Failure is an option: How failure can lead to disruptive innovations

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Abstract

We analyze how a failure-embracing mentality can lead to disruptive innovations. Grounded in the extensive data obtained from the study of space industry leader SpaceX and its revolution of reusable rocket boosters, we suggest that appropriate organizational processes can be highly effective in generating technological disruptive innovations. Our results mainly contribute to the identification of the foundational elements that need to be in place, as well as to the definition of sequential actions to be executed, for a successful innovation cycle. In the former, the organization must ensure that appropriate knowledge management mechanisms have been implemented, and that the individuals involved are prepared for the innovation process. In the latter, the detection and analysis of failure, followed by an optimization of further experiments and an adjustment of the roadmap, must proceed iteratively and sequentially to build upon the cumulative experience gained. These findings are important because they suggest that successful disruptive innovation is not fortuitous but can be achieved through systematic processes. Moreover, we bring a different perspective to a popular literature stream which to date had focused on why incumbent firms were successful or not in responding to disruptive innovations, rather than on how failure can be leveraged to successfully introduce in the market a disruptive innovation. In addition to the contributions to the learning by failure and disruptive innovation literatures, this work also adds to the very limited managerial studies of the fast-growing and increasingly relevant *New Space Economy*.

Keywords: learning from failure, deliberate experimentation, disruptive innovation, space economy, SpaceX

1. Introduction

"3…2…1…0…and we have liftoff of Falcon 9" (Davenport, 2015).

At 8:29 p.m. on December 21st, 2015, SpaceX's Falcon 9 rocket launched from Florida on a mission to deliver commercial satellites into space. A few minutes later, the second stage (the Falcon 9 is a multistage rocket – i.e., it uses two or more rocket stages, each of which contains its own engines and propellant) separated from the first and headed outside of the atmosphere, while the 40-meter-long first stage booster performed an aerial U-turn and headed back to Earth.

"The Falcon has landed" (Davenport, 2015).

Guided by fins on the side of the rocket and slowed down with its engine thrust, the Falcon 9's first stage steered toward the landing pad and touched down vertically with incredible precision. The event marked the first time in history that a rocket booster landed after reaching orbital altitude, bringing the space industry one step closer to its holy grail: fully reusable rocket launchers.

Reusability of rocket launchers is one of the most significant disruptive innovations (Bower & Christensen, 1995) in the space industry of the past decade. Disruptive innovation is a term used to describe a technology that creates a new market and value network and eventually displaces established firms, products, and alliances (Christensen, 1997). At first, the disruptive innovation tends to display inferior characteristics compared to the incumbent design for the performance attributes considered most important by the majority of existing customers. To succeed, therefore, it is usually introduced in a niche market where the attributes sought are different. With time, as it starts to deliver a comparable or higher performance than its predecessor, the disruptive innovation begins appealing to mainstream consumers and eventually becomes the dominant design (Bower & Christensen, 1995).

In the case of SpaceX, the reusable rocket launcher came with lower costs. This attribute was however not deemed essential by the main customers at the time, namely governments and space agencies, which instead valued primarily reliability. Initially, in fact, SpaceX appealed to private actors that had budget constraints and could not afford to fly with incumbent launch providers, which boasted a successful track record but asked for significantly higher prices. With time however came experience, and so did reliability. As SpaceX's capabilities improved, so did its market share. While in 2013 the company captured only 5% of the global commercial launch market, by 2018 it had reached over 60% (Bennett, 2018).

The SpaceX revolution was built on a failure-embracing, iterative development process of trial and error. This approach stands in stark contrast with the space industry's conservative mentality, historically oriented towards preventing or mitigating any failure. While the crosschecks and burdensome review processes that were in place increased system reliability, the overwhelming bureaucracy was detrimental to agility and innovativeness. Therefore, after years of stagnation both in the rocket launchers market and in the broader space industry (Summerer, 2012), SpaceX kickstarted a shift in mindset largely based on a novel approach to failure. The company learned to embrace failure, and the entrepreneurial spirit of "fail fast, iterate quickly" became SpaceX's predominant operating model.

This shift in attitude leverages the broad and widely accepted realization that learning by failure is a fundamental step to success. Indeed, researchers have found that a certain number of failures are an essential prerequisite for organizations to develop an optimal innovation strategy (Guzzini et al., 2018). Cyert and March (1963) even argue that firms learn mainly by their failures rather than from their triumphs. However, failure can result in tangible (e.g., monetary costs) and intangible (e.g., grief and embarrassment) fallouts (Edmondson, 2011; Shepherd & Kuratko, 2009). Turning innovation failure into success is therefore a necessary but complex challenge.

In the past few years, failure has become an important subject of study. Many articles in the business press highlight the benefits of failure (e.g., Bloomberg, 2006; The Economist, 2011). Failure has also become popular in academic research (e.g., Eggers, 2012; Khanna et al., 2016; Madsen & Desai, 2010; Muehlfeld et al., 2012; Shepherd et al., 2013). Several authors have analyzed how failure provides opportunities for individuals and organizations to modify their practices and improve performance (Sitkin, 1992). Moreover, recent research has begun to shift its focus from why and how failure occurs to how organizations do or do not learn from failure (Dahlin et al., 2018). From large-scale disasters (Madsen & Desai, 2010) and bankruptcies (Kim & Miner, 2007), to product recalls (Haunschild & Rhee, 2004) and accidents (Baum & Dahlin, 2007; Haunschild & Sullivan, 2002), studies on failure learning have covered multiple levels of analysis.

While a variety of factors that affect failure learning have been validated, however, there appears to be a lack of consensus on how to best learn from failure (Dahlin et al., 2018). In their literature review, Cannon and Edmondson (2005) identify three main organizational activities through which organizations learn from failure: (1) identifying failure, (2) analyzing failure, and (3) deliberate experimentation. In this paper we focus on the latter, studying how deliberate experimentation can be leveraged to achieve disruptive innovations. As noted by Cannon and Edmondson (2005), deliberate experimentation is a double-edged sword that increases the frequency of failure, but also augments the possibility of generating novel solutions to problems. Indeed, with deliberate experimentation new ideas are put to the test, but in a monitored context. Yet, while prior research has confirmed that organizations that experiment effectively are likely to be more innovative, productive, and successful than those that do not take such risks (Thomke, 2003), it remains unclear what processes can be implemented to effectively convert deliberate experimentation into disruptive innovations.

To address the literature gap, in this paper we analyze the case of SpaceX, the firm that has arguably had the greatest influence in shaping the space industry over the past twenty years. Our focus is on how, in its early days, SpaceX's deliberate experimentation processes helped it introduce in the market one of the most consequential disruptive innovations in the history of the space sector: reusable rocket launchers. Specifically, we seek to answer the following research question: "How can failure driven by deliberate experimentation support the development of disruptive innovations?"

This paper is original because, to the best of our knowledge, very little research has been carried out to date which analyzes the relationship between the concepts of learning by failure, specifically through deliberate experimentation, and disruptive innovation. Indeed, understanding this relationship is fundamental because disruptive innovations are paramount for the societal economic growth, prosperity, and competitiveness. Therefore, establishing the right processes and promoting an adequate mindset to incentivize and support disruptive innovations is fundamental for both managers and policymakers.

Based on our findings, we suggest that to be successful in the development of technology-based disruptive innovations, organizations must firstly establish the foundational elements that are necessary, but by themselves not sufficient, to support the innovation cycle. On an individual level these include a risk-prone, curious mentality. On the organizational level instead they involve well-defined, structured processes for planning and executing experiments, dealing with failure, and absorbing new knowledge. Moreover, we find that for a sustainable pursuit of disruptive innovations, organizations must be able to balance the trade-offs between speed of execution and risk of failure. Technological innovation is a resource-intensive process; expenses increase with the number of failures, but also with the duration of the innovation cycle. Therefore, it is unwise to deliberately experiment and purposely fail just to find the formula that does not work, but it is also unsustainable to constantly try to perfect the experiment.

This article is structured as follows. In Section 2 we provide theoretical background on learning by failure and on the concept of disruptive innovations. In Section 3 we outline the methods of our research, with a dedicated focus on SpaceX. In Section 4 we present the findings. In Section 5 we discuss our results, providing concluding remarks and general recommendations in Section 6.

2. Theoretical Background

There is broad consensus on how the ability to innovate is essential for the survival and growth of firms (Chen & Huang, 2010; Gök & Peker, 2017; Hernandez-Espallardo et al., 2012; Kraśnicka et al., 2018; Lee et al., 2010; Schmidt et al., 2009; Tahirsylaj, 2012). Drawing on a wide survey of 1,757 executives (Shelton & Percival, 2013), the professional services firm PWC found that 51% of them considered innovation as a competitive necessity. While multiple kinds and levels of innovation can be distinguished (Edwards-Schachter, 2018), one type of technological innovation that has recently emerged as strategically important in practice is represented by the "disruptive innovation."

The concept of disruptive innovation was proposed by Bower and Christensen (1995). It is a term used to describe a technology that creates a new market and value network and eventually displaces established firms, products, and alliances (Christensen, 1997). According to the original theory, the disruptive innovation is first introduced in a niche market, gradually appealing to mainstream consumers as it starts to deliver a similar or superior performance compared to its predecessor (Bower & Christensen, 1995). Disruption occurs once mainstream customers begin to purchase the entrant's offering in volume, and the new solution becomes the dominant design (Adner, 2002). Examples of disruptive innovations include the personal computer, which replaced the workstation, or digital photography, which replaced chemical photography. Disruptive innovations differ from sustaining innovations, which are incremental improvements to existing products or services that cater to the same set of customers and have the objective of maintaining a position in the market (Christensen, 1997).

To build new-growth businesses, organizations can therefore pursue two different routes (Christensen et al., 2003). On the one hand, they can acquire existing market share from a well-established incumbent with sustaining innovations (Reinhardt & Gurtner, 2015). On the other, they can challenge a competitor with disruptive innovations that either create new markets or that attract customers disregarded by the incumbent (Petzold et al., 2019). The superior resources of the incumbents compared to new entrants are key strengths that will likely guarantee their superiority with sustaining innovations. However, research finds that new entrants almost always win battles when they bring to market disruptive innovations (Christensen et al., 2003; Obal, 2013; Roy & Sarkar, 2016).

This interesting outcome is due to the strong challenges faced by incumbent firms when attempting to adapt to disruptive innovations introduced by new entrants (Christensen, 1997). Among reasons for incumbents' inertia, scholars have identified factors including demand uncertainty (Adner, 2002), rigidity of existing routines and competences (Gilbert, 2005), adherence to established value networks (Hill & Rothaermel, 2003), legitimacy and power (Danneels, 2018), and organizational tensions in managing the different demands of disruptive innovations (Markides, 2006). Together, these drivers have shaped the course of organizations and even entire industries (see, e.g., Christensen et al., 2016; O'Reilly & Tushman, 2016), such as with the famous cases of Blockbuster and Netflix (Voigt et al., 2017) or Polaroid and digital cameras (Tripsas & Gavetti, 2002).

Indeed, amongst the many factors that influence a company's success, the ability to introduce in the market disruptive innovations has been regarded as fundamental (Ansari & Krop, 2012; Assink, 2006; Petzold et al., 2019). Hamel (2003) even posits that only disruptive innovations lead to growth. However, disruptive innovation projects come with high levels of uncertainty, related for instance to the choice of technology, time of entry, reception of the market, and resources required (Eggers, 2012). In fact, while innovating is a necessity that has become a pillar of economic growth and sustainability agendas worldwide (Fagerberg, 2018; OECD, 2016), it is also a tortuous path up made of numerous difficulties and failures (Perin et al. 2016). An analysis of multiple studies by Rhaiem and Amara (2019) shows that innovation projects that failed range from 40% to 90%, highlighting an undeniable relationship between the pursuit of innovation and failure.

Failure – interpreted as the situation in which the outcome of an action does not meet expectations (Bennett & Snyder, 2017; Cannon & Edmondson, 2005; Danneels & Vestal, 2018; Lattacher & Wdowiak, 2020) – is thus an inherent consequence of innovation projects (D'Este et al. 2015; Jenson et al. 2016; Maslach 2015; Rhaiem & Amara, 2019)) and seems especially preponderant in developing and responding to disruptive innovations (Cozzolino et al., 2018; DaSilva et al., 2013; Groen et al., 2008; Hwang & Christensen, 2008; Sharma et al., 2017; Yu & Hang, 2010). Some authors even suggest that its frequency can be directly linked to the degree of innovativeness (Kamoto, 2017; Sharma et al., 2017). Whereas successes reinforce current knowledge, failures enhance learning by challenging the previous understanding of organizational actions and related outcomes (Baumard & Starbuck, 2005; Khanna et al., 2016; Zollo & Winter, 2002).

Since failure is considered central for individual and organizational learning, managers have been encouraged to tolerate and even embrace failure to extend the firm's knowledge base and promote innovation (Danneels & Vestal, 2018; Yamakawa & Cardon, 2015). Nevertheless, research to date on how organizations learn from experience (Byrne & Shepherd, 2015; Gavetti & Levinthal, 2000; Zollo & Winter, 2002) do not support the argument that simply tolerating or embracing failure enhances innovation. As confirmed by Danneels and Vestal (2018), in fact, the key is to support innovation through purposeful reflection and analysis of past failures. In their work, the authors propose two modes of coping with failure, normalizing and analyzing. The former appreciates the inevitability of failure but recognizes that mere tolerance for failure does not lead to the learning. The latter instead refers to purposeful analysis of past mistakes, identifying and validating cause-effect assumptions for optimal learning.

Since failure can be, under certain circumstances, a positive outcome, some organizations have gone beyond the reactive mechanism of identifying and analyzing failure and have embraced a proactive attitude towards failure, referred to as deliberate experimentation (Cannon & Edmondson, 2005). Deliberate experimentation is a provocative process that increases the chances of failure with the express purpose of learning and innovating. Indeed, while such experimentation can increase the frequency of failures, it also improves the possibility of devising novel solutions to problems. Research confirms that organizations which experiment effectively are likely to be more innovative, productive, and successful than those that do not take such risks (Thomke, 2003). Rather than a purposeful search for failure, therefore, deliberate experimentation seeks to create a monitored environment for new ideas (Cannon & Edmondson, 2005).

In the deliberate experimentation process, firms often pursue innovations by recombining existing knowledge components (Hargadon, 2002; Lo Storto, 2006; Weiss & Gangadharan, 2010; Savino et al., 2017). Indeed, as suggested by Kogut and Zander (1993), a firm's capacity to develop technological innovations is affected by its ability to search and recombine existing knowledge elements. Therefore, firms can enhance their chances to develop valuable innovations by leveraging appropriate mechanisms to acquire external knowledge, experiment with different types of combinations, share it internally, and integrate it with existing stocks (Hamel, 1991; Leonard-Barton, 1992; Hargadon, 2002; Hargadon & Sutton, 1997).

Despite the abundant literature on learning by failure, however, the paucity of in-depth qualitative case studies has led to a neglect of the process through which organizations may pursue the development of disruptive innovations by learning from failure (Eggers, 2012; Madsen & Desai, 2010; Muehlfeld et al., 2012). Prior research has also failed to examine how the risks and benefits of deliberate experimentation can be effectively balanced to pursue and achieve innovation. Moreover, failure in the context of disruptive innovation has only been analyzed as an outcome, rather than a means to an end. In fact, several authors (e.g., Christensen et al., 2018;

Cozzolino et al., 2018; Raynor, 2011) have studied why and how incumbent firms were successful or not in responding to disruptive innovations. However, there is a complete lack of literature that investigates the other side of the spectrum, namely how failure can be leveraged to successfully introduce in the market a disruptive innovation. Therefore, no empirical relationship between learning from failure and disruptive innovation has been yet found. Consequently, we know little about whether and how embracing failure, and specifically deliberate experimentation, can lead to disruptive innovation.

In this paper, we address this literature gap through the following research question: "How can failure driven by deliberate experimentation support the development of disruptive innovations?" Our objective is to enhance our understanding of how firms can balance the tradeoff between risks and rewards of deliberate experimentation, identifying the organizational mechanisms and processes through which failure driven by deliberate experimentation can be converted into disruptive innovation.

3. Methods

The need to fill the relevant gaps in the extant literature on the mechanisms that can convert failure through deliberate experimentation into disruptive innovation, along with the lack of adequate empirical evidence on this issue, led us to carry out an inductive study (Eisenhardt, 1989). Following Yin (1994), the case study was deemed an appropriate research strategy to understand the phenomenon under investigation since it relies on several sources of evidence. Case studies, in fact, make it possible to mobilize multiple observations on complex relational dynamics (Eisenhardt & Graebner, 2007; Gioia et al., 2013) and are particularly useful in developing inductive theory and shaping thorough insights into a theoretically novel phenomenon (Edmondson & Mcmanus, 2007). Moreover, we decided to rely on a single case study because, given the limited number of cases that can usually be studied, it makes sense to choose extreme cases and polar types in which the process of interest may be clearly recognized (Pettigrew, 1988).

3.1 Sampling strategy

Building on recommendations made by Glaser and Strauss (1967), and consistent with the case selection procedure proposed by Eisenhardt (1989), we opted for theoretical sampling to pick out a case which exemplified how failure through deliberate experimentation could lead to disruptive innovation (Eisenhardt & Graebner, 2007). For the theoretical sampling, we began by identifying industries that had recently undergone significant technological change. After narrowing the pool to automotive, energy, and space, we sought to distinguish real technological breakthroughs from simple changes in market dynamics. Reusability of rocket boosters soon appeared as the fundamental driver beneath the latest upheaval of the space industry, documented in reports (e.g., OECD, 2020; UNOOSA, 2021; Bryce Space and Technology, 2022), news outlets (e.g., Mansfield, 2022; Morrison, 2019; SpaceX, 2017), and even research articles (e.g., Reddy, 2018). Importantly, this technology was introduced in the market by a single company and within a single project, facilitating the process of isolation. Moreover, the noteworthiness of the entrepreneur behind this company meant that a significant amount of documentation was available, clearing the way for an effective and efficient research process.

Based on these premises, we conducted an in-depth case study of how a failure-prone mentality that embraced the practice of deliberate experimentation was essential for U.S. space firm SpaceX to successfully develop the Falcon 9 rocket. SpaceX thereby achieved one of the most consequential disruptive innovations in the space industry: reusability of rocket launchers. This is a critical and extreme case (Eisenhardt, 1989; Yin, 1994) of an organization that challenged the conventions and practices of incumbents by implementing a radically novel approach to failure, and that was able to secure unprecedented levels of innovation.

Indeed, the Falcon 9 case fits perfectly in Bower and Christensen’s (1995) definition of disruptive innovation, classified as a technology that creates a new market and value network and eventually displaces established firms, products, and alliances (Christensen, 1997). We consider the reusability achievement of the Falcon 9 a disruptive innovation for several reasons. First, disruptive innovations tend to initially display inferior characteristics compared to the incumbent design for the performance attributes deemed most important by existing customers. Back when the Falcon 9 started flying, the customers of the space launch market were mainly governments and space agencies. These entities boasted large budgets, and therefore valued the reliability and heritage of incumbents over the lower price promised by new entrants. Consequently, the Falcon 9 rocket initially catered to a new set of actors that had until then been mostly disregarded, or at least priced out of the market, by launch providers. These actors were prevalently private companies, including but not limited to satellite operators, which could generally not afford to pay the price asked by incumbents and preferred to take the risk of flying with SpaceX rather than not flying at all. More recently, terrestrial businesses (e.g., manufacturing, healthcare, mining, even hospitality) have taken note of the facilitated access to space, devising diverse strategies to best take advantage of these opportunities. In other words, the reusability breakthrough has become a catalyst for the creation of new markets.

With time, successful disruptive innovations start to deliver a comparable or higher performance than their predecessors, thereby appealing to mainstream consumers and eventually becoming the dominant design (Bower & Christensen, 1995). This is exactly what we saw with the Falcon 9: with time came experience, and so did reliability. While in 2013 SpaceX captured only 5% of the global commercial launch market, by 2018 it had reached over 60% (Bennett, 2018). Today, the Falcon 9 is used to deliver in space even the most high-profile payloads, including those from space agencies and from military entities around the world. Indeed, with a nearly 99% track record of flight success, the rocket is amongst the most reliable ever developed.

Interestingly, the Falcon 9 can be considered both a disruptive and radical innovation. Indeed, not all radical innovations are disruptive and vice versa (Govindarajan & Kopalle, 2006). A radical innovation is a new product that is based on a substantially new technology compared to the state of the art (Chandy & Tellis, 1998; Colarelli O'Connor, 1998), that can be targeted either at a mainstream market or at an emerging one (Govindarajan et al., 2011). A disruptive innovation is instead a new product that, relative to what already exists, exhibits a different set of performance attributes (Bower & Christensen, 1995). In this study, we focus on the disruptive nature of the Falcon 9 innovation.

Finally, regarding the reasons why the Falcon 9 case study exemplifies the process of learning by failure through deliberate experimentation, documentary information indicates that many attempts and iterations were performed by SpaceX before achieving the desired result. Although the learning process was very resource-intensive and even put the very survival of the company at risk, many failures incurred were not accidental, but were deliberate experiments undertaken to build the knowledge necessary for a successful outcome.

3.2 Setting

3.2.1 The New Space Economy

The overarching setting of our investigation is the New Space Economy, defined by the OECD (2020) as "*the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilizing space.*" The dawn of the New Space Economy can be traced back to the late 20th century, when technological innovations and shifting market dynamics created not only a new generation of companies, but rather a radically new approach of doing business in the space industry. In the Traditional Space Economy, the market configuration was that of a centralized system based on government purchases from prominent aerospace firms. In the New Space approach, private firms share in both the risks and potential returns of investments in space (Vittori et al., 2022). Agencies such as NASA are now customers and partners, not supervisors of private contractors, providing insight rather than oversight (Weinzierl, 2018).

The New Space Economy is broadly divided between upstream and downstream sectors, each composed of various verticals. The former covers activities that lead to the development of space infrastructure, including R&D, production, and deployment of satellites and launchers. The latter primarily relates to the activities that use the data provided by the space infrastructure, such as broadcasting, communication, navigation, and Earth Observation (European Space Policy Institute, 2015). The New Space Economy was valued at $370bn in 2021 (Euroconsult, 2022). This industry is forecasted to grow by 74% to 2030 and reach $642B (implying a compound annual growth rate of 6.3%). Moreover, it is expected be a major driver of global economic growth in the long term not only as an industry itself, but also as an enabler for other sectors – similar to the

Internet revolution from over two decades ago. With this disruption imminent, our investigation can also be deemed relevant for future works where the space industry will be not only a research setting, but also the subject of analysis.

3.2.2 SpaceX: a History of Successes

Space Exploration Technologies Corporation, commonly known as SpaceX, is an American aerospace company founded in 2002 by Elon Musk, a South African-born businessman and entrepreneur. By age 30, Musk had made an initial fortune by selling his two successful companies Zip2 (purchased by Compaq for $307 million in 1999) and PayPal (purchased by eBay for $1.5 billion in 2002). Musk spent a significant portion of his $100 million reported fortune, coming from these two financial exits, to start SpaceX. There was broad skepticism that he would be successful, as no private company had ever stated an ambition as grandiose as sending man to another planet.

SpaceX first began with the Falcon 1, a two-stage liquid-fueled rocket designed for small satellites. Thanks to the broad adoption of commercial off-the-shelf components, along with a vertically integrated supply chain and a modular operating approach of modern software engineering, the Falcon 1 was significantly cheaper to build compared to other launch vehicles (i.e., those developed by publicly owned and government-funded companies such as Lockheed Martin and Boeing). After three failed attempts, in September 2008 the Falcon 1 delivered a 165kg spacecraft into low Earth orbit, marking the first successful orbital launch of any liquid-propelled, privately funded and developed rocket.

In 2010 SpaceX introduced the Falcon 9, a more powerful rocket so named for its use of nine engines. The Falcon 9 first stage would later become the first reusable rocket launcher in history. In the same year, SpaceX also became the first commercial company ever to release a human-rated spacecraft – the Dragon capsule – into orbit and successfully return it to Earth. SpaceX again made history in 2012, when its Dragon capsule docked with the ISS. In 2018 SpaceX first flew the Falcon Heavy, a heavy lift vehicle that the company hoped would be the first to break the $1,000 per pound ($2,200 per kg) to orbit cost barrier – a staggering reduction when compared to the Space Shuttle's estimated $60,000 per kg (Figure 1). Then in 2020, with the crewed flight of a Dragon capsule, SpaceX became the first private company to ever send astronauts to space.

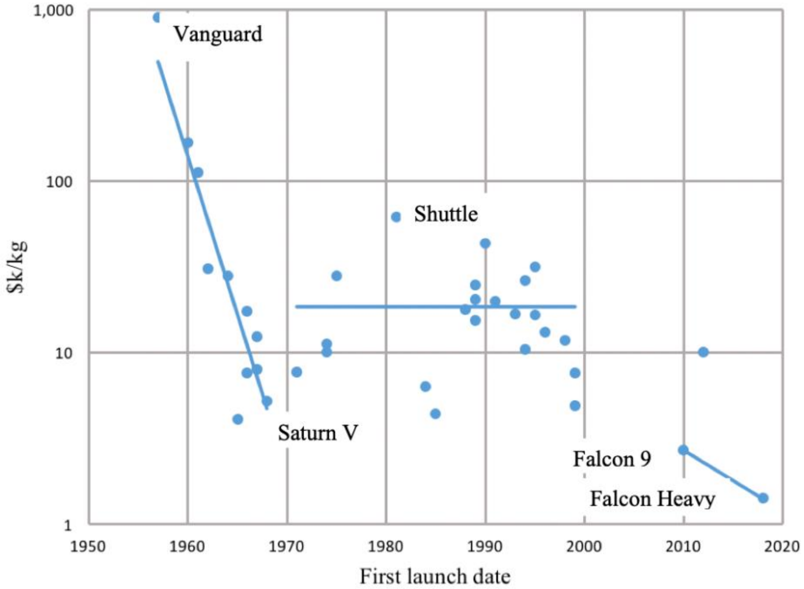


Figure 1: Evolution of launch costs (Jones, 2018)

Since 2019, SpaceX has been testing the successor to the Falcon 9 and the Falcon Heavy: Starship. Claimed to be capable of lifting over 100,000 kg to low Earth orbit (compared to the Falcon 9's 22,800 kg), Starship has been designed to land payloads and astronauts on the Moon and Mars, and could even be used to provide fast transportation between cities on Earth. The fully stacked two-stage Starship vehicle, assembled on a launchpad for the first time in August 2021, stands at 120m tall. That is over 9m taller than NASA's massive Saturn V moon rocket which first brought humans on the Moon. Elon Musk has estimated the cost per mission of Starship could be as low as $10m, implying a cost per kg to orbit of just $100.

SpaceX's other current major project is Starlink, a satellite internet constellation that provides global satellite Internet access and which was started in 2015. As of May 2022, Starlink consisted of over 2,200 mass-produced small satellites in low Earth orbit (LEO), but the company has received permission to deploy as many as 42,000. Thanks to all these businesses, SpaceX is amongst the most valuable private companies in the world, with an estimated valuation of about $120bn according to public news outlets.

Although both the Starship and Starlink projects could be classified as disruptive innovations themselves, for the purpose of this paper we focus only on the Falcon 9 since the former two are still in the development phase. Moreover, the Falcon 9 has already reached maturity and commercial sustainability, therefore there is abundant information that can be analyzed.

3.2.3 The Case of Falcon 9: a History of Failures

Reusability had historically been the main barrier impeding truly affordable travel to and from space, therefore this breakthrough was poised to drive momentous change in the industry. In 2015 SpaceX reached the milestone, as a Falcon 9 first stage successfully returned to Earth near its launch site. Such an incredible success was built on a streak of experimentations and failures that had started over a decade earlier with SpaceX's first rocket, the Falcon 1. In 2006, the maiden Falcon 1 rocket ended up crashing into the oceans because of a fuel line leak and subsequent fire soon after liftoff. A year later, another Falcon 1 failed, spinning out of control just before reaching orbit. A third attempt in August 2008 ended again in a fiery failure when the first and second stages of the rocket crashed into each other after they separated. After the third failure, SpaceX had nearly run out of cash. Fortunately, the fourth time turned out to be the charm: just eight weeks after their third attempt, the successful launch of a Falcon 1 made SpaceX the first company ever to send a privately funded liquid-fueled rocket into orbit.

Despite the significance of this achievement, SpaceX was just getting started. The company had been conceptualized from the very beginning with rocket reusability as a non-negotiable pillar of future missions, a feature that nobody else in the industry had (and still today has) been able to achieve. In fact, still today, nearly all rockets are used just once. After launch, the boosters fall back to Earth and burn in the atmosphere. This approach, comparable to disposing of an airplane after each flight, is extremely inefficient and expensive. To make spaceflight more like air travel and unleash the full potential of the Space Economy, rockets capable of landing, being refueled, and being launched to orbit again was the fundamental breakthrough needed.

According to SpaceX engineer Lars Blackmore (2016), reusability with precision landing is incredibly challenging. First, a vehicle entering an atmosphere from space goes through extreme forces and conditions. Communication with the spacecraft may also be denied for all or part of reentry due to ionized air interfering with radio communications, calling for an entirely automated process. Second, reusability dictates an extremely small margin for error. If the rocket engine reaches zero velocity too low, it will crash; if it reaches zero too high, it will start going back up, at which point stopping the engines and falling is the only option. Third, the touchdown itself is hard. A dedicated system, such as landing legs, is usually used to attenuate the loads of landing and prevent it from tipping over after landing. Being able to design legs that can do this as mass- and space-efficiently as possible is a challenge. Fourth, achieving precision landing requires resistance to disturbances such as winds. For a space reentry vehicle, this is a unique problem since it is neither a ballistic missile nor an airplane. A ballistic missile tries to hit its target at high speed, so it leverages a high velocity to avoid being affected by disturbances. An airplane instead has wings which give it the control authority to correct for disturbances. A rocket landing vertically has neither of these advantages.

Despite being conscious of these challenges, the engineers at SpaceX persevered in the face of adversity, following a path of consistent trial-and-error. Failure after failure, each flight served as an experiment from which data and knowledge were acquired, and which were then leveraged to build an incrementally improved version of the technology for further testing. Starting from 2012, approximately 13 flights were carried out by prototype test rockets for a reusable Falcon 9, simulating the low-altitude, low-velocity testing.

Throughout the trials, SpaceX continued to make iterative and incremental changes to the booster design, as well as to the specific reusable technologies, descent profile, and propellant margins. The first full test flight took place in 2013, after which Elon Musk declared "We now believe we have all the pieces of the puzzle. If you take the [prototype] tests, where we were able to do a precision takeoff and landing of a Falcon 9 first stage, and you combine it with the results from this flight – where we were able to successfully transition from vacuum through hypersonic, through supersonic, through transonic, and light the engines all the way and control the stage all the way through – we have all the pieces necessary to achieve a full recovery of the boost stage" (Belfiore, 2013).

Several additional controlled-descent tests were conducted in the remainder of 2014 through 2015, including attempts to land on a ship, but none of which resulted in a successful landing. Then on December 21, 2015, at 20:38 local time, the first stage of a Falcon landed successfully on target. A livestream of the company's mission control center showed SpaceX engineers cheering and crying from joy. "I do think it's a revolutionary moment. No one has ever brought an orbital class booster back intact," SpaceX founder and CEO Elon Musk told reporters in a teleconference after the 2015 launch and landing success. As noted by Musk, it costs SpaceX $60 million to manufacture the Falcon 9, but only $200,000 to fuel. Eliminating the $60 million expense was poised to drastically reduce launch costs.

In total, from 2013 to 2016 sixteen test flights were conducted, six of which achieved a soft landing and recovery of the booster. Since 2017, SpaceX has stopped referring to landing attempts as "experimental", indicating that they have become a routine procedure. Moreover, in 2017 the first used booster was successfully re-used, and once again recovered. Since then, rockets from the Falcon 9 family have been launched 218 times, resulting in 216 full mission successes. No competitor has been able to achieve the same technological milestone of reusability yet, and SpaceX has become the undisputed leader for the provision of commercial launches. In 2022, a single rocket booster was re-used for a record-breaking 14 times. In other words, the disruptive innovation achieved by SpaceX has changed not only the course of the company itself, but also of the wider space industry and potentially of humanity.

3.3 Data Collection

Data collection and analysis on SpaceX's Falcon 9 case study lasted over a year, from May 2021 to September 2022. Multiple sources were analyzed, leveraging the benefits of triangulation for more accurate findings (Eisenhardt, 2002; Jick, 1979). The data collection process was chronologically divided in four steps: (i) gathering information on the New Space Economy to gain a deep understanding of the research backdrop; (ii) collecting datapoints on SpaceX from a myriad of online resources; (iii) conducting face-to-face interviews with managerial personnel of the selected case study; (iv) discussing findings with industry experts, and repeating the first three steps as necessary based on the feedback received. The two categories of data sources can be therefore broadly divided between documentary information and individual interviews.

3.3.1 Documentary information

The peculiarities of the space industry, along with the nuances of the New Space Economy, made it essential to acquire a solid grasp of setting-specific dynamics. We thus started the data gathering process by consulting several sector reports (OECD, 2020; UNOOSA, 2021; Statista, 2022; Bryce Space and Technology, 2022). We also analyzed third-party interviews of company representatives (including but not limited to SpaceX) and specialized news outlets (e.g., space.com, spacenews.com). Finally, we referred to several books as the source of codified knowledge on the business and economic characteristics of the space industry.

Once a sufficient understanding of the backdrop conditions was achieved, we proceeded to identify news specific to SpaceX and to its Falcon 9 rocket. These were based on (i) corporate website, which displays amongst others the firm's mission, value proposition, products and services, and team; (ii) press releases; (iii) third-party reports, blogs, articles, and videos. The latter was especially prevalent due to the secretive nature and low propensity towards disclosure of SpaceX. Overall, the documentary sources were mostly used to develop the knowledge foundation for the interviews and to complement the initial findings rather than to extract innovation-specific information.

3.3.2 Individual interviews

Secondary information was complemented by interviews with three former personnel of the company analyzed and with four key informants, as reported in **Table 1**. We were unable to interview current employees of SpaceX because of rigorous internal policies on information disclosure. Therefore, we had to rely on individuals that were no longer at the company but still willing to provide input, but at the condition of anonymity. The key informants instead had relevant insights into the workings of the industry, and to a limited extent also into SpaceX, thanks to their lengthy experience in the space sector. Their input was mostly used to confirm the findings and to fill missing gaps in the information gathered.

The interviewees are summarized in **Table 1**.

Table 1. List of interviewees

Category	Interviewee	Role
SpaceX	Ex. manager #1	(former) Senior Manager
	Ex. manager #2	(former) Vice President
	Ex. manager #3	(former) Senior Principal
Key Informants	Luca del Monte	Head of Commercialization Dept. at European Space Agency
	Pietro Giacalone	Space Attaché Advisor at Italian Embassy in Washington DC
	Roberto Vittori	European Space Agency Astronaut
	Ex. NASA manager	(former) NASA Flight Manager

The interviews were semi-structured in nature, allowing the conversations to flow in the direction that interviewees felt most appropriate to answer the questions. Moreover, the format of the interviews was adapted to pursue interesting and particularly relevant insights as they emerged (Eisenhardt, 1989). To limit bias in the discovery process we started with no hypotheses to test, only using disruptive innovation, learning by failure, and search and recombination theory as a guide for our initial interview questions. Informants were also not made aware of the resulting output sought. Lastly, the interviews were recorded and transcribed.

Interviews lasted approximately one hour each. The interview structure was designed to tackle our research topic from multiple points of view and was divided in three main sets of questions. In the first, interviewees were asked to comment on the approach to failure within SpaceX, focusing on the case of Falcon 9. Then, interviewees were solicited to discuss the role of innovation within organizational practices. Finally, strong attention was devoted to the disruptive innovation of reusable rocket launchers.

3.4 Data analysis

Data analysis followed an iterative process as suggested by Strauss and Corbin (1998). We first gathered relevant information on the *New Space Economy* setting. Then we delved into the rocket launcher industry, analyzing the evolution and trends to date. After cementing a strong understanding of the backdrop conditions, we reviewed company-specific data deriving from primary and secondary sources. The next step consisted in combining the various sources of information to clarify all the steps that, in the case study, led to the reusability milestone.

For our analysis, we relied mostly on induction – i.e., collecting data and looking for patterns. However, as suggested by Eisenhardt (1989), we compared the emerging concepts with existing literature to define our contribution in relation to what had been previously found by other researchers. Indeed, examining literature which confirms but also conflicts with the research findings can result in stronger validity and wider generalizability (Eisenhardt, 1989).

Throughout the interviews two high-level concepts emerged almost immediately, (i) an initial focus on laying a set of foundational elements in preparation for the innovation cycle, and (ii) a series of repetitive actions and activities to execute the innovation process. Having identified these rough themes, we then went on to develop the theoretical framework. Following the methods described by Eisenhardt (1989), we compared the emerging model, data from the interviews, and relevant literature (with a focus on disruptive innovation and learning from failure) to guide decisions about the emerging model itself.

Specifically, to generate the link between collecting data and developing a theory that explained it, we implemented a three-phase coding approach. Initial coding was used to identify basic similarities and differences in the data (Mills et al., 2014). Following the interviews with SpaceX personnel, two of the authors manually undertook the initial coding. They began with a thorough reading of the data (Corbin and Strauss, 1990), independently identifying and retaining statements deemed most relevant. The disagreements that arose were resolved through discussion. We then passed on to intermediate coding, seeking relationships and refining the analysis to transform basic data into more abstract concepts (Birks & Mills, 2015). Statements were initially labeled in basic themes, and then grouped into organizing themes to maximize consistency and agility of our effort. As the theory started to emerge, we then implemented advanced coding to obtain the final grounded theory (Birks & Mills, 2015). The findings are presented as a set of interrelated concepts as opposed to presenting themes (Corbin & Strauss, 2008). This output enabled us to create a storyline and culminated in the explication of the theory. A key quality of this theory is transferability rather than generalizability, meaning that even a single observation can represent a principle that applies to many different contexts (Gioia, 2020).

To give an example on practical implementation, we can refer to Timestep 3: ensure all participating team members are conscientious and well prepared (see Table 2 in Section 4). From the interviews we conducted, the phrases identified in the first phase of coding included “It is about not being fearful of the fast-paced, iterative process”, “all team members need to be aligned”, “it is a matter of frame of mind”, “the attitude must be embraced from all members”, among others. Contextualized in the broader sentences, more abstract concepts of preparedness, adequate mentality, and interpersonal qualities emerged. These were then compared with other concepts from all interviews, and finally synthesized in the keywords of “conscientiousness and preparedness.” Therefore, while only word processing software was used, we followed with precision the rigorous guidelines of grounded theory. Moreover, three authors independently performed the data analysis to ensure excellence of the final product, and to confirm the sound logic of the coding steps. Findings, refined and modified as appropriate by ensuring that the developing framework fit with each case, were then reached gradually as evidence was analyzed.

Indeed, we assured data integrity in several ways. First, we reviewed and analyzed all the information multiple times, from archival documents to interview transcripts. Second, we independently performed the three-phase coding approach to compare results. Third, we triangulated the different sources to increase the robustness of our findings. Finally, the interpretations were discussed not only amongst researchers to ensure their validity, but also with the interviewees themselves. We therefore consider the final output to be sufficiently grounded empirically and theoretically.

4. Findings

The present research has the objective of identifying how organizational-level failure, driven by deliberate experimentation, can lead to disruptive innovation. We focused on SpaceX, a highly innovative company in the space industry, as in-depth case study. SpaceX has revolutionized how humans travel to and from space thanks to the disruptive innovation of reusable rocket launchers, achieved with its Falcon 9 vehicle. Such an innovation was largely built on an approach to failure and experimentation throughout the development process that was unprecedented in the sector. Thanks to its mentality and continuous pursuit of improvement, SpaceX is today the leading provider of rocket launches, as well as one of the most valuable private companies in the world.

Our findings, grounded in extensive primary and secondary qualitative data, reveal a close connection between SpaceX's ability to learn from failure through deliberate experimentation, and the achievement of the rocket reusability innovation. In particular, we find that it is not only fundamental to have the right foundational elements in place, such as organizational procedures and interpersonal attitude, but there is also a specific logical sequence of actions and events that appears to be highly effective in generating disruptive solutions.

The key timesteps identified, along with their description and supporting quotes from the interviews, have been aggregated in **Table 2**.

Table 2 – Representative Quotes

Timestep	Description	Representative Quote
1	• Define the long-term vision (i.e., 10 years away) • Delineate a roadmap with incremental goals and objectives (i.e., 6 months duration) that are ambitious but realistic	• "The core principle SpaceX applies to innovation is that of pushing the envelope: we do not know where the envelope is, what will or will not work, or what can be achieved, until we try it. That is how we define our vision." (Ex. manager #1) • "SpaceX was conceptualized to be innovative. Our ambition was always to seek novel solutions, to build something better than what currently exists – and never to copy. Reusability was part of this vision." (Ex. manager #2) • "The goal of achieving first stage reusability has been embedded in the company from the first day of operations." (Ex. manager #3) • "With respect to the landing, we tried to find out what was possible. Reusability is a very hard thing to achieve. There were a handful, maybe dozen or so missions, where the landing failed. Although we tried to avoid it, we accepted the risk. And that is why we succeeded." (Ex. manager #2). • "Outside of SpaceX, especially in Europe, we were all very skeptical that SpaceX's vision of reusable rockets could be achieved. But as the saying goes, 'Most people overestimate what they can do in a year and underestimate what they can do in a decade.' The SpaceX team understood this, and over that span of time they persevered until they reached their objective" (R. Vittori). • "The old guard at NASA remained conservative and, to be honest, even skeptical of the SpaceX approach. Their vision was even mocked by some. But we did not understand their drive, conviction, and intrepid attitude in the face of failure. In the end, that is what made them so successful" (Ex. NASA manager). • "The other big differentiator of SpaceX is not posing limits to what the company can achieve. In the case of reusability, we knew it was very challenging and that nobody before had achieved it. But from a physics perspective it was possible, so we were confident we could do it." (Ex. manager #3) • "In business school, they teach you 3-4 years plan. That is complete nonsense. SpaceX has the 6-month goals, and the 10-year goals. And you keep on moving that. By having a smaller amount of time to hold yourself accountable to achieve objectives, you actually achieve those objectives." (Ex. manager #1)

		- "You cannot predict the future 3-4 years out. But you can predict 3 or 6 months. By setting these shorter, incremental goals, you give yourself much more accountability whilst maintaining an end target that is far out. This is a big differentiator for SpaceX that nobody talks about, but you can only understand it when you start to connect the business, financial, technological aspects. This is how SpaceX always stays ahead." (Ex. manager #3)
2	- Review the state of the art, analyze knowledge from other sectors, aggregate internally developed heritage, perform virtual simulations to progress while controlling costs, and review historical precedents	- "We looked at applications above and beyond rockets, even outside the realm of our industry. These included airplanes, missiles, and more, increasing refinement of our starting point little by little." (Ex. manager #1) - "For the reentry control, for instance, we had all the knowledge from the field of aerodynamics that we could leverage. We started performing experiments in the atmosphere, building on data from airplanes." (Ex. manager #2) - "At the end of the day, it is nearly always possible to extract knowledge, or at least draw inspiration, from other sectors or applications – even if seemingly unrelated. This requires an ability to think outside of the box, which is something certainly not missing at SpaceX." (Ex. manager #3)
3	- Ensure all participating team members are conscientious and well prepared	- "You can assume that people are averagely smart across companies, so that is not a key differentiator. You can also assume that the access to financing is similar. So why do some companies make it and some do not? The difference is in the mindset, in the approach. It is about not being fearful of the fast-paced, iterative process. However, all team members need to be aligned. They need to be prepared for the journey ahead." (Ex. manager #1) - "We tried to build the company with people that not only had solid technical knowledge, but that were also very curious. The teams were always seeking out problems and trying to find the best way to solve them and improve upon the status quo." (Ex. manager #2) - "There are those that just do not understand this process of deliberate experimentation mentally. Some people, for instance, would prefer to spend time analyzing theoretical data and trying to perfect every launch attempt rather than just experimenting in the real world. Those people do not last in a company like SpaceX and are not part of the innovation cycle – they are dinosaurs that will become extinct." (Ex. manager #1) - "What stops other companies from adopting the SpaceX mentality? That being like SpaceX is an uncomfortable position. It is a matter of frame of mind, of acceptance that you can gloriously fail and never recover from it. But you still give it a shot. It is a team effort, and the attitude must be embraced from all members, from the very beginning. Unfortunately, most people out there are not able to sustain it." (Ex. manager #1) - "Most people do not change things when they are working. At SpaceX, that is not the mindset. Even if it is working, at SpaceX we always want to find out if and how it can be improved." (Ex. manager #3) - "When I first visited the SpaceX premises, I could not believe my eyes. Very young engineers, in shorts and T-shirt, with their head upside down in rocket engines. But when I spoke to some of them, I understood I was witnessing something exceptional. They all stood by the company vision, convinced about what they were trying to achieve, with no doubt on their chances of success" (Ex. NASA manager).
4	- Initiate the innovation cycle - Start the deliberate experimentation activities	- "When you are developing something very complex, with many moving parts, some of them which you cannot control, you are then going in a chaotic problem. To solve a chaotic problem, physics teaches you that you need many datapoints because you bring it down to the statistics aspects. The only way to understand it is to do the experiment, failing again and again until you succeed." (Ex. manager #1) - "We were following an approach of monitored but deliberate experimentation from the very beginning, with the Falcon 1, where the first order of unknowns to discover was the production aspect (materials, heating, vibration). Our incremental objective was just to understand

		what happened from an external forces point of view during reentry." (Ex. manager #3) • "The reentry fins went through endless iterations of trying to find the right number, the right shape and material, the right grids, the right balance between big and small." (Ex. manager #1) • "It is hard to balance speed and risk. Often, we would identify a risk for a certain component, but there were no good tests or further improvements we could think of. In those cases, we would proceed with the deliberate decision of flying." (Ex. manager #2) • "A famous quote in the space sector, associated with the Apollo 13 mission, is 'Failure is not an option'. For SpaceX, this motto was basically turned into 'failure is a necessity to ultimately succeed'. Failure after failure, the company fought its way to success" (Ex. NASA manager).
5	• When failure occurs, understand what happened and why • Review and codify the new knowledge • Adapt the incremental goals based on the new knowledge	• "When first investigating what happens to a cylinder as it reenters the atmosphere, there were theoretical but not practical answers. So, we needed to create and capture all the relevant data. Each time we learned something new it became part of our knowledge base. It was not long before we were able to build the rocket with a structure that at least survived the reentry, checking that off the '*I don't know how to do'* box. Then we went to the next step once we understood this. We started to adjust, we made pods that were supposed to survive the breakage, which we would fish out of the water, and that would record that phase from when you lose telemetry." (Ex. manager #1) • "You are in a controlled freefall, and you need instruments that allow you to perform well in any landing condition (water, land, sand), and so all the necessary instruments went through endless iterations and testing – alone and within the rocket. Each time new knowledge was created, for instance related to the behavior of one of those instruments, the design would be modified, and the goals updated to reflect the discovery." (Ex. manager #3) • "When a small failure occurred, we would write a ticket and follow the ticket workflow. For bigger failures there were plans on how to approach the issue, forming a group that looked at the evidence, going through the knowledge systematically. Our approach was very thorough, and some failures took us months to close out. There was a lot of documentation, a lot of testing and work going in to fix the issues. It was very extensive and in-depth." (Ex. manager #2) • "We were constantly discovering something new, and we kept iterating every time. Innovative ideas from all levels were embraced, and whatever worked best would often be chosen as the way to proceed. The plan would be reviewed, the short-term goals amended, and we would go through the entire process again" (Ex. manager #3) • "I do not believe there is a magic recipe to what was achieved with the Falcon 9. It is obvious that SpaceX team was able to build on favorable environmental conditions, such as the initial capital provided by Elon Musk. However, the SpaceX team was unquestionably exceptional at implementing optimal knowledge management processes, learning from each failure and improving each incremental experiment" (L. Del Monte).
6	• Leverage the cumulative experience to optimize future iterations of deliberate experimentation • Identify the successes, even if small, and integrate them in the innovation process • Analyze and measure the results, ensuring	• "The Falcon 1 was a great datapoint to understand how the shape, the material, the dynamics behaved. Every Falcon 1 first stage, since the second flight, was instrumental to acquire telemetry to understand the breakage during reentry in the atmosphere. We were gathering telemetry solely with the scope of increasing and improving the datapoints and understanding at which altitude, which temperature, which dynamics we were seeing. Each time we iterated, the results were better and better." (Ex. manager #1) • "SpaceX has a model where you build something and try to catch all the failures. It is like with Swiss cheese, when all the holes line up and you can see through it. When you catch certain problems or certain anomalies, you may have to add another test to make sure that each part does not fail. However, if the test was a success, we would make

	that improvements are being obtained	sure to note why and how every parameter held up, integrating the knowledge in the innovation process." (Ex. manager #2) • "It was clear that, with every test, we were making incredible strides forward. Sometimes we would swap out parts and subsystems even before testing them, as soon as minor improvements or optimized designs were devised." (Ex. manager #3) • "There is not one point in time where you aim for failure. You do not go into an exercise or demo hoping it will fail. The only time is when you do purpose destructive tests, such as blowing up a tank, is to verify the analysis. With exception to those cases, at all other times you plan for success." (Ex. manager #1) • "The Falcon 9 spectacular failures were well known and diligently followed by the whole space community. We went from 'who are these crazy engineers, they will never make it' to 'oh wow, they are actually making interesting progress.' By the end of the Falcon 9's prototyping phases, each flight kept everyone on their toes" (P. Giacalone)
7	• Continuously keep track of employee performance • Do not punish for honest mistakes • After each failure, ensure the root cause is identified. If it was avoidable, i.e., it was due to faults such as insufficient preparation, lack of process understanding, or inadequate mentality, consider letting go of that person	• "For SpaceX, behind any technical failure, at the end of the day there is always human failure. You can fix the issue by changing the process, requiring certain tests, implementing a better design review, or requiring more scrutiny on the data. But it always boils down to human error. Depending on case specificities, certain measures would be taken." (Ex. manager #2) • "Each time you fail it costs money; it is an investment. Every time you make an investment and do not achieve what you were trying to achieve, because someone did not do their job (e.g., forgot an instrument, did not check the connection, etc.) that is when people pay the consequences. Not because of the failure itself. We celebrated each time things went bad, but we learned from it." (Ex. manager #1) • "There is a line of too much failure. This is the line of unpreparedness. At no point in time are you allowed to be unprepared for what is about to happen. And that is the definition of failure." (Ex. manager #1) • "SpaceX holds people accountable, but managers do not fire people that make honest mistakes. At the end of the day, there are always two responsibility levels: the person that makes the mistake, and the whole team that reviews it. More often than not, it is a broadly collective failure with shared responsibilities" (Ex. manager #3) • "Once you have gone through sufficient failure and understood how to succeed, that is when failure does not become acceptable anymore. You had your chance to experiment and play, once you are done it is not accepted anymore. The business of launching, of sending humans and cargo to space, are not geared towards failure – quite the opposite." (Ex. manager #1)
8	• Ideally, achieve the disruptive innovation • If it becomes evident that this cannot be achieved, perhaps due to technological limitations or inadequate expectations, adjust the end goal and repeat the entire process	• "There is an optimal balance between cost, time, and overall resources invested and lost due to failures, to achieve disruptive innovation. But every time you need to make a breakthrough, I do not see any other way of sooner rather than later facing the ultimate challenge of seeing how close you are to that. It can be a matter of rockets, of satellites, of airplanes before that, of cars even earlier. People had to keep on facing this type of iteration to innovate and break through the plateaus." (Ex. manager #1) • "If more companies followed the SpaceX mentality, I think we would see a tremendous amount of innovation from everywhere else." (Ex. manager #1) • "SpaceX is still working on improving its processes, including reusability. As SpaceX builds more data, more targeted inspections can be carried out, and turnaround time can be decreased." (Ex. manager #2) • "I don't think there was ever a risk we would not achieve reusability. The physics proved it was possible, and that was what we always used as valuation metric. It could happen that we set overly ambitious goals, but the simple solution was to re-evaluate the objective and adjust as necessary." (Ex-manager #3)

		- "We did not move faster because we worked less, but because we just worked longer. I do not have the experience to say we are the most rigorous company out there, but I can confidently say that we are very high up on the rigor scale. This rigor is what helps us set goals that are ambitious but theoretically possible in the first place and execute to reach them thereafter." (Ex. manager #2)

4.1. Laying the foundational elements

When preparing the foundational elements to prepare for the innovation cycle, the priority is to define the right vision to be pursued in the first place. This vision, especially if technological in nature, should be shared with a parallel business strategy that will ensure a viable route to market. Moreover, as far in the future as it may be, the end goal shall be challenging but achievable. In the case of SpaceX, the objective of rocket launcher reusability posed a variety of complexities due to which no other company in the world had been able to achieve it before (Blackmore, 2016). However, "from a physics perspective [reusability] was possible, so we were confident we could do it" (ex. manager #3, personal interview). Thereafter, a path to success must be defined, with incremental short-term goals of three to six months – which is quite different from the goals of multiple years that are commonly set in organizations (Ayling, 2021). "By having a smaller amount of time to hold yourself accountable to achieve objectives, you actually achieve those objectives" (ex. manager #1, personal interview). Moreover, "by setting these shorter, incremental goals, you give yourself much more accountability whilst maintaining an end target that is far out. This is a big differentiator for SpaceX that nobody talks about, but you can only understand it when you start to connect the business, financial, technological aspects. This is how SpaceX always stays ahead." (ex. manager #3, personal interview).

With a clear long-term objective and an outline of shorter, incremental goals, it is warranted to gather all the knowledge available that can contribute to a running start. In the case of technological innovation, this background expertise is not only related to research papers and scientific know-how, but also historical precedents and knowledge from other sectors. "We looked at applications above and beyond rockets, even outside the realm of our industry. These included airplanes, missiles, and more, increasing refinement of our starting point little by little" (ex. manager #1, personal interview). This process of knowledge accumulation itself is quite challenging, as it "requires an ability to think outside of the box" (ex. manager #3, personal interview). Additionally, preliminary low-cost work, in the form of virtual simulations, can also be leveraged to minimize upfront investments in the initial development process.

The third foundational element that needs to be in place is on the individual level. The most important asset of any organization is its people; therefore, it is imperative that the right people, with the right mindset, are committed to the process (Jackson, 2017). "The difference [between SpaceX and other companies] is in the mindset, in the approach. It is about not being fearful of the fast-paced, iterative process. However, all team members need to be aligned. They need to be prepared for the journey ahead" (ex. manager #1, personal interview). This identification of the right people starts even before they are part of the organization. In the case of SpaceX, hiring managers "tried to build the company with people that not only had solid technical knowledge, but that were also very curious" (ex. manager #2, personal interview). Indeed, those individuals that do not understand or embrace such a mindset "do not last in a company like SpaceX and are not part of the innovation cycle – they are dinosaurs that will become extinct" (ex. manager #1, personal interview).

4.2. Executing the innovation cycle

Once the foundational elements are in place, the innovation cycle can begin. In this critical phase, the deliberate experimentation activities are closely monitored to ensure an optimal trade-off between velocity of execution and maximization in chances of success. “It is hard to balance speed and risk. Often, we would identify a risk for a certain component, but there were no good tests or further improvements we could think of. In those cases, we would proceed with the deliberate decision of flying” (ex. manager #2, personal interview).

The knowledge accumulated when preparing the foundational elements can be a valid starting point, but to obtain a result that “nobody before had achieved” (ex. Manager #3, personal interview), the development of brand-new hardware and software systems, manufacturing processes, and integration techniques is necessary. The Falcon 9’s engine (called Merlin), for instance, was designed and developed entirely in-house by SpaceX, and is amongst the most efficient rocket engines every built. Engines which are used for the first stages of rockets are typically designed to be only used once, and often have difficult, complex startup requirements that rely on power, temperature conditioning, ignition, and monitoring by ground equipment, and are not designed to be used more than once. The Merlin instead can restart multiple times in flight, which is essential for reusability, and can throttle deeply enough for a precise landing (Everyday Astronaut, 2022). Therefore, the Merlin engine is a fundamental pillar of the Falcon 9’s capabilities and it would have been impossible to obtain only based on previous know-how.

To obtain such incredible results, deliberate experimentation is essential, and thus failure becomes an outcome that is to be expected (Berger, 2020). Although failure itself is not an inherently desirable outcome, it is often necessary to progress (Huddlestone, 2018). “When first investigating what happens to a cylinder as it reenters the atmosphere, there were theoretical but not practical answers. So, we needed to create and capture all the relevant data. Each time we learned something new it became part of our knowledge base. It was not long before we were able to build the rocket with a structure that at least survived the reentry, checking that off the ‘I don’t know how to do’ box” (ex. manager #1, personal interview). Indeed, to maximize the chances of success, failure must be paired with the right knowledge management procedures. “When a small failure occurred, we would write a ticket and follow the ticket workflow. For bigger failures there were plans on how to approach the issue, forming a group that looked at the evidence, going through the knowledge systematically. Our approach was very thorough, and some failures took us months to close out. There was a lot of documentation, a lot of testing and work going in to fix the issues. It was very extensive and in-depth.” (ex. manager #2, personal interview). The new knowledge is then also used to amend and update the short-term incremental goals to ensure that the best processes are in place. “The plan would be reviewed, the short-term goals amended, and we would go through the entire process again” (Ex. manager #3, personal interview).

Throughout the deliberate experiments, cumulative experience is built (Huddlestone, 2018; Howell, 2022). While failures are accepted, the organization shall always plan for success. “If the test was a success, we would make sure to note why and how every parameter held up, integrating the knowledge in the innovation process” (ex. manager #2, personal interview). Results shall be measured and monitored to ensure that everything is on track (Fernholz, 2022). SpaceX managers were confident on their progress as “it was clear that, with every test, we were making incredible strides forward. At times we would swap out parts and subsystems even before testing them, as soon as minor improvements or optimized designs were devised” (ex. manager #3, personal interview).

Just like when preparing the foundational elements, also in the innovation cycle the interpersonal component is highly relevant (Mejia, 2017). At the end of the day, “behind any technical failure there is always human failure. You can fix the issue by changing the process, requiring certain tests, implementing a better design review, or requiring more scrutiny on the data. But it always boils down to human error” (ex-manager #2, personal interview). Of course, honest mistakes shall be accepted. Even at SpaceX, where there is a high level of accountability (Cipparone, 2020), "managers do not fire people that make honest mistakes" (ex-manager #2, personal interview). Indeed, "we celebrated each time things went bad, but we learned from it" (ex-manager #1, personal interview). Yet there is a line of too much failure, that of unpreparedness. "At no point in time are you allowed to be unprepared for what is about to happen. And that is the definition of failure" (ex-manager #1, personal interview). Depending on the case specificities, therefore, appropriate action must be taken.

Iterations and experiments can be many, but each time the end goal should be moving closer (Reddy, 2018). Ideally, the organization should seek to achieve the "optimal balance between cost, time, and overall resources invested and lost due to failures, to achieve disruptive innovation" (ex-manager #1, personal interview). Working fast is therefore an optimal way to also reduce the expenses related to disruption (Mann, 2020; Agan, 2013). Yet, the work must always be thorough, and no shortcuts should be taken. "We did not move faster because we worked less, but because we just worked longer. I do not have the experience to say we are the most rigorous company out there, but I can confidently say that we are very high up on the rigor scale. This rigor is what helps us set goals that are ambitious but theoretically possible in the first place and execute to reach them thereafter" (ex-manager #2, personal interview). SpaceX was able to achieve its goal of reusability, as "the physics proved it was possible, and that was what we always used as valuation metric" (ex-manager #3, personal interview). However, this might not always be the case for companies pursuing a technological innovation. In those cases, driven for example by technological limitations or inadequate expectations, the end goal can be adjusted, and the process repeated.

4.3. Summary schematic flow

Figure 2 below depicts the sequential activities extrapolated from the case study that can usher the organization from initial vision to disruptive innovation. The figure reflects the timesteps delineated in Table 2 but has been represented with a higher level of abstraction to maximize generalizability.

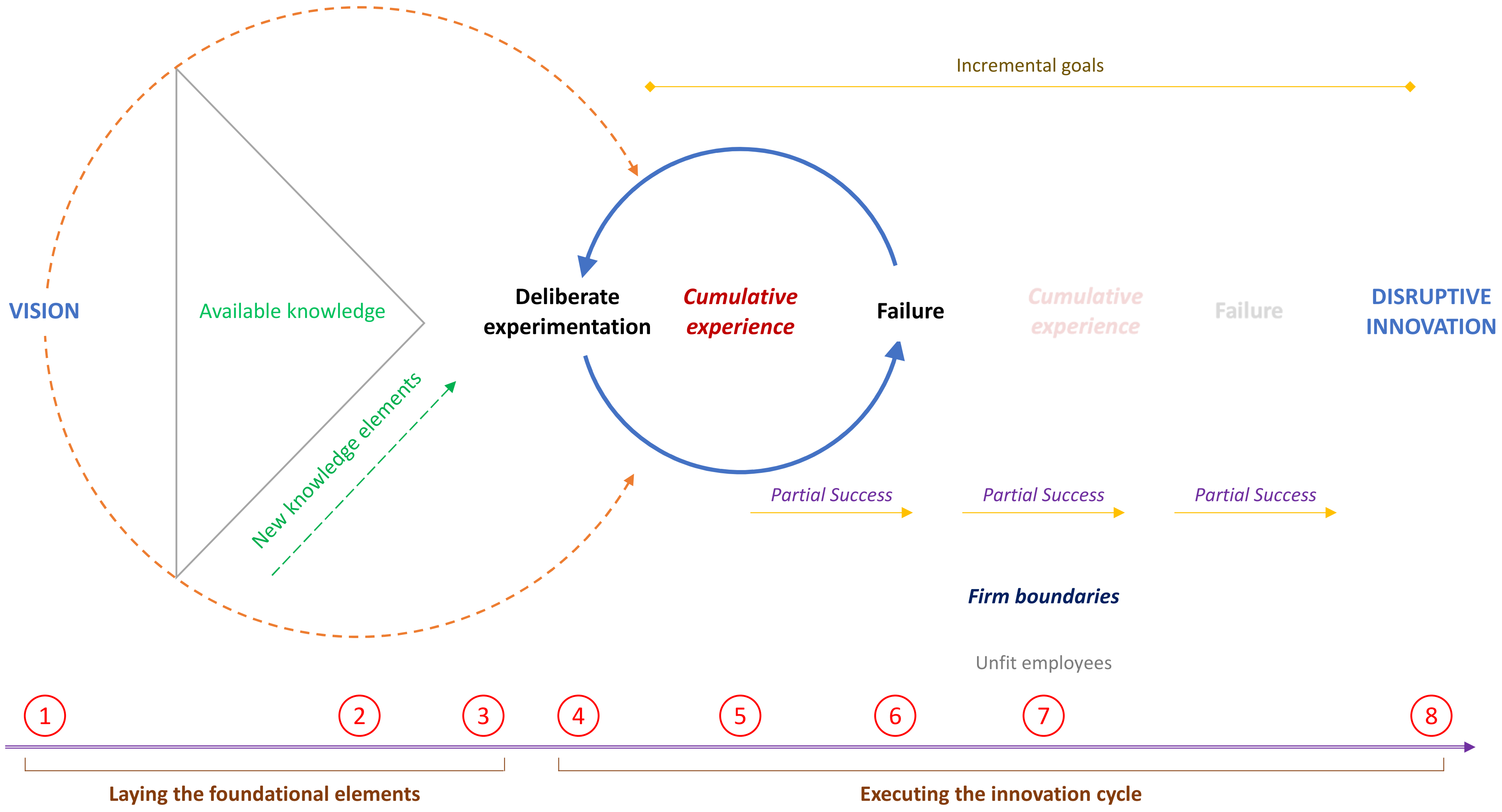
Figure 2 is to be interpreted as follows. The company or subject of interest shall start by defining its disruptive vision *(timestep 1)*, which can be a technology such as the reusable rocket launcher. The technical and interpersonal foundational elements that need to be in place to pursue this innovation shall then be laid. First, as much knowledge as possible shall be aggregated to secure a strong starting point for the innovation cycle, ensuring that no significant resources are spent in futile or useless work, and no trivial or easily avoidable mistakes are made. In the case of technological innovations, this knowledge can consist of the latest research or academic state of the art, as well as lessons from other sectors, internally developed heritage, historical precedents, and low-cost virtual simulations *(timestep 2)*. Second, it is necessary to ensure that the right team is in place. This necessity covers not only technical capabilities but also mindset, as all those working on the ambitious project shall be mentally prepared for the tumultuous and challenging times ahead *(timestep 3).*

Once the foundational elements are in place, the process of deliberate experimentation begins, marking the start of the innovation cycle *(timestep 4)*. After every iteration, the results are evaluated. If failure occurred, the issue is thoroughly analyzed. With the new knowledge, cumulative experience is built, and the successive experiments and iterations are optimized accordingly *(timestep 5)*. Indeed, the successes are also tracked and monitored to ensure that progress is being made, concurrently improving the process *(timestep 6).*

Throughout this iterative process, employee performance needs to be tracked. Honest mistakes should not be disregarded, but they should also not be punished. However, if the root cause of the failure detected can be traced back to faults such as insufficient preparation, lack of process understanding, or inadequate mentality, managers shall consider taking appropriate action such as letting go of that person (*timestep 7)*.

Building on the incremental successes, and learning from the failed experiments, the end goal should be inching closer. This iterative process shall continue until final success is obtained. If the disruptive innovation is simply not achievable, perhaps because of an overly ambitious goal, or simply due to technological limitations or lack of resources, the end goal shall be adjusted without being afraid of going back to the drawing board (*timestep 8).*

Figure 2: Learning by failure through deliberate experimentation to achieve a disruptive innovation.



5. Discussion

In this paper we analyze how learning by failure through deliberate experimentation can lead to disruptive innovation. Our findings suggest that successful disruptive innovation is not fortuitous but can be achieved through the implementation of systematic processes at the organizational level. Specifically, our results contribute to the identification of the foundational elements that need to be in place, as well as to the definition of sequential actions to be executed, for a successful innovation cycle.

Our study builds on and departs from previous research in four key ways. The first falls in the learning by failure domain; the second is within the disruptive innovation theory; the third contributes to the search and recombination literature; the fourth relates to the goal setting literature. In all four of these segments, our findings are either new contributions or represent an extension of previous studies in a novel empirical setting (i.e., the New Space Economy).

5.1. Contributions to the learning by failure literature

With regards to the learning by failure stream, while some authors have identified the factors that influence how and why organizations learn from failure (e.g., Garcia-Morales et al., 2009; Rhaiem & Amara, 2019), there seems to be no study that explicitly focuses on the foundational elements that need to be in place, and processes to be followed, for a successful learning outcome. In this article we address this gap, analyzing and outlining these two faces of the same coin, and providing important contributions to both theory and practice.

A survey of previous works (e.g., Drupsteen & Hasle, 2014; Carmeli & Gittell, 2009; Cannon & Edmondson, 2005) reveals that authors traditionally classify learning from failure as a process composed of multiple steps, but which is either linear or nonlinear. According to the linear process perspective, the overarching sequence of actions consists of identifying the error, analyzing the error, and extrapolating lessons learned (Rhaiem & Amara, 2019; Cannon & Edmondson, 2005). Differently, according to other studies, learning from failure is seen as a nonlinear process of trial and error that culminates with the desired result (Drupsteen & Hasle, 2014). Our analysis suggests instead that, because of the inherent complexity of the objective pursued, both processes are valid when the target objective is a disruptive innovation. In fact, the innovation cycle is divided in smaller, incremental cycles of trial and error in which failure is identified, analyzed, and key lessons are extracted. Once the incremental goal is achieved, the next round of trial and error starts. In other words, it is not an either or, but a combination of both linear and nonlinear processes that must be applied in the context of disruptive innovation development.

A further contribution we bring to this line of research is the identification of the overarching process of learning by failure – starting from the necessary but not sufficient foundational elements, all the way to the achievement of disruptive innovations. Danneels and Vestal (2018) recently investigated explorative product innovation as a consequence of failure, focusing on the difference between tolerating and analyzing failure, and on empirically demonstrating their distinct effects. In our paper, we respond to the authors' call for further research offering more specific insights into the mechanisms of learning, particularly in technological initiatives. Moreover, we extend the Vestal and Danneels (2018) research by (i) employing an alternative methodology of analysis, (ii) investigating firms which operate in a different environment, and (iii) examining different performance metrics.

We also complement previous findings by Garcia-Morales et al. (2009) who posit that the absence of a shared vision can be one of the most important causes of failure in organizational learning. Specifically, we find that organizations must establish the foundational conditions to support the development of technology-based disruptive innovations. For instance, our results indicate that risk-prone, curious mentality in the shared company culture is a necessary, but not sufficient, element for success. Along with the shared values amongst team members, in fact, structured processes for planning and executing experiments, dealing with failure, and absorbing new knowledge, must also be integrated in the organization's operational activities.

Additionally, following Madsen and Desai (2010) and Khanna et al. (2016), we find that the learning process does not necessarily stem from catastrophic events. Instead, organizational learning can actually be more effective when connected to smaller, frequent failures in the nominal experimentation process. In fact, these small failures can provide firms with critical feedback for exploration and are often the only way to learn about causal relationships when a complete understanding of the underlying science is unavailable to decision makers (Fleming & Sorensen, 2004). Moreover, higher rates of experimentation will increase the number of failures but also the likelihood of a successful outcome (Khanna et al., 2016). In our study, we found evidence of both types of failure. Small but frequent failures were preponderant, and they helped SpaceX make the incremental improvements to arrive to a satisfactory flight-ready version of the Falcon 9. Larger, even catastrophic, events were instead quite rare, and only happened when the reusable rocket had to be tested in its entirety. Moreover, the latter are significantly more expensive and take more time to recover from, therefore an excessive reliance on large failures would have drained too many resources.

5.2. Contributions to the disruptive innovation literature

With regards to our contribution to the disruptive innovation theory, this paper is original because failure in the context of disruptive innovation had only been analyzed as an outcome rather than a means to an end. In fact, several authors (e.g., Christensen et al., 2018; Cozzolino et al., 2018; Raynor, 2011) had studied why and how incumbent firms were successful or not in responding to disruptive innovations. However, there is a complete lack of literature that investigates the other side of the spectrum, namely how failure can be leveraged to successfully introduce in the market a disruptive innovation. Our article fills this exact research gap, providing effective tools for organizations that seek to increase their innovative potential.

Building on previous works, we confirm that disruption, i.e., the radical change to an existing industry or market due to technological innovation (Bower & Christensen, 1995), is a process rather than an outcome (Langley, 2007; Petzold et al., 2019). A process is nothing other than a series of actions, which can be analyzed and replicated even for different outcomes. While our investigation focused on rocket reusability, therefore, our findings can be deemed relevant for a variety of disruptive innovations. Moreover, within the disruption process, we find that failure is an inherent and recurring byproduct, as well as a necessary consequence of the attempts to solve problems and secure progress (Leoncini, 2016).

It is important to acknowledge that, according to the traditional theory of disruptive innovation (Bower & Christensen, 1995), disruption is not only connected to the inherent innovativeness of the technology or business model, but also to its commercialization. The two aspects are closely interconnected and, when defining the vision at the very beginning, even overlapping. Hence, during the R&D period, a parallel "commercial" workstream must be executed to ensure compatibility of the technology being developed with the market needs. It is useless to disrupt the status quo if there is no demand for the new offering. In the case of SpaceX's Falcon 9, it was clear that a large part of the potential market for access to space had been neglected due to the high entry barriers. Reusability was one of the keys to unlocking lower costs and paving the way for a more democratized access to space. The innovation was a necessary milestone needed to open access to space to those customers that had not been able to participate until now. The SpaceX team understood this from the very beginning, and that is why it has succeeded.

Finally, we point out that, while the lessons extrapolated from the Falcon 9 case study are specific to disruptive innovations (as explained in Section 3.1), they can be of course extended to radical innovations in those instances where the disruptive innovation is also radical in nature.

5.3. Contributions to the search and recombination literature

This paper also contributes to the search and recombination literature. In the Falcon 9 case study, the search process begins with an exploration of the repertoire of already known elements and combinations (Savino et al., 2017; Arthur, 2007; Fleming, 2001). For firms operating in industries with high complexity, searching for knowledge elements from external sources and recombining them with internal knowledge may be very effective to develop innovations (Lo Storto, 2006; Katila & Chen, 2008; Ray & Ray, 2011; Sammarra & Biggiero, 2008). In the interviews we conducted, in fact, the informants emphasized the relevance of an extensive review of the existing knowledge across technological sectors at the beginning of the innovation cycle.

Interestingly, literature suggests that the involvement of external partners, such as suppliers and customers, has a key impact on the innovation potential of a firm (Fabrizio, 2009). Universities in particular have been regarded as a source of external knowledge that can be critical for the development of innovations (Chen et al., 2011; Fabrizio, 2009; Fontana et al., 2006; Grimpe & Sofka, 2009; Kohler et al., 2012; Sofka & Grimpe, 2010). In our case study, instead, we find that partnerships with external players was limited, and that SpaceX preferred to perform the majority of innovative and experimentative activities in house. In fact, SpaceX builds 85% of its launch hardware (rocket engines, rocket stages, spacecraft, principal avionics) and nearly all software in-house in their California facility, which is extremely unusual for the aerospace industry (Carlos, 2021). The likely reason for this choice is that, in disruptive innovations with a strong technological component, the amount of iterations and failures required for a successful outcome is often so large that relying on third parties would represent a key bottleneck.

Once sufficient external knowledge has been searched and gathered to validate the possibility of achieving the disruptive innovation and to understand the missing elements, the firm's recombination process takes a foothold, as evidenced by SpaceX's open office culture. In fact, the engineers who design the rockets are located in offices with large windows that have a clear view of the manufacturing floor (Everyday Astronaut, 2022). This arrangement incentivizes continuous social interactions and sharing of knowledge between employees of different roles.

Indeed, as confirmed by literature, physical proximity facilitates the development of social capital (Fleming, 2002). The open office working environment is complemented by informal social interactions arising, for instance, in the SpaceX corporate cafeteria, that have also been found by literature to create recombinant potential (e.g., Carnabuci & Operti, 2013; Chou, 2011; Cillo & Verona, 2008; Fleming, 2002; Garud et al., 2011; Grigoriou & Rothaermel, 2014). Engineers in SpaceX are even encouraged to interact with members from entirely different departments for various purposes, such as understanding the business model and commercial objectives that can then guide them towards the development of the appropriate scalable and performant solutions (Martin & Popper, 2021).

While it is clear that search and recombination of previous knowledge has been a key enabler of the Falcon 9 reusability innovation, attributing such success solely to a reuse of existing knowledge is a limitation. This emerges clearly, for instance, in the development of the separation mechanism of the Falcon 9's two stages. In other rockets this mechanism is usually executed through a sophisticated pyrotechnic system of exploding bolts. The Falcon 9 instead uses a revolutionary all-pneumatic stage separation method (Matuszak, 2022). Additionally, landing of the Falcon 9 first stage is fully automated thanks to a complex integration of breakthrough hardware and software capabilities. The tanks and domes are fabricated entirely in-house by

SpaceX, with the support of highly specialized welders that can execute the most reliable welding technique available (NASA, 2015).

Our key contributions to this literature stream are therefore multiple. First, we find that for disruptive innovations that are technological in nature the recombination of existing knowledge is a necessary but not sufficient condition. Known elements can constitute a valid starting point, but new technological enablers will have to be developed from the ground up. Moreover, relying on external partners is an effective way to rapidly acquire knowledge in the initial phases of development, but for the implementation and execution it is necessary to bring in-house critical activities to maintain control over timeline and budget.

Additionally, we add a temporal perspective to search and recombination in the context of disruptive innovations. Specifically, we find that the search for know-how within the firm boundaries takes place after a broad assessment of the external knowledge available. Throughout the execution, this process of search and recombination is amalgamated by a team leader (Cillo & Verona 2008; Currie & White, 2012; Persaud, 2005), in our case study the founder Elon Musk, that instills in the team a shared sense of purpose, drive, and ambition.

5.4. Contributions to the goal setting literature

Another theme that became evident in the data gathering and analysis process is the relevance of goal setting. Accordingly, our findings may contribute to the goal setting literature. Indeed, since goal setting research seems to be largely inconclusive with regards to both the definition and the effectiveness of proximal and distal goal setting (Locke & Latham, 2019; Jeong et al., 2021), with our work we further preliminary but not definitive findings.

In this research, we noticed a fascinating convergence of goal setting theory with that of learning by failure. For example, Frese and Zapf (1994) noted the importance of active search for feedback and of quick responses in dynamic situations to attain long-term goals. In fact, the authors suggest that setting proximal feedback is a valuable source of information that can improve error management (Frese & Zapf, 1994). More recently, Jeong et al. (2021) reached a similar conclusion, confirming that short-term goals can be a useful indicator of progress towards an ultimate long-term goal, suggesting that setting both proximal and distal goals help facilitate goal attainment.

Taking stock of this past literature, we can extrapolate novel contributions of our work also to this theoretical stream. First, we further the debate on the effectiveness of time-bound goal setting and suggest that, in highly technological innovation efforts, implementing both short-term and long-term goals has a positive impact on performance. Second, and perhaps more importantly, we posit that short- and long- term goals should not be defined on a strictly temporal basis, but instead they should be bounded by the usefulness of the feedback gathered in a specific iteration or implementation cycle. In other words, we suggest that it is more effective for firms to set outcome-based incremental goals (e.g., successful testing of a component, or sufficient data gathered for a specific decision) rather than short-term goals defined by a timely cadence (e.g., weekly, monthly). Finally, in the context of organizational culture and firm-level innovation, we highlight a clear distinction between long-term goals which inspire and guide, and short-term goals for which actors are held accountable.

6. Conclusion

This study investigates how learning by failure through deliberate experimentation can lead to disruptive innovations. Specifically, we analyze what organizational procedures must be in place, and what processes must be followed, to achieve a disruptive technological innovation. The research is based on an inductive methodology and carried out on a single case study, SpaceX's Falcon 9 rocket. Our results show that successful disruption can be achieved by a combination of foundational elements that need to be in place, both at the organizational and the individual level, as well as a temporal sequence of actions to be executed. In the former, the organization must ensure that appropriate knowledge management mechanisms are in place, and that the individuals involved are mentally prepared and predisposed for the process. In the latter, the detection and analysis of failure, followed by an optimization of further experiments and an adjustment of the roadmap, must proceed iteratively and sequentially to build upon the cumulative experience gained.

6.1 Implications for Theory

The present research contributes to the existing literature in several ways. First, the value of our insights lies in the identification of a strong relationship between learning from failure through deliberate experimentation and disruptive innovation. From the interviews, in fact, we found a clear and chronologically sequential connection, both on an organizational and personal level, between the definition of a goal, the experimentation process, and the achievement of success. Moreover, there seemed to be a time-bound iterative approach that was followed, and that even now is being replicated for other disruptive innovations within SpaceX. These findings are important because they suggest that successful disruptive innovation is not fortuitous but can be achieved through systematic processes.

In addition, we contend that mere tolerance to failure does not lead to innovation. Traditionally, academic as well as practitioner-oriented writing has assumed that failure experiences generate learning (Byrne & Shepherd, 2015; Gavetti & Levinthal, 2000; Zollo & Winter, 2002), but the mechanism through which such a process occurs had not been explicated in detail. Although "in terms of tools, there is no magic solution" (ex-manager #3) behind an effective approach to failure, the key is to be very thorough and rigorous in the detection, analysis, and optimization of failed iterations. As Danneels and Vestal (2018) noted, the key is to support innovation through purposeful reflection and analysis of past failures. Therefore, although it shall always aim and plan for success, the organization must be ready to deal with failure and learn from it.

Furthermore, contrary to what was found by Cannon and Edmondson (2005), we find that – when implemented in the right way – a culture where the responsible individual is held accountable for mistakes is not necessarily toxic and counterproductive. In fact, the ability to trace back the root cause of failure to a single person and tackle it at the source is fundamental for accountability, thus contributing to the development of cumulative knowledge. Of course, when dealing with failures organizations must be willing to define when and where human error is acceptable and when it is not, thereby taking appropriate action.

We also define the boundaries of deliberate experimentation (Cannon & Edmondson, 2005) which, especially in complex technological environments, can be very resource intensive. Indeed, we find that for a sustainable pursuit of disruptive innovations, organizations must have the ability to gauge where the optimal trade-off between speed of execution and risk of failure lies. Innovation in fact requires investments, both in terms of time and money. Expenses increase with the number of failures, but also with the duration in the period of iterations. Therefore, it is unwise to deliberately experiment and purposely fail just to find the formula that does not work, but it is also unsustainable to constantly try to acquire as much data as possible, and perfect the experiment, each and every time.

Last but not least, we add to the very limited managerial studies of the New Space Economy, an industry that is gaining increasing importance in everyday activities and growing at a rapid pace (Paladini, 2020; Space Foundation, 2020). As the industry's market verticals, such as rocket launchers and satellites, become more mature, and new competitors emerge, being able to have the right procedures and guidelines in place to promote disruptive innovations will boost the odds of long-term success for the participating players.

6.2 Managerial Implications

Our findings have substantial real-world implications that could be implemented by practitioners to promote and support innovation, especially in complex environments where failure can be very expensive. First and foremost, we recommend that managers who want to pursue ambitious disruption processes plan out the innovation cycle with short-term, incremental goals that can be closely monitored and measured. Setting the right long-term vision is important, but – especially in technological disruptions where the R&D period can last many years – there are too many variables involved to accurately define a multi-year plan. Goals of three to six months, that can be amended or changed, help increase the accountability of all team members involved.

In addition, we encourage managers seeking to promote organizational innovation to ensure alignment amongst all team members on the purpose and techniques of learning by failure through deliberate experimentation. Individuals shall be conscious of the upsides of failure when handled appropriately, and not shy away from taking responsibility when honest mistakes are made. Moreover, managers shall review their internal policies and procedures and ensure that the right knowledge management systems are in place for an efficient and effective experimentation process. All team members must be equipped with the necessary tools to understand when failure is acceptable and when it is not, and thereby how to make the most of it. In other words, there should be clearly defined guidelines to usher individuals through the learning by failure process, from the detection and analysis of the failure to the integration of newly created knowledge in the collective heritage.

Given the resource-intensive nature of failing and learning through deliberate experimentation, it is also necessary that managers instill in all relevant team members the ability to gauge the trade-offs between speed of execution and progress, establishing clear priorities and metrics for success. Based on a multitude of factors such as nature of the innovation being pursued, technological challenges to be overcome, expected timeline of the innovation cycle, financial standing of the company, and strategic organizational priorities, it should be feasible for decision makers to implement an optimal experimentation approach which does not overly jeopardize the project success.

Furthermore, we suggest that managers promote an organizational culture of curiosity that can be leveraged to continuously iterate and improve upon the status quo. As stated by the interviewees of our case study, such a mindset can be incentivized within the organizational boundaries, but it must also be sought as an interpersonal characteristic even before the individuals in question join the company.

Finally, our considerations are relevant for New Space Economy players. The case study analysis has revealed setting-specific dynamics which can be used by managers of new and incumbent New Space firms as a guide for their corporate innovation strategies. From the findings on time-bound processes, mindset, definition of goals, and expectations from team members, Space Economy participants can extrapolate context-specific lessons as best practices for their daily operations in this industry.

6.3 Limitations and Directions for Future Research

As with any qualitative study, this work is not void of limitations – providing however an opportunity for further research. Firstly, the generalizability of our findings is constrained by the case study approach. Indeed, our results are not necessarily applicable to industries with different characteristics compared to the setting that we analyze. To empirically test our propositions, substantial quantitative data from diverse organizations and settings could be collected. Therefore, future studies could use such methodology to confirm and refine our findings, consequently increasing their generalizability. Second, we limited our research to a single company and a single disruptive innovation. Hence, further research on more diverse firms (in terms of sector, country, size, age) and types of innovation (of the technology, the business model, etc.) could allow to better understand the consistency of the observed mechanisms and extend our findings to different contexts. Third, interviewees from SpaceX were bound by legal employment agreements (even if they are no longer part of the company), limiting access to in-depth information. Additional case studies with companies that are more open to sharing information could be valuable to extend our findings. Fourth, the case analyzed is peculiar also because of the distinctive nature of the entrepreneur behind its rise, namely Elon Musk. Future studies could gather more information on how Mr. Musk, and more in general strong organizational leaders, can influence corporate culture of embracing failure for learning. Finally, we focused exclusively on the technological side of disruptive innovation, without considering the commercial strategy and implications. In follow-up studies, it could be interesting to analyze both tracks in parallel to understand how they are related and, therefore, further our comprehension on the use of deliberate experimentation to support learning and innovation.

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