What does the proof-of-concept (POC) really prove? A historical perspective and a cross-domain analytical study

Caroline Jobin, Pascal Le Masson, Sophie Hooge

To cite this version:

Caroline Jobin, Pascal Le Masson, Sophie Hooge. What does the proof-of-concept (POC) really prove? A historical perspective and a cross-domain analytical study. XXIXème conférence de l'Association Internationale de Management Stratégique (AIMS), Jun 2020, Online, France. hal-02570321

HAL Id: hal-02570321
https://hal.archives-ouvertes.fr/hal-02570321

Submitted on 21 May 2020

What does the proof-of-concept (POC) really prove?
A historical perspective and a cross-domain analytical study

Jobin, Caroline[1,2], Le Masson, Pascal[1], & Hooge, Sophie[1]

[1] MINES ParisTech, PSL University, Center for Management Science (CGS),
i3 UMR CNRS, 60 Bd St Michel 75006 Paris, France
[2] les Sismo, 30 rue du Temple 75004 Paris, France
caroline.jobin@mines-paristech.fr

Résumé :

En dépit du fait que la preuve de concept ou POC soit devenue une pratique courante des organisations dans les processus de prise de décision et de coordination internes et externes, la littérature en management stratégique s'est jusqu'à présent peu emparée du sujet. Dans ce papier, nous nous sommes intéressés aux questions suivantes : D'où vient la notion de POC et comment a-t-elle évoluée au fil du temps ? En quoi le POC constitue une catégorie particulière de preuve ? Pour répondre à ces questions, nous avons d'abord réalisé une étude historique de la genèse du concept, à savoir dans l'écosystème aérospatial et aéronautique américain. Puis, nous avons mené une étude analytique du transfert de la notion dans les écosystèmes du biomédical, de la recherche publique, du développement de nouveaux produits / de l'innovation / de l'entrepreunariat et enfin des technologies de l'information. Ce papier a permis de montrer que le terme, qui est né dans les années 1960, a progressivement rencontré un succès dans les contextes où il a fallu faire entrer de nouveaux acteurs dans la chaîne de valeur de la conception qui était jusqu'alors très intégrée, et ce souvent par l'amont. En ce sens, le POC, en tant preuve de validation et d'exploration, semble être un outil particulièrement utile aux « acheteurs » et aux « vendeurs » dans des processus avec une dimension exploratoire.

Mots-clés : POC, TRL, conception, validation, exploration

What does the proof-of-concept (POC) really prove?

A historical perspective and a cross-domain analytical study

INTRODUCTION

The proof-of-concept or POC which is presented as a ‘critical step’ in the innovation process (Bendavid and Cassivi, 2016) is widely used by companies and their ecosystem. Christophe Reinert, Head of Open Innovation at EDF Group – global leader in low-carbon energy –, does not hesitate to describe the POC as “a step towards innovation and value creation, a learning step that is often decisive if it is well managed” (Comité Richelieu and Le médiateur des entreprises, 2019). However, the POC remains until now abandoned by strategic management research. It may be because the POC is consider either as a solely technical milestone (Eesle et al., 2014) or a buzz word among others in communities of innovative practitioners and what is more an ill-designed notion.

The objective of this paper is to restore the POC by showing that it designates an important strategic and critical moment in value chain evolutions. We will see that the POC concept has survived since its creation in the 1960s and amplified over the last decades to address specific challenges of the innovation process. Thus, the POC appears to be a key concept for organizing strategic exchange in design. On the one hand, one must prove that one part is true, and on the other hand, one must show that there are still design activities to be carried out.

In this paper, we seek to investigate two research questions: (1) Where does the concept of ‘proof-of-concept’ come from and how has it evolved over time? (2) How does ‘proof-of-concept’ relate to a peculiar category of proof? To address these research questions, we will use two approaches. The first approach is about conducting a historical perspective to trace back the genesis of the POC concept. The concern is to begin to identify the contexts of use of ‘proof-of-concept’ in industrial ecosystem and the nature of the associated proof. The second approach is about conducting a cross-domain analytical study to explore the appropriation of the proof-of-concept by a wide range of actors and sectors. The aim of such a study is to extract from the plural practices of POC a core of common characteristics and a halo of domain-specific specificities. We believe that this common core could be described by the concomitance or even the original articulation between proof and demonstration of residual unknown to explore.

The paper is articulated as follows. In the next section, we will start by recalling the research questions and presenting the research hypothesis before providing an in-depth description of the research approach. We will perform the historical perspective and then the cross-domain analytical study in devoted sections. Then, we could built on these results to discuss the contribution of POC concept for strategic management.

1. RESEARCH HYPOTHESES AND METHODOLOGY

1.1. RESEARCH HYPOTHESES

To understand POC concept's emergence and diversity of meaning, our first hypothesis is that the term was coined by NASA in 1970s in relation to the Technology Readiness Levels (TRLs) and spread over a variety of disciplines such as biomedical and computer sciences. Secondly, despite the existence of plural definitions, we assume that POC handles an original type of proof – a 'double proof' – that bears both known and unknown dimensions of demonstration.

1.2. RESEARCH DESIGN

The following research was carried out in two large sequences. The first step was to identify and describe the origins of the term 'proof-of-concept' to reconstruct its genesis. Particular attention was given to tracing the context and environment associated with the first occurrences of this term to finely account for the properties that this type of proof bears. The second step was to analyze the diffusion of 'proof-of-concept' through four or five 'transfers'. A transfer is defined as an appropriation of 'proof-of-concept' by another ecosystem or discipline than the aerospace and aeronautic ecosystem where the notion was born.

1.3. DATA COLLECTION AND ANALYSIS

To undertake the first part of the study, which is based on a historical perspective, two major methods were used. The first method was to start from the myth concerning POC coming from NASA TRLs – the analysis will show that the cradle of emergence was older. In an operational manner, we started by looking at scientific articles that were written by NASA's collaborators, especially to understand the elements that motivated its emergence. Afterwards we tried to get to the root by investigating reports from NASA and the U.S. government, and affiliating them to major events in U.S. and international aerospace history. We also looked at more recent reports and scientific articles for a complete timeline. To facilitate understanding and reading of the historical perspective, it was broken down in five major phases. A summarized illustration closes this historical perspective. The second method used was to cross-reference this first genealogical study to confirm it and possibly complete it by investigating the first occurrences of 'proof-of-concept' that can be found in academic literature. In an operational manner, we made a query on JSTOR database using the keywords "proof-of-concept" OR "proof of concept", choosing a publication period prior to 1980 (this date was chosen in view of the historical perspective), with documents in all languages and on the basis of all content. This search yielded twenty-five results. Six results were removed because they were not journal articles (5) or the source that was not accessible (1) prevented us to perform our analysis. Our aim was not to provide a complete and thorough analysis of this literature. We focused our attention on the authors of these articles, especially on behalf of: i) which organization they wrote which is almost always mentioned in the article and ii) their positions in this organization at that time which is almost never mentioned in the article, but knowable through archives on the internet.

To undertake the second part of the study, which is based on a cross-domain analytical study, we investigate 'transfers' in four ecosystems: (1) biomedical, (2) public research, (3) NPD, innovation and entrepreneurship, and (4) information technology. Two principles guided the choice of these ecosystems. The first principle was to study ecosystems that concentrate contemporary POC practices. We validate the first point by a detailed analysis of the ecosystems that could be linked to the first sixty results of a Google query made on 21 April 2020 with the following keywords "proof of concept" OR "proof-of-concept". The second principle was to build a sample of transfers with enough material for defining qualitatively to identify redundant and differentiating properties. We sought to understand what motivates the introduction of the proof-of-concept by trying as much as possible to associate these transfers with trends that have marked the history of the domain and therefore also provide rough temporal landmarks. All in all, it allows us to build conjecture on adoption or specific meanings associated to transfer, and propose a cross-domain analytical study that enlighten the function and context of use of the proof for each ecosystem. We adopt a presentation of the transfers that provide a harmonious unfolding of meaning diversity moreover than transfers' temporality.

2. GENESIS OF ‘PROOF-OF-CONCEPT’ IN U.S. AEROSPACE AND AERONAUTIC ECOSYSTEM: AN HISTORICAL PERSPECTIVE

In this section, we trace the history of the ‘proof-of-concept’ in the U.S. aerospace and aeronautic ecosystem where this concept was born. In order to better understand the issues and problems that motivated the creation and deployment of the proof-of-concept, particularly through the Phased Review Process (PRP) and the Technology Readiness (TRL) scale, we review some major dates in American and world spatial history. This section also allows us to make a list of the characteristics of this type of proof with chronological markets. These properties will be taken advantage of in the cross-domain analysis study.

In the first part of this section we focus on the geopolitical context which prompted the creation of NASA. In a second part we trace back the first occurrence of ‘proof-of-concept’ in relation to the Phased Review Process. In a third part we investigate the dynamics of emergence of the TRL scale then we cross this historical perspective with the analysis of the first academic publications which mobilized this notion before the end of the 1980s. In a fourth part we describe the deployment and integration of the TRL scale in NASA’s ecosystem. Finally, in a fifth part we stress modern uses of TRLs in NASA’s and worldwide aerospace and defense sector.

2.1. 1940S-1950S: COLD WAR, SPACE RACE, AND NASA’S FOUNDATION

After World War II began a period of geopolitical battle, known as the *Cold War*, between the United States (U.S.) and the Soviet Union and their respective allies. In this context, space became a great competitive arena between the two major powers. Through the *Space Race* each of them sought to show the world its technological superiority and *in fine* its model superiority. In this competition the Soviet Union achieved a major milestone that was not palatable to most Americans in the fall of 1957 : they launched the first man-made objects into Earth orbit – *Sputnik 1* and *Sputnik 2*, the first spacecraft which carried out a living animal.

Although the U.S. finally succeed to launch their own satellite *Explorer 1* in February 1958 which had been developed by the Army Ballistic Missile Agency, the U.S. Congress remained worried about national security and technological leadership. Therefore, in a message to the Congress in April 1958, President Eisenhower proposed the establishment of a National Aeronautics and Space Agency (NASA) as an independent agency of the U.S. Federal Government that would absorb staff, laboratories and aerospace research activities of the present National Advisory Committee for Aeronautics (NACA). The creation of NASA was acted in July 1958. NASA was created to be responsible for civilian or 'peaceful' space science and aeronautical research in its own facilities or by contract and would also perform military research if required by the military departments (Emme, 1961).

2.2. 1960S: PHASED REVIEW PROCESS AND PROOF-OF-CONCEPT

Another huge milestone in this *Space Race* performed by the Soviet Union touched the U.S. in their pride and leadership and pushed them to react. Indeed, in April 1961, the Soviet cosmonaut and pilot Yuri Gagarin was the first human to journey into outer space when his *Vostok* spacecraft while he completed an orbit of the Earth. This event triggered the launch of the *Apollo Program* in May 1961 by President Kennedy. The goal was simple and clear – putting a man on the moon and returning him safely before the decade was out.

To achieve such a challenge and more generally meet the national space policy, NASA developed in the 1960s the Phased Project Planning, commonly referred as the Phased Review Process (Cooper, 1994). According to Cooper (1994), the purpose of the Phased Review Process was to take apart the development process into discrete phases. This process breakdown by phases not only provided a better framework for funding and drawing up contracts, but also aimed at reducing technological risks. Indeed, this measurement and control was a safeguard for NASA that all the requirement had been met, especially that the engineering tasks had been completed by its teams or its contractors and suppliers before moving on to the next phase. As evidenced by more recent NASA's resources such as the report of David D. Few from the NASA's Ames Research Center (Few, 1987), Phase II was to be named 'proof-of-concept' or 'POC'. This assumption is historically confirmed by a 1966's report which "summarizes and reports the results of the Phase II (proof-of-concept) program for the development of an Advanced Meteorological Sounding System." (Griggs and Wood, 1966). Information about this report was published on the website of the Defense Technical Information Center (DTCI). DTCI is the repository for research and engineering information for the U.S. Department of Defense (DoD) and its ecosystem who also adopted the Phased Review Process as project management methodology (Cooper, 1994).

Although this methodology has been criticized by some executives, it probably helped to meet President Kennedy's challenge. Indeed, in July 1969 the mission *Apollo 11* allowed two of the three crew astronauts (Neil Armstrong and Buzz Aldrin) to set a foot on the moon and safely come back home.

2.3. 1970S: EMERGENCE OF THE READINESS LEVELS AT NASA

In September 1969, a few months after this exploit, a report of the Space Task Group entitled 'The Post-Apollo Space Program: Directions for the Future' was published. In this one, the Task Group took stock of the *Apollo Program* and made recommendations for future space activities (Space Task Group, 1969). It recognized that *Apollo Program* stimulated the creation of subsequent technological capability. It is about "the growth of a valuable reservoir of highly trained, competent engineers, managers, skilled workmen and scientist within the government, industry and universities" with the support of "facilities, technology and organizational entities capable of complex management tasks". One of the characteristics of the balanced program for the future envisioned by the Task Group in the same report is 'opportunity'. Indeed, it is stated as a goal that "[a]bundant opportunities exist for further exploitation of this capability. A balanced program will permit adequate attention to applications and science while also creating new opportunities through development of new capability". This is how the *Supporting Research Technology (SRT) Program* and their mission planners became in charge of adding value to the technological capability developed during the 1960's *Apollo Program* through their integration into future missions. According to Sadin et al. (1989), the duty of mission managers was to use "program funds to adapt and requalify the "shelf-stored" technology inventory". On the other side, the *Advanced Research Technology (ART) Program* and their researchers were responsible for pursuing new concepts (*ibid.*). This approach called 'technology push' or 'opportunity driven' completed the dominant model of 'program pull' or 'need driven' commonly used at NASA where a specific technology was only developed in response to a need previously formulated by the mission planners (Héder, 2017; Sadin et al., 1989).

Such a paradigm shift was successful in some cases but also often raised issues in the 1970s (Sadin et al., 1989; Straub, 2015). According to Sadin et al. (1989), "the differing perceptions of the researchers and the mission planners between the intended and actual proof of readiness was often the cause of an aborted handoff, or technology transfer, of ART [Advanced Supporting Research Technology] to the SRT [Supporting Research Technology] users". They also explained that the definition of the following categories: 'basic research', 'feasibility', 'development' and 'demonstration' "have caused ambiguous understandings between, the researchers, their management, and the potential program users”. NASA’s first challenge was to enhance the understanding of the researchers and the mission planners about the ‘technology readiness’ in order to perform the technology transfer at the good point.

This new paradigm also raised another issue regarding the ‘flight readiness’ because new concepts and technologies could be developed regardless a space mission. Indeed, a framework was needed to assess "how proven a certain technology was" in a context where "they cannot necessarily prove their feasibility in an actual space mission at the time of development" (Héder, 2017). NASA’s second challenge was to evaluate the ‘technology readiness’ on a regularly basis during its development process.

To respond to these two challenges the NASA Office of Aeronautics and Space Technology (OAST) laid the foundation of the concept of ‘readiness levels’ in 1974 (Mankins, 2009; Straub, 2015) that were later codified in a paper (Sadin et al., 1989). The terminology ‘proof-of-concept’ is used to describe the third level named “Proof-of-concept demonstrated, analytically and/or experimentally” (*ibid.*). More generally, readiness levels are claimed to “provide the Agency [NASA], and the communities with which it interact a more precise means of describing the depth to which a research and technology program is to be pursued” (Sadin et al., 1989). In that sense, the formalization of readiness levels echoes “the creation and management of boundary objects” which is presented by Star and Griesemer (1989) as “a key process in developing and maintaining coherence across intersecting social worlds”. They are “objects [that may be abstract or concrete] which are plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites” (*ibid.*). To that extent, TRL 3 or ‘proof-of-concept’ may be characterized as a ‘boundary object’.

Let us continue by crossing the beginning of this historical perspective with the analysis of academic literature prior to 1980. The institution and position of the authors of the seventeen journal articles, their related use of POC concept (quote), and references are presented in Table 1. We have not yet succeeded in finding the positions for all the authors, we thus used the expression ‘to be defined (TBD)’ in Table 1 to characterize these holes.

Looking for POC roots, we also found two isolated articles in philosophy without correlated interpretation but, it remains important to specify that one of them constitutes the first academic article found which use the notion as early as 1963 (Rotenstreich, 1963). This first article is about the construction of a philosophical system. The author uses POC term to underline the ability to manage the unity of knowledge acquisition through concepts assumption (teleological proof of knowledge unity). The second article (Bunge, 1970) is about the benefits of the interplay between physicists and philosophers. POC is used to designate a step of abstraction within the reasoning in physics (technique of proof of concept independence).

With the exception of these two references in philosophy, the collected information is consistent with our above declaration. Indeed, most of the authors who embrace the terminology have technical management or engineering positions in the U.S. aerospace and aeronautic ecosystem (cf. Table 1). They worked either at NASA, or in a company or university which most likely had a contract with NASA. Moreover, sometimes articles were written in collaboration between the two institutions, as it can be seen in the last section of the table. Research on vertical and/or short take-off and landing (V/STOL) aircraft, which are aircrafts that do not require or limited runways without being helicopters, has largely catch the attention of these papers. To a lesser extent, another stream of literature, that can be extracted from the sample, is related to the National Science Foundation (NSF) and its contracts to translate research efforts into general public-use applications.

Table 1: Analysis of the first stakeholders who embrace the terminology of ‘proof-of-concept’ in academic literature (before 1980)

INSTITUTION / SUB-INSTITUTION	**AUTHOR’S(S’) POSITION (Year)** * TBD: To be defined	**Use of POC Concept (Quote / reference)**
U.S. Federal Agencies		
National Aeronautics and Space Administration		
Ames Research Center	Manager of Advanced VTOL Projects Office & Research Leader of STOL joint flight programs (1973)	“A candidate V/STOL research aircraft design is one that fea- tures a promising V/STOL propulsion/control concept, is suitable for **proof-of-concept flight investigations**, and meets the objectives of austerity and maximum ...” Deckert, W. H., & Holzhauser, C. A. (1973), Evaluation of V/STOL Research Aircraft Design, SAE Transactions, 3122-3127.
Langley Research Center	Chief of the Research Aircraft Flight Division, Aerospace Engineer, & TBD	“... for FAA **proof-of-concept evaluations** ...” Reeder, J. P., Taylor, R. T., & Walsh, T. M. (1974), New Design and Operating Techniques for Improved Terminal Area Compatibility, SAE Transactions, 1714-1731.
Lewis Research Center	Project Manager (1976)	Final **proof-of-concept type tests** in fullscale engines are needed to quantify the achievable levels as well as to evaluate the impact of increased complexity on engine operational characteristics ... Rudey, R. A. (1976), The Impact of Emission Standards on the Design of Aircraft Gas Turbine Engine Combustors, SAE Transactions, 2838-2849.
Headquarters	Chief of General Aviation Technology Office & TBD (1976)	“and Avco-Ly coming, are carrying out the development of a system for **proof-of-concept testing** ...” Winblade, R. L., & Westfall, J. A. (1976), NASA General Aviation Research Overview-1976, SAE Transactions, 1576-1650.
Jet Propulsion Laboratory (California Inst. of Tech.)	Geophysical Evaluation Manager, TBD, & TBD (1979)	“During some 3 months of orbital operations, Seasat collected a unique set of global synoptic data on ocean winds, waves, temperature, and topography. all indications from a preliminary analysis of these data are that most of the mission's **proof-of-concept objective** - the demonstration of nearly all-wheather microwave surveillance of the world's oceans - will be met ...” Born, G. H., Dunne, J. A., & Lame, D. B. (1979), Seasat mission overview, Science, 204:4400, 1405-1406.
National Science Foundation		
Office of Intergov. Science and Research Utilization	Director (1974)	“... But the issue now is: How do we go from the **proof-of-concept stage** to creatingg the kind of driving, self-sustaining force for application of technology which will begin to make a national impact ...” Hersman, M. F. (1974), Science and the Public Sector: A National Policy Overview, Proceedings of the National Academy of Sciences of the United States of America, 71:6, 2565.
Science Education Directorate	Project Manager of the Technological Innovation in Education Group (1975)	“...The Foundation's efforts have been aimed at **"proof-of-concept" experiments, demonstrations and field tests** designed to reduce the uncertainty for the commercial sector and to offer compelling educational evidence to the academic community ...” Molnar, A. R. (1975), Viable goals for new educational technology efforts in science education, Educational Tech., 15:9, 16-22.

Air Weather Service – redesignated the Air Force Weather Agency in 1997	Captain (1974)	Hayes, J., 1974: Progress towards the proof of concept of a method of determining winds and pressure in planetary boundary layer over oceans by means of the S193 combined microwave radiometer—scatterometer on Skylab in the first two manned periods. Unpublished Paper Prepared for First IAMAP/IAPSO Assemblies, Melbourne, Australia. Arnold Jr, C. P. (1975), Selective reconnaissance program of the western North Pacific, Bull. of the Am. Meteorolog. Soc., 56:3, 362-371.
U.S. Companies		
Pratt & Whitney Aircraft – subsidiary of Raytheon Tech. Corp.	Aeronautic Engineer (1971)	"... further **analytical and experimental "proof of concept" technology programs** must be undertaken to determine the "best" propulsion system ..." Godston, J. (1971), STOL Engine Systems and Sensitivity Factors, SAE Transactions, 1644-1653.
Rockwell International Corp. – aerospace and defense activities were sold to Boeing in 1996	Supercritical Wing Specialist & TBD (1972)	"... To provide **proof-of-concept flight data** on the thick super-critical wing, the U.S. Navy, NASA, and NR-C have teamed up to conduct a series of flight tests on a modified Navy T2-C Buckeye trainer aircraft ..." Palmer, W. E., & Elliott, D. W. (1972), Thick-Wing Flight Demonstrations, SAE Transactions, 1225-1232.
	TBD (1973)	"... It is a modified **Gulfstream II proof of concept vehicl**e intended to demonstrate advances in lift-fan..." Ford, J. C. (1973), Lift-Fan Propulsion/Control System, SAE Transactions, 1229-1242.
Dynatech Corp.	Government Marketing Manager, TBD & Vice President (1976)	"... A **proof-of-concept experimental** program has been developed to fill in the gaps of knowledge in order to permit a confident design of a full-scale processing facility for the production of fuel gas from solid waste ..." Kispert, R. G., Sadek, S. E., & Wise, D. L. (1976), An evaluation of methane production from solid waste, Resource Recovery and Conservation, 1:3, 245-255.
U.S. Universities and Research Organizations		
Institute of Gas Technology (IL)	Scientists (1976)	"... Bisselle et al. reported on the results of a study undertaken to provide background for a so-called **proof-of-concept experiment** to be conducted by the NSF..." Ghosh, S., Conrad, J. R., Packer, M., Van Ryzin, E. (1976), Anaerobic processes, J. of Water Pollution Control Fed., 48:6, 1115-1137.
University of Charlottesville (VA)	Meteorology Scientist (1978)	... On the right, the confirmatory or **"proof of concept" experiment** is shown, with models to estimate seedability, radar survaillance and a rain sampling subprogram ... ... On the most important lessons learned in weather modification is the necessity of sequential develoment, with an "exploratory phase" followed by a confirmatory or **"proof of concept" phase** ... ... After digesting and interpreting theses results, a **"proof of concept experiment"** logically follows, which can be modeled, measured and analyzed futher by subprograms in parallel with the randomized core program ... Simpson, J. (1978), What weather modification needs—a scientist's view, Journal of Applied Meteorology, 17:6, 858-866.
U.S. Collaborations		
NASA Ames Research Center & Boeing Corp.	Research Leader of STOL joint flight programs, TBD, Aeronautical Engineer, & TBD (1971)	... The research had advanced to a point by early 1970 that **a proof-of-concept** ... Quigley, H. C., Sinclair, S. R. M., Nark Jr, T. C., & O'Keefe, J. V. (1971), A Progress Report on the Development of an Augmentor Wing Jet STOL Research Aircraft, SAE Transactions, 2514-2527.
University of Kansas (KS) x NASA Flight Research Center	Professor in Aerospace Engineering, Project Engineer & Project Manager (1973)	"... and faster than the PA-30. It is doubtful whether the PA-30 type of airplane is flown very often through that type of tur- bulence. SUMMARY It has been shown that the separate surface approach to all- attitude control systems is feasible. It appears that an **in-flight proof-of-concept** ..." Roskam, J., Barber, M. R., & Loschke, P. C. (1973), Separate Surfaces for Automatic Flight Controls, SAE Transactions, 1040-1050.
McDonnell Douglas Corp. x NASA Ames Research Center	TBD & Aerospace Engineering (1977)	"...This comparison served as **a proof of-concept** for the simulator test technique in that good agreement was obtained with the conventional technique..." Eigenmann, M. F., & Bailey, R. O. (1977), Development of the Propulsion Simulator-A Test Tool Applicable to V/STOL Configurations, SAE Transactions, 3406-3417.

2.4. 1980s-1990s: Development and Integration of the Technology Readiness Levels (TRLs) in NASA's ecosystem

Another landmark event in American spatial history pushed the use of the 'readiness levels' by NASA's practitioners and ecosystem. In January 1986, the terrible accident of *Space Shuttle Challenger* cost life of all the seven crew members abroad. Presidential Commission on the Space Shuttle Challenger Accident called 'Rogers Commission' stated that the contribution cause of the accident was linked to deep issues in NASA's decision-making processes (Presidential Commission on the Space Shuttle Challenger Accident, 1986, p83). This dramatic event fostered the revision of the U.S. national space policy that President Reagan approved in January 1988 as explained by the fact sheet released in February 1988 (Office of the Press

Secretary, 1988). We learned that among Presidential Directive's goals and objectives, the revised national policy encouraged more coordination and collaboration inside the civil sector (i.e., between NASA and other governmental agencies, companies and universities), between sectors (civil, national security, commercial), and with international (allies) partners. To continue in this direction President George H. W. Bush announced the *Space Exploration Initiative* on the 20th anniversary of the Apollo 11 Moon landing. According to Mankins (2009), this space public policy continued and expanded the use of 'readiness levels' that was enriched with an eight and a ninth level and probably had already taken the shape of a scale before the formalization of Technology Readiness Levels (TRLs) scale by Mankins in a white paper in 1995. Such a tool appeared to be even more useful "due to the need to communicate technology readiness status and forecasts between the technology research community and the exploration mission planning community" (Mankins, 2009). This newly expanded TRL scale was also employed in the *Integrated Technology Plan for the Civil Space Program* in 1991 (OAST, 1991). Indeed, in 1995 Mankins formalized the TRL scale as "a systematic metric/measurement system that support assessments of the maturity of a particular technology and the consistent comparison between different types of technology" (Mankins, 1995). In this white paper the TRL 3 is reformulated as follows in the new 9-level scale: "Analytical and experimental critical function and/or characteristic proof-of-concept". The paper also provided a short description of each level with an example and its attainment criteria. For the TRL 3, we can read:

> At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory. Cost to Achieve: Low 'Unique' Cost (technology specific) (Mankins, 1995).

In a later paper, Mankins (2009) enriched the definition he provided few years earlier. For our research question, a modification and clarifications can be emphasized. The paper clarified the point that a class of inventions may be "proven" analytically whereas another class of inventions "require physical experimental validation – such as those involving highly complicated concepts or those involving environmentally dependent phenomena or novel material effects" (Mankins, 2009). Moreover, the costs to achieve that were previously presented as low and unique are therefore presented as "low to moderate" because "the costs can vary significantly from one area of research and development to another". The article also stated that "[b]ecause of the relatively high risk and long lead times, it is less likely that funding at TRL 3 or below would be available from most types of venture funding sources" (Mankins, 2009).

2.5. 2000S-2010S: MODERN USES OF TRLS IN NASA'S ECOSYSTEM AND WORLDWIDE AEROSPACE & AERONAUTIC ECOSYSTEM

In their paper, Straub et al. (2015) provided a review of NASA's uses of TRLs depicted in their public documentation. Table 2 provides a chronological summarized analysis of these uses.

Table 2: Synthesis of NASA's uses of TRLs (adapted from Straub et al., 2015)

TITLE OF THE DOCUMENT	PURPOSE OF THE DOCUMENT OR ASSOCIATED PROGRAM	PURPOSE OF TRL SCALE
NASA Research Announcement for the Instrument Incubator Program – NRA 01-OES-xx (2001)	Develop technology activities leading to new systems and measurement techniques to be developed in support of ESE science research and applications.	Framework to evaluate proposals that must provide the current TRL assessment of the system technology, and the anticipated progression of TRL levels throughout the proposed efforts - starting and exit TRL must meet NASA Research Announcement policy.
NASA Risk-Informed Decision Making Handbook – NASA/SP-2010-576 (2010)	Provide guidance for implementing the risk-informed decision making requirements of NASA Procedural Requirements document.	Risk and uncertainty assessment framework for mission analysis.
NASA System Safety Handbook – SP-2010-580 (2011)	Present the overall framework for system safety to provide the general concepts needed to implement the framework.	Help whether the system design meet the minimum tolerable level of safety or vulnerability to unknown hazards.
NASA Strategic Space Technology Investment Plan (2012)	Provide a focused investment approach to guide NASA's space technology investment over the next four years within the context of a 20-year horizon.	Guide NASA's technology investment strategy and portfolio execution though a principle that impel to have a balanced investment across all TRL
NASA Systems Engineering Processes and Requirements – NPR 7123.1B (2013)	Clearly articulate and establish the requirements on the implementing organization for performing systems engineering.	Accurate assessment of technology maturity throughout the life cycle of the project and capabilities to moving to higher TRLs. A differentiated description of technology maturity between hardware and software is proposed in appendix.
NASA Systems Engineering Handbook – NASA/SP-2016-6105 Rev 2 (2016)	Provide general guidance and information on systems engineering useful to the NASA community.	Framework used during the Technology Readiness Assessment (TRA) to systematically determine a system's technological maturity in terms of TRLs and the difficulty to move to the next TRL.

In 1999, the Armed Services Committee of the U.S. Senate asked the Government Accounting Office (GAO) to investigate the situation of the Department of Defense (DoD). Such an investigation was carried out because the DoD planned to increase funding for new development programs while previous "programs very often suffered significant delays and vast cost increases" (Héder, 2017). In its report, GAO applied the framework of the TRL scale to assess various programs to better understand why some of them well or poorly performed. They found that DoD integrated technologies anywhere from TRL 2 to TRL 9 and programs that integrated TRL 6-technologies no longer experienced any additional cost. The main message of this report was therefore that by formalizing the maturity of technologies on the TRL scale and by refusing to support technologies that are too immature (below TRL 7 in any circumstances, with the preferred TRL 8 TLR 9), DoD will improve the performance of these acquisition programs (GAO, 1999; Jean, 2018). The DoD adopted the TRL scale in 2000.

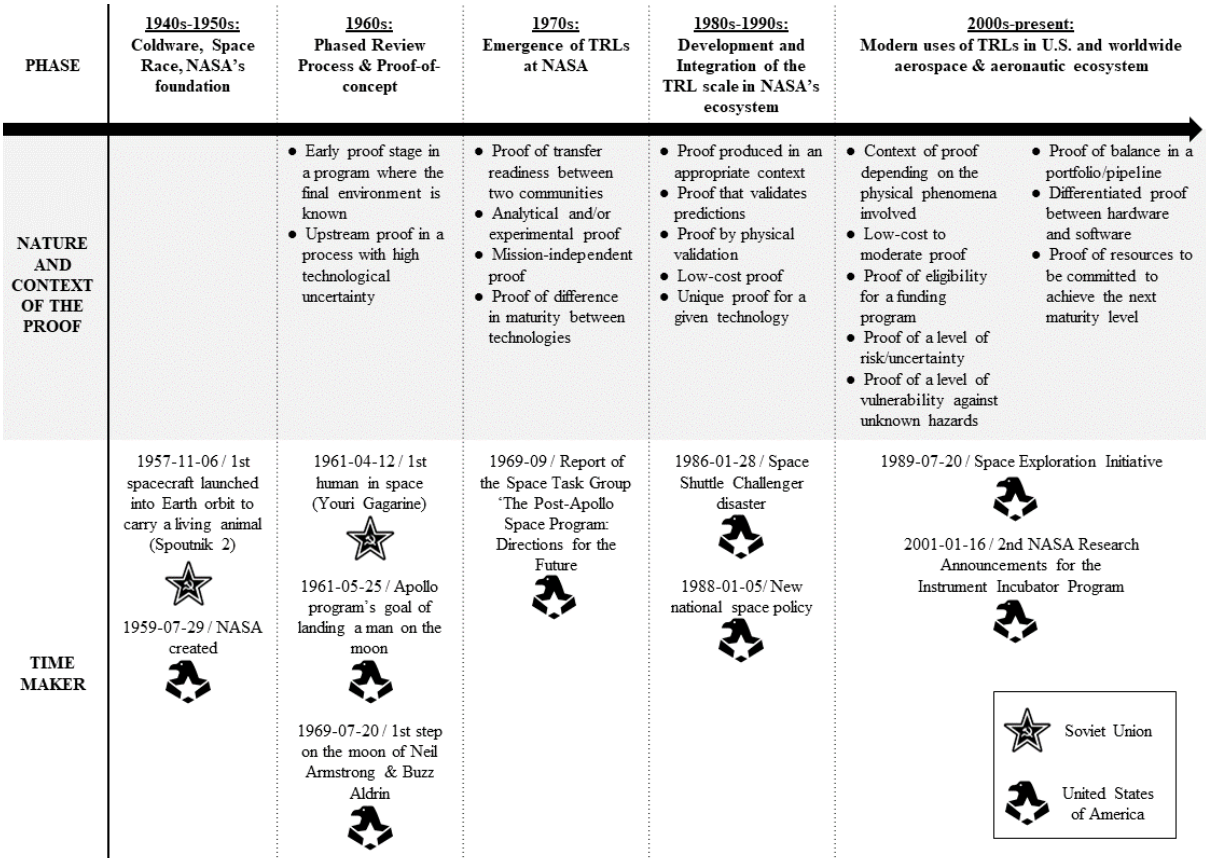
Other U.S. governmental agencies "beyond NASA adopted a NASA-derived or NASA-like TRL system" (Straub, 2015). Indeed, on the one hand, some of U.S. governmental agencies such as the Department of Defense (DoD) or the Department of Homeland Security (DHS) closely adopted the TRL with minor wording modifications, and on the other hand, others such as the Department of Energy (DoE) applied major modifications to the 9-level scale.

In the 2000s, the TRL also crossed the border of the U.S. and inspired international space agencies and their contractors such as the European Space Agency (ESA) that adopted the TRL scale in the mid-2000s. In a handbook published in 2008, ESA declared that "the purpose of timely and accurate technology readiness assessments is to inform management and support decisions as part of the implementation of advanced technology system development projects" and "[t]he Technology Readiness Levels have been defined to provide a common metric by means". In this handbook, ESA took the NASA's thermometer diagram without change and closely followed the technological levels while definitions provided in Mankins' white paper (1995) were enriched. Moreover, the handbook had an appendix section with "guidelines for the definition of the software technology readiness levels". In 2013, the TRLs were canonised through the ISO standard 16290 'Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria assessment' which is highly inspired by NASA and DoD. ISO 16290 replaced ESA's own internal document since (Héder, 2017).

Since the beginning of the 21st century, TRLs has globally gained popularity in numerous organizations (Mankins, 2009) not only in aeronautical and defense sector but more generally in high-tech industry such as automobile, spreading POC concept as TRL 3.

2.6. HISTORICAL PERSPECTIVE OVERVIEW

In Figure 1, we provide an overview of this historical perspective that described the genesis of 'proof-of-concept' in the U.S. aerospace and aeronautic ecosystem.



PHASE	**1940s-1950s:** **Coldware, Space Race, NASA's foundation**	**1960s:** **Phased Review Process & Proof-of-concept**	**1970s:** **Emergence of TRLs at NASA**	**1980s-1990s:** **Development and Integration of the TRL scale in NASA's ecosystem**	**2000s-present:** **Modern uses of TRLs in U.S. and worldwide aerospace & aeronautic ecosystem**	
NATURE AND CONTEXT OF THE PROOF		• Early proof stage in a program where the final environment is known • Upstream proof in a process with high technological uncertainty	• Proof of transfer readiness between two communities • Analytical and/or experimental proof • Mission-independent proof • Proof of difference in maturity between technologies	• Proof produced in an appropriate context • Proof that validates predictions • Proof by physical validation • Low-cost proof • Unique proof for a given technology	• Context of proof depending on the physical phenomena involved • Low-cost to moderate proof • Proof of eligibility for a funding program • Proof of a level of risk/uncertainty • Proof of a level of vulnerability against unknown hazards	• Proof of balance in a portfolio/pipeline • Differentiated proof between hardware and software • Proof of resources to be committed to achieve the next maturity level
TIME MAKER	1957-11-06 / 1st spacecraft launched into Earth orbit to carry a living animal (Spoutnik 2) ★ 1959-07-29 / NASA created 🦅	1961-04-12 / 1st human in space (Youri Gagarine) ★ 1961-05-25 / Apollo program's goal of landing a man on the moon 🦅 1969-07-20 / 1st step on the moon of Neil Armstrong & Buzz Aldrin 🦅	1969-09 / Report of the Space Task Group 'The Post-Apollo Space Program: Directions for the Future 🦅	1986-01-28 / Space Shuttle Challenger disaster 🦅 1988-01-05/ New national space policy 🦅	1989-07-20 / Space Exploration Initiative 🦅 2001-01-16 / 2nd NASA Research Announcements for the Instrument Incubator Program 🦅	

★ Soviet Union

🦅 United States of America

Figure 1: Historical perspective overview

3. TRANSFERS OF 'PROOF-OF-CONCEPT' IN OTHER ECOSYSTEMS: A CROSS-DOMAIN ANALYTICAL STUDY

In this section, we will show that 'proof of concept' appropriation in various ecosystems greatly contributed to its broad expansion. The term which appeared in the 1960s has since TRL scale stabilization in the 1990's become widely democratized, as the Google NGRAM graph in Figure 2 clearly shows. .

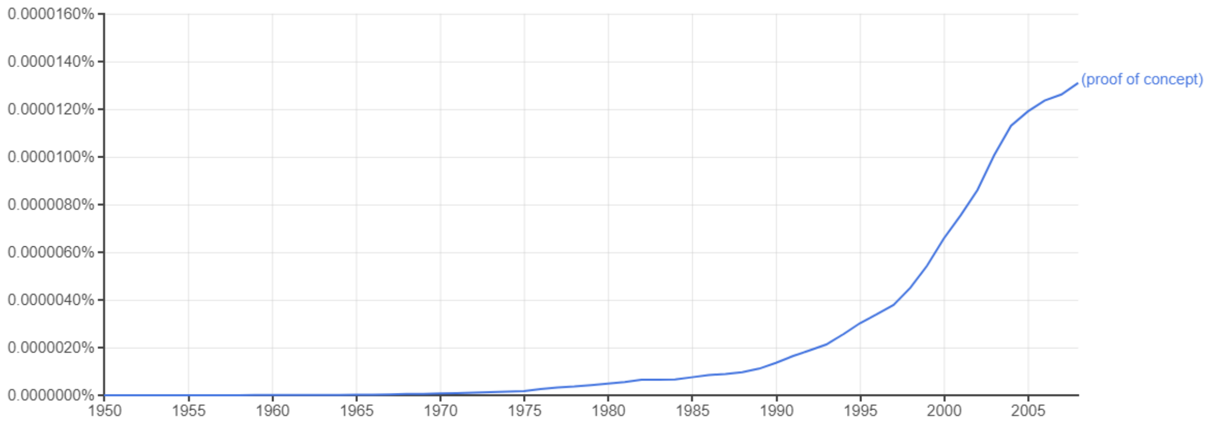


Figure 2: Google NGRAM graph of 'proof of concept'
(literature between 1950 and 2008 from the corpus 'English (2012)')

3.1. BIOMEDICAL TECHNOLOGY: DEVELOPMENT AND DISCOVERY/DESIGN

The sector of POC transfer that adopt the concept with the closest philosophy is biomedical technology. It is well known fact that bringing a new drug to the market is a business of high risk. Indeed, it generally costs about $2.5 billion and lasts more than twelve years (Avorn, 2015) while the attrition rate along the life cycle is tremendous (Waring et al, 2015). Moreover, following the tradition of modern medicine as an evidence-based practice and responding to the excesses that have marked our history, the pharmaceutical and biomedical industry sectors are today characterized by one of the most regulated environments related to safety and ethics (Jekunen, 2014).

3.1.1. Biomedical Technology Development

The development process of new pharmaceuticals has been broken into phases for many years. The same mechanism was later employed in the 1960s by NASA through its Phased Review Process. It was probably around the 1980s that the transfer of the 'proof-of-concept' occurred through its insertion in existing stage phases for which regulatory authorities (FDA, ANSM, Health Canada, …) are guarantors. At that time, such stages became convenient indicators in corporate dashboards for investors who were not necessarily specialized in the biomedical field. Indeed, in a contemporary way, the second phase of these clinical trials (Phase IIa) is generally presented as 'proof of concept' studies (Cartwright, 2010; Corr and Williams, 2009; Preskorn, 2014, Yuan et al., 2015). During this stage, "the study drug is tested for the first time for its efficacy in patients with the disease or the condition targeted by the medication" (Corr and

Williams, 2009), i.e., experimental studies are performed into an appropriate context because the concept involve an environment-dependent phenomena - to be in line with the description of TRL 3 by Mankins (2009). Furthermore, according to the Pharmaceutical Research and Manufactures of America (PhRMA), "[t]he POC demonstrates that the drug did what it was intended to do, that is, interacted correctly with its molecular target and, in turn, altered the disease" (Corr and Williams, 2009). Contrary to later stages of clinical trials, 'proof of concept' studies "typically involv[es] a small number of subjects and more latitude in statistical requirements" (Preskorn, 2014). Such 'proof of concept' or 'POC' studies must "provide evidence that a molecule is likely to be successful in later stages of drug development process (i.e., late phase II and large-scale phase III studies required for U.S. Food and Drug Administration [FDA] approval)" (Preskorn, 2014). In the same way, PhRMA presented the POC as "the earliest point in the drug development process at which the weight of evidence suggests that it is 'reasonably likely' that the key attributes for success are present and the key causes of failure are absent" and "perhaps the key deliverable of exploratory drug development" (Cartwright et al. , 2010). In addition of being a milestone in an internal development process to "allow drug developers to make 'Go/No Go' decisions about proceeding with larger, more expensive studies" (Preskorn, 2014), such studies are a an 'obligatory passage point' (Callon, 1984) that must sufficiently convince the competent authorities to obtain their agreement to pursue larger clinical trials.

3.1.2. Biomedical Technology Discovery/Design

In the same vein of Cooper's stage-gate process (1994) that aim to 'capture the entire process from idea through to launch, and not just the middle stage, Development", 'proof-of-concept' terminology shifted to upstream process steps to describe "up-front homework or pre-development work" (Cooper, 1994). Indeed, 'proof-of-concept' is used to describe discovery (or design, see Elmquist and Segrestin (2007) phase studies (Evans and Varaiya, 2003) or preclinical tests/studies (Detela and Lodge, 2019; Fink, 2009) by leveraging in vitro or in vivo models of disease (Detela and Lodge, 2019). This transfer probably occurred in the 1990s with the massive arrival of new technologies (e.g., high-throughput screening) to address drug discovery (Drews, 2000). Drug discovery was then increasingly driven by external biotechnology experts in universities or biotechnology companies rather than chemistry experts of large pharmaceutical companies (Corr and Williams, 2009). Indeed, it appears that the POC was needed to organize the externalization of the upstream process. This more upstream interpretation is largely found through academic literature in biological and biomedical sciences (for instance see Stone et al., 2020). This interpretation is also depicted for pharmaceuticals in the Biomedical Technology Readiness Levels provided in appendix of the Technology Readiness Assessment (TRA) Deskbook of the DoD (Office of the Director Defense Research and Engineering, 2009). Indeed, we can read that TRL 3 decision criterion is about "[i]nitial proof-of-concept for candidate [drugs or biologics/vaccines] constructs is demonstrated in a limited number of in vitro and in vivo research models". For medical devices, "in vivo and in vivo research models" is replaced by "laboratory model (may include animal studies)" whereas for medical Information Management/Information Technology (IM/IT) and medical informatics, decision criterion is expressed as follows: "Medical informatics data and knowledge representation schema are modeled".

The concomitance of these two interpretations of POC in the world of new biomedical technologies (e.g., in a single research article, see Detela and Lodge (2019)) causes confusion when it comes to technology transfer between laboratories or research organizations to pharmaceutical or medical device companies. In fact, the former type of stakeholders often speaks of POC to describe the fact that they had successfully conducted pre-clinical trials while this language refers to clinical trials for the latter type of stakeholder. This ambiguity in practices was revealed to us by a Technology Transfer Project Manager at SATT Lutech, a French structure that accompanies innovative projects from academic laboratories to the market. Indeed, he said that "the researcher may consider having established his POC by validating the mechanism of action on a few human cells while the industrialist thought that the drug had already been tested on several dozen sick patients" (interview date: 4 February 2019).

3.2. PUBLIC RESEARCH: TECHNOLOGY TRANSFER AND FUNDING

Proof of concept' is not only used by researchers in biological or biomedical sciences, but also more generally in public research ecosystem independently of the discipline. Two main uses of 'proof of concept' can be described.

3.2.1. Technology transfer

The first use, i.e., technology transfer (Feller, 1990), draws inspiration from the assessment of technology maturity to ensure that the transfer between researchers (ART) to the mission planners (SRT) took place at the good point (Sadin et al., 1989). For instance, Jensen and Thursby (2001) used the terminology of 'proof of concept' to describe a stage of development for university inventions when they were licensed. In the same line, Markman et al. (2005) found that licensing strategy of university-based technology is "strongly influenced by the stage of the technology, which they classify into four overlapping categories including early-stage inventions, proof of concept, reduction to practice, and prototyping". For 'proof of concept' stage described as follows: "[a]n idea or new technology has been developed to the point that it shows signs of having the proposed effect", licensing for sponsored research is preferred while "market applications are still unclear" (Markman et al., 2005). Clarysse et al. (2007) who studied the creation of academic spin-offs said "[t]he stage of NPD of the spin-off at start-up was defined on a scale where: 1 = idea phase; 2 = proof of concept, i.e. α prototype; 3 = prototype that works in a real-life environment, i.e. β prototype; 4 = concrete market-ready product".

3.2.2. Funding program

The second use draws inspiration from the 'proof of concept' funding programs of the U.S. National Science Foundation in 1970s (Kispert et al., 1976). Indeed, it is not uncommon for governmental (for example, 'BRIDGE Proof of Concept' from the Swiss National Science Foundation) and intergovernmental agencies to offer 'proof of concept' grants (for example, 'ERC PoC 2019' or 'ERC PoC 2020' from the European Research Council in the framework of Horizon 2020 program, the E.U. research and innovation funding program). On the French portal of the Horizon 2020 program, it is explained that such grant is offered in order to support the researchers who develop ideas to be able to reach the market and cross the 'valley of death' of innovation. Several universities also support 'proof of concept' activities thanks to challenge funds (Mosey and Wright, 2007). These funds can come from University Technology Transfer Offices (UTTOs) (Markman, 2005) or 'PoC Centers' which help researchers in "the development and verification of a commercial concept, the identification of an appropriate target market, and the development of additional required protectable IP" (Maia and Claro, 2013). The general objective of these grants and incubation programs that sometimes use the reference of TRL 3 is to bring universities and research organizations results closer to the industrialization and commercialization.

3.3. NEW PRODUCT DEVELOPMENT, INNOVATION AND ENTREPRENEURSHIP

The ‘proof of concept’ is often used to describe an early phase in New Product Development (NPD) process (Clarysse, 2007; Heirman, 2007) and innovation processes (Bendavid and Cassivi, 2012) in line with the NASA’ Phased Review Process. The transfer occurred in the 1980s and early 1990s (Cooper, 1994) probably due to the large representation of TRL scale’ users within the circles of technological management diffusion. In the definition of ‘proof-of-concept’ given by Bendavid and Cassivi (2012), i.e., the demonstration of the technical feasibility of the concept, one can easily see the footprint of NASA's TRL 3 definition here. Moreover, as materiality is needed to perform a POC, its occurrence very often goes together with the term ‘prototype’, and even sometimes the two terms are combined to form a unique concept: ‘proof of concept prototype’ (Yu et al., 2018).

‘Proof-of-concept’ is also used to describe a new firm’s development stage (Eesley, 2014). Moreover, with the birth of the startup phenomenon in early 2000s, entrepreneurs have massively embraced this wording and practice because of its powerful attractiveness, especially towards potential investors (Eesley, 2014). With such label, entrepreneurs hope to attract and convince them that the concept and the business is worth investing in while providing early evidence of success. This evidence of success can be related to technical or business/market issues. For instance, it is recognized that investors such as Venture Capitalists (VCs) prefer to invest in a technology that has proven its technical feasibility (Clarysse et al., 2017). Moreover, POC enriches market survey that has its limitation regarding radical innovations for which functional requirements remain to be conceived. The POC will help to determine them through the test of pseudo-solutions on pseudo-users. In the context of B2B or B2BC start-ups, entrepreneurs also aspire to attract potential clients through a ‘proof of concept’ contract, sometimes paid, sometimes free. These clients are often large groups given the market and the promotional image that can represent to the start-up and the widespread practice of open innovation in large groups (Chesbrough, 2003, Weiblen and Chesbrough, 2015). According to Bpifrance, the French public investment bank, on the side of start-ups, POC is an opportunity to “generate revenue by acquiring customers [and] to engage quickly with large groups, with few technical constraints, and demonstrate the value of a start-up’s services” while on the side of large groups, POC “allows to assess the capacity of the solution to meet the expectations of the large group and to see whether collaboration between the two stakeholders can be considered on a larger scale”. In addition, ‘proof of concept’ is increasingly found in support structures such as (corporate) incubators and accelerators to depict either an entry or an exit point in the same line of NASA’s Instrument Incubator Program. In addition, the POC is not confined to cases of entrepreneurship but also applies to cases of intrapreneurship. In that case, the target audience of the POC is internal to the company. Performing a ‘proof of concept’ study can help intrapreneur “selling the initiative internally and justifying funding” (Hienerth et al., 2011) similarly to entrepreneurs or generate internal feedback before presentation to the client. Finally, the POC is increasingly represented in the world of design thinking (Brown, 2008; 2009) and design sprint (Knapp et al., 2016). Even if this term is very weakly present or even absent from the original texts and seems to appear from nowhere, it has a real stake and interest in the contracting between design agencies and their clients in a reverse view of NASA and its contractors/suppliers. Indeed, the POC was also appropriated by SMEs such as ‘les Sismo’, a French independent industrial design and innovation agency. Les Sismo began to use the POC term to put a word on existing practices in the late 2000s. Then, les Sismo embrace the POC in the mid-2010s to characterize a service that can be sold to clients through a quote and therefore to ensure a remuneration while the final innovation is still under design.

3.4. INFORMATION TECHNOLOGY (I.T.): IMPLEMENTATION AND SECURITY

Finally, we also find ‘proof-of-concept’ in the context of implementation and security management, as in I.T. industry.

3.4.1. I.T. Implementation

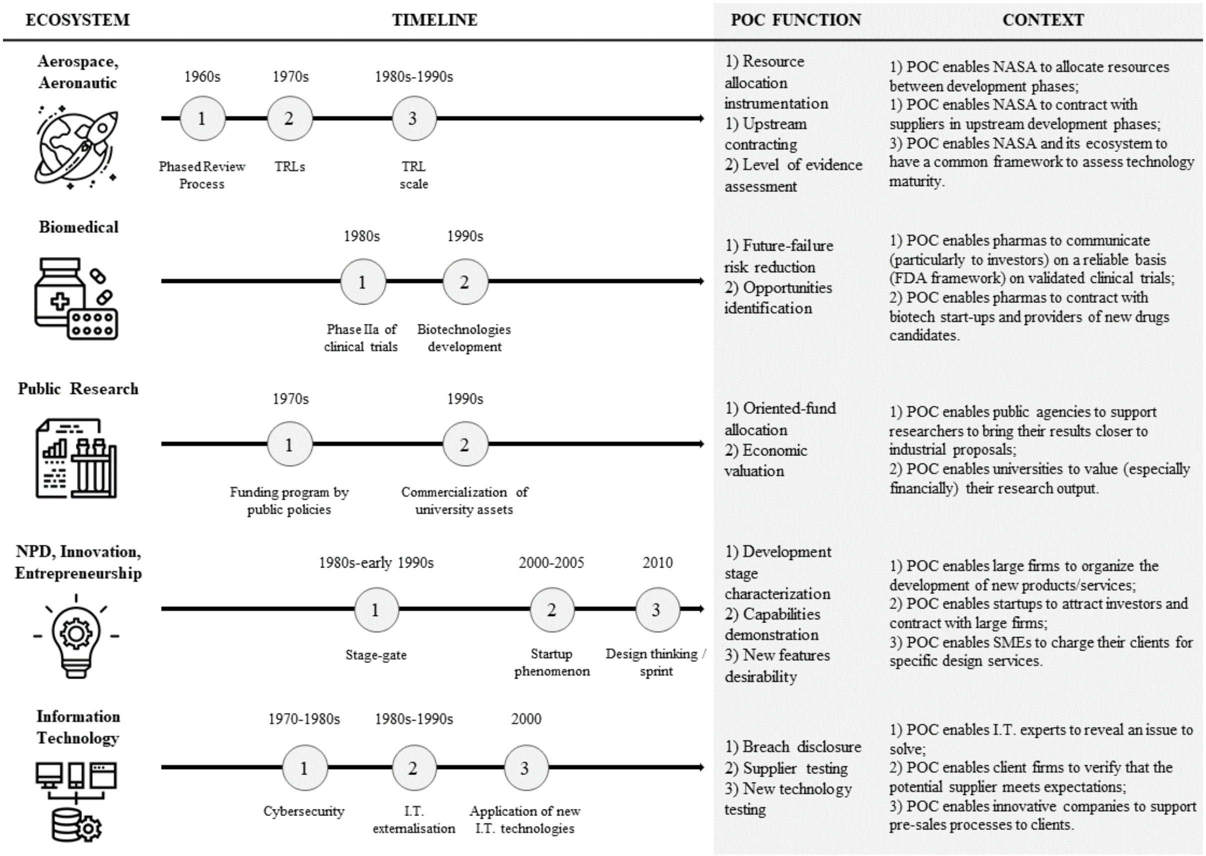
Some companies which are looking for implementing a new software or I.T. solution do not content themselves to base the choice-making process of publisher solely by on fact sheets, presentations, or ‘off-the-shelf’ demos. They engage with potential suppliers through a POC in a similar manner that NASA does with contractors, or large companies with start-ups. Indeed, it allows the client company to both have a first sight on the future efficiency, compatibility, and user acceptability of the solution, and on the reliability and capability of the potential supplier. As for the other sectors, this transfer probably took place in the 1980s-1990s when companies have undertaken large waves of outsourcing of their I.T. by entrusting external companies such as IBM. Since the rise in capacities of these same companies which has become proposal forces as well as the emergence of start-ups specialized in breakthrough I.T. technologies in the 2000s-2010s, the proposal to conduct a POC only comes from the I.T. company which would like to prospect clients by reassuring them about the value and feasibility in applying their cutting-edge technology (Big data, IA, blockchain, IoT, …) into use cases of interest for the prospect. The POC can then mark the beginning of a broader collaboration between companies and even a co-design collaboration.

3.4.2. IT Security

The transfer to the I.T. security ecosystem is probably old because the experts in cybersecurity (i.e., defense and aerospace/aeronautic companies) are the same that first embrace the proof-of-concept terminology. Nevertheless, POC meaning is here more distant : Proof-of-concept is used to stress the vulnerability of an I.T. system to a (potential) cyber-attack or characterized the program or system that revealed this vulnerability or security breach (Wilson et al., 2016). Such security vulnerability can constitute an entry point for a malware capable of altering the DNA of the software or I.T. system and thus reprogramming it to divert its initial use or crashing it. The defect can be identified by developers or security experts before its release or by attackers after its release. Contrary to the numerous tests required to characterize an I.T. solution as ‘attack-proof’, a proof-of-concept only needs to work once and do not call more development (e.g., optimization) than those requested to achieve the intended purpose. Proof-of-concept initiative aims to raise awareness about the existence of such a flaw and thus an opportunity or the rest to be done to correct it (Wilson et al., 2016).

3.5. CROSS-DOMAIN STUDY ANALYSIS OVERVIEW

In Figure 3, we provide an overview of this cross-domain analytical study that described transfers of ‘proof-of-concept’ in other ecosystems than the U.S. aerospace and aeronautic.



ECOSYSTEM	TIMELINE	POC FUNCTION	CONTEXT
Aerospace, Aeronautic	1960s 1 Phased Review Process 1970s 2 TRLs 1980s-1990s 3 TRL scale	1) Resource allocation instrumentation 1) Upstream contracting 2) Level of evidence assessment	1) POC enables NASA to allocate resources between development phases; 1) POC enables NASA to contract with suppliers in upstream development phases; 3) POC enables NASA and its ecosystem to have a common framework to assess technology maturity.
Biomedical	1980s 1 Phase IIa of clinical trials 1990s 2 Biotechnologies development	1) Future-failure risk reduction 2) Opportunities identification	1) POC enables pharmas to communicate (particularly to investors) on a reliable basis (FDA framework) on validated clinical trials; 2) POC enables pharmas to contract with biotech start-ups and providers of new drugs candidates.
Public Research	1970s 1 Funding program by public policies 1990s 2 Commercialization of university assets	1) Oriented-fund allocation 2) Economic valuation	1) POC enables public agencies to support researchers to bring their results closer to industrial proposals; 2) POC enables universities to value (especially financially) their research output.
NPD, Innovation, Entrepreneurship	1980s-early 1990s 1 Stage-gate 2000-2005 2 Startup phenomenon 2010 3 Design thinking / sprint	1) Development stage characterization 2) Capabilities demonstration 3) New features desirability	1) POC enables large firms to organize the development of new products/services; 2) POC enables startups to attract investors and contract with large firms; 3) POC enables SMEs to charge their clients for specific design services.
Information Technology	1970-1980s 1 Cybersecurity 1980s-1990s 2 I.T. externalisation 2000 3 Application of new I.T. technologies	1) Breach disclosure 2) Supplier testing 3) New technology testing	1) POC enables I.T. experts to reveal an issue to solve; 2) POC enables client firms to verify that the potential supplier meets expectations; 3) POC enables innovative companies to support pre-sales processes to clients.

Figure 3: Cross-domain analytical study overview

4. DISCUSSION AND CONCLUSION

As a reminder, we seek to address the two following questions in the paper: (1) Where does the concept of 'proof-of-concept' come from and how has it evolved over time? (2) How does 'proof-of-concept' relate to a peculiar category of proof?

We showed that the 'proof-of-concept' was born in the 1960s in the U.S. aerospace and aeronautics ecosystem to organize resource allocation and drawing contracts with research and development partners, with the strong objective of putting a man on the Moon before the end of the decade. We saw that the concept was then used in contexts where there was a need to agree on the object of the transaction, in particular to reassure mission planners about the level of evidence achieved by the technology before allowing its transfer and integration into a future mission. A proof was therefore needed even if it could only be partial, knowing that the complete system was not yet there, and the tests were not carried out in the operational environment. We found this same logic of partial proof, or 'double proof', proof of validation and proof of exploration in transfers in the various ecosystems under study. It is quite easy to see a correlation between the appropriation of the POC by an ecosystem and an opening logic of the value chain that occurred. Thus, it is likely that the POC makes possible the entry of new actors. What is rather surprising is that this is not an entry through the downstream, which is rather usual, i.e., a company A handles the entire design and development process and then delegates the manufacturing to a company B. In the context of NASA and transfers, it is rather an entry through the upstream. It is about contractualization management knowing that the design activities have not yet been completed. The POC seems therefore to enable the disintegration of design value chains. When resource allocation or contracting processes already existed, they absorbed the POC while for those, such as public research, who did not, they adopted the TRL scale. While the exploratory nature of the proof is not easily identifiable in NASA's POC; to that end, one must look at the entire process, the articulation of these two types of proof is more easily palpable in the information systems ecosystem.

Characterizing the proof-of-concept as a double piece of proof could help to better position this object relative to other concepts that may appear in the first place as synonyms and are often used interchangeably. Among these terms, we think on the one hand of the 'test bench' or the 'prototype' (in the sense of a validator, see Ben Mahmoud-Jouini and Midler, 2019) or which are only oriented towards proof of validation. On the other hand, we can distinguish the POC from the 'mock up', 'concept car/object' or 'stimulators' (*ibid.*) which are rather centered on proof of the need of further exploration as these boundary objects reveal problems, make desirable the learning, etc.). As for the concept of 'demonstrator' (*ibid.*), the difference with the POC is more ambiguous because it contains both a demonstration logic (in the almost mathematical sense) and an exhibition logic (of the unknown). The POC might be distinguished from the demonstrator thanks to its supposed ability not only to gather proof of validation and proof of exploration but also to articulate both. Figure 4 underlines this dual function of proof managed by POC concept.

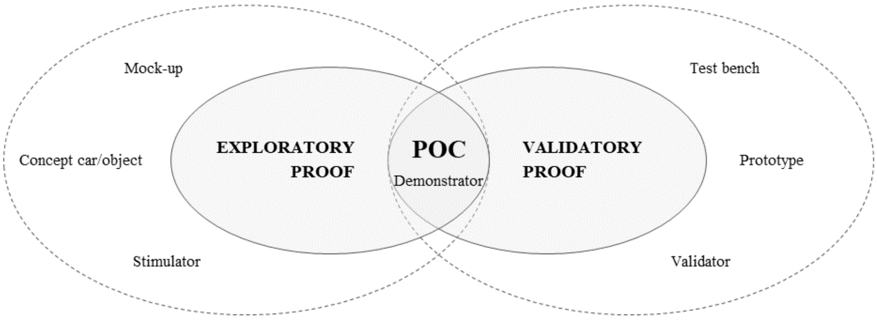


Figure 4: The dual proof function of POC

We saw in this paper that the POC was mobilized in contexts where there were strategic issues regarding the design and evolutions of its value chain, and most often upstream. In this sense, the POC has emerged as a particularly useful tool in crystallizing the intermediate stages of knowledge and relationships. The POC has also appeared in this paper as a powerful tool for decision-making thanks to its time pacing effect and the robustness and mastery it brings, even in contexts where uncertainty or even unknown are very present. As such, the POC seems to be part of limited small number of objects that are capable of supporting decision-makers in highly exploratory contexts.

This paper does have limitations that need further study to address them. Additional work in the dating of transfers deserves to be done to validate our conjecture. Even more, descriptions of transfers especially in the I.T. ecosystems need to be better supported by academic references. For those which are starting to be corroborated, it would be interesting, in the manner of cladistic phylogeny, to demonstrate more finely the common ancestries and go back to the closest of the transfer time. In addition, in the discussion, we started very succinctly to position the POC in relation to other ‘synonyms’. Further research could likely deepen this investigation to better characterize the overlapping areas between POC and these other objects (e.g., experimentation (Thomke, 2003, Gillier and Lenfle, 2019) as well as what makes the specificities of the POC. Continue to investigate the thesis that we began to sketch in this article is a stimulating perspective : in particular, we strive to study how the POC can not only concatenate proof of validation and proof of exploration but go further by articulating both and thus obtaining synergistic phenomena.

REFERENCES

Avorn, J. (2015), The $2.6 billion pill–methodologic and policy considerations, New England Journal of Medicine, 372:20, 1877-1879.

Bendavid, Y., & Cassivi, L. (2012), A ‘living laboratory’environment for exploring innovative RFID-enabled supply chain management models, International Journal of Product Development, 17:1-2, 94-118.

BenMahmoud-Jouini, S., & Midler, C. (2020), Unpacking the notion of prototype archetypes in the early phase of an innovation process, Creativity and Innovation Management, 29:1, 49-71.

Brown, T. (2008), Design thinking, Harvard business review, 86:6, 84.

Brown, T. (2009), Change by design: How design thinking creates new alternatives for business and society, New York: Collins Business.

Bunge, M. (1970), The physicist and philosophy, Zeitschrift für allgemeine Wissenschaftstheorie, 1:2, 196-208.

Callon, M. (1984), Some elements of a sociology of translation: domestication of the scallops and the fishermen of St Brieuc Bay, The sociological review, 32:1_suppl, 196-233.

Cartwright, M. E., Cohen, S., Fleishaker, J. C., Madani, S., McLeod, J. F., et al. (2010), Proof of concept: a PhRMA position paper with recommendations for best practice, Clinical Pharmacology & Therapeutics, 87:3, 278-285.

Chesbrough, H. (2006), Open business models: How to thrive in the new innovation landscape, Boston: Harvard Business Press.

Clarysse, B., Wright, M., Lockett, A., Mustar, P., & Knockaert, M. (2007), Academic spin-offs, formal technology transfer and capital raising, Industrial and Corporate Change, 16:4, 609-640.

Comité Richelieu and Le médiateur des entreprises (2019), Osez l'innovation, De l'idée à l'industrialisation : réussissez votre preuve de concept, Ministère de l’Economie et des Finances, Paris.

Cooper, R. G. (1994), Third-generation new product processes, Journal of Product Innovation Management, 11:1, 3-14.

Corr, P., and Williams, D. (2009), The pathway from idea to regulatory approval: examples for drug development, in: Lo, B. and Field, M.J (Eds.), Conflict of Interest in Medical Research Education and Practice, Washington D.C.: National Academies Press, 375-383.

Detela, G., & Lodge, A. (2019). EU regulatory pathways for ATMPs: standard, accelerated and adaptive pathways to marketing authorisation. Molecular therapy. Methods & clinical development, 13:1, 205-232.

Drews, J. (2000), Drug discovery: a historical perspective, Science, 287:5460, 1960-1964.

Elmquist, M., & Segrestin, B. (2007), Towards a new logic for Front End Management: from drug discovery to drug design in pharmaceutical R&D. Creativity and Innovation Management, 16:2, 106-120.

Emme, E. M. (1961), Aeronautics and astronautics: An American chronology of science and technology in the exploration of space, 1915-1960, Washington D.C.: US Government Printing Office.

Evans, A. G., & Varaiya, N. P. (2003), Anne Evans: assessment of a biotechnology market opportunity. Entrepreneurship Theory and Practice, 28:1, 87-105.

Eesley, C. E., Hsu, D. H., & Roberts, E. B. (2014), The contingent effects of top management teams on venture performance: Aligning founding team composition with innovation strategy and commercialization environment, Strategic Management Journal, 35:12, 1798-1817.

Feller, I. (1990), Universities as engines of R&D-based economic growth: They think they can, Research Policy, 19:4, 335-348.

Fey, D.D., (1987), A Perspective on 15 Years of Proof-of-Concept Aircraft Development and Flight Research at Ames-Moffett by the Rotorcraft and Powered-Lift Flight Projects Division, 1970-1985, Scientific and Technical Information Office, NASA (National Aeronautics and Space Administration), Washington D.C.

Fink, D. W. (2009), FDA regulation of stem cell–based products, Science, 324:5935, 1662-1663.

GAO (Government Accounting Office). (1999), Best practices: Better Management of Technology Development Can Improve Weapon System Outcomes, United States General Accounting Office), Washington D.C.

Gillier, T., & Lenfle, S. (2019), Experimenting in the unknown: lessons from the Manhattan project, European Management Review, 16:2, 449-469.

Golder, P. N. and Mitra, D. (Eds.). (2018), Handbook of research on new product development, Cheltenham: Edward Elgar Publishing.

Griggs, W. M., Wood, J.K. (1966), An advanced meteorological system, phase II (proof-of-concept). [online] Defense Technical Information Center. Available at: https://apps.dtic.mil/docs/citations/AD0655389 (accessed 30.04.2020).

Hatchuel, A., Le Masson, P., Reich, Y., and Weil, B. (2011), A systematic approach of design theories using generativeness and robustness, Proceedings of the 18th International Conference on Engineering Design (ICED 11), Lyngby/Copenhagen, Denmark, August 15-19, 2011, Impacting Society through Engineering Design, 2: Design Theory and Research Methodology, 87-97.

Hatchuel, A., Le Masson, P., Reich, Y., and Subrahmanian, E. (2018), Design theory: a foundation of a new paradigm for design science and engineering, Research in Engineering Design, 29:1, 5-21.

Héder, M. (2017), From NASA to EU: The evolution of the TRL scale in Public Sector Innovation, The Innovation Journal, 22:2, 1-23.

Heirman, A., & Clarysse, B. (2007), Which tangible and intangible assets matter for innovation speed in start-ups?, Journal of Product Innovation Management, 24:4, 303-315.

Hienerth, C., Keinz, P., & Lettl, C. (2011), Exploring the nature and implementation process of user-centric business models, Long Range Planning, 44:5-6, 344-374.

Jean F. (2016), L'échange génératif de technologies innovantes : engagement conceptif et conception de la valeur [PhD Thesis], PSL Research University.

Jekunen, A. (2014), Decision-making in product portfolios of pharmaceutical research and development–managing streams of innovation in highly regulated markets, Drug design, development and therapy, 8:1, 2009-2016.

Jensen, R., and Thursby, M. (2001), Proofs and prototypes for sale: The licensing of university inventions, American Economic Review, 91:1, 240-259.

Karlsson, C. (Ed.) (2016), Research methods for operations management, London: Routledge.

Kispert, R. G., Sadek, S. E., & Wise, D. L. (1976), An evaluation of methane production from solid waste, Resource Recovery and Conservation, 1:3, 245-255.

Knapp, J., Zeratsky, J., and Kowitz, B. (2016), Sprint: How to solve big problems and test new ideas in just five days, New York: Simon and Schuster.

Le Masson, P., Weil, B., and Hatchuel, A. (2010), Strategic management of innovation and design, Cambridge: Cambridge University Press.

Maia, C., & Claro, J. (2013), The role of a Proof of Concept Center in a university ecosystem: an exploratory study, The Journal of Technology Transfer, 38:5, 641-650.

Mankins, J. C. (1995), Technology Readiness Levels: A White Paper, Advanced Concepts Office, Office of Space Access and Technology, NASA.

Mankins, J. C. (2009), Technology readiness assessments: A retrospective, Acta Astronautica, 65:9-10, 1216-1223.

Markman, G. D., Phan, P. H., Balkin, D. B., & Gianiodis, P. T. (2005), Entrepreneurship and university-based technology transfer, Journal of business venturing, 20:2, 241-263.

Marvel, J. A., Saidi, K., Eastman, R., Hong, T., Cheok, G., and Messina, E. (2012), Technology readiness levels for randomized bin picking, In Proceedings of the Workshop on Performance Metrics for Intelligent Systems, College Park, Maryland, March 20-22, 2012, 109-113.

Mosey, S., & Wright, M. (2007), From human capital to social capital: A longitudinal study of technology–based academic entrepreneurs, Entrepreneurship theory and practice, 31:6, 909-935.

OAST (Office of Aeronautical and Space Technology), 1991. Integrated Technology Plan for the Civil Space Program, NASA (National Aeronautics and Space Administration), Washington D.C.

Office of the Director Defense Research and Engineering. (2009). Technology Readiness Assessment (TRA) Deskbook, Department of Defense, Washington D.C.

Office of the Press Secretary (1988), Fact sheet: Presidential Directive on National Space Policy, NASA (National Aeronautics and Space Administration) Historical Reference Collection, History Office, NASA Headquarters, Washington D.C.

Plattner, H., Meinel, C., and Leifer, L. (Eds.). (2018), Design Thinking Research: Making Distinctions: Collaboration Versus Cooperation, Cham: Springer.

Presidential Commission on the Space Shuttle Challenger Accident. (1986). Report of the President. NASA (National Aeronautics and Space Administration), Washington D.C.

Preskorn, S. H. (2014), The role of proof of concept (POC) studies in drug development using the EVP-6124 POC study as an example, Journal of Psychiatric Practice, 20:1, 59-60.

Ries, E. (2011), The lean startup: How today's entrepreneurs use continuous innovation to create radically successful businesses, New York: Crown Books.

Rotenstreich, N. (1963), On constructing a philosophical system, Logique et Analyse, 6:21/24, 179-194.

Sadin, S. R., Povinelli, F. P., and Rosen, R. (1989), The NASA technology push towards future space mission systems. In Selected Proceedings of the 39th International Astronautical Federation Congress, Bangalore, India, October 8–15, 1988, March 20-22, 2012, 73-77.

Sekaran, U. (1992), Research methods for business, New York: John Wiley & Sons.

Space Task Group (1969), The Post-Apollo Space Program: Direction for the Future, NASA (National Aeronautics and Space Administration) Historical Reference Collection, History Office, NASA Headquarters, Washington D.C.

Star, S. L., and Griesemer, J. R. (1989), Institutional ecology, translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39, Social studies of science, 19:3, 387-420.

Stone, V. M., Hankaniemi, M. M., Laitinen, O. H., Sioofy-Khojine, A. B., Lin, A., Lozano, I. D., ... & Hytönen, V. P. (2020), A hexavalent Coxsackievirus B vaccine is highly immunogenic and has a strong protective capacity in mice and nonhuman primates, Science Advances, 6:19, eaaz2433.

Straub, J. (2015), In search of technology readiness level (TRL) 10, Aerospace Science and Technology, 46:1, 312-320.

Thomke, S. H. (2003), Experimentation matters: unlocking the potential of new technologies for innovation, Boston: Harvard Business Press.

Waring, M. J., Arrowsmith, J., Leach, A. R., Leeson, P. D., Mandrell, S., Owen, R. M., ... & Wallace, O. (2015), An analysis of the attrition of drug candidates from four major pharmaceutical companies. Nature reviews Drug discovery, 14:7, 475-486.

Weiblen, T., & Chesbrough, H. W. (2015), Engaging with startups to enhance corporate innovation, California management review, 57:2, 66-90.

Wilson, A., Schulman, R., Bankston, K., & Herr, T. (2016), Bugs in the system. Washington D.C.: New America.

Yu, F., Pasinelli, M., and Brem, A. (2018), Prototyping in theory and in practice: A study of the similarities and differences between engineers and designers, Creativity and Innovation Management, 27:2, 121-132.

Yuan, J., Pang, H., Tong, T., Xi, D., Guo, W., & Mesenbrink, P. (2016), Seamless phase IIa/IIb and enhanced dose-finding adaptive design, Journal of biopharmaceutical statistics, 26:5, 912-923.