the R&D units (universities, Institutes, etc.), attempt to reduce the distance from academic environment to commercial application [10], and open innovation strategies, which perform a substantial role in the development of these new businesses, supporting the development of new products and services with a significant content of innovation that retain disruptive characteristics. Another relevant aspect represents the rise of the emerging need for organisations to become agile, not only their product development, which theme was highly associated with, but to respond quickly to the needs and desires of the market, that is, all the components of the socio-technical that the organisation and/or system is inserted must be agile. This characteristic contrasts with the development of deep-techs, which, as previously described, are based on scientific discoveries and have an indefinite time-to-market.

Founded on the concepts described above and performing systematic literature review, this work proposes to answer the following research question*:* ***"Product Lifecycle Management and Open Innovation approaches can support Deep-tech Start-ups?***".

The subsequent sections of the paper are organised as follows. Section 2 presents the method. Section 3 presents the results and Sect. 4 discusses the elements and concludes the work.

2 Method

With the aim to answer the research question described in Sect. 1, we conducted a Systematic Literature Review (SLR) and content analysis of the literature on PLM and OI applied to the universe of DTS. To answer this question, we searched on two electronic data base platforms, i.e., Scopus and Web of Science. The time span selected was from 2011 until 2021. We exclusively selected articles published in journals and which language is English. The queries searched for DTS, PLM, OI and related terms on titles, abstracts, and keywords of the articles. The query that retrieved documents from DTSs and OI is *("deep tech*" OR "scientific discover*" OR "engineering innovation*" OR "technological innovation*" OR "science based start-up*" OR "university spinoff" OR "applied research") AND ("open innovation").* The query that retrieved articles from DTSs and PLM is *("deep tech*" OR "scientific discover*" OR "engineering innovation*" OR "technological innovation*" OR "science based start-up*" OR "university spinoff" OR "applied research") AND ("product life cycle" OR "PLM" OR "product information" OR "product data" OR "beginning of life" OR "BOL" OR "middle of life" OR "MOL" OR "end of life" OR "EOL").*

The two queries (DTS AND OI, and DTS and PLM) returned 478 articles that meet the search strategy. We removed 115 duplicates and retrieved the remaining 363 documents. The screening of titles, abstracts and keywords indicated ten articles and one article were included. We additionally searched for the articles published by the authors of the ten articles and included another seven articles which fulfil the criteria, totalizing seventeen articles to final selection.

3 Results

In this section, we present the findings from the systematic literature review about DTSs, PLM and OI, which can be combined into the schema in Fig. 1. The schema was conceived using inductive reasoning (drawing conclusions by going from the specific to the general).

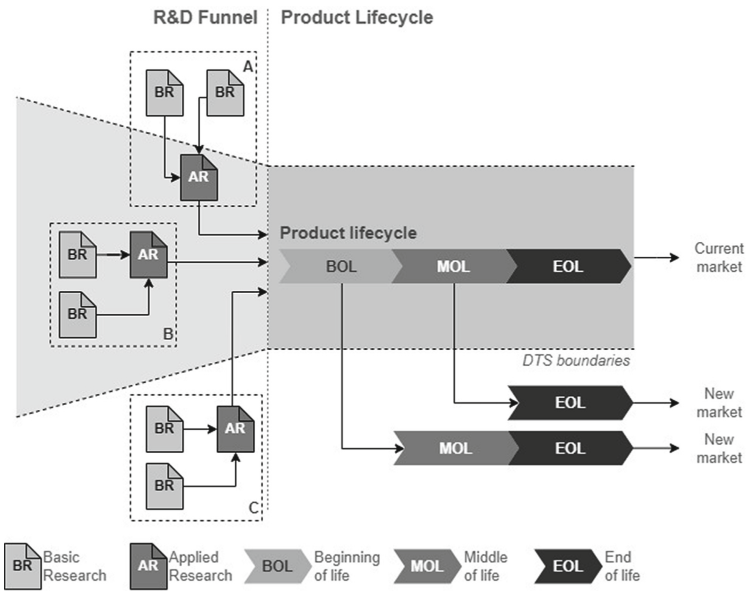

Fig. 1. General schema

The results indicate two clusters of studies: R&D-funnel and Product lifecycle. The cluster R&D-funnel is composed by studies that mostly use metric information studies (MIS) to harvest potential technologies and analyses whether technologies analysed mostly in scientific papers and patents are in the maturity level suitable to be translated into viable commercial products. Meanwhile, the other cluster, Product lifecycle deals with the challenges of translating research into a commercially viable product.

The section is presented in two subsections according to the findings. Subsection 3.1 describes the direct influence of OI on PLM applied to DTSs, while Subsect. 3.2 describes the indirect influence of OI on PLM regarding the DTs universe.

3.1 R&D Funnel

Most articles that contribute to the R&D funnel section massively use MIS to harvest and assess whether a technology has achieved its maturity to be developed and launched to the market, or to be commercially viable. The eight articles of this section and their contributions and applications are described below.

Lezama-Nicolás et al. [11] developed an approach to obtain the technology Readiness Level (TRL) from scientific articles, intellectual property documents, and news records, diminishing the level of bias in the analysis (compared to TRL) and avoiding the costs and drawbacks associated with assessing technological maturity through expert opinions. The proposed method could be employed to assess the maturity level of a technology or part of a technology which the DTS is willing to acquire rather than develop. Whilst Yeo et al. [12] proposes a bibliometric analysis of research papers that can be used as a proxy to measure the degree of uncertainty in a product's technological innovation. The method is applicable for "cherry-picking" promising products among vast numbers of candidate products.

Yeo et al. [13] developed a recommendation algorithm to suggest promising technologies to SMEs. The experimental method contains a distinct goal of finding forward technologies on the technology-value-chains and to recommend promising technologies to SMEs that need "knowledge arbitrage" and to help SMEs produce ideas on new R&D. Meanwhile, Su et al. [14] explore the likelihood of product commercialization and the speed of product commercialization with thirteen patent indicators classified into three perspectives of R&D strategies: collaboration, knowledge, and legal protection. R&D organizations can consume the patent indicators to understand how to attain product approval and accelerate product commercialization speed.

Su [15] discuss the possible correlation of patent characteristics that reveal significant variances at transitions with the change of patent characteristics over time and its strategic implications. The No. of Patent References, No. of Non-Patent References, No. of Foreign References, No. of IPCs, No. of UPCs, and litigated patent promises technology lifecycle indicators for detecting and forecasting technology lifecycles. The application of this work remains the possibility of studying technology lifecycle and uncovering technological development strategies with carefully selected patent characteristics.

Rodríguez-Salvador [16] propose a hybrid data model that combines the assessment of scientific publications and patent analysis production and is further supported by experts' feedback. The model uncovered the core areas of research of the analysed topic in his work. The proposed model helps (i) to study emerging technological innovations, (ii) to assess ongoing research trends and expose the knowledge landscape, and (iii) to better understand any emerging technologies that are currently coming onto the market.

Jun et al. [17] use patent documents as objective data to develop a model for vacant technology forecasting. The authors propose a matrix map that provides broad vacant technology areas. The model identifies the vacant technology areas of a given technology field by operating the results from both matrix map and K-medoids clustering based on support vector clustering. The proposed technology forecasting model can be applied to diverse technology fields, including R&D management, technology marketing and intellectual property management.

Wang et al. [18] shows that two contingency variables (absorptive capacity and technological uncertainty) produce a moderating impact on the relation between the external technology scouting of open search and a firm's open innovation generation. The industry dynamism provided a significant impact on the relation between external technology scouting and innovation generation in the intensely competitive high-technology environment.

3.2 Product Lifecycle

The second cluster deals mostly with product development in the product lifecycle and the impacts of open innovation. The nine articles selected to this section are described below.

Bahemia et al. [19] examine the effect of including eleven distinct types of external parties within an NPD project. The authors develop and evaluate a novel measurement scale that examines three dimensions of "openness": breadth, depth, and partner newness. The aggregation of the three dimensions might influence on the desired outcomes of the innovation project and the strength of patents. The study equally extends the extant supplier involvement in new product development literature to examine the effect of up to eleven types of external actor in NPD projects.

Bazan [20] designs a framework as a structured methodology based on the Stage-Gate® model, best practices in translational research, project management, new product development, business development, science of team science, and IP management. The proposed translational R&D model and methodology helps link university science and engineering research to commercial outcomes, i.e., to promote a seamless transition from research to business. The translational R&D model and methodology can be used to understand, describe, and implement their research as translational activities conducive to delivering their ideas to market. The framework is equally relevant to university researchers who might not intend to turn their early-stage innovations into businesses but advance the development of the innovations to the point where they become attractive for others, to embrace the challenge of developing the innovations farther for the market.

Also based on the Stage-Gate®, Bers et al. [21] builds new stages and new dimensions, partitioning the product–market focus of Stage-Gate® into four concurrent, interwoven tracks: market/societal, scientific/technological, business/organizational, and innovation ecosystem. The first represents a stage of strategy development, not around the company but around the innovation itself. The second new stage is designing organizations around the innovation. The other stages include a pre-discovery period and three post-launch periods, which provide for the extended experimentation and incremental improvement required of radical innovation. The model facilitates entry and exit of the multiple parties involved in radical innovations and proposes a technique (discrete real options analysis) that enables each party to assess the financial value of the innovation as it unfolds. The model can assist scholars and university managers in the developing of organizations (potentially spin-offs) around the innovation itself, in an inside-out approach, rather than an outside-in.

Moaniba et al. [22] contributes to the understanding of drug commercialization by constructing knowledge-based indicators that should allow researchers to quantitatively track and measure the effectiveness of the diversity of knowledge acquired in the contexts of countries involved in the co-invention (of the new drug), and the industrial and technological varieties. The study introduces a new indicator of the intensity of knowledge search by taking into consideration the geographic distance considered in the search for external knowledge, the significant effects of both the intensity of the knowledge sourced and the geographic distance considered in the search extend the existing understanding of the broader concept of innovation strategy.

Germann et al. [23] describes the different modalities of cross-fertilisation between basic university or publicly funded research institutions and the applied research and development activities within the pharmaceutical industry. The study states that innovation opportunities found in more narrow windows are easier to find, select, develop, and translate into the own organisation of the pharmaceutical company because of the closeness of the idea towards the receiving organisation and the scientific expertise. The study proposes the primary elements of innovative translational research from academic perspective and how to integrate it to a product development process of a big pharmaceutical company perspective.

Slavova [24] concludes university-industry interactions demonstrate a direct association with a firm's engagement in open systems of scientific knowledge exchange. University-industry alliances are conduits for transfer of industrial practices like entrepreneurial activities and patenting to academia. Firms with direct ties to universities are better-off at generating inventions of greater quality, greater impact, and more quickly.

Zhu et al. [25] demonstrate that OI breadth and OI depth positively affect NPD speed. Varying types of business models must be aligned with OI breadth and depth to better facilitate NPD speed. Additionally, OI breadth increases NPD speed through accessing diverse information sources, recombining complementary information, and capturing innovation opportunities, however, OI depth advances NPD speed through information utilization, such as information sharing and transfer. External information sources widely and deeply employed can provide innovative ideas and resources for gaining more innovation opportunities and thus speed up NPD processes. To regulate the NPD desired speed, managers can select the appropriate depth and breadth of OI in their operations.

Zou et al. [26] show that during the stages of growth and maturity, firms experience a more active trend of valuing, acquiring, assimilating, transforming, and exploiting external knowledge than in the introduction and decline stages of the product lifecycle. A firm's potential and realized absorptive capacities achieve their peak during the product lifecycle growth stage. The changing tendency of a firm's technology-innovation achievements is consistent with the product lifecycle curve, which means that technology-innovation achievements are driven typically by market demand of product lifecycle. The study suggests on how firms can adjust management policies to improve their absorptive capacity and technological innovation performance during different product lifecycle stages.

4 Discussion and Conclusion

We have selected to link PLM to OI in DTSs, because PLM provides an adequate understanding of the product lifecycle, from inception to disposal, and especially because PLM encompass and at the same time look beyond product development and product lifecycle from marketing's point of view. Since many organisations acquire competitive advantages using PLM to manage their product lifecycles, this affirmation could not be different from a start-up perspective. To narrow the gap of information to support PLM, we complete this study with OI, representing all the information flow to the development of a DTS. Therefore, we conducted a systematic literature review of PLM and OI applied to DTSs and the results provided scientific evidence to develop a preliminary conceptual model. From the selected articles, we divided them in two clusters. The first primarily addresses aspects related to MIS to harvest and assess science knowledge and intellectual properties that could be use in DTS. The latter provided a comprehensive vision of the surroundings of OI on PLM application in DTSs and the translation of fundamental research to a commercial product.

Start-ups in general lack of formal managerial structures due to its size and activities risks. To minimise adversary situations to their existence, start-ups rely on the ecosystems to evolve and then at some point of their lifecycle exit via IPO, M&A, etc. Therefore, start-ups are learning organisations that need information to expand and achieve their milestones. Depending on closed innovation does not represent an option when developing innovative technologies. From founder's perspective, learning remains an ongoing activity. The ecosystem equally represents valuable opportunities to develop collaborative networks, which helps to share the risks founders typically take when they decide to initiate a start-up. DTSs sustain an inside-out business and technology push strategy, their value proposition is built round the unique and hard to reproduce developed technology. Therefore, it is challenging for an organisation to generate all the critical knowledge required for the innovation process internally. Especially for start-ups that have minimal structures and sometimes inexistent structures, relying in support structures within innovation ecosystems. Summarising the reasons of DTSs success, it would be noteworthy to identify which factors could be more relevant to the DTS universe.

As exposed in previous sections of this work, information performs a significant role in DTSs. DTSs rely in maturity levels which can move forward with the adoption of external sources of information, amongst then collaboration, i.e., OI. Additionally, to perform the proper management of the product information of technological innovation being developed by DTSs, PLM provides solutions that DTSs faces when dealing with their product lifecycle. Absorbing external knowledge from scientific sources, using proper tools to manage the project, DTSs can excel the initial phases of their existence and increase the product maturity, therefore surpassing the valley of death.

We have not found studies covering end-of-life (EOL) stages of product lifecycle, and this is a yet to be discussed topic even among practitioners. It is comprehensive that most of the effort necessary to establish a radical technological solution must be in the initial stages of the product lifecycle. Also, some models found in SLR performed by this study suggests that customer and users play a substantial role in the technology development and the preliminary stages of product lifecycle. This affirmation is not entirely applicable to DTSs. Because the strategies to develop their products, DTSs exist to solve big Environmental and Social issues and their attractiveness to investments increases due to a change of society's value and eager for radical innovations, which is incorporating sustainable elements to its set of relevant values.

DTSs have naturally an advantage over other start-ups, the abundance of information surrounding their business that could help to reduce uncertainty related to their business application. Although few studies are being conducted about DTSs, they represent until now an increasing field of study. Nevertheless, the increasing number of investments in these companies, innovation governments policies, technological advances and the future depletion of "offline to online business model innovation start-ups", must push an increasing number of DTSs entrepreneurs to develop radical solutions to solve even more complex problems of the present and futures.

This work contributes to promote the foundations of "research to market" and academic entrepreneurship performed by Universities and Research Centres. It provides guidelines to players of innovation ecosystems develop their own frameworks to support radical innovations in DTSs using PLM and OI.

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