Leaders and followers: challenges and opportunities in the adoption of metal additive manufacturing technologies

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Jaime Bonnín Roca

M.S., Aeronautical Engineering, Technical University of Madrid

Carnegie Mellon University

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Abstract

Policymakers in the United States and elsewhere have recognized that a broad and competitive manufacturing sector is crucial to a robust economy and that to remain competitive, a nation must invent and master new ways of making things. Moving technologies from laboratory to commercial success poses considerable challenges however. If the technology is radically new, this transition can be so risky and investment-heavy that only very large private firms can attempt it. One such new technology is metal additive manufacturing (MAM). MAM provides a vivid illustration of the tensions policymakers must resolve in simultaneously supporting the commercialization of early-stage innovations of strategic national interest, while fulfilling the government's duty to ensure human health and safety. After an initial chapter with a general overview of additive manufacturing technologies, this dissertation explores these tensions from the perspective of two very different industrial contexts: the U.S. as a technology leader and trailblazer in the development of the technology, and Portugal as a technology follower with severely constrained resources.

In the first case study, I use the extreme case of MAM (an emerging technology with many sources of process uncertainty) in commercial aviation (an industry where lapses in safety can have catastrophic consequences) to unpack how the characteristics of a technology may influence the options for regulatory intervention. Although my work focuses on the U.S. and the Federal Aviation Administration's regulation, I expect this work to have an international scope, given that in most countries regulation is heavily influenced by, if not an exact copy of, the U.S. regulation. Based on my findings, I propose an adaptive regulatory framework in which standards are periodically revised and in which different groups of companies are regulated differently as a function of their technological capabilities. I conclude by proposing a generalizable framework for regulating emerging process-based technologies in safety-critical industries in which the optimal regulatory configuration depends on the industry structure (number of firms), the performance and safety requirements, and the sources of technological uncertainty.

In the second case study, I analyze the adoption of polymer (PAM) and metal (MAM) additive manufacturing technologies in the Portuguese molds industry, both of which offer important benefits to their products. Leveraging archival data (related to the history of Portuguese

institutions, and the development of additive manufacturing both globally and in Portugal), insights from 45 interviews across academia, industry, and government; and 75 hours of participant observations, we develop insights about why institutional instability affected the adoption of Polymer Additive Manufacturing (PAM) and Metal Additive Manufacturing (MAM) differently. In both cases, Portugal invested in the technology relatively early, and in the case of PAM the research community has been able to move towards high-tech applications. In contrast, the adoption of MAM has been modest despite its potential to greatly improve the performance and competitiveness of metal molds. From the comparison between PAM and MAM, we generate theory about which technological and contextual factors affect their 'technological forgiveness', defined as the resiliency of a new technology's adoption to institutional instability. We conclude by proposing a generalizable framework for 'forgiveness' in different industrial contexts.

The final chapter of this dissertation contains practical recommendations for regulators and managers interested in adopting the technology. Policymakers in the aviation industry may want to encourage the creation of programs to gather more flight experience with MAM parts. Small aircraft and other applications with higher risk tolerance than commercial aviation might represent more important channels to gather information, as the history of composite materials suggests. More importantly, regulators may need to introduce clauses in their rules to regulate MAM to avoid situations of 'regulatory lock-in' which could harm the long-term potential of the technology.

Despite the potential of additive manufacturing, we believe that near-term expectations for it are overblown. In general, additive manufacturing holds great promise, but in many areas the cart has gotten ahead of the horse. Much of the technology is still under development. The history of comparable technologies such as composite materials and high-performance castings shows that the problems may take decades to resolve. For now, additive manufacturing is cost-competitive only in niche applications — for instance, those involving plastics. Businesses that want to plunge into additive manufacturing should be cognizant of the challenges. Determining whether it makes sense to invest in additive manufacturing will require experimentation and learning.

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1 Industrial background: institutional drivers in the adoption of additive manufacturing technologies

Additive manufacturing (AM), also known as 3D-printing, involves a family of diverse manufacturing technologies which allow the user to build an object layer-by-layer from a digital design. Some of AM's advantages, as compared to traditional manufacturing technologies, include the ability to create very complex geometries, reduction of material waste, and in some cases, reduction in the time-to-market (Harris, 2011). Some authors have also claimed that these technologies may change the optimal supply chain configuration, making localized production of some parts more desirable (Gebler et al., 2014; Petrick and Simpson, 2013).

Early developments in AM took place during the 1960s and 1970s, led by the Battelle Memorial Institute in the USA, which used materials developed by DuPont, and with the help of DARPA funding (Wohlers, 2005). What most consider to be the first prototype AM machine – able to cure photopolymers in a similar process to current stereolithography (SLA) equipment – was invented in 1980 in Japan by the researcher Hideo Kodama, at the Nagoya Municipal Industrial Research Center (Wohlers, 2005). In Europe, French researchers working for the Cilas Alcatel Industrial Company filed a patent of an AM machine which used a single laser as a heat source (Wohlers, 2005). In 1987 the first SLA machine was commercialized by the American company 3D Systems, and a number of Japanese and European competitors joined the market in the early 1990s (Wohlers and Gornet, 2016). Selective laser sintering (SLS) machines were commercialized first by the American company, DTM, in 1992 (Wohlers and Gornet, 2016), and in 1994, the German company, EOS, presented the first prototype of their Direct Metal Laser Sintering (DMLS) machine, commercialized in 1995 (EOS, 2017).

In its early stages, AM technology was primarily used to more rapidly build prototypes and thus accelerate the development of new products (Yan and Gu, 1996). As the technology matured, improvements in speed, dimensional accuracy and the development of new materials made rapid prototyping technologies progressively more suitable for the production of final parts (Gibson et al., 2010). Because of significant differences in the underlying science, industrial applications, market stakeholders and level of maturity, we distinguish between polymer additive manufacturing (PAM) and metal additive manufacturing (MAM).

Nowadays, an application of particular interest for MAM is civil and military aerospace (Lyons, 2014), which is central to national economic and military competitiveness. In the U.S., for example, the civil aviation industry accounts for the largest share by annual value of exports of manufactured goods (U.S. Census Bureau, 2015). However, aviation demands extraordinarily high standards of safety, which are currently difficult for MAM to achieve. This is because fabrication processes at the technological frontier have not been standardized and rely heavily on the careful calibration of individual machines and extensive testing of finished parts, making it expensive to guarantee the mechanical integrity of each component. Broad adoption of MAM will thus require regulation that is proactive in giving industry practical guidance, and in safeguarding public safety when the technology is immature, but which also adapts as models are developed to establish relationships between process inputs and outputs for a variety of customized geometries and materials. A difficult balance between multiple factors thus exists, as demonstrated by criticisms of what some would argue are arbitrarily-selected and erratically-applied safety factors for titanium castings in aviation (Khaled, 2014).

Another application where MAM may offer important benefits is the tooling industry. MAM allows for the creation of conformal cooling channels in metal molds, which allow for a faster heat exchange and shorter cycle times (Wang et al., 2011). Being able to inject faster is very valuable for customers (Dimla et al., 2005), who might be willing to pay more for the mold. In addition, MAM may allow for substantial simplification in the manufacturing process. However, MAM materials show certain limitations with respect to traditional machined processes: MAM materials present higher porosity, and thus lower fatigue resistance (Frazier, 2014); higher surface roughness (Jahn et al., 2015); lower toughness (Seifi et al., 2016); lower corrosion resistance (Cabrini et al., 2016); and lower thermal conductivity (Yasa et al., 2011). Moreover, these properties are also very sensitive to the manufacturing process itself (Tolosa et al., 2010). This degradation and variability of the physical properties of the material is critical in the manufacturing of molds, which need to withstand a high number of cyclical loads and contain highly corrosive polymers.

The United States, China, Singapore and the European Union are devoting hundreds of millions of dollars to develop and promote additive manufacturing technologies (Bonnín Roca et al., 2016; European Commission, 2014). Countries at the technological frontier perceive AM technology as providing an opportunity to revitalize their national manufacturing industry and decrease their dependency on foreign countries for parts (European Commission, 2014). For instance, the U.S. leads the applications of MAM and accounts for about 40% of the sales of MAM equipment (Wohlers Associates, 2016). U.S. companies like GE are investing billions of dollars to push MAM's boundaries in areas such as defense, aerospace and biomedical (GE, 2016a). However, the most important MAM equipment manufacturers are European: SLM, EOS and Concept Laser in Germany, Arcam in Sweden, or Renishaw in the UK. One of the most important software providers, Materialise, is Belgian. In China MAM is seen as offering a chance to leapfrog some of their missing capabilities in the manufacturing of large titanium components (E. Anderson, 2013). There is also interest in MAM in developing countries such as South Africa, which has invested highly in MAM since 1994 (Campbell et al., 2011) and plans to increase their investment to promote activities in the biomedical and aerospace sectors (Wohlers Associates, 2016). PAM also holds promise to potentially revolutionize a variety of fields. For instance, in biotechnology PAM could be used to print organic tissues and even entire organs (Murphy and Atala, 2014). In industries where lightweighting provides important financial benefits such as aerospace applications, high performance polymers, including high-performance composite materials (Ning et al., 2017), could be used to replace metallic structures (Kerns, 2016). PAM can also be used in traditional industries such as shoemaking to produced customized, high-performance soles (Tepper, 2017).

Policymakers in the United States and elsewhere have recognized that a broad and competitive manufacturing sector is crucial to a robust economy and that to remain competitive, a nation must invent and master new ways of making things (PCAST, 2012). Moving technologies from laboratory to commercial success poses considerable challenges however. If the technology is radically new, this transition can be so risky and investment-heavy that only government or very large private firms can attempt it. To help move new manufacturing technologies across this "valley of death", the executive branch of the US government has funded seven National Network of Manufacturing Innovation (NNMI) Institutes and intends to fund at least another two (Rockefeller, 2013). One such new technology, and a core area of the first NNMI Institute, America Makes, is additive manufacturing. Additive manufacturing provides a vivid illustration of the tensions policymakers must resolve in simultaneously supporting the commercialization of early-stage innovations of strategic national interest, while fulfilling the government's duty to ensure human health and safety.

However, there are also reasons for countries *not* to invest in additive manufacturing technologies, especially in situations of resource scarcity. In recent years, there has been increased criticism of the mainstream view that AM is going to revolutionize global manufacturing. These critics argue that AM is overvalued and is only going to change the industrial landscape dramatically in cases where customization plays an important role, or geometrical complexity has an important influence in the lightweighting and overall cost-performance of components (Bonnín Roca et al., 2017a; Holweg, 2015; Laureijs et al., 2017).

2 When risks cannot be seen: Regulating uncertainty in emerging technologies[1]

2.1 Introduction

New manufacturing techniques bring challenges associated with their technological uncertainty, which requires the development of process understanding and control procedures to transition "from art to science"(Bohn, 2005). This can be critical to broader commercial viability and adoption. Examples in the literature include biotechnology (Pisano, 1991), chemicals and pharmaceuticals (Pisano, 1997; Straathof et al., 2002), semiconductors (Bassett, 2002; Bohn, 1995; Holbrook et al., 2000; Lécuyer, 2006), optoelectronics (Fuchs and Kirchain, 2010) or aircraft manufacturing (Mowery and Rosenberg, 1981).

Traditionally, approaches to regulate risk have been divided into technology-based, performance-based and management-based regulation (Coglianese et al., 2003). Each approach incentivizes a different level of innovation at firms, and tackles technological uncertainty in a different way. Technology-based regulation decreases uncertainty by mandating the use of a certain technology, but may limit innovation and the adoption of new technologies and processes (Dudek et al., 1992; Jaffe and Stavins, 1995; La Pierre, 1976; Stewart, 1991). Performance-based regulation allows firms greater opportunities for innovation, but it does not work well when it is difficult to demonstrate that the desired performance has been achieved (Coglianese et al., 2003; Downer, 2007; Notarianni, 2000). Management-based regulation aims to shift the decision to the actor with the most information (Coglianese and Lazer, 2003; Downer, 2010). Such actors have a better understanding of the risks and benefits of the technology. However, implementing management-based regulation is more difficult than the other approaches, and history shows that engineers may underestimate risks (Petroski, 1992). Independent of the approach taken to regulating them, the emergence of new and uncertain technologies such as biotechnology, nanotechnology or climate change mitigating technologies, has led to an increasing demand for adaptive regulation that is periodically revised to ensure that it updates its content to incorporate the latest available knowledge (McCray et al., 2010; Oye, 2012; Wilson et al., 2008).

[1] This chapter has been published in essentially the same form as:
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We use metal additive manufacturing (MAM), an example of an emerging technology with many sources of uncertainty; and civil aviation, an industry with stringent safety standards but for which MAM promises many performance benefits, to analyze regulatory needs as a function of technological uncertainty. We triangulate archival data, 37 semi-structured interviews, and 80 hours of participant observations (Jick, 1979), including insights from an invitational workshop we ran in Washington, D.C. with 25 leaders from government, industry and academia. We use grounded theory-building methods (Eisenhardt, 1989; Glaser and Strauss, 1967) to reveal the process by which MAM and other technologies are regulated in commercial aviation, and the complex intertwine between innovation and uncertainty.

We find that there are still many sources of uncertainty surrounding MAM in terms of material supply, equipment configuration, process control, and post-processing procedures. In an industry such as aviation with a marked "learning by using" component, some of this uncertainty may only be revealed with flight experience. There are also important differences across the supply chain in terms of knowledge, financial resources, goals, and regulatory oversight which may result in additional sources of risk. Current certification procedures are not well-suited to dealing with this uncertainty and with the variation in competence across the industry. At the same time, currently proposed mechanisms to regulate MAM products may affect the long-term competitiveness of the technology. To balance the need for safety and innovation, new adaptive regulation mechanisms are needed for when the technology is still immature.

This paper contributes to the literature by clarifying how, for a specific emerging technology, different sources of uncertainty may change the optimal regulatory design. In addition, we show how the differences in their underlying motivations and technology capabilities across supply chains may create the need for additional collective action to ensure an adequate level of safety. We leverage the extreme case of MAM in civil aviation. Iterating between our findings and existing theory on technological uncertainty and the regulation of technological risks, we propose a new typology for considering the regulatory tradeoffs between safety and the sources of technological uncertainty across different technologies and industries.

2.2 Technological uncertainty in immature technologies

Development of an emerging technology is marked by a progressive decrease in the levels of technological uncertainty and variability in the production outputs, a transition which Vincenti

(1990) coined as "from infancy to maturity" and Bohn (2005) as "from art to science".[2] Examples of industries where these uncertain maturation processes have been paradigmatic include biotechnology (Pisano, 1991), chemicals and pharmaceuticals (Pisano, 1997; Straathof et al., 2002), semiconductors (Bassett, 2002; Bohn, 1995; Holbrook et al., 2000; Lécuyer, 2006), optoelectronics (Fuchs and Kirchain, 2010) and aircraft manufacturing (Mowery and Rosenberg, 1981). These examples are notably dominated by chemical- and advanced-material-based products, as well as in the case of aircraft manufacturing, complex, multi-part interdependent systems.

In the early years of an emerging technology, scientists and engineers often have difficulty explaining why a particular piece of equipment or process does or does not work as expected. Production yields are low due to the inability of establishing robust relationships between production inputs and outputs. There is also a lack of adequate process control (Bohn, 1995); Learning which production step is the cause of such variability can be slow (Balconi, 2002). For instance, Collins (1974) explains how in the early stages of the development of laser technology, a group of scientists made what appeared to be an exact replica of a working laser, yet failed to make it work and finally gave up.

As experts start accumulating knowledge, they forge intuitive models about the underlying mechanisms that govern the processes and begin to implement some amount of process control. At this stage, similar to traditional crafts in which apprentices learn from their masters (Bohn, 2005), knowledge is mainly tacit (Polanyi, 1958) and thus results cannot easily be replicated even within the same firm, and often less in an outside firm (Teece et al., 1997). Yields improve as knowledge is created, but when the science of production at large volumes is fundamentally different than that at small volumes, it may still not be good enough for commercialization (Pisano, 1997). The same may be true if the emerging technology is unable to be profitable against the incumbent technology given consumer preferences in present-day markets (Fuchs and Kirchain, 2010). Even when knowledge improves through experience to the point that it can be

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[2] The transition described by Bohn (2005) is closely related to the classic literature of product life-cycle, including the dynamics of product and process innovation (Gort and Klepper, 1982; Utterback and Abernathy, 1975; Vernon, 1966). These papers put more focus on the implications of the dynamics of technological change for industry structure and entry and exist of firms, as well as the destruction of established ones. As we are more focused on the evolution of technological uncertainty in manufacturing, we focus our discussion more around the literature by Bohn (2005) and Vincenti (1990).

codified, as for example in the form of checklists and standard operating procedures, it may take a long time for the basic underlying science to be understood well enough for that knowledge to be applied in contexts that are substantially different from those in which the experience was gained (de Solla Price, 1984; Semmelweis and Murphy, 1981). Often only after the development of theories and mathematical models to explain the behavior of the technology, is knowledge generalized such that results can be systematically replicated, arriving at what Bohn (2005) calls "science."

During the maturation period, firms may acquire knowledge in a different manner which allows them to control the sources of uncertainty and reduce manufacturing costs. For the design of complex parts, Fleck (1994) describes a process he calls "learning by trying", in which engineers perform small changes to the constituents until a final working configuration is achieved. Similarly, in the context of manufacturing, Arrow (1962) describes a process he calls "learning by doing" in which through repeated experience producers become familiar with the problems that arise during the manufacturing process and are able to implement slight modifications. In the context of aircraft manufacturing, Wright (1936) proposed one of the first models of a "learning curve," an empirical relationship between the number of units produced and a decline in unit cost. Nevertheless, some aspects of a technology may only be revealed in the use phase of the final product, due to the inability to cost-effectively simulate those conditions (or the length of exposure thereto) in a test environment. This "learning by using", had a central role in reducing uncertainty about the performance of new aircraft in the early 20th century (Mowery and Rosenberg, 1981). Learning by using has proved particularly important in reducing the uncertainty surrounding new materials like advanced composites in aircraft (RAND, 1992). Learning by using sometimes reveals unexpected behaviors like the propagation of fatigue cracks that occurred along the square-shaped windows of the De Havilland Comet aircraft, and which led to a series of catastrophic accidents (Withey, 1997). Downer (2011a) coined the term "epistemic accidents," defining them as "accidents that occur because a scientific or technological assumption proves to be erroneous, even though there were reasonable and logical reasons to hold that assumption before (although not after) the event." Epistemic accidents are unpredictable and more likely to occur when working with emerging technologies (Downer, 2011a).

The speed at which technology is able to mature from art to science is affected by both its particular characteristics and by contextual factors. Technology characteristics include the number of input variables and their interaction (Macher, 2006), the total number of parts (Singh, 1997), the total amount of information (von Hippel, 1994), the existence of appropriate measurement techniques (Brown and Duguid, 2001), and the ability to test during intermediate production stages (Lécuyer, 2006). Furthermore, innovation in the form of new procedures (Fleck, 1994; Pisano, 1997), new process control mechanisms (Hatch and Mowery, 1998) and complementary technologies such as specific testing equipment (Lécuyer, 2006) are normally needed to reduce variability in manufacturing. Examples of contextual factors affecting technology's evolution are technological diversity (David and Rothwell, 1994), scale (Slayton and Spinardi, 2015), the situated nature of adaptive learning (Fuchs and Kirchain, 2010; von Hippel and Tyre, 1995) and user accessibility (von Hippel, 1976).

When it is successful, the learning and convergence processes described above ultimately lead to the standardization of a technology, which can provide substantial benefits to firms by reducing uncertainty. However, in the case of a rapidly evolving technology, it can also trap firms in an obsolete standard (Farrell and Saloner, 1985). This potential for becoming trapped in a sub-optimal solution creates a difficult relationship between standardization and innovation (Allen and Sriram, 2000). Overcoming this trap may require an evolutionary regulatory approach over the course of the life cycle of the technology to avoid early inhibition of innovation (Tassey, 2000). Technological diversity - that is, having a variety of strategies to solve a certain technological problem – can be important when a field is immature and uncertainty about the final performance of each solution is high (Holbrook et al., 2000). As uncertainty decreases, replicability (within a firm or between firms) can be improved through the implementation of shared practices which facilitate knowledge transfer (Brown and Duguid, 2001).

Based on the literature, we define an immature technology as one which has not yet made the transition from art to science (e.g., Vernon, 1966; Collins, 1994; Teece et al., 1997; Pisano, 1997; Bohn 2005).

2.3 Regulation of technological uncertainty

From a regulatory perspective, there are several options to manage the uncertainty posed by an immature technology. Coglianese and Lazer (2003) divided regulatory intervention into management-based, technology-based, and performance-based regulation, depending on whether it targeted the planning, acting, or the outcome stage in the production process, respectively.

Technology-based regulation mandates the adoption of a certain technology to achieve a certain regulatory objective. Although regulation may in principle give firms some flexibility to achieve compliance through several different technologies or strategies, firms frequently have strong incentives to conform in adopting a particular solution (Stewart, 1991). For example, the Environmental Protection Agency (EPA) standards often define a "best practicable technology" assessing both the effectiveness in reducing pollution and the implementation cost for firms (McCubbin, 2005). Such behavior has been seen in diverse fields like pollution control in the Clean Air and Clean Water Acts (La Pierre, 1976; Maloney and McCormick, 1982; Shapiro and McGarity, 1991; Wagner, 2000), and also in occupational health and safety (Maloney and McCormick, 1982; Wagner, 2000).

Claimed advantages of technology-based approaches include the possibility of a higher-than-market valuation of non-market goods (Shapiro and McGarity, 1991; Viscusi, 1983), the reduction of equity problems (Shapiro and McGarity, 1991), the reduction of the needs for monitoring (Wagner, 2000), ease of promulgation, and superior enforceability (Wagner, 2000). Although it has been argued that firms under a technology-based environment still have incentives to develop new technologies to meet the targets more efficiently than with the available technology (Wagner, 2000), a wide body of literature suggests that firms may have less incentives to innovate and go beyond compliance (Dudek et al., 1992; Jaffe and Stavins, 1995; La Pierre, 1976; Stewart, 1991). This is especially true in contexts where demonstrating success to regulators is particularly burdensome. For instance, the introduction of new nuclear technologies is limited by the unsuitability of current regulation for new nuclear technologies other than light-water reactors, the currently dominant technology (Lester, 2016). Thus, competing technologies which are not endorsed by the regulation, but which nevertheless might be more efficient in accomplishing the regulatory goals, may lose an important market for their development (Stewart, 1991). Other disadvantages are that implementation costs might be higher than the benefits provided by the new technology (Shapiro and McGarity, 1991; Stewart, 1991); and the suboptimal character of applying the same technology for everyone, without accounting for the differences between players (Stewart, 1991).

Performance-based regulation (including, but not limited to, performance-based standards) mandates a certain outcome, but does not specify how that outcome must be achieved (Coglianese et al., 2003; Spogen and Cleland, 1977). Such standards give manufacturers the flexibility to choose the solution they prefer. For instance, the Federal Aviation Administration (FAA) requires that aircraft taking off be capable of achieving a minimum climb rate (14 CFR 25.111), but engine and aircraft manufacturers have the freedom to design any product capable of achieving that rate. Other industries which have adopted performance-based standards include automotive (Vinsel, 2015), food (Henson and Caswell, 1999), electric utilities (Sappington et al., 2001) and building safety (May, 2003).

Performance-based regulation can accommodate technological change better than technology-based standards, and may help draw more attention to the real objectives and levels of uncertainty (Coglianese et al., 2003). However, this approach presents challenges when the standards are not well-defined, performance is difficult to measure, or there is a high level of uncertainty in the relationship between the outcome level and the risk it poses (Coglianese et al., 2003; Notarianni, 2000). One example is the testing of jet engines for bird strikes, which the FAA (2014a) estimates costs hundreds of millions of dollars and hundreds of thousands of hours of aircraft downtime (FAA, 2014a) annually in the U.S. Many problems arise in trying to define a test to replicate these real life situations (Downer, 2007). Even when there is agreement that the tests appropriately simulate the actual event, and the engine performs adequately, there can be disagreement about what constitutes the worst case scenario. For example, the highest-speed impact may in some cases do less damage than a low-speed impact. Given that each such test would do substantial damage to a jet engine, exploring the entire envelope of possibilities (including, for example, size and velocity of the bird, point of impact, engine fan speed at impact) can be prohibitively expensive. As such, even defining the appropriate performance standard requires a judgment call (Downer, 2007). In addition, performance-based standards increase the monitoring costs (Coglianese et al., 2003) and often suboptimal standards are achieved depending on agency implementation procedures (Gaines, 1976).

In management-based regulation, or "enforced self-regulation" (Ayres and Braithwaite, 1995), the government requires “a range of processes, systems, and internal management practices” of private firms (Coglianese and Lazer, 2003). Instead of defining specific technologies to use, or outputs to achieve, firms establish their own internal plan and standards to achieve goals defined by the regulators (Coglianese et al., 2003; Gunningham and Sinclair, 2009). A variant to the concept of management-based regulation is “meta-regulation” (Gilad, 2010; Parker, 2002), in which firms are expected to provide regulators with continuous evaluation of their compliance systems so as to enhance regulators’ knowledge (Gilad, 2010). The primary role of regulators is not to check direct compliance with legislation, but rather to audit the corporate management systems, and in some cases to review documentation provided by the firm to show compliance (Coglianese and Lazer, 2003; Gunningham and Sinclair, 2009). In aviation, for example, manufacturers employ designees whose mission is to bridge the gap between the regulator and the regulated, and provide authorities with information regarding manufacturing activities (Downer, 2010). Similar approaches have been implemented in food safety (Coglianese and Lazer, 2003; Henson and Caswell, 1999), environmental safety, like the Massachusetts Toxic Use Reduction Act (Coglianese and Lazer, 2003), and occupational health and safety (Gunningham and Sinclair, 2009; Hutter, 2001).

Management-based regulation can be an appropriate approach when regulatory outputs are relatively difficult to monitor, moving the locus of decision-making towards the players who possess the most information (Coglianese and Lazer, 2003). They can also be particularly effective when firm incentives are aligned with regulatory incentives – for example, lethal or highly disruptive accidents might reduce business for the firm. Management-based regulation provides firms with greater flexibility to respond to changes in technology or safety requirements, especially in cases where internal management is easier to change than federal regulation (Bennear, 2006). For firms, such an approach is usually cheaper than government-imposed standards, and in certain cases, such as in the pharmaceuticals industry, has been shown to be more effective (Ayres and Braithwaite, 1995). Management-based regulation can also create incentives for firms to look for new and more innovative solutions (Coglianese and Lazer, 2003), and ameliorate problems that can arise due to the lack of resources at public agencies (Coglianese and Lazer, 2003). Finally, compliance might be higher if employees perceive internal rules as more reasonable than external rules (Ayres and Braithwaite, 1995; Kleindorfer, 1999).

However, management-based regulation also has drawbacks. Experience suggests that engineers can underestimate the technological risks in their new designs (Petroski, 1992), which might not be detected by the authorities. Furthermore, implementation requires a far more complex relationship between regulators and the private sector (Coglianese and Lazer, 2003), and there is higher danger of regulatory capture (Downer, 2010). To be effective, management-based regulation requires internalization of the rules across the entire company (Gilad, 2010), and faces the risk of those internal rules being broken by employees (Hutter, 2001). The implementation of such internal rules might not be suited for small organizations with limited resources (Fairman and Yapp, 2005)(Fairman and Yapp, 2005), and be very complex in large organizations (Haines, 2009; Hutter, 2001).

Choosing a path that strikes the right balance between safety and technology adoption is a complex dance between companies, non-corporate players such as academics with deep technical knowledge, industry standards bodies incentivized to commercialize those technologies, and regulators whose job is to focus on safety rather than to facilitate the adoption of new technology. These regulators are incentivized to reduce risks by adopting defensive postures following the "precautionary principle" (Kriebel et al., 2001; Sunstein, 2005), which states that, if an activity poses a potential public risk, in the absence of scientific consensus, the proponent of such activity must bear the burden of proving that it poses an unacceptable risk.

To achieve the right balance between technology innovation and risk mitigation, Mandel (2009) has made a series of recommendations, including: the promotion of data gathering and sharing, the avoidance of regulatory gaps, the promotion of knowledge and collaboration across agencies, and the provision of adaptive regulation. Making data public can also force firms to improve compliance due to increased public pressure, as happened after EPA released the Toxic Release Inventory in 1989. The release of this information caused important financial losses to some companies with higher pollution (Hamilton, 1995). Regarding adaptive regulation, Van Calster (2008) explains in the context of technologies to combat climate change: “over-reliance on one instrument, especially in the early stages of regulatory design, prevents the benefits of trial and error.” In an industry with stringent certification procedures like pharmaceuticals, Yu (2008) argues that traditional approaches to quality control may be hindering quality and performance by restraining flexibility in manufacturing process and testing. Rathore and Winkle (2009) suggest that the uncertainty surrounding regulatory aspects of new pharmaceutical technologies causes reluctance among manufacturers to adopt innovations. This need for adaptive regulation with transparent procedures and timelines has been recognized in other new fields of knowledge like biotechnology and nanotechnology which may pose unknown health and environmental risk to society (Levidow et al., 1996; Lin, 2007; Mandel, 2009; Oye, 2012), and climate change mitigation (Wilson et al., 2008).

Regardless of the regulatory approach taken, the writing and enforcement of regulation regarding emerging technologies takes place in the presence of significant uncertainty, and requires substantial regulator discretion. Unfortunately, regulators may not have sufficient knowledge to adequately exercise such discretion (A.M. Blayse and K. Manley, 2004; Chan et al., 1995; Downer, 2010). For instance, in the context of environmental science, data used for policy-making are frequently limited by uncertainty about the associated risks and costs, leading to "gray areas" where policymakers must exercise their judgment (Kriebel et al., 2001; Stone, 2002). Within these uncertain areas, "street-level bureaucrats" (Lipsky, 1980) such as the officials in charge of checking compliance at a manufacturing facility, have a relatively high level of discretion to interpret and enforce the rules (Evans and Harris, 2004; Lipsky, 1980). Street-level bureaucrats act according to a set of tacit rules, which evolve as they face new situations and interact with their colleagues, helping spread new rules across the organizations to which they belong (Piore, 2011; Piore and Schrank, 2008). In local communities, the adoption of "problem-oriented policing" strategies, which rely on officials to proactively identify new problems, has helped reduce crime (Goldstein, 1990). While too much discretion is undesirable because it can lead to a loss in agency accountability, Susskind and Secunda (1998) argue that to promote technological and regulatory innovation, agencies should allow greater discretion by regulators on the ground.

Even in the case of technology-based regulation, which substantially limits regulators' discretion by narrowly identifying the technological option to implement (Wagner, 2000), dialogues between the regulator and the regulated take place. Latin (1991) explains how EPA officials, forced to apply a technology-based standard without having had time to acquire the proper technical knowledge and skills, ended bargaining with each company to determine the appropriate measures and implementation timeline to comply with the Clean Air Act. In the case of performance-based regulation, the level of discretion possible depends on how precisely the rules are defined (Coglianese et al., 2003). For management-based regulation, negotiation processes are paramount. This strong social and moral dimension may raise concerns about the susceptibility of regulatory agencies to "regulatory capture" by manufacturers in industries with powerful interest groups, which may introduce additional risks when manufacturers' risk tolerance is affected by market pressures (Dana and Koniak, 1999; Downer, 2010). To reduce the risks of capture, Ayres and Braithwaite (1995) argue that the participation of public interest groups, assuming that there are groups in the required technical domain, is vital in the regulatory process, although these groups might also be captured. An example of a such group with technical expertise and strong legal capabilities is the Environmental Defense Fund (Esty, 2000).

Literature on the regulation of technological risks (e.g., Coglianese and Lazer, 2003; Gilad, 2010) lays out the advantages and disadvantages of the different types of regulatory approaches. In contrast, adaptive regulation (e.g., Wilson et al., 2008; Mandel, 2009) offers a series of policy mechanisms to balance technology uncertainty and the need for innovation, independent of regulatory style. Currently, both literatures treat all technologies equally, missing the links between the characteristics of a technology and the type of regulation. There is also little work on how these regulatory approaches apply to a situation where stakeholders in the industry have different capabilities. Our work presents a new typology for regulation to take into account a technology's maturity as well as variance in capabilities across industry structure, to achieve a regulator's desired balance between safety and innovation.

2.4 Methods

We conduct inductive research to "(1) enable predication and explanation of behavior, and (2) be useful in theoretical advance [in the social sciences]" (Glaser and Strauss, 1967). In theory, we seek "a story about why acts, events, structure, and thoughts occur" (Sutton and Staw, 1995), "the model of that portion of the socioeconomic world which the participants themselves use in making decisions…, [and] models that... [represent] direct reflection of reality" (Piore, 1979).

Following grounded theory-building, we "compare systematically the emergent frame with the evidence from each case in order to assess how well or poorly it fits with case data.... constantly compare theory and data – iterating towards a theory which closely fits the data" (Eisenhardt, 1989). We focus on the theoretical insights possible from a single, unusually revelatory and rich case (Eisenhardt and Graebner, 2007; Gersick, 1994; Hargadon and Douglas, 2001; Mintzberg and Waters, 1982; Yin, 2013).[3] While some single-case study research focuses on a case of success (Galunic and Eisenhardt, 2001, 1996; Hargadon and Sutton, 1997; Mintzberg and Waters, 1982), we focus on an extremely constrained case, in the interest of shedding insight into the implications for other contexts where one or more of those constraints might be removed. Other such examples of focusing on a constrained case include Fuchs and Kirchain (2010), Fuchs (2014) and Rosenkopf and Tushman (1998). In contrast to examples which focus on an individual (Ibarra, 1999), organization (Gibson and Smilor, 1991; Hargadon and Sutton, 1997), region (Avnimelech and Teubal, 2006; Piore and Schrank, 2008), or nation (Wonglimpiyarat, 2016; Zhao and Aram, 1995) as the unit of analysis, our unit of analysis is the emerging technology itself (Becker, 2013; Collins, 1974; Fuchs and Kirchain, 2010) in a particular industrial context (Bernstein and Singh, 2006; Holbrook et al., 2000) (and in this paper, one that is particularly stringent or constraining).

Our specific case is metal additive manufacturing (an emerging technology) in the context of the civil aviation industry. We use grounded theory-building methods (Eisenhardt, 1989; Glaser and Strauss, 1967) to gain insight into technological uncertainty and the regulatory process in this immature technology in this safety-critical industry. We triangulate archival data, 37 semi-structured interviews, and 80 hours of participant observations (Jick, 1979). As part of our participant observations, we ran a day-long, invitation-only expert workshop (See Tables 2.1, 8.1).

Aeronautics is an industry characterized by a high degree of tacit knowledge (McNichols, 2008), making interviews with industry insiders a critical source of insight and data. The thirty-seven interviews constituted our primary source of information, and helped us identify the focal themes of our study. We selected our interviewees with the goal of gaining insights from the full range of stakeholders in the regulatory process: Engine and Aircraft Original Equipment Manufacturers (OEMs), Suppliers, MAM Equipment Manufacturers, Public Agencies, and Research Centers. Continuous communication with various FAA officials has helped us gain a deeper

[3] Yin (2013) writes, “Theoretical sampling of single cases is straight-forward. They are chosen because they are unusually revelatory, extreme exemplars, or opportunities for unusual research access.”

understanding of the development of certification practices and of how past experiences with composite materials or powder metallurgy might affect the Agency's attitude towards MAM. We complement the insights from the interviews with archival data (Table 2.1). In Table 2.1, we group our archival data into different subcategories: FAA regulation, orders, and advisory material; international agreements; other industry/government reports; press releases, and technical documents about MAM.

In addition, we conducted participant observations at several meetings and project reviews organized by America Makes, the National Advanced Manufacturing Innovation Institute. This consortium includes representatives from government, industry, and academia. Through our collaboration with the additive manufacturing laboratory at Carnegie Mellon University, we have also been able to directly observe, and interact with, MAM experts using the machines, and thereby gain knowledge of the technical nuances of different AM processes. Finally, as noted above, on June 19th 2015, we organized a closed-door meeting in Washington, D.C. with 25 leaders from government, industry and academia in which participants discussed how to overcome the challenges of technology introduction, material process qualification, and other technological and regulatory challenges. The meeting, which we ran under Chatham House Rules[4] to foster openness in the discussion of delicate policy issues (Corner, 2013; Petticrew et al., 2004), helped us gain greater understanding of the issues at play in the industry and the advantages and disadvantages, as perceived by industry stakeholders, of potential solutions to the challenges in regulating an emerging technology like MAM.

[4] "When a meeting, or part thereof, is held under the **Chatham House Rule**, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed." (Source: http://www.chathamhouse.org/about/chatham-house-rule)

Table 2.1 Summary of archival data sources used in this chapter

Archival data category	Documents	References
Aviation industry	Title 14 of the Code of Federal Regulation	§21.97 §21.150 §21.179 §25.603 §25.605 §25.613 §25.621 §33.15
	FAA Orders related to certification procedures	8100.15, 8120.22, 8110.4C 8110.42D, 8120.23, 8130.2H
	FAA Advisory Circulars	20.613, 21.43, 23.1309-1E
	International Agreements	(EASA, 2014; FAA, 2010; USA and CE, 2011)
	Other government/industry reports	(FAA, 2014a, 2014b, 2013, 2009a, 2009b, 2000; GAO, 2013; IATA, 2016; Khaled, 2015, 2014; NTSB, 2013; Pearce, 2014, 2013; PRI, 2016; RAND, 2001, 1992; Simons, 2007; Spafford et al., 2015; Torrey et al., 1989)
	Press releases	(Hollinger and Powley, 2015; Ostrower, 2016; Ostrower et al., 2013; Sloan, 2014)
MAM state of the art	Industry reports	(Harris, 2011; Wohlers Associates, 2016)
	Government reports	(European Commission, 2014; GAO, 2015; Morris, 2014; NSTC, 2014; PCAST, 2012; STPI, 2013)
	Press releases	(3ders.org, 2014; GE, 2016b, 2015a, 2015b; GE Aviation, 2014; Materialise, 2015; Staff, 2015, 2014)
	Technical documents	(Horn and Harrysson, 2012; Jahn et al., 2015; Kranz et al., 2015; Laureijs et al., 2017; Manfredi et al., 2013; Seifi et al., 2016)

2.5 Findings

2.5.1 Private and public interest in promoting metal additive manufacturing in aviation

MAM is a family of near net shape manufacturing processes in which digitally created three-dimensional objects can be built up by depositing material in successive layers. "Near net shape" means that the geometry of the product after the primary production process is very close to the final shape, although it still requires some removal of material afterwards. In contrast to "subtractive" processes, which remove material to create a shape, "additive" manufacturing processes, by building the shape layer by layer, generally have less material waste. Although there are multiple MAM technologies, the most commonly used in aeronautics are powder bed fusion systems. In powder bed fusion, consecutive layers of powder with a thickness of 100 micrometers or less are deposited while a heat source melts the material only in those areas which correspond to the desired geometry. This heat source can be a laser, in which case the process is called Direct Metal Laser Sintering (DMLS), or an electron beam, in which case the process is called Electron Beam Melting (EBM). The distribution and melting of the powder to achieve the desired "near net shape" occurs inside a closed chamber with an inert atmosphere to reduce impurities in the final product. Private and public parties around the globe interested in building, maintaining and strengthening their national comparative advantage in manufacturing are eager to promote MAM's adoption (European Commission, 2014). To that end, in 2012, the U.S. saw the creation of America Makes, the National Additive Manufacturing Innovation Institute.

Aeronautics is an industrial sector which could greatly benefit from MAM adoption because it involves low-volume, high-value products which need to be lightweight. While important in its own right, the aviation industry is also central to national economic and military competitiveness. In the U.S., civil aviation represents more than 5% of the GDP, supports more than 11 million jobs and is the greatest net export (FAA, 2014b). Several aeronautical manufacturers are active members of America Makes, as is the Department of Defense, spearheaded by the U.S. Air Force. As well as being customers, their involvement represents an important source of funding of America Makes.

The use of MAM in aviation could lead to substantially shorter development times (GE, 2015a); the repair and production of parts in the field; reduced material use (Harris, 2011); and light-weighting and reduced aircraft fuel consumption, this last which accounts for about 30% of airlines operating costs (Pearce, 2014). However, MAM is still an immature technology, and as such presents significant challenges, including control of variability within and across batches.

This technological uncertainty also creates regulatory challenges in industries where technological risks directly impact safety. Despite MAM's immaturity, several leading commercial aviation manufacturers have started to make parts using MAM. In less than five years, parts with increasing levels of criticality have been and are expected to continue to be introduced: In 2015, GE certified the first MAM replacement part, a cobalt-chrome sensor housing to retrofit about 400 engines (GE, 2015a). In the end of 2015, GE also started the certification of a new fuel nozzle for their new LEAP engine (GE, 2016). Each engine will contain 19 of these nozzles, and the MAM design presents many advantages when compared to the older version: it builds as a single piece what used to be a subassembly of more than 20 parts; it reduces the weight by 25%, has a five-fold increased durability; and production costs are 30% lower (Morris, 2014). In the near future, GE also plans to substitute low pressure turbine blades with new MAM titanium aluminide blades which are 50% lighter (Wohlers Associates, 2015). Ground testing of the new GE9X engine with those blades has already started (GE, 2015b), and this engine is expected to enter into service in 2018 with the new Boeing 777X (GE, 2015c). The failure of a turbine blade would be more harmful consequences than the failure of a single fuel nozzle, which again would be more harmful than the failure of a case that houses a sensor. While each of these parts is the result of more than a decade of intense research and development activities (Morris, 2014), they introduce new risks due to the uncertainty surrounding MAM parts in terms of real in-flight performance (learning by using).

In the case of aviation, some technical failures can have catastrophic[5] consequences. These catastrophes often shape the way organization (firms and regulators) work (March et al., 1991), and their occurrence can halt use of, and progress in, a technology indefinitely (Dreshfield and Gray, 1984). Aviation authorities have the difficult task of certifying that MAM parts are safe under conditions of high uncertainty. The possibility of catastrophic failures is of even greater concern in an industry where "learning by using" is required in order to know the real performance of a new product (Mowery and Rosenberg, 1981; RAND, 1992). In the 1950s, the

[5] The FAA defines catastrophic as "Failure conditions that are expected to result in multiple fatalities of the occupants, or incapacitation or fatal injury to a flight crewmember normally with the loss of the airplane" (AC 23.1309-1E, 2011).

first jet-powered commercial airliner, the De Havilland Comet, suffered several fatal accidents only after thousands of flight-hours, due to the unexpected propagation of fatigue cracks from the corners of the Comet's square shaped windows (Withey, 1997). Demand for aircraft parts made with powder metallurgy grew rapidly in the 70s, but then stalled after the accident of an F-18 combat aircraft in 1980 was traced back to a material failure in its turbine disk which was made using powder metallurgy (Dreshfield and Gray, 1984). In 2013, Boeing 787s around the world were grounded due to a failure in their lithium-Ion batteries which caused several fire incidents (NTSB, 2013).[6] Regulators incentives are such that they seek to avoid any fatal accidents. As Ralph Keeney, a world leading authority in risk analysis in policymaking, has said: "we cannot banish life-threatening risks, but we can and should learn better ways to deal with them" (Keeney, 1995).

2.5.2 Sources of uncertainty in MAM

When compared with other process-sensitive technologies, several characteristics of MAM result in higher variability and make its regulation particularly challenging.

In a stable manufacturing process, contamination is often traced back to a particular batch. For example, imagine the machine's chamber wasn't correctly closed in a particular batch, and so contaminants were introduced into the parts just in that batch, reducing their strength. This problem may have been limited to a single batch, or may have occurred for a series of batches. There is typically no way to know until the problem is identified. In a less mature process, such as is the current state of MAM, lack of process control can mean that each new batch can have different processing parameters, and thus different part outcomes. Thus, the potential for cross-batch variability is higher than for stable processes.

Given current part and chamber sizes, batch sizes in MAM are also much smaller than in semiconductors or pharmaceuticals. To produce a certain number of parts with a small batch size, requires running more batches than in a process with a larger batch size. Each time a machine is run, there is the potential for some aspect of the production environment or process to change (cross-batch variability). Build parameters in MAM are tightly coupled, and, at least,

[6] Not every accident is caused by a regulatory failure, and not every regulatory failure causes an accident. One could argue that the Comet had an accident due to a lack of knowledge, while the case of a Lithium-Ion batteries is one where some steps in the manufacturing process were inconsistent with industry practices, and where "Boeing's and the FAA's oversight of suppliers manufacturing the 787 power conversion subsystem components could have been more effective" (NTSB, 2013).

with the current state of the technology, one cannot simply change one of them "ceteris paribus" and achieve a predictable behavior. Changing the part geometry or the part's position inside the MAM manufacturing chamber can affect its microstructure, and thus its performance and safety. In addition, MAM machines have "smart algorithms" which optimize some of the process parameters according to the input. When changing batch size, the design used as an input changes, and revised build parameters are chosen by the machine. Further, if the batch size is changed – building, for example, in one batch four parts at a time instead of two –the heat transfer conditions inside the machine change (heat transfer across unmelted powder is different than across the solid part or across air) and thus changing the boundary conditions under which the material is solidified.

High process variability requires additional testing to ensure part quality. Manufacturers do not want to test 100% of the components they make because testing adds cost to the production process: doing a lot of testing can add significant expense (Laureijs et al., 2017). Manufacturers seek only to test enough parts to be sufficiently certain that the parts' required performance specifications are upheld, given the cost (i.e., consequences) of the part not meeting performance specifications. In a stable manufacturing process, obtaining sufficient certainty might involve testing one part per batch or even one part per thousand batches. In immature process cases like MAM, lack of process control can make the cost/benefit tradeoff be such that it is important to test one part per batch or even multiple parts per batch to have sufficient certainty that parts are meeting performance specifications. Because batches in MAM are very small, a requirement to test one part per batch requires testing more parts than if there were larger batches. When drug manufacturers make pills, their batches are of thousands or tens of thousands. Therefore, taking out several dozen pills to test the whole batch represents, proportionally, a much smaller fraction of total output than in the case of AM. If the batch size is eight, then testing even just one component per batch means that 12.5% of all parts must be tested.

To understand the variability described above, it is important to understand the sources of uncertainty in the MAM manufacturing process. The MAM manufacturing process involves three broad sources of uncertainty: material source and properties, the process of making the part with the MAM machine, and post-processing of the part (Jahn et al., 2015; Seifi et al., 2016).

For material source, there are three different types of MAM processes -- wire-fed, powder-fed and powder bed, each of which requires that the material be supplied in a different form, and requires that a different set of parameters be monitored (Horn and Harrysson, 2012). Within a single process, characteristics of the source material can vary widely depending on the material supplier. Morphology – such as the diameter of the powder particles for powder-fed systems, base material composition and the use of additives to improve materials, all vary with supplier capabilities, and affect the quality of the final part (Manfredi et al., 2013).

Options for the MAM machines using these material sources also vary widely and are based on different fundamental principles. For example, the heat source used to melt the material can be either a laser (Direct Metal Laser Sintering, Direct Metal Deposition), an electron beam (Electron Beam Melting) or a plasma arc (Plasma Deposition), each of which use different physical processes and thus have different requirements (e.g., manufacturing atmosphere, release of residual stresses, etc.) for the MAM build and post-processing steps (Horn and Harrysson, 2012). Within a single MAM approach the total number of input parameters which affect the final product, and therefore which need to be controlled to reduce variability, is more than 150 (Materialise, 2015; *Workshop*, 2015). This variability causes difficulties in establishing robust process control procedures. Building the same part in different locations in the chamber or with different orientations can lead to different results (Kranz et al., 2015). Indeed, as with semiconductors 50 years ago (Lécuyer, 2006), running the same design with the same parameters on the same MAM machine still often leads to different final results (Interviews 1,2,3).

After the part is built with the MAM machine, it must typically go through several post-processing steps. These may include a thermomechanical treatment to reduce porosity and remove residual stresses; fine machining to adjust part tolerances; or surface treatment to improve resistance to fatigue or corrosion. Similar post-processing steps applied to parts coming out of different build machines can lead to different mechanical properties (Jahn et al., 2015).

2.5.3 Structure of aviation regulation

The situation described in 2.5.2 poses challenges for the regulatory system as governed by the Federal Aviation Administration. In addition, recent analysis suggests, the FAA has increasingly constrained resources and is suffering an increasing workload caused by greater introduction of new technologies (GAO, 2013).

As we learned through our interviews and archival work, determination of the airworthiness of new technologies for commercial aviation involves a complex, iterative back-and-forth between the FAA and industry (Interviews 4,5,6,7,8), which constitutes an example of management-based regulation. Building upon a generic technology-neutral Code of Federal Regulation, orders are written by FAA officials with input from industry to provide the specific procedures necessary to comply with regulation (Interviews 6,9). In contrast to orders, advisory materials are not compulsory, but developed by the FAA and industry representatives to support interpretation in the context of specific technologies, and to reduce uncertainty that might otherwise increase the cost of compliance for both regulators and firms (Interview 6). Finally, certificates are provided based on FAA officials' assessment that compliance has been achieved (Interview 10). This dialogue between the FAA and industry is facilitated by two types of officers: Organization Designation Authorization, or ODAs, in OEMs and spare part manufacturers[7] are employees of the OEMs designated by the FAA to act as their liaisons. Manufacturing inspection officers are employed by the FAA, and go to all types of factories to confirm whether products comply[8] (Interviews 6,7).

The Federal Aviation Regulations, found under Title 14 of the U.S. Code of Federal Regulations (CFR), govern the certification of new products for commercial aviation (Interviews 1,6). These rules, while hard to change, are subject to interpretation. For example, they say "Each new aircraft fabrication method must be substantiated by a test program" (14 CFR 25.605 b), but they do not describe the requirements of that test program. The regulatory code is supplemented by orders, which are compulsory. For example, order 8120.22 (2013) provides guidance related to the "evaluation and approval of production activities of manufacturers and their suppliers" (8120.22, 2013). Accidents or certification experiences can result in new rules (Code and orders) to make the certification process more efficient and address a safety issue that was missed in the past (Interviews 5,11).

[7] Some small companies have not reached ODA status and are served by FAA consultants called designated engineering representatives (DERs).
[8] Although we focus on the United States and FAA regulation, there are international working groups and bilateral agreements to ensure that regulation and advisory materials written by other aviation authorities like the European Aviation Safety Agency are harmonized. In some cases, like Brazil, regulation and advisory materials are exact copies of those in the U.S. Interpretation will vary with the officers in each country. This said, we expect lessons learned from the FAA to be applicable to other regions like Canada, Europe, Japan and Brazil.

Federal Aviation Administration chief scientific and technical advisors and senior technical specialists provide recommendations for how to achieve compliance with the Federal Code in specific technological circumstances through advisory material (Interview 6). This advisory material is "adaptive," as it is revised periodically according to the needs of the industry, and is easier to change than the CFR. The writing of this advisory material is guided by ODAs in OEMs, and also the manufacturing inspection officers who go to the factory and check whether products comply (Interview 6). This type of advisory material has a role similar to technology-based regulation. Although the applicant for a certificate is free to suggest an alternative method, following the methods described in advisory material can offer significant time and cost savings in achieving certification (Interviews 6,12). The draft (2014) of the still unapproved Advisory Circular (AC) 20.613, for instance, provides applicants with a list of handbooks which contain values of mechanical properties that have already been approved by the FAA, so that applicants do not need to perform additional mechanical testing to prove that those materials are safe.

To show compliance with the regulations, a product must undergo three consecutive certifications: Type Certificate, Production Certificate, and Airworthiness Certificate (See Figure 2.1).

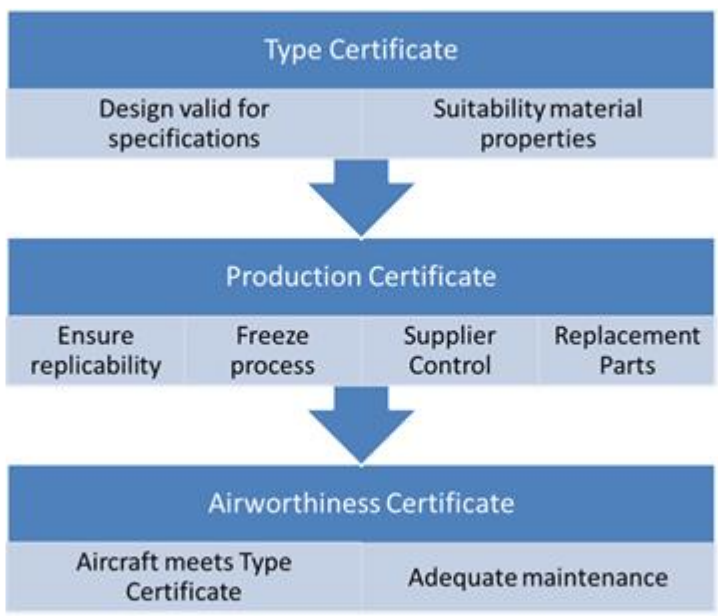

Figure 2.1 Three different FAA certificates are needed to fly an aircraft

A Type Certificate (TC), or design approval, certifies the airworthiness of a given design. To obtain a TC, materials' durability must be empirically proven and meet approved material specifications to guarantee the properties assumed in the designs (14 C.F.R. § 25.603, 25.613). Companies need not perform extensive testing for well-known materials. In the draft of the AC 20.613, which is written to replace the outdated AC 25.613-1, the FAA recognizes external sources of material properties which designers can use as a reference. For process-sensitive materials like composite materials, and for MAM in the foreseeable future, the applicant must go through an "equivalency sampling exercise" to prove that they can replicate the properties (performance) in such databases. Alternatively, applicants may use nonstandard materials like the ones used in and created by using MAM but, in that case, abundant testing is needed to statistically support the mechanical properties being claimed.[9] Creating such datasets may require up to 10,000 test samples for structural parts, a major cost driver in the introduction of new materials (RAND, 2001). As with any performance-based approach, it is challenging to define specifications in the presence of uncertainty: decision-makers typically respond to this uncertainty by employing safety factors, which translates into weight penalties and higher costs (RAND, 2001).

A Production Certificate certifies that the applicant has established a robust quality system and supplier control to ensure the replicability of the properties, which appear in the TC. Once production approval is granted, the manufacturing process is "frozen" under configuration control, meaning that any change made to the process must be approved by FAA (14 C.F.R. § 21.150). For MAM, this implies that a manufacturer with a machine certified to produce a certain part would not be allowed to produce a different part without recertifying that machine for both the previous part and the new part (Interviews 1,2,13). This lack of flexibility affects the economic viability of MAM for the production of parts at low volumes, precisely where MAM might be more competitive against traditional manufacturing techniques (Bonnín Roca et al., 2015).

Finally, the Airworthiness Certificate is "FAA's official authorization allowing for the operation... valid as long as the aircraft meets its approved type design, is in a condition for safe

[9] The amount of data needed is statistically determined in what are called "A-Basis" and "B-Basis" values, depending on the application. An A-Basis value, for example, is defined as the value at which "at least 99% of population equals or exceeds value with 95% confidence or the specification minimum when it is lower" (Jackson, 2007).

operation and maintenance…" (FAA, 2009b). This certificate is "transferred with the aircraft" (14 C.F.R. § 21.179), so the final user is responsible for performing adequate maintenance.

Completing the certification process described above can take years or even a decade. ODAs at OEMs and spare parts manufacturer facilities shepherd firms' acquisition of Type and Production Certificates by acquiring and providing the required data for certification to the Aircraft Certification Office (for Type) and Manufacturing Inspection District Offices (for Production) of the FAA. Separately, Aircraft Certification Officers and Manufacturing Inspection Officers make regular visits to factories to confirm that products comply. Inspectors from the Flight Standards organization check that maintenance procedures required to maintain an Airworthiness Certificate are continually upheld by the organization operating the aircraft, and that pre-approved maintenance organizations are used to conduct that maintenance.

2.5.4 Aeronautics industry structure, incentives and oversight

Although regulation is the same for every company in the industry, different actors have different capabilities, market strategies, profitability and relationships with FAA regulators, and as a consequence very different incentives.

2.5.4.1 OEMs

OEMs in the commercial aviation industry can be divided into two categories: jet engine manufacturers, and "airframers" (airframe manufacturers and assemblers).

Three major manufacturers supply jet engines for commercial aircraft: GE Aviation, Rolls Royce and United Technologies. Each is part of a large diversified industrial group; so their interest extends beyond aeronautics. MAM is very appealing to this constituency because engines have thousands of small parts with complex geometries, which are expensive to manufacture using traditional manufacturing techniques. In addition, jet engine manufacturers have a longstanding tradition of high-performance alloy development for engine blades, and this expertise is a core competitive advantage. Jet engine manufacturers have chosen to develop MAM competencies in-house (Interviews 3,4,14), including acquiring existing MAM part production companies. For instance, to bring the knowledge in-house and avoid undesired competition, GE acquired two different MAM companies, Morris Technologies and Avio Aero, which have enabled it to produce its fuel nozzles and the titanium low pressure turbine blades, respectively (Wohlers Associates, 2015).

The market for large commercial aircraft is a duopoly formed by Boeing and Airbus (Nolan, 2012). For smaller aircraft, two other manufacturers, Embraer and Bombardier, hold about three quarters of the market (Nolan, 2012). Commercial aircraft manufacturers are companies focused only on the aerospace industry. In addition, in the last decades they have become "integrators" of increasingly complex aircraft sections manufactured by their Tier-1 suppliers (Slayton and Spinardi, 2015). For instance, Boeing only performed about a third of the total production activities for their 787 model. The manufacture of critical parts of the airframe such as wings, wingtips, several fuselage sections and horizontal stabilizers were outsourced to domestic (e.g., Spirit, Vought) and foreign companies (e.g., Alenia, Mitsubishi, Kawasaki) (Horng, 2006; Tang et al., 2009). Thus, although they have internal R&D programs in MAM, they would like to have a pool of MAM suppliers from which they could choose and diversify their production (Interviews 15,16,17).

Interestingly, while regulation is almost the same for both engines and airframes, there are differences in some of the regulatory requirements as well as the regulators themselves, which have both technological and organizational roots (Interviews 6,8,18). Both products have a different level of criticality: while the failure of a single engine is not necessarily critical because there is another engine on board,[10] airframe failures have a high probability of having fatal consequences. From an organizational perspective, not only are the manufacturing companies and their business strategies different, the officials writing the rules for aircraft and engines are also different, and are located in entirely different Directorates within the Federal Aviation Administration. Thus, different "traditions" (regulatory methods and customs based on historical precedents) have organically grown within different Directorates (Interview 8). An example of these differences is “Casting Factors” (14 C.F.R. § 25.621). Casting Factors are safety factors which the FAA requires manufacturers to employ in addition to designers’ safety factors to account for the increased variability in the mechanical properties of castings, compared to wrought or forged metals. Casting Factors must be applied to airframe components made with casting but not to engine components. Given the lower criticality of engine parts, the cost that additional safety factors would impose in terms of weight penalties would arguably be greater

[10] As Downer (2011b) points out redundancy is not always a good criteria because some events may affect all engines at the same time. For example, in 2009, an airplane had to land on the Hudson river after multiple bird strikes caused both engines to fail (Downer, 2011b).

than the reduction in risk (Khaled, 2014). Castings are used widely today in engine components. Since the 1980s airframe industry members have claimed that casting technology has evolved enough to control variability and that the use of casting factors could be dropped (Eylon et al., 1983; Torrey et al., 1989). However, casting factors remain in the regulation relevant to airframers (14 C.F.R. § 25.621) and have become an example of regulatory lock-in.

OEMs have daily interaction with the FAA, and when they introduce a novel design, they discuss with the FAA the procedure required to achieve compliance (Interview 6). The interaction between FAA and manufacturers is a good example of a management-based approach: it happens through designees who have been granted a special Organization Designation Authorization (ODA). Designees are employed by manufacturers. They have the responsibility to communicate with the FAA the details about the manufacturers' activities, serving as a way for the FAA to access manufacturers' tacit knowledge (Downer, 2010). Due to the large knowledge asymmetry between OEMs and the FAA, OEMs have a significant influence over the impressions of the FAA's officials, who end up evaluating "trust" in the people they are certifying rather than technology[11] (Downer, 2010). After the interaction between the OEM's ODA and the FAA, the FAA formally answers the OEM by writing an "Issue Paper" with a proposal for means of compliance (Interviews 6,19). These issue papers are not publicly available to protect the intellectual property of the manufacturer.

One of the greatest fears OEMs have is that "rogue suppliers" (suppliers who implement changes to their production process without the consent of the OEMs) could start making MAM parts without the required knowledge and statistical substantiation of quality (*Workshop*, 2015). This is a matter of both public safety and competitive advantage: OEMs know that an early failure of an MAM part could severely slow or even for a period halt the commercial adoption of the technology in which they have invested heavily (Interview 4). Therefore, they have incentives to create some degree of public knowledge, and they have expressed their willingness to share aspects of their data which are not core to their competitive advantage (*Workshop*, 2015).

[11] Nevertheless, our interactions with industry, civil and military suggest that OEMs have internal employees with safety requirements which are much more stringent than FAA's.

2.5.4.2 Suppliers

OEMs have a wide variety of suppliers. However, we would expect MAM to be attractive to companies like "machine shops" which manufacture the type of products which can be substituted by MAM, and to MAM manufacturers which currently do not supply to the industry but would like to expand their business. Becoming a supplier for the aeronautics industry is not easy, given the many barriers to entry, like high capital requirements and complex certification requirements (Pearce, 2013). In addition, profit margins have decreased over the last decades due to strategic sourcing (Rossetti and Choi, 2005). However, being able to occupy a niche like MAM in the market would likely increase suppliers' bargaining power and profitability.

Suppliers are an increasingly important part of the industry, given that airframers have substantially increased the number and complexity of outsourced content in the latest generation of their aircraft (Slayton and Spinardi, 2015). While some of these suppliers are in the U.S., many are located abroad and serve as a mechanism for OEMs to enter foreign markets (FAA, 2008). One example is Japan, where Boeing's suppliers have in the last half century developed capabilities, such as composite materials manufacturing, which may be higher than Boeing's (MacPherson and Pritchard, 2007).

Suppliers are FAA-certified through the OEMs, to whom they give the minimal amount of information about their product, and they generally do not have communication with the FAA (Interviews 7,20,21). In cases where suppliers have higher capabilities than OEMs, issues related to knowledge asymmetry could also appear. The concentration seen among the "system integrators" in aerospace is also apparent among the OEMs, and among their suppliers (Nolan, 2012). These suppliers are specialists, with unique capabilities, and regulating them to ensure safety is a challenge for OEMs, and ultimately for the regulator. To help OEMs in the supplier selection process, institutions like the Performance Review Institute, a cooperative industry effort which groups OEMs and suppliers, develops "checklists" which serve as a basis to accredit suppliers (PRI, 2016). However, our conversations suggest that, although there is an industry-wide interest in developing such checklists for MAM because of a growing interest among suppliers, balance has to be found between the amount of proprietary information that firms are willing to share compared to the information that is necessary for a complete and thorough checklist (Interview 17).

In the U.S., FAA performs Supplier Control Audits (SCA) to randomly chosen high-tier suppliers (Order 8120.23, 2013). Results from past SCAs conducted at Boeing, where 40% of its audited suppliers had at least 1 nonconformance, suggest that unsatisfying manufacturing practices do arise (Simons, 2007). The lack of oversight of suppliers is an increasingly important problem due to the increased subcontracting in the industry, where airframers have started outsourcing not only small parts but important sections of their aircraft to Tier 1 suppliers, which might be located abroad (Slayton and Spinardi, 2015). The oversight of the increasing number of foreign suppliers make it even harder for the regulators, who see how their resources diminish. An audit to the FAA supplier audit procedures states:

> "*We acknowledge that it is not FAA's responsibility to provide oversight of manufacturers' suppliers. However, in our view, it is counterintuitive to decrease the number of supplier audits that FAA performs when use of suppliers has steadily increased and FAA has consistently determined that supplier oversight is a problem*" (FAA, 2008).

The opacity of the relationships across the supply chain creates additional problems to ensure safety. For instance, the B787 was the first airliner to use lithium-ion batteries, but those batteries were not manufactured by Boeing but by Yuasa, a Japanese manufacturer. The electrical system was designed by Thales, a European company, which subcontracted the battery components to Yuasa. In 2013, after two severe incidents involving batteries catching fire, the FAA decided to ground all B787s worldwide (Ostrower et al., 2013). In 2013, after the investigation of one of these fire incidents, the National Transportation Security Board (NTSB) released a report stating:

> "*FAA's oversight of Boeing, Boeing's oversight of Thales, and Thales' oversight of GS Yuasa did not ensure that the cell manufacturing process was consistent with established industry practices*" (NTSB, 2013).

The same document further reports "insufficient guidance for manufacturers… in determining and justifying key assumptions in safety assessments" and "Insufficient guidance for FAA certification engineers to use during the type certification process to ensure compliance with applicable requirements" (NTSB, 2013).

Summing up: taking into account the recent evolution of the industry, the increased complexity of the supply chain, the lack of communication with regulators and the increased complexity of the subsystems they produce, suppliers may become a more important source of risk than OEMs.

2.5.4.3 *Spare parts manufacturers*

The aftermarket constitutes the most lucrative business in aeronautics: engine companies may sell the engine below cost and make their profit in the aftermarket (Hollinger and Powley, 2015). In 2016, Boeing forbad Spirit Aerosystems to sell spare parts directly and obliged Spirit to sell them through Boeing, as part of an ambitious plan of tripling the sales of their business in parts and services (Ostrower, 2016). For this business segment, MAM is very attractive because it would allow companies to reduce inventory costs and the need for additional equipment (Holmström et al., 2010).

Spare parts can be fabricated either by the OEM, or by third party suppliers that need to obtain a Parts Manufacturers Approval (PMA), which "is a combined design and production approval for modification and replacement articles. It allows a manufacturer to produce and sell these articles for installation on type certificated products" (FAA, 2013). If predictions that MAM will eventually dominate aftermarket sales prove true,[12] PMA holders who do not invest in MAM risk losing a significant share of their business. However, a 2015 survey suggests that aftermarket suppliers lack the capital availability and innovative culture to introduce new technologies (Spafford et al., 2015).

OEMs claim that some of these third-party suppliers may constitute an additional source of risk, as PMA holders and FAA designees who certify them, often lack enough knowledge to develop safe replacement parts (FAA, 2009b). The argument is that a PMA, although they may produce a part which has the same geometry and looks the same as a part manufactured by the OEM, have not gone through the same statistical performance substantiation. On the other side, PMA holders claim that their products offer substantial cost savings with respect to the components sold by OEMs, and are safe and that their business viability is being hurt by having to go through a mandatory FAA review and approval for each specific part (Doll, 2015; FAA, 2009b).

An FAA Commission was established in 2007 to resolve this dispute. In 2009, a report was released stating that TC holders – that is, the OEMs – had not always been objective in their statements, and that the major driver of the debate was economic (FAA, 2009a). Related to this point, in March 2016, IATA, representing the airlines, officially joined a European Commission

[12] The technical community doesn't yet know how changes in raw materials over time may affect the mechanical properties of future MAM spare parts

investigation by filing a complaint against OEMs for abuse of dominant market position in the spare parts market (IATA, 2016).

Independent of the business case, the level of complexity and technological knowledge required to manufacture aircraft parts continues to increase, as more and more safety-critical parts are considered for MAM. As long as these concerns are not properly addressed, risks derived from inappropriate spare parts may also rise. Arguing for greater FAA involvement in the regulation of PMA holders, one FAA official writes, *"Aftermarket suppliers do not generally have the same **resources or talent pools** available to OEMs"* (Khaled, 2015).

Due to the lack of financial resources and human capital, spare parts manufacturers might be able to handle technological uncertainty less effectively than OEMs, thus becoming a more relevant source of risk.

2.5.4.4 Summary

In Section 4.3, we categorize the players in the aeronautics industry into OEMs, suppliers and spare part manufacturers. Each type of player has different market incentives, technical knowledge, financial resources and a different level of regulatory oversight. Table 2.2 contains a summary of our findings.

Table 2.2 Different players in the aeronautics industry have different incentives and levels of resources to tackle technical challenges

	Engines OEMs	**Airframe OEMs**	**Suppliers**	**Spare parts manufacturers**
Profitability	Low in new products, high in spares	Low in new products, high in spares	High for niche applications, low otherwise	High
Regulatory Oversight	Direct and continuous	Direct and continuous	Rare, indirect through OEMs	Direct, but not continuous
Technical capabilities	High	High, but some core competences outsourced	Depending on the application, higher or lower than OEM	Lowest
Financial resources	High	High	Constrained	Lowest
Incentives	Keep MAM in-house Increase barriers to entry Gain aftermarket	Have multiple MAM suppliers Gain aftermarket	Occupy niche Gain bargaining power	Reduce inventory Reduce equipment costs

Concerns	An early accident could abruptly stop the introduction of MAM	An early accident could abruptly stop the introduction of MAM	OEMs not helping develop industry-wide guidelines	Losing market share to OEMs if not investing in new technology

Differences across players also create differences in the ability of different players to abate technological risks. Risks coming from MAM's technological uncertainty might be higher outside the OEMs. Therefore, regulation must balance innovation and safety, and accommodate the differences across the diverse range of stakeholders.

We turn now to a discussion of some of the solutions proposed to minimize risks posed by MAM.

2.5.5 Solutions being considered to safely introduce MAM in commercial aviation

At the moment of writing, FAA has not written any regulation for MAM, but FAA has been communicating with firms about the best way to tackle MAM's challenges and there are already some solutions being considered (Interviews 4,8,18). These solutions were also discussed during workshop we organized, operating with Chatham House Rules as a neutral party with industry and government leaders. First, under a scenario in which no additional action is taken by the FAA, OEMs would individually certify their suppliers and spare part manufacturers to ensure they comply with their manufacturer requirements (Interviews 4,14). Second, currently manufacturers are over-engineering their MAM parts, voluntarily increasing their factors of safety to account for technological uncertainty (Interview 4). The use of safety factors could also be mandated by the FAA, as they were in the case of Casting Factors (Interview 15). Third, public resources could be used to create shared material specifications (such as process or performance specifications), which could be directly used in the FAA certification process (Interviews 1,2,22). This has successfully been done with composite materials, where the creation of a public database at Wichita State University allowed for a decrease of an order of magnitude in certification cost, and more than two years the certification time (Tomblin et al., 2002). Companies that have invested significant R&D resources in being at the technological frontier will have little incentive to share knowledge core to their competitive advantage (Interviews 4,16,17). That said, technological leaders may have incentives to share second or third generation knowledge, to increase supply chain capabilities, increase competition among their suppliers and thereby reduce costs (*Workshop*, 2015). They may also have incentives to share such knowledge to reduce the risk of other companies' failures hurting the public image of, or regulatory friendliness to, MAM and thereby preventing the front-runner from being able to use a technology in which they are heavily invested. In both the second and third cases, care would need to be taken to update regulations and material specifications to match the latest in technological capabilities. While "technology-forcing" regulation can accelerate technology development towards a currently unattainable policy goal (e.g. Gerard and Lave, 2005; Lee et al., 2010); overly prescriptive regulation can create a disincentive to explore newer, better, and (at least initially) riskier technologies.

2.6 Discussion

2.6.1 Regulating an emerging technology, given varying capabilities across the supply chain

Regulators (in the case of aviation, the FAA) of emerging technologies are faced with balancing increasingly stringent safety requirements, risks associated with technological uncertainty, and opportunities for innovation, which could bring extended social benefits (Mandel, 2009). Technology-based, performance-based, and management based regulation each have advantages and disadvantages with respect to these trade-offs (e.g., Coglianese and Lazer, 2003; Gilad, 2010); while adaptive regulation (e.g., Wilson et al., 2008; Mandel, 2009) offers a series of policy mechanisms to balance technology uncertainty and the need for innovation, independent of regulatory style. However, both literatures fall short when addressing challenges classic to emerging technologies. Such challenges include needed links between the characteristics of a technology (such as technology maturity and sources of uncertainty) and the type of regulation, and differences in technological knowledge and capability across players in the same industry.

Developing performance-based regulation for immature technologies is challenging due to the lack of reliable physical models, of clear specifications when there is uncertainty around which parameters matter, and of control in manufacturing (Coglianese et al., 2003; Notarianni, 2000). Proponents of management-based approaches argue that firms normally have more knowledge about their technology than regulators (Coglianese and Lazer, 2003). However, not all firms in the same industry necessarily have the same knowledge, no less the same capabilities: In our case of MAM in aviation, while some companies have more knowledge than the FAA, others have less. Regulators obtain their knowledge directly from trailblazers. At the same time, suppliers have economic incentives to implement the technology but do not have the financial resources and human capital to internally develop the same level of knowledge as the leading companies. These suppliers might benefit from technology-based approaches, which provide specific guidance on how to reliably produce proven technologies. In the case of suppliers, the reduction in incentives for innovation associated with technology-based regulation may be of less concern, since they are unlikely to be focused on innovation, given their resources. Thus, the reduction in incentives to innovate in this case might easily be outweighed by a reduction in the technological risk. Focusing on a restricted set of technologies, if matched with requirements to share data, also could increase available process and performance data to help improve understanding and reduce uncertainty with respect to the technology. Finally, technology-based approaches could potentially decrease the risks derived from an inadequate oversight of suppliers by the OEMs.

We propose a typology in which, given the risk preferences of the regulator, the regulatory approach could depend on the level of technological uncertainty at each firm across the supply chain, and which evolves over time (Figure 2.3). Our framework is an example of what McCray et al. (2010) called "Planned Adaptation", a regulatory system which is revised when knowledge is improved, and which takes proactive action to produce such knowledge (McCray et al., 2010; Petersen and Bloemen, 2015; Wilson et al., 2008). Coming back to the concepts of "Art" and "Science" introduced by Bohn (2005), we define a state, "Craft", which corresponds to an intermediate stage in the learning process where there have been important advances in terms of replicability, but the scientific understanding is still limited (Figure 2.2). The regulatory approach (given the risk preference of a particular regulator) would then depend on the stage of the learning process that firms are in (Figure 2.3).

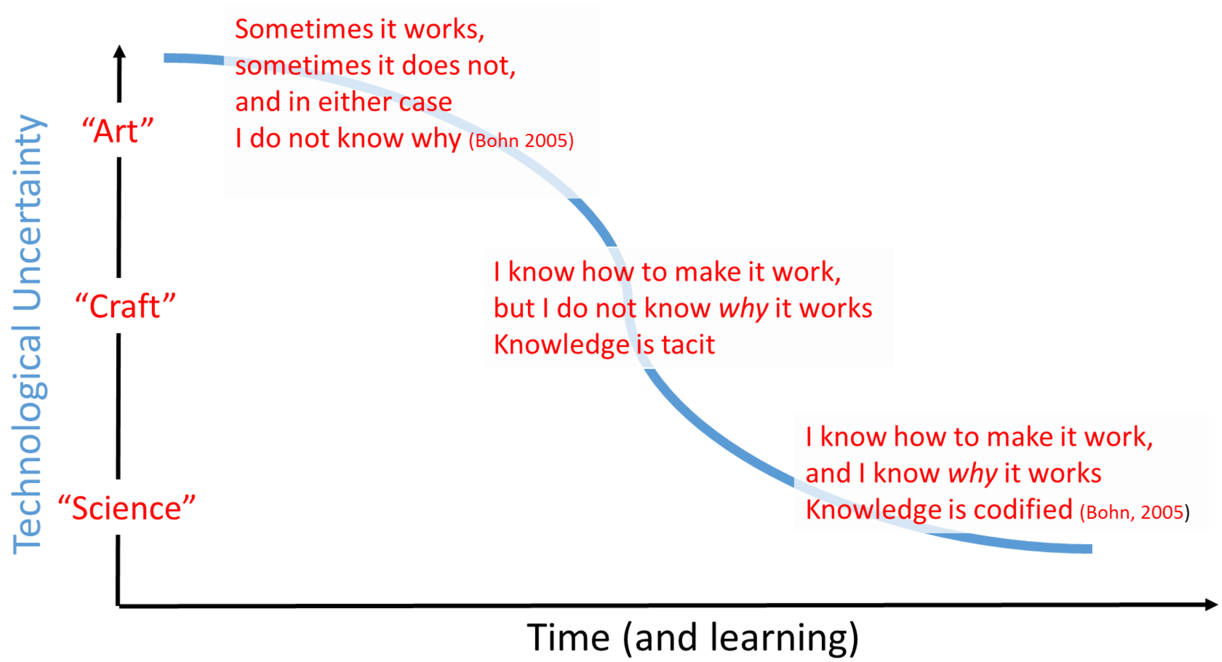

Figure 2.2: *Graphical representation of the evolution of technological uncertainty, and the correspondence with the concepts of "Art,", "Craft," and "Science"'*

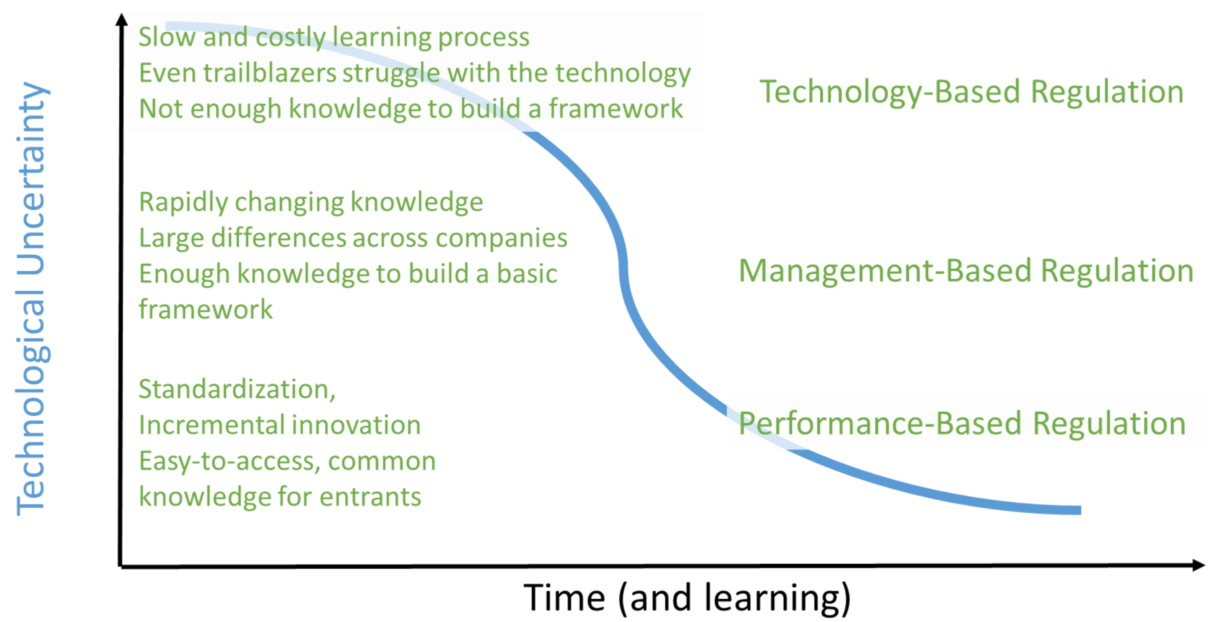

Figure 2.3*: The risk-benefit trade-offs of Technology-, Management-, or Performance-Based regulation depends on the level of technological uncertainty*

Under this framework, technology-based approaches are applied to firms whose knowledge is far behind the technological frontier. Meanwhile, leading companies who have developed in-house knowledge which is well ahead of their competitors, would benefit from management-based mechanisms. This would give manufacturers at the technological frontier the opportunity to implement the technology in more critical applications while transferring their knowledge to the regulators, which could use this new information to adapt existing regulation.

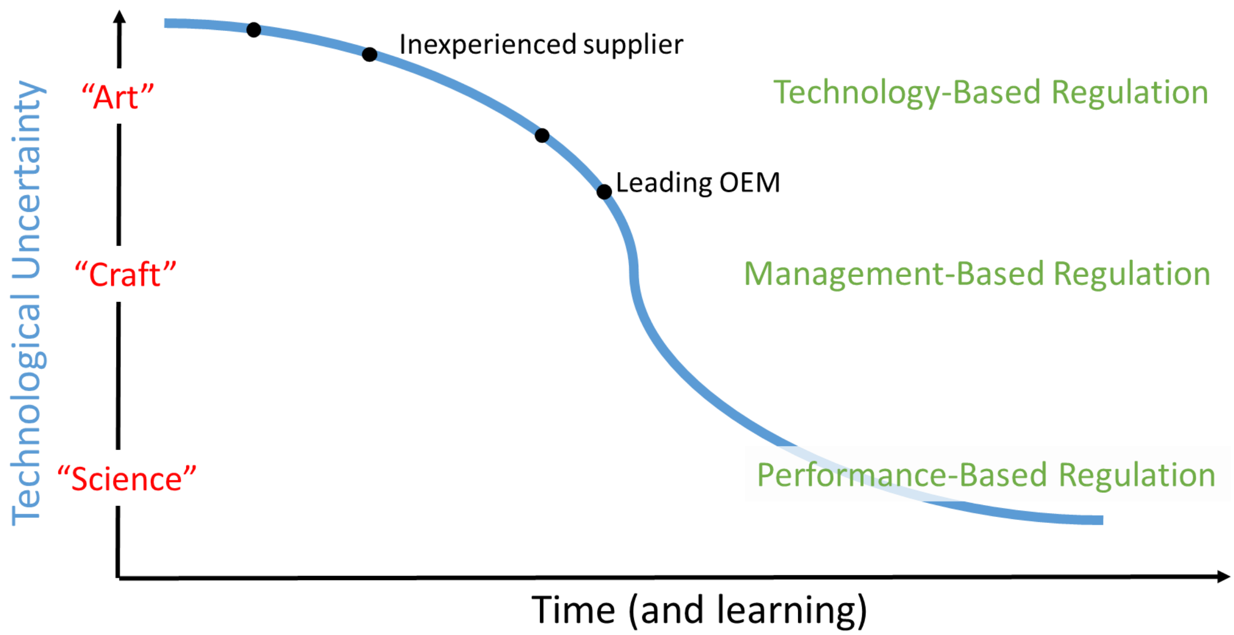

Figure 2.4: *Interpretation of difference of knowledge across players for the current state of MAM*

Once a technology is sufficiently mature, its performance predictable, and adequate standards developed, the system would transition to a performance-based approach where any player could take advantage of the full potential of the technology.

To avoid situations of "regulatory lock-in," regulations should also be established with the mechanisms to ensure transition from one approach to the next. One possible mechanism is the establishment of sunset clauses to ensure the periodic revision of the regulation (Posner and Vermeule, 2003; Sunstein, 2013; Wilson et al., 2008). In this case, one challenge might be establishing a revision frequency short enough to accommodate rapid changes in technology, but long enough for industry to assimilate the regulatory changes. A second mechanism could be the creation of a formal review process through which single firms could prove to regulators that they have mastered the technology enough to go beyond the pre-approved applications. In aviation, this would mean extending FAA's direct oversight to those suppliers specialized in MAM. Such a review process would increase the opportunities for innovation in the industry, but creating the guidelines for a public review process while the technology is still highly uncertain and information is held as proprietary within leading OEMs would likely be difficult.

One strategy to bypass this hurdle would be to increase the discretion of the certification officers employed by the FAA, the street-level bureaucrats. These certification officers possess more knowledge than they are allowed (and perhaps even able) to codify in formal guidelines due to their interaction with the OEMs around proprietary information, and could perform informal reviews of suppliers to assess their capabilities compared to the industry leaders. They also have contextual knowledge specific to each company, which can be instrumental in identifying how best to implement the spirit of the Code and Orders in the context of the organization. Notably street-level bureaucrats might be incentivized to adopt the most conservative posture and maintain the status quo, since a failure could jeopardize their career and have significant economic consequences. At the same time, the risk of capture could also increase, the career paths of certification officers are often such that they come from industry and might go back to consulting to industry or industry itself (Johnson, 1983).

Increased discretion still requires checks and balances. Organizational culture can be controlled through selection and training of the street-level bureaucrats (Hill, 2003; Piore and Schrank, 2008). Management can augment coherence across cases, and exert a greater influence over the organizational process, by dividing firms into comparable categories, where the type of problems and the ways of solving them are similar (Piore and Schrank, 2008). Creating mechanisms for FAA agents and companies regulating suppliers to compare interpretation of regulation within the context of OEMs, suppliers, and aftermarket suppliers independently, could help toward this end. Finally, generation of publicly available scientific data to inform the review process, similar to what was done with composite materials; and increased certification office discretion, are likely instrumental to minimizing the risks of regulatory capture, as well as to eventual technology maturity and use by all. In addition to providing factual information, this publically available scientific data also serves as a form of "popular participation" (Piore and Schrank, 2008) or "tripartism" (Ayres and Braithwaite, 1995). To aid the broader advance of the technology, the publicly available scientific data need not come from the latest generation of products still instrumental to corporate competitive advantage, Although there are strong market pressures to develop MAM, research shows that it can take decades before new materials and process technologies are well-codified, well-understood scientifically, and thus mature (Bohn, 2005; NSTC, 2014). The evolution of advanced composite materials, in which levels of federal investment were much higher than MAM (Bonnín Roca et al., 2016), serves as an example. Despite being first introduced in aviation in 1950s (RAND, 1992), a Boeing executive suggested that today, more than sixty years later, composites are still insufficiently well understood by the aeronautics industry, resulting in suboptimal designs (Sloan, 2014). The prospect of such long, or even longer, development times, is yet another incentive to develop adaptive regulation with discretion in implementation.

2.6.2 Lessons from MAM for regulating emerging technologies in other industries

Theory-building seeks "to guide and inspire new ideas, not to validate existing ideas" (Hargadon and Sutton, 1997).[13] Based on the knowledge gained from our extreme case of MAM in civil aviation, we propose a framework to guide both further refining of our theory in other industrial contexts as well as eventual theory-testing with Table 2.3 and Figure 2.5.[14]

To help contrast MAM with other manufacturing technologies, we leverage existing literature to highlight differences in sources of uncertainty and in learning mechanisms across industries in Table 2.3. We use bicycle assembly as an example of a component assembly-focused (in contrast to process-based) manufacturing activity. In Table 2.3, the number of constituents represents the number of unique components in a product. The number of constituents for pharmaceuticals is low, as pharmaceuticals are composed of only a handful of active ingredients (Ma'ayan et al., 2007). In contrast, the number of constituents in genetic engineering is high, due to the need for accurate positioning of nucleotides in extensive DNA strings (Mullis et al., 1986). While the development of semiconductors required new testing techniques (Lécuyer, 2006) – as does MAM (Mani et al., 2015), pharmaceuticals benefit from generic quality control procedures developed for other types of chemicals (Gowen et al., 2008). Semiconductor microchips can be tested during intermediate steps of their production, like the wafer testing performed before the

[13] In the words of Hargadon and Sutton (1997), "The extent to which our model generalizes to other industries and technologies can only be determined by hypothesis-testing research in large, representative samples of other organizations involved" in the regulation of emerging technologies.

[14] Here, by hypothesis-testing research we intend to refer to research that, in contrast to our paper, sets up natural experiments that generate data that is amenable to the use of standard econometrics methods for the evaluation of the impact of certain types of regulations in safety (e.g., number of incidents/accidents) and innovation (e.g., patents).

wafer is cut (Zant, 2014), and the manufacturing process of pharmaceuticals can be tested and controlled during production via spectroscopy (Blanco et al., 1999). Conversely, in other manufacturing processes like MAM or genetic engineering (Li et al., 2015), testing can be challenging or impossible mid-process, and is mainly performed at the end of the process. Even when testing can be done at the end of the process, it's not always true that all performance can be predicted by those tests. Performance of semiconductors can to a large extent be measured and thus tested once fully assembled (Zant, 2014). Thus, learning by using is comparatively low. In contrast, pharmaceuticals can have unpredicted side effects on certain patients even after they are approved for commercialization, due to differences across the population (Wood et al., 2003), therefore learning by using is high.

Some of the above-described differences arise from the differing levels of maturity of the industries we are comparing. For example, semiconductor devices are today testable at intermediate stages, and do not need much learning by using. Neither of these was true when semiconductor manufacturing was at a level of maturity comparable to MAM today (Lécuyer, 2006). As a technology matures, e.g., evolves "from art to science," there is an evolution in the sources of uncertainty and learning mechanisms. With increasing levels of maturity, learning by using generally has decreasing returns, the need for new testing techniques decreases, and new ways to test the product in intermediate stages emerge.

Table 2.3 Different manufacturing processes have different sources of uncertainty and learning mechanisms which shape the optimal regulatory approach

	Genetic Engineering	**Pharmaceuticals**	**Semiconductors**	**MAM**	**Bicycle assembly**
Number of constituents	High	Low	High	High	Low
New measurement techniques required	Yes	No	Yes	Yes	No
Testability during intermediate phases of production	Not yet	Yes	Yes	Not yet	Yes
Learning by using	High	High	Low	High	Low

The extreme case of MAM in civil aviation provides important insights for the regulation of immature process-based technologies. MAM in civil aviation is a more constrained case than many technologies in other contexts in its level of safety requirements, level of technological uncertainty -- including the extraordinary number of variables, challenges in testability, and requiring learning by using, and variety of capabilities in its players. In Figure 2.5 below, we identify three constraints for which MAM is extreme: industry structure (number of firms in the industry given vertical disaggregation and competitive dynamics), safety implications for human life, and contributors to technological uncertainty, and then show where various emerging technologies are on those spectrums in particular industrial applications. Here, the industry structure and safety dimensions will vary with industrial application, while the contributors to technology uncertainty will vary with the technology itself. By looking at the extreme case of MAM for commercial aviation, we are able to shed insights into how regulatory approaches can differ when each of the constraints are removed. The comparison across technologies in Table 2.3 helps build our framework insofar as it provides comparative measures for the type and number of uncertainty sources in a particular industry, and the increased impact on human safety and well-being in sectors where learning by using plays a more important role.

The top category in Figure 2.5 is industry structure, and depends on the number and variety of firms and the level of vertical disaggregation. We combine the variety of firms and level of vertical disaggregation into this single measure due to the correlation between the vertical disaggregation of an industry and the number of opportunities for uncertainty to be introduced in the final product. Vertically integrated firms have fewer suppliers than horizontally integrated firms, and therefore the sources of uncertainty arising from firm heterogeneity are reduced. In addition, the larger the number of firms in an industry, the more difficult it is for the regulators to oversee all of them.[15] For instance, the pharmaceutical industry faces similar challenges to MAM in terms of safety requirements and uncertain performance, but R&D activities are concentrated in a much smaller pool of large companies (Comanor and Scherer, 2013).

[15] To locate an industry along the first axis, one option for regulators might be to use an index such as the HHI (Rhoades, 1993), which quantify the level of integration of an industry as a function of the number of firms N and the market share of each firm s_i ($HHI = \sum_{i=1}^{N} s_i^2$). A limitation of this measure include the relatively large value when one of the firms has a very large market share, when compared to a market where each player has the same share. Another measure might be the number of steps along the supply chain from raw material to final product. More work would need to be done to find the ideal measure.

Managing this concentrated pool of large players requires fewer resources, and thus common management-based regulation may be sufficient.[16]

The second category in Figure 2.5 is safety implications for human life. This category combines the number of lives endangered by a single accident, and the ease for meeting desired safety levels without negatively affecting the expected technical performance. For instance, the automotive industry is a highly regulated industry, for which in the last decades many responsibilities have been transferred from the OEMs to small suppliers (Whitford, 2005). However, an accident in aviation incurs a much larger loss in terms of human lives than a car accident. Furthermore, in automobiles the weight gain caused by using a higher safety factor has a much lower impact on performance than in aviation, the latter for which additional mass translates into a more immediate and even greater increase in operating costs due to increased fuel consumption. As such, using MAM in automotive entails lower risks than in aviation and fewer performance trade-offs, which may allow for an earlier transition to performance-based regulation. Safety levels used by regulators could be used to locate an industry along the axis for the second category. For instance, Starr (1969) compares technologies estimating the probability of an accident per person-hour of exposure. Similarly, the goal set by FAA is 1E-9 catastrophic accidents per operational hour (FAA, 2000).

The third category in Figure 2.5 is the relative magnitude of technological uncertainty. This category aggregates the effects of technological complexity, difficulties in testing a product during and after its manufacturing process, and needs for "learning by using." Emerging biotechnology fields like synthetic biology are more similar to MAM in terms of variety of player capability because lowered barriers of entry have allowed the entry of players which are much smaller than it would be expected for an emerging technology (Oye, 2012). However, in contrast to synthetic biology, MAM suffers from additional within-part variability. In MAM, some sections may not melt perfectly, resulting in almost undetectable defects. Further, in MAM

[16] We do not include firm-level heterogeneity as an axis in Figure 2.5, because in our framework firm-level heterogeneity is primarily relevant for management-based regulation (not technology-based or performance-based regulation). While firm-level heterogeneity could be taken into account in technology-based (different firms could have different technology implementation requirements) or performance-based regulations (different companies could have different performance requirements), within a single country such regulatory differences are rare. (In contrast, for example, to different regulatory requirements across developed versus developing countries such as agreed upon in the Montreal Protocol (Velders et al., 2007).

the effect of the particular engineer configuring and overseeing the equipment might be higher than synthetic biology, which may increase the need for street-level bureaucrat discretion (regardless of whether a technology, management, or performance-based approach is taken).

One option for policymakers to assess uncertainty in emerging technologies could be expert elicitation, but results are subject to overconfidence and in general do not take into account variables which go beyond well-established knowledge (Morgan, 2014). In industries where accidents are rare, regulators may also collect information about past microevents and near-misses which can be used to prevent future accidents (March et al., 1991). The participation of regulators in industry events and standard-setting committees may also accelerate the transfer of knowledge about technology change. In any exercise seeking to collect quantitative measures, we suggest using the different dimensions in Table 2.3 as a typology for thinking about sources of uncertainty in emerging technologies, and thus informing the data collection. Given that uncertainty has not only the "known unknowns" but also the “unknown unknowns” (Morgan et al., 1992), any estimation of the uncertainty will be incomplete.

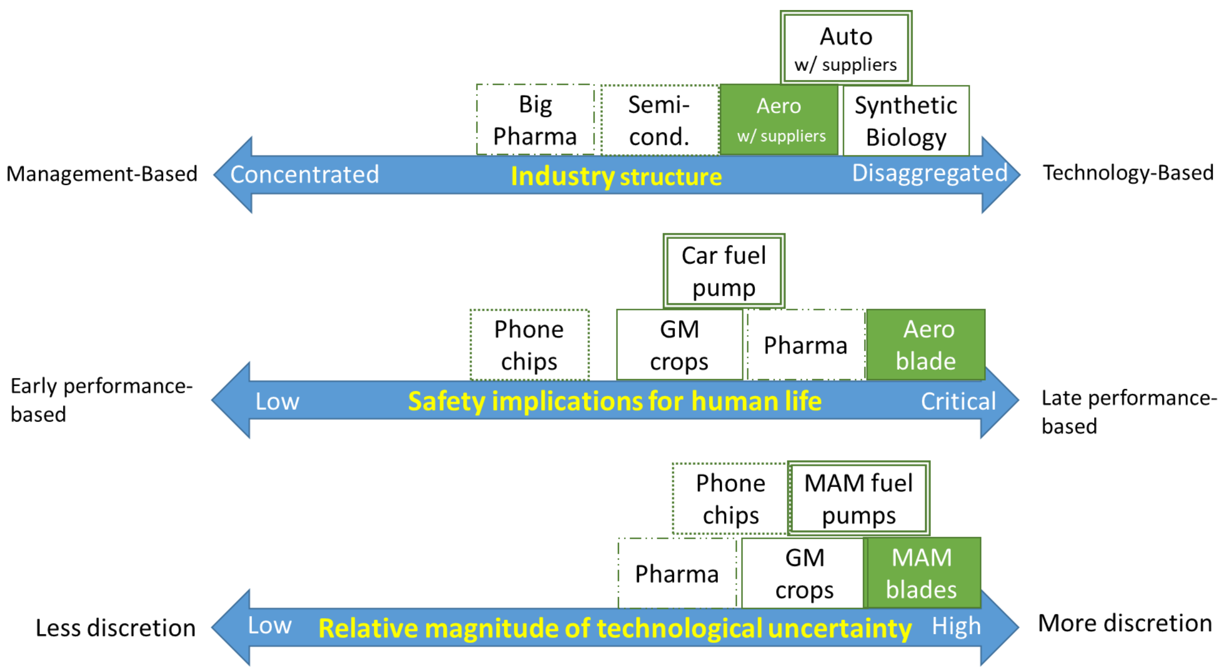

Figure 2.5: *The appropriate regulatory approach, which depends on the structure of the industry, its safety implications and the relative magnitude of technological uncertainty, varies with technology and industrial context.*

The regulatory approach that has the most promise to balance safety and innovation depends on technology and industrial context, and requires combining all three dimensions of Figure 2.5.

Our typology suggests that current FAA certification procedures might not be well suited to achieving public safety goals, due to the differences in knowledge, resources and regulatory oversight across industry members, and the high sources of uncertainty in the case of MAM. To balance safety and innovation in the case of MAM in civil aviation, our typology suggests 1) an early technology-based regulation for suppliers not under direct FAA oversight, 2) delaying transition to performance-based standards until further technology maturity to avoid catastrophic accidents early-on prior to industry acceptance of the emerging technology, and 3) increasing regulatory discretion of designees and certification officers given the high sources of technological uncertainty.

However, policymakers may have reasons to move out of this balance point. For instance, in safety-sensitive industries like pharmaceuticals and aeronautics, where the accidental loss of human lives can have a large impact, regulators may want to be even more risk averse (Fischhoff et al., 1978). In that case, they will likely want to reduce regulatory discretion and create technology-based regulation such as the use of special safety factors, or the creation of material databases as discussed in Section 4.4. Unfortunately, removing these safety factors may be very difficult once greater knowledge has obviated their need. The specific policy ultimately depends on the product being regulated, even within the same industry. For instance, in civil aviation, sensor housings are less safety critical than turbine blades. Likewise if we look at the pharmaceutical industry, safety factors can be applied to some products like antibiotics or cosmetics, but not to others like cancer treatments.[17] Conversely, for some regulators the promotion of innovation might weigh more than the safety concerns. In that case, regulators might choose to refrain from using technology-based standards and move towards performance standards relatively early, letting industry experiment the best ways to reach the regulatory goals.

Our typology, as with any model, is a simplification of reality and should only be viewed as a tool to think about the problem at hand: here regulation of emerging technologies to balance innovation and safety. Further metric development and theory testing would be necessary to propose precise measures. While our work focuses on process-based manufacturing technologies, lessons from our case of MAM in civil aviation for the regulation of emerging technologies might also be useful for "traditional" industries such as banking, which are

[17] We thank one of our anonymous reviewers for this example.

undergoing large changes due to the emergence of technologies such as virtual currencies or blockchain.

2.7 Conclusion

Our work uses the extreme case of an immature technology with high technological uncertainty in a safety-critical industry – MAM in civil aviation – to shed light into how the characteristics of a technology and its industry structure should be taken into account in regulatory design. Our contributions to the literature are twofold: First, we suggest that not all immature technologies should be regulated in the same way, because the sources of uncertainty behind these technologies can be different. Second, past literature on risk regulation has treated industry members as homogenous, ignoring the variation in firms' underlying motivations and technology capabilities, and the changes in both of these over time. Our findings suggest sources of uncertainty across industry players come not only from differences in knowledge and technological capabilities, but also differences in their financial interests, business traditions, position in the supply chain, and regulatory oversight. Given this situation, technology-based regulation, which has traditionally been reviled as an innovation-constraining approach, could serve as a useful tool both to control risks and to enhance the gathering of knowledge. Such knowledge gathering is essential in technologies where certain aspects of performance can only be discovered through use (and thus a marked "learning by using" component.) Possible interventions to address the variety in capabilities in an emerging technology across an industry and change therein over time include creation of adaptive regulation mechanisms such as sunset clauses, the establishment of formal case-by-case review processes, and an increase in street-level bureaucrats' discretion.

Our findings, by focusing on the extreme case of MAM in civil aviation, offer important insights for how regulation may need to differ with technology and industrial context. It also offers important, specific, insights for regulation in other immature, process-based technologies such as synthetic biology, semiconductors, and chemicals, and other market applications with high safety standards such as automotive and pharmaceuticals. To this end, we first present a framework for thinking about sources of uncertainty across different technology contexts. We conclude with a typology for how regulatory configuration could take into account industry structure (number of firms), performance and safety requirements, and the relative magnitude of technological uncertainty.

3 Policy strategies to foster learning in aviation[18]

That MAM technology is in the earliest phases of development poses two distinct, yet closely intertwined, problems. First, there is as yet insufficient ability to accurately and consistently predict the mechanical properties of a particular design, produced using a particular feedstock, on a particular machine (Frazier, 2014). Thus if a new, nominally identical, machine is acquired to make an existing MAM-produced part, extensive testing and validation is required because, given the current state of the technology, obtaining an identical part to that fabricated on a different machine cannot be taken as certain. Second, Federal Aviation Administration (FAA) standards for material design require that manufacturers demonstrate they can reliably produce a part that is extremely unlikely to fail (14 CFR 25.613). For other technologies, the FAA has worked with industry to translate this performance standard into more explicit design guidelines (14 CFR 25.621). This has not yet happened for MAM.

Overcoming this first challenge requires advancing understanding of the basic science. For MAM's full potential to be realized, basic materials processing knowledge must improve and investment must be made in reducing variability in microstructure, surface finish and geometric tolerances (all of which affect mechanical performance), which is currently inherent to MAM parts. One way to achieve this is for closed-loop control processes to be developed: the material could be monitored in situ, and the manufacturing process adjusted to correct aberrations. While all the parameters that affect part microstructure are not known, the research community and manufacturers are at the earliest stages of building the ability to monitor a few of the parameters that are known to be important. For example, one electron beam melting machine offers a camera-based system to monitor the build process (Wohlers Associates, 2016). Another gages the temperature of the pool of molten metal (which determines the part's eventual microstructure) created by the laser beam striking the powder bed by sensing its brightness. It then compares this stream of data to that gathered from parts that have been built successfully in

[18] This chapter has been published in essentially the same form as:
Bonnín Roca, J., Vaishnav, P., Fuchs, E., Morgan, M.G., 2016. Policy Needed for Additive Manufacturing. Nat. Mater.

the past, and uses this history to alert operators when defects are likely to arise (Wohlers Associates, 2016).

Data about the pivotal relationship between processing conditions and microstructure are being generated at considerable expense by some corporations working at the frontier of integrating MAM into their products. These firms closely guard their data and have little incentive to share these with each other however, or with the wider community of suppliers to the aerospace industry, as their early adoption is explicitly with the intent of developing competitive advantage. If the data could be shared, the public good – through improved regulatory framework and more rapid adoption across industry with associated fuel savings and environmental benefits – could be much greater than the private benefit to these firms (National Research Council, 1987). Thus, the acquisition of fundamental knowledge and eventual pace of uptake by aviation and a number of other industries, of MAM technology could be greatly enhanced. A classic approach which may help in this instance is for government to provide basic technical and institutional infrastructure, such as material databases, for this data to be collated and curated. For example, NASA Aeronautics helped to fund the collection and publication of much of the basic data on composite material properties such as the static and dynamic (that is, fatigue) strength of composite materials in different operating conditions (National Research Council, 1987). These datasets eventually contributed to commercial products such as the Boeing 787 Dreamliner and the Airbus A350 XWB. In the case of MAM, the government might not only provide funding. It may also act as a steward to ensure that access to such a repository is managed fairly, and that it serves the broader goal of enabling the development of a new technology, in which the government has made significant investment given its potential to enhance national economic and military competitiveness. Serving as a steward would require a focused and well-resourced effort that builds on the work currently being done under the auspice of America Makes. Current resources, however, may not be enough for America Makes to fulfil this role. America Makes is set to receive up to $50 million in federal funding, with an additional $39 million from corporate members and the states of Ohio, Pennsylvania, and West Virginia (Wohlers Associates, 2016) to help accelerate the adoption of additive manufacturing. Between 1986 and 2015, the National Science Foundation "has expended more than $200 million on additive manufacturing research and related activities" (GAO, 2015). In contrast, during critical development periods, the U.S. federal government may have been investing annually in composite materials the equivalent to what it has invested in total on additive manufacturing to date. RAND Corporation (RAND, 1992), a think tank, estimates that the federal government in 1987 was spending an equivalent of $240 million (2014 dollar rates) per year on advanced composites. At that point, the technology was far more mature than MAM is today, in terms of being application-ready: advanced composites funding by the US Air Force alone peaked at $160 million (2014 dollar rates) per year in 1964-5 (RAND, 1992). Excluding manufacturing and structural or flight-testing, $1 billion in federal research and development funds was spent on composites in the quarter century between the mid-1960s and 1990 (RAND, 1992). Including those activities, federal spending on advanced composites amounted to several billion dollars. These snapshots suggest that large early-stage funding was likely critical to setting composites on the path to wide adoption. While an estimate of total federal spending in MAM is not readily available, it is unlikely the US federal R&D spending is anywhere near the amount invested in the development and adoption of composites. This lack of investment is likely a major constraint on the development of MAM.

Overcoming the second challenge – translating the FAA's general performance standard into specific guidelines for part fabrication and testing by MAM – requires not only expanding basic knowledge (our preceding first challenge), but also the emergence of consensus on manufacturing and testing standards. Standard-setting bodies have not yet specified what parameters of the build process must be controlled (and to what degree) for safety-critical aircraft components. Testing organizations have also not prescribed, or developed, non-destructive tests that can economically verify that additively-manufactured metallic components do indeed possess the claimed properties (Slotwinski, 2013). It therefore falls to standards developed by other, independent, bodies (ASTM, ASME, ISO etc.) to translate that goal into specific requirements and guidelines. For example, a standard may list a series of parameters that must be controlled within specified tolerances to ensure that successive parts of the same design made on the same machine have identical properties. Standard-setting bodies must take into account the special needs of the aviation industry, and produce a standard that is sufficiently exacting. If an appropriate independent standard does not emerge, history suggests (Weiss and Sirbu, 1990) that the practices of the financially dominant firm will become the de facto standard, regardless of technical merit. Another possible outcome is that no widely accepted standard emerges. In that case, each firm would pursue its own way of doing things, resulting in a fragmented approach that stunts growth of the technology.

3.1 Cross-country lessons for additive manufacturing.

The introduction of a new technology like MAM creates major technical and institutional challenges, even for highly-developed countries such as the US, which have an established industrial base and a priority of maintaining military superiority. Countries that have a less developed manufacturing base, and less prominent military priorities, would be well advised to develop technical know-how in additive manufacturing by applying it in industries where the inherent barriers to entry are lower. Japan is an example of a country that built a manufacturing base in new materials technologies (e.g., composites and ceramics) in comparatively low-risk industries (sports goods and automobiles) (Office of Technology Assessment, 1988). As a consequence of this accumulated expertise, Japanese industries have been extraordinarily successful in leveraging this manufacturing base to make themselves indispensable to the US civil aviation sector (MacPherson and Pritchard, 2007).

China is approaching additive manufacturing in a focused and coordinated manner (Wohlers Associates, 2016). While it is inevitable that Chinese manufacturers will "learn by flying," it can be argued that accumulating a large number of flight hours is, by itself, not enough to develop the understanding and maturity required to create products or equipment that are reliable. For example, the de Havilland Comet jet aircraft was flown for millions of cumulative hours with square windows and punch riveting before stress concentrations led to metal fatigue failure, resulting in several instances of the fuselage breaking up mid-flight. These disasters, caused by a lack of understanding of the relevant failure mechanisms alongside manufacturing flaws, set the British aircraft industry back by years.

While European manufacturers dominate production of MAM fabrication equipment, the US leads in terms of MAMs application in designs and products. Just over 40% of all industrial additive manufacturing systems are installed in the United States (Wohlers Associates, 2016). Germany, Japan and China each have 9% of the installed base. Overall, Europe accounts for 28%. Given that the technology is not mature enough for part design and manufacturing to be decoupled from equipment design and calibration, to maintain and enhance their competitiveness in MAM, countries will likely need to develop expertise in those aspects of the technology (equipment or application) in which that country's industry is not currently skilled.

3.2 Three US policy recommendations

First, to catalyse the growth of MAM, the US Congress should provide significantly larger, sustained funding to improve understanding of the materials and processes involved in additive manufacturing. Given the global environmental and national economic and security benefits of MAM, this knowledge should be viewed as a public good (that is, a good whose production produces larger gains to society than a self-interested producer could capture) and managed by a public body: NASA's Aeronautics Research Mission Directorate could oversee its creation and ensure broad, fair access while ensuring that information that is critical to national security is protected.

As described in the preceding discussion, MAM machines are being equipped with the ability to monitor production in increasing detail. The data that these monitoring systems capture should be shared (if necessary, under agreements with time-bound confidentiality clause) with materials scientists who can analyze them to build better models of the physical processes involved (heat transfer to the feedstock, microstructure development etc.). These models could, in turn, be used to better control the production process. Researchers must additionally address the technical challenge of capturing, structuring, and processing vast quantities of data in real time. The Materials Genome Initiative in the US aims to promote the sharing of data and the enabling tools (NSTC, 2014); however, it is currently focused on data that emerge from Federally funded projects, and does not include all of the necessary stakeholders. Government should undertake the institutional work necessary to forge extensive collaboration and data sharing between key stakeholders across industry, government labs, and academia.

Second, strategies should be developed to allow US industry to "learn by doing" without compromising safety, in the same way that was vital to the advance of composite materials. For example, Boeing's ecoDemonstrator program adds new technologies to one of three aircraft in order to test their performance in actual flight, with the aim of improving environmental performance (Boeing, 2015). These aircraft are taken out of commercial service, but are of a type that is currently in commercial use. Boeing's approach makes it possible to not only test safety, but to prove and quantify their advantages of nascent technologies and help make the case for their adoption. More such programs, including at least some in which the resulting knowledge and data are put in the public domain, would help accelerate this critical in-flight learning.

Technological and regulatory barriers are lower, and risks smaller, in general aviation (e.g., recreational and business aircraft) than in commercial aviation, which includes all scheduled services (that is, airlines) (NASA, 1993). This makes general aviation an attractive platform for gaining experience in a new technology. The government and the civil aviation industry should explore ways to encourage general aviation to play this role in metallic additive manufacturing, as it did for composite materials.

Third, while early regulatory approaches must inevitably reflect the technology's immaturity, regulators should be careful to avoid lock-in. Provisions must be made so that rules can adapt to become less onerous as knowledge of MAM improves and microstructure becomes more predictable across a range of custom MAM materials and geometries. For example, rules could be accompanied by a "sunset provision", requiring that the regulatory strategy be substantially rethought at regular time intervals until the technology is deemed mature.

The challenges associated with generating the basic and applied knowledge to confidently utilize additive manufacturing in aviation, where both the risks and the opportunities are great, are daunting. The US clearly has the research and development and industrial capacity to surmount these challenges. However, the benefits to individual private firms may not be large enough to stimulate the necessary level of investment. The uptake of MAM thus requires the government to play a catalytic role, as it has successfully done for many other technologies, including advanced composites in aviation, and nanotechnology in general (National Research Council, 2002). Doing so may prove important to maintaining US competitive advantage in the aviation industry, and to ensuring that a promising technology meets the potential that it holds to influence global manufacturing in a number of industries.

4 Technology Forgiveness: The different Institutional Resilience of Polymer and Metal Additive Manufacturing in Portugal

4.1 Introduction

Institutional support can play an important role in supplementing private investment in innovative activities (Lerner, 1996; Martin and Scott, 2000), and, in some cases, support may be needed through the entire maturation process of a technology (Cohen and Noll, 2002). Technology follower nations must decide how to allocate scarce resources for acquisition and further development of foreign technology (Breznitz, 2007). There is not a one-size-fits-all solution and the most appropriate institutional framework depends on the particular reality of each country (Fagerberg and Godinho, 2005; Furman and Hayes, 2004; Zeitlin and Herrigel, 2000).

Upgrading the technological capabilities of a country is a slow process which requires a long term commitment (Amsden and Chu, 2003; Breznitz, 2007; Freeman, 2002; Lee, 2013; Lin and Chang, 2009). Perceived lack of governmental commitment and fluctuations in program goals and funding can undermine private investment (Bevan et al., 2004; Ferraz and Kupfer, 1999; Mowery et al., 2010). One reason for sudden changes in the institutional landscape can be macroeconomic shocks such as the recent 2008-10 "Great Recession" (Godinho and Mamede, 2016; Goldstein and Bergsten, 1998; Perez, 2010). The effects of a financial crisis can be aggravated by a fall in public R&D budgets (Sanz-Menéndez and Cruz-Castro, 2003), and increased risk aversion at firms which can shift some firms' strategies towards the short term (Arza, 2005; Oakey, 1990; Paunov, 2012). The combination of these effects may exert a strong selective influence in the adoption of one technology over another (Arthur, 1989; Nelson and Winter, 1982). At the same time, economic downturns might be an opportunity to remove the least efficient production techniques (Caballero and Hammour, 1991). In fact, based on multifactor productivity data, Field (2003) coined the period after the Great Depression, 'the most technologically progressive decade of the century'.

To better understand technology adoption in nations that are technology followers, we focus on the adoption of two emerging technologies -- polymer (PAM) and metal (MAM) additive manufacturing – between 1990 and 2015 in Portugal, a high-income technology follower which experienced additional resource constraints as a result of the 2010 financial crisis. We focus our work on the Portuguese molds industry, a sector in which the country's industry is globally competitive (CEFAMOL, 2017; Santos, 2009). This sector is the lead user of PAM and MAM in Portugal.

We present a longitudinal two-case study (Eisenhardt, 1989; Yin, 2013) in which we triangulate insights from archival data (on Portuguese macroeconomic conditions and research institutions, and activities in PAM and MAM), 45 interviews, and 75 hours of participant observations (Jick, 1979) to rebuild the history of both PAM and MAM technologies in Portugal.

We find that in both cases, Portugal invested relatively early in the technology. Both PAM and MAM suffered from institutional instability at the regional, national and European levels. However, while the country has been able to develop a robust PAM knowledge base and transition to high-end applications, MAM's adoption remains low and comes close to being technology lockout (Arthur, 1989; Schilling, 1998). We analyze how changes in macroeconomic conditions and funding programs may have affected MAM more than PAM. From a technical perspective, MAM presents higher levels of technological uncertainty than PAM.

From the comparison between PAM and MAM, we generate theory about which technological and contextual factors affect their 'technological forgiveness', defined as the susceptibility of the adoption of a certain technology to institutional instability. We create a framework where forgiveness depends on technological uncertainty and industry-related risks, which also determine the maturation rate of the technology. Policymakers may use our framework to determine the extent of institutional stability necessary for a technology to be successfully adopted in a specific industrial context. Latecomer countries investing in less-forgiving technologies need to establish long-term policies to secure private investment and the development of the national know-how, and explore the possibility of applying the same technology in less challenging industrial applications.

4.2 Theoretical background: institutional support for technology adoption

The maturation of emerging advanced manufacturing technologies has been modeled as a transition "from art to science" (Bohn, 2005), where "art" refers to the early stage where replicability is low and knowledge is highly tacit, and "science" refers to the most advanced stage where replicability is high and knowledge can be codified (Bohn, 2005). This transition is strongly linked to a progressive decrease in technological uncertainty, which happens mostly during a period when the technology is considered a "craft". During this craft period, lead users know how to make the technology work but a lack of scientific understanding hinders the codification of knowledge (Bohn, 2005; Bonnín Roca et al., 2017b; de Solla Price, 1984). A slow transition from art to science is especially characteristic of advanced manufactured products whose innovations are based on new materials or new chemical processes (in contrast to assembly) such as chemicals (Pisano, 1997), photonics (Fuchs and Kirchain, 2010) and electronic (Bohn, 1995; Holbrook et al., 2000) semiconductors, pharmaceuticals (Pisano, 1991), or additive manufacturing (Bonnín Roca et al., 2017b).

These process-based technologies require significant capital investment and can involve significant time to reliably achieve a desired outcome, if at all. As a consequence of this risk, firms and venture capitalists can be reluctant to invest (Department of Energy, 1989). To balance potential undersupply of private investment compared to the socially optimal level in certain innovation activities, particularly in advanced materials and processes (NSTC, 2014) , public intervention may in certain cases be needed through the maturation process (Cohen and Noll, 2002; Lerner, 1996; Martin and Scott, 2000). To successfully support the adoption of an immature technology, public funding may need to pay special attention to the gap left between early experimentation and a maturation state in which the private sector feels comfortable to invest in the technology (Butler, 2008; Weyant, 2011).

Notably, there are large differences between countries in their institutions, in those institutions' ability to create and support innovations, and in the incentives for upgrading their technology base (Nelson, 1993). Countries at the technological frontier are typically more likely to have the necessary human capital and may in some cases more easily be able to afford the financial resources to engage in the knowledge-intensive, costly, and risky development of a new technology (Krugman, 1979). Technology followers, on the other hand, may not always have the same talent pools or available capital. In some cases these followers may benefit from second-mover advantages (Cho et al., 1998) and opportunities for leapfrogging (Lee, 2013; Lee and Lim, 2001). Technology selection happens after the initial invention and at times even innovation (e.g. early commercialization) process, which reduces uncertainty about the performance of the technology (Forbes and Wield, 2000) and requires a lower pre-existing level of knowledge (Perez and Soete, 1988). Given limited resources, followers need to make decisions about which know-how to acquire, how then to acquire the relevant foreign know-how and further develop it, and how to fund those efforts (Breznitz, 2007). These decisions often imply the creation of infrastructure to generate knowledge, develop incentives to guide industry's efforts, and construct institutional frameworks to shape policy-making and firms' strategies (Armanios et al., 2017; Veloso and Soto, 2001).

Southern European countries like Portugal, Greece and Spain have become high-income countries without significant changes in their industry structure (Fagerberg & Godinho, 2005). Economic growth in these countries has benefitted from their inclusion in the European Union (EU) and EU's regional policy (Beugelsdijk and Eijffinger, 2005; Cappelen et al., 2003). However, convergence in Europe has slowed during the last decades due to differences in factors such as R&D efforts, industrial structure, or unemployment (Fagerberg and Verspagen, 1996). After the recent financial crisis the technology gap between European technology leaders and followers has widened further (Archibugi and Filippetti, 2011).

4.2.1 Policies to foster technology upgrading in technology followers

The most appropriate institutional framework and policy mix to foster technology adoption by technology followers will inevitably depend on a nation's industrial landscape and culture (Fagerberg and Godinho, 2005; Furman and Hayes, 2004; Zeitlin and Herrigel, 2000).

For instance, a country may decide to promote foreign direct investment (FDI), which can allow for the transfer of know-how through the education of indigenous labor working in foreign multinational corporations (MNCs) and in trade relationships with local suppliers (Amsden, 2003; Buckley and Ruane, 2006; Haskel et al., 2007). However, if foreign firms do not have incentives to share their technology (Lee, 2005) there is a risk that local suppliers can end up being relegated to the production of low-value components (Aitken and Harrison, 1999) with little or no technology spillover occurring to local firms (Reis et al., 2016).

A country may also decide to develop the technology on its own (Amsden, 2003). In this case, capital requirements are normally large (Amsden and Chu, 2003). To increase available capital, countries may increase their R&D subsidies to high-risk research (Feldman and Kelley, 2006) or create dedicated venture capital funds (Breznitz, 2007; Wonglimpiyarat, 2016). Initially, foreign technology can be acquired through licensing, co-development, the creation of R&D offices abroad, scouting of key researchers, or mergers and acquisitions(Lee, 2005). Talent may also be attracted by creating science parks, where companies may enjoy financial, reputational, and informational benefits (Armanios et al., 2017; Yang et al., 2009).

To further develop needed technical knowledge, geographical proximity can be crucial (Mansfield and Lee, 1996; Maskell and Malmberg, 1999; Teece et al., 1994), although excessive clustering in a single geographic location may lead to technology lock-in (Boschma, 2005). Emerging technologies are often characterized by a high degree of tacit knowledge which is difficult to transfer (Polanyi, 1958; von Hippel, 1994) so that results cannot easily be replicated (Collins, 1974; Teece et al., 1997). In such cases, learning may only be able to happen at the location where the technology is used (Tyre and von Hippel, 1997). Hence firms' innovation capabilities can depend on their local access to experts with key knowledge (Andersson and Ejermo, 2005).

Coordinating public efforts to acquire and expand relevant know-how can be particularly challenging when local industry mostly consists of small and medium enterprises (SMEs). Due to their size, SMEs suffer important financial constraints (Kaufmann and Tödtling, 2002; Madrid-Guijarro et al., 2009), which may increase risk-aversion with respect to the adoption of new technologies (Oakey, 1990; Pontikakis et al., 2006). Technical managers at SMEs may not have enough time to explore innovations because they need to perform a large number of different tasks associated with their ongoing business (Hadjimanolis, 1999). In addition, many SMEs do not perform formal R&D and are increasingly reliant on external R&D (Attewell, 1992; Santamaría et al., 2009). With limited knowledge, technology adoption decisions are based more on beliefs about the perceived benefits than on the real potential of the technology (Marcati et al., 2008; Marra et al., 2003; Nasco et al., 2008).

To overcome their resource scarcity and risk aversion, competing SMEs may need to cooperate (Gnyawali and Park, 2009). To facilitate this cooperation and bridge the gap between industry and academia, intermediary organizations (Howells, 2006) can play a vital role (Armanios et al., 2017; Kirkels and Duysters, 2010; Zeng et al., 2010). Examples of such intermediary organizations include technology transfer offices (Debackere and Veugelers, 2005), technology centers (Asheim and Isaksen, 1997), service providers (Czarnitzki and Spielkamp, 2003), university outreach programs and vocational training centers (McEvily and Zaheer, 1999). These institutions often need to generate enough trust to encourage knowledge transfers (Keeble and

Wilkinson, 1999) and, in extreme cases, they may become a source of continuous instability, rather than stability (Fligstein and McAdam, 2012).

4.2.2 Effect of instability on technology upgrading

Upgrading the technological capabilities of a country is a slow process which requires a long term commitment (Amsden and Chu, 2003; Breznitz, 2007; Freeman, 2002; Lee, 2013; Lin and Chang, 2009). In the case of emerging technologies, institutions may help reduce the inherent market risks and incentivize entry (Sine et al., 2005). The proposed institutional framework needs to be flexible to adapt to rapid changes in the technology and industrial environment (Amsden & Chu, 2003; Breznitz, 2007). At the same time, this commitment needs to be 'credible' (North and Weingast, 1989) and changes in the institutional framework must be legitimated (Bergek et al., 2008). Otherwise, the perception of a lack of governmental commitment, plus fluctuations in program goals and funding can undermine (Mowery et al., 2010) both domestic (Ferraz and Kupfer, 1999) and foreign (Bevan et al., 2004) private investment.

Institutional instability can be caused by macroeconomic instability which obliges institutions to adapt to a new and changing financial landscape (Godinho and Mamede, 2016; Goldstein and Bergsten, 1998; Perez, 2010). The rise of domestic tensions in the absence of important external threats may decrease government's interest in promoting innovation (Taylor, 2016). As a result, during periods of crisis, the public R&D budget may decrease (Sanz-Menéndez and Cruz-Castro, 2003). Volatility in R&D funding has been shown to hinder long-term research (Schuelke-Leech, 2014) and to especially affect the early career of the youngest generation of researchers (Freeman and van Reenen, 2008). In the private sector, macroeconomic and institutional instability may increase risk aversion and shift firms' strategies towards the short-term (Arza, 2005; Oakey, 1990; Paunov, 2012). Among SMEs, a decrease or stop in public R&D subsidies may even cause R&D activities to cease (González and Pazó, 2008). The availability of venture capital may also decrease (Paik and Woo, 2014), and startups may experience higher failure rates during periods of recession (Geroski and Gregg, 1997). However, instability could also help innovation. A financial crisis might incentivize firms to increase overall efficiency (Caballero and Hammour, 1991). Likewise, the years after the Great Depression showed an exceptional increase in multifactor productivity, due to the development of new technologies across multiple industrial sectors (Field, 2003).

Sudden changes in the institutional landscape can also influence the probability of success of some technologies. In technology adoption, “history matters” (Maskell and Malmberg, 1999) as the creation of knowledge and its related practices can be highly path-dependent (Nelson and Winter, 1982). The early stage in the introduction of a technology is critical and even “small events” may decide whether a technology is locked in or locked out (Arthur, 1989). In the absence of institutional support, an emerging technology which is technically superior may be locked out if standards fail to meet industry’s expectations or the timing of adoption is inadequate (too early or too late) (Schilling, 1998).

While the literature on institutional support required for technology adoption is very large, the literature on institutional instability and its effects on technology adoption is relatively modest and polarized. On one hand, some authors (Freeman and van Reenen, 2008; Oakey, 1990; Schuelke-Leech, 2014) have explored the effect of funding volatility on long-term research by technology leaders. These studies have largely focused on infrastructure technologies such as renewable energy (Mowery et al., 2010; Narayanamurti et al., 2011; Schuelke-Leech, 2014), other electricity technologies (Jamasb and Pollitt, 2006), telecommunications technologies (Henisz and Zelner, 2001), or technology fields where long-term basic research is needed, such as healthcare or biotechnology (Freeman and van Reenen, 2008; Oakey, 1990). A different set of authors have examined institutional instability in terms of large events in developing countries, such as the fall of the Soviet Union(Hitt et al., 2004), the Chinese economic transition (Hitt et al., 2004), or the Arab Spring (Armanios and Adly, 2016); or in terms of systemic political instability (Arza, 2005; Cassiolato and Lastres, 2000). A third group of authors, mainly in the economics literature, has analyzed the effect of economic downturns in indicators such as productivity (Caballero and Hammour, 1991; Field, 2003), patenting (Nabar and Nicholas, 2010; Shu et al., 2012), venture capital (Paik and Woo, 2014) and employment (Bowlus, 1995; Brunelloa, 2009).We are, however, not aware of research on how instability may affect differently the lock in or lock out of non-competing technologies in follower countries.

4.3 Industrial background: additive manufacturing technologies

Additive manufacturing (AM), also known as 3D-printing, involves a family of diverse manufacturing technologies which allow the user to build an object layer-by-layer from a digital design. Some of AM's advantages, as compared to traditional manufacturing technologies, include the ability to create very complex geometries, reduction of material waste, and in some cases, reduction in time-to-market (Harris, 2011). Some authors have also claimed that these technologies may change the optimal supply chain configuration, making localized production of some parts more desirable (Gebler et al., 2014; Petrick and Simpson, 2013).

Early developments in AM took place during the 1960s and 1970s, led by the Battelle Memorial Institute in the USA, which used materials developed by DuPont, and benefitted from DARPA funding (Wohlers, 2005). What most consider to be the first prototype AM machine – able to cure photo*polymers* in a similar process to current stereolithography (SLA) equipment – was invented in 1980 in Japan by the researcher Hideo Kodama, at the Nagoya Municipal Industrial Research Center (Wohlers, 2005). In Europe, French researchers working for the Cilas Alcatel Industrial Company filed a patent of an AM machine which used a single laser as a heat source (Wohlers, 2005). In 1987 the first SLA machine was commercialized by the American company 3D Systems, and a number of Japanese and European competitors joined the market in the early 1990s (Wohlers and Gornet, 2016). Selective laser sintering (SLS) machines were commercialized first by the American company, DTM, in 1992 (Wohlers and Gornet, 2016), and in 1994, the German company, EOS, presented the first prototype of their Direct *Metal* Laser Sintering (DMLS) machine, commercialized in 1995 (EOS, 2017).

In its early stages, AM technology was primarily used to more rapidly build prototypes and thus accelerate the development of new products (Yan and Gu, 1996). As the technology matured, improvements in speed, dimensional accuracy and the development of new materials made rapid prototyping technologies progressively more suitable for the production of final parts (Gibson et al., 2010). We distinguish between polymer additive manufacturing (PAM) and metal additive manufacturing (MAM) because of significant differences in the underlying science, industrial applications, market stakeholders, and level of maturity of the two technologies.

The United States, China, Singapore and the European Union are devoting hundreds of millions of dollars to develop and promote additive manufacturing technologies (Bonnín Roca et al., 2016; European Commission, 2014). Countries at the technological frontier perceive AM technology as providing an opportunity to revitalize their national manufacturing industry and decrease their dependency on foreign countries for parts (European Commission, 2014). For instance, the U.S. leads the applications of MAM and accounts for about 40% of the sales of MAM equipment (Wohlers Associates, 2016). U.S. companies like GE, United Technologies, and Boeing are investing billions of dollars to push MAM's boundaries in areas such as defense, aerospace and biomedical (GE, 2016a; Wohlers Associates, 2016). However, the most important MAM equipment manufacturers were born in Europe: SLM, EOS and Concept Laser in Germany, Arcam in Sweden, and Renishaw in the UK. One of the most important software providers, Materialise, is Belgian. In China MAM is seen as offering a chance to leapfrog some of their missing capabilities in the manufacturing of large titanium components (E. Anderson, 2013). There is also interest in MAM in developing countries such as South Africa, which has invested highly in MAM since 1994 (Campbell et al., 2011) and plans to increase their investment to promote activities in the biomedical and aerospace sectors (Wohlers Associates, 2016). PAM also holds promise to potentially revolutionize a variety of fields. For instance, in biotechnology PAM could be used to print organic tissues and even entire organs (Murphy and Atala, 2014). In industries where lightweighting provides important financial benefits such as aerospace applications, high performance polymers, including high-performance composite materials (Ning et al., 2017), could be used to replace metallic structures (Kerns, 2016). PAM can also be used in traditional industries such as shoemaking to produced customized, high-performance soles (Tepper, 2017).

However, there are also reasons for countries *not* to invest in additive manufacturing technologies, especially in situations of resource scarcity. In recent years there has been increased criticism of the mainstream view that AM is going to revolutionize global manufacturing. These critics argue that AM is overvalued and is only going to change the industrial landscape dramatically in cases where customization plays an important role, or geometrical complexity has an important influence in the lightweighting and overall cost-performance of components (Bonnín Roca et al., 2017a; Holweg, 2015; Laureijs et al., 2017).

4.4 Methods

We use a longitudinal comparative two-case study (Eisenhardt, 1989; Yin, 2013) methodology to analyze the introduction of PAM and MAM in Portugal within the Portuguese molds industry, and the challenges to each technology's further adoption at firms. Our analysis spans approximately 25 years, from the early adoption of PAM technologies in the 1990s up through the end of 2016. We triangulate 44 interviews, 75 hours of participant observations and archival data (Jick, 1979).

Given the path-dependent nature of technology adoption (Maskell and Malmberg, 1999; Patel and Pavitt, 1997; Teece and Pisano, 1994), we start our analysis with a history of PAM and MAM in Portugal. We then examine differences in capital requirements and operating costs between PAM and MAM, and how changes in capital availability may have affected the accessibility to both technologies. We also discuss differences in the technical and production environment, which may cause one technology to be more resilient to institutional instability than the other.

We selected our 45 interviews (see Appendix) to cover a broad range of stakeholders including firms in different sectors, technology centers and research organizations, to contrast different perspectives about the challenges in the adoption of MAM technology. Our first interviewees were selected based on the list of attendants to “Portugal3D”, a private initiative to bring together all the relevant players with experience in the use of additive manufacturing in the country (Portugal3D, 2015, p. 3). This first group of interviews and visits to factories helped us better understand the types of PAM and MAM applications that are attractive to Portuguese industry, and the existing conditions in terms of capital and know-how available.

After a first round of contact, we snowball-sampled (Denzin and Lincoln, 2011) our next interviewees, and extended our sample to sectors such as aeronautics or automotive which were not present at the Portugal3D event but represent two of the main markets for MAM (Wohlers Associates, 2016). This second group of interviews helped clarify why many companies might be interested in the technology, but have not yet purchased equipment.

With the objective of analyzing the path-dependency of both PAM and MAM, and reconstructing the history of both technologies in Portugal, we also sought out people who have been working with both technologies in the country for over twenty years. We complemented their oral history interviews with publicly available data from Portuguese and European funding agencies and other publications from research organizations.

We complement our 45 interviews with archival data (Table 4.1). We divide our archival data sources into different types: macroeconomic data; history of Portuguese institutions; history of PAM, MAM and their market applications; technical documents about PAM and MAM; and history of PAM and MAM in Portugal.

Table 4.1 Summary of archival data sources used in this paper.

Archival data category	Documents	References
Portuguese institutional landscape	Macroeconomic Data	(European Commission, 2015; European Innovation Scoreboard, 2016; INE, 2011; PORDATA, 2017; World Bank, 2016)
	Portuguese institutions and their history	(Augusto Mateus & Associados, 2013; COMPETE, 2014; Contzen et al., 2006; Cunha, 1993; Diários da República, 2006; Godinho and Mamede, 2016; Mamede et al., 2014)
PAM and MAM state of the art	History of additive manufacturing and market applications	(3ders.org, 2014; E. Anderson, 2013; BCC Research, 2016; BeeVeryCreative, 2016; Campbell et al., 2011; de Jong and de Bruijn, 2013; EOS, 2017; European Commission, 2014; GE, 2016a; Guillot, 2017; Kellner, 2017; Kerns, 2016; Linear AMS, 2017; Petrick and Simpson, 2013; Rayna and Striukova, 2016; Saunders, 2017a, 2017b; Tepper, 2017; Wohlers Associates, 2016; Wohlers, 2005; Wohlers and Gornet, 2016)
	Technical documents	(Cabrini et al., 2016; Gatto and Harris, 2011; Gibson et al., 2010; Harris, 2011; Hebert, 2016; Murphy and Atala, 2014; Ning et al., 2017; Yan and Gu, 1996)
	History of additive manufacturing in Portugal	(3ders.org, 2016; AdI, 2003; CATIM, 2017; CDRSP, 2014; CORDIS, 2013, 2002, 1991; Esperto and Osório, 2008; Faria, 1999; Henriques and Osório, 2002; Interreg, 2016; IPL and SLM, 2012; Lino and Neto, 2000; Minho, 2016; Pontes et al., 2005; Portugal3D, 2015; RAMATI, 2007)

In addition, we conducted approximately 75 hours of participant observations. These included: 23 visits to AM manufacturing and research facilities, to observe and understand the conditions and restrictions of the Portuguese industry; plus attendance at conferences and attendance at fairs and public forums where the applications of additive manufacturing technologies were discussed. In addition, we attended a day-long workshop organized by the Portuguese Minister of Science where high-level public officials and managers of Portuguese research institutions discussed the health and needs of the Portuguese innovation system.

4.4.1 Case Selection: Portugal and the Portuguese molds industry

Portugal is the westernmost country in continental Europe, and has a population of approximately 10.5 million people (INE, 2011). From 1933 until 1974 Portugal was a dictatorship, which isolated the country from the European integration process after World War II (Royo and Christopher Manuel, 2003) and resulted in a serious lag in education due to the opposition by elites to the modernization of the educational system (Cunha, 1993). The effects of this structural lag can still be felt. According to the European Innovation Scoreboard (European Innovation Scoreboard, 2016), Portugal ranks 24th out of 28 in terms of completion of tertiary education in the European Union. This lack of individuals with tertiary education likely constrains the human resources available to invent and adopt advanced technologies.

In 1986, Portugal joined the European Community (Lochery, 2017). Between 1986 and 1992, FDI represented an annual contribution of 3% of its GDP, directed mostly towards the manufacturing sector (Guimarães et al., 2000). In 1999, Portugal joined the Eurozone. In association with its entry into the Eurozone and global events such as the entry of China into the World Trade Organization (WTO), Portugal’s competitiveness as a manufacturing location and as a destination for FDI diminished (Mamede et al., 2014). The state’s ability to invest in education and R&D was further diminished by the 2009-2010 financial crisis, which saw Portugal’s debt soar to 130% of GDP. (World Bank, 2016).

Manufacturing value added from medium and high-tech manufacturing in Portugal is below the European average (12% in Europe vs 5% in Portugal). An industry that has somewhat bucked this trend is molds manufacturing industry (here, metal molds for plastic parts). This is a highly export-oriented industry: 85% of output is exported (CEFAMOL, 2016). Portugal ranked eighth in terms of exports of metal molds in 2015, and was the country in the world with the highest 'revealed comparative advantage' (RCA).[19] (Balassa, 1965; Laursen, 2015)

The molds industry has been an early adopter of both PAM and MAM in Portugal. While PAM was initially used to build prototypes of molds, MAM holds the potential to incorporate complex internal cooling channels in molds. Such complex cooling channels could reduce the time required to produce each part, increasing the productivity of each mold. Nonetheless, producing molds using MAM presents several challenges such as higher porosity, less resistence to fatigue, lower corrosion resistance, and lower thermal conductivity, among others. Overcoming these potential disadvantages to MAM-manufactured mold performance require R&D and precise control of the MAM manufacturing process.

Despite its potential benefits, the level of introduction of MAM technology is low across the Portuguese molds sector, and more generally across the country. In contrast, countries which are direct competitors in the mold-making industry, such as China, United States and Germany, are investing hundreds of millions of dollars in the promotion of MAM (European Commission, 2014). Given the potential benefits of the technology, Portugal may risk losing its competitive advantage in mold manufacturing if it does not successfully adopt metal additive manufacturing.

In contrast to MAM, Portugal, and in particular its mold industry, successfully adopted PAM. In this paper we ask why Portugal has lagged in the adoption of MAM, even though such adoption is important to the industry's continued success. To better understand why the molds industry adapted and invested in PAM but not (MAM), we investigate in parallel differences in the technologies and the institutional environments that prevailed in Portugal as the technologies matured.

[19] The RCA is equal to the share of the country's exports of a certain product divided by the share of world exports of that same product. If RCA is above 1, it is said that the country is specialized in that particular product (Laursen, 2015).

4.5 Findings

4.5.1 A Tale of two Technologies: Instability in the development of PAM and MAM in Portugal.

The histories of PAM and MAM in Portugal reveal that both technologies experienced instability, but their outcomes were quite different.

4.5.1.1 Polymer AM: Early Growth and Transition to High-end applications

The history of PAM in Portugal began in 1990, only 3 years after the commercialization of the first stereolithography (SLA) machines (Wohlers, 2005), when researchers from the Instituto Superior Técnico (IST) in Lisbon joined the INSTANTCAM project, a European consortium led by Danish researchers and funded under the EU's second Framework Program (CORDIS, 1991). INSTANTCAM studied the processes of stereolithography, solid ground curing, selective laser sintering (SLS, commercialized in 1992) and laminated object manufacturing (LOM), using a variety of polymers (Dolenc, 1994).

In 1992 Portugal acquired their first SLA machine, which was set up at ITEC, a research institute in Lisbon (Lino and Neto, 2000). Work continued between 1994 and 1998 under the project PROTOTYPING, funded by NATO's "Science for Stability" program. The project's aim was introducing PAM in the manufacturing chain of the foundry industry (Faria, 1999). PROTOTYPING was led again by IST in Lisbon, but included two firms and a training center from the North of the country (Faria, 1999).

In 1997, the National Network of Rapid Prototyping (*Rede Nacional de Prototipagem Rápida*, or RNPR, was created using EU funds (Henriques and Osório, 2002). The RNPR was the cornerstone of the introduction of polymer AM technologies in Portugal, given that it was a horizontal project encompassing companies in design, molds and foundry processes; four different research institutions; and the technology center for the molds industry (CENTIMFE) (Henriques and Osório, 2002). The project, which lasted until 2000, and brought together players from all across the country, not just from Lisbon but also from the cities of Porto, Braga, Évora and Leiria; and bridging the gap with industry. New equipment was bought to complement the existing SLA equipment in Lisbon: LOM at a research center in Porto, and SLS at CENTIMFE, in Leiria (Henriques and Osório, 2002). The resulting access to equipment with a broad range of capabilities allowed researchers to analyze the tradeoffs and possibilities across different material and equipment systems. During this period, Portugal joined RAPTIA, a European project constituted by 26 organizations for the promotion of rapid prototyping in both polymers and metals (CORDIS, 2002). By the end of the year 2000, nine polymer machines had been installed in the country, including five in the private sector (Lino and Neto, 2000).

In 1999, ITEC went bankrupt but a subgroup inside the research organization created a spin-off called Agiltec (Interview 7), which became a technology transfer center for efficient production technologies. The SLA machine was transferred to Agiltec, whose employees kept working inside RNPR and other projects related to PAM and MAM (Interviews 7,8). In 2005, Agiltec had to close as well due to financial difficulties (Interview 7).

After the end of the RNPR project, the development of PAM was led by CENTIMFE, which has since then participated in 12 different projects related to PAM, 6 of them at the European level (CENTIMFE, 2016). Between 2002 and 2005, the project Rapid Tooling (*Fabrico Rápido de Ferramentas*, or FRF) continued the work started during RNPR (AdI, 2003). In parallel, two other projects called *Protomolde* (1999-2001) and *Hibridmolde* (2002-2005), led by the molds company Moliporex and with the support of CENTIMFE, the University of Minho and the Polytechnic of Leiria (IPL), explored further applications of PAM in the molds sector (Pontes et al., 2005).

In 2007, a new boost was given to PAM through the creation of the Centre for Rapid and Sustainable Product Development (CDRSP) at IPL[20]. CDRSP was located in Leiria due to its closeness to the mold making companies, which were the main users of PAM technology in the country (Interviews 7,9). Since the creation of CDRSP, PAM research in the country has shifted towards higher-end and more technically challenging applications, especially in the development of biocompatible polymers and tissue engineering (CDRSP, 2014). Most of these projects are in collaboration with the University of Coimbra and with the leading molds companies.

As of September 2016, there were at least a hundred industry-graded PAM machines in the country (Interview 10). In addition, every technical university has PAM equipment (usually

[20] As a polytechnic, IPL offers a more professionally-oriented education than universities, and cannot offer PhD diplomas.

desktop machines), which students can use to become familiar with the technology (Interviews 9,10,11,12,13). In 2011, Portugal's first manufacturer of desktop 3D printers, BeeVeryCreative , was founded at the University of Aveiro. BeeVeryCreative participates in research projects with local companies and the university to develop new materials for their printers (Interview 14).

The development of PAM in Portugal suffered some major setbacks such as the 1999 closure of ITEC, which first brought SLA technology to the country, the closure of Agiltec, and the end of nationwide research consortiums. Nevertheless, the country was able to transition from less sophisticated applications in the area of prototyping in the foundry and molds industries, to becoming a reference center in the area of biopolymers and achieving high visibility in PAM at universities and other higher education institutions (Figure 4.1). Private actors took leadership in the adoption of PAM in traditional sectors. As we will see below, the same levels of adoption have not occurred for MAM.

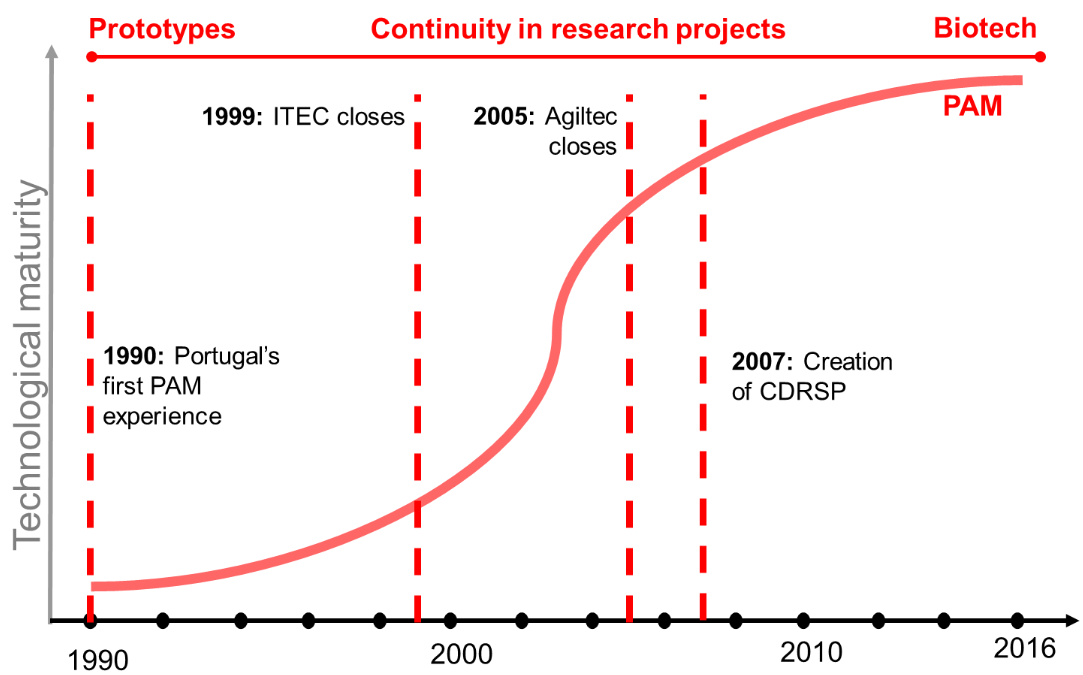

Figure 4.1 Despite some setbacks in institutional support, PAM evolved from low-tech applications such as prototypes, to high-tech applications such as biotech

4.5.1.2 Metals AM: Early Instability and Stagnation

The first contact of Portuguese researchers with MAM was during the PROTOTYPING project funded by NATO in 1994. As part of the project, one (out of 38) prototypes made for the foundry industry was made using a Direct Metal Laser Sintering (DMLS) machine – a machine only first commercialized in 1995 – in France (Faria, 1999). In a final report industry suggests it was satisfied with the results from the PAM prototypes, however, for the MAM prototype, accuracy was "not [good] enough for sand casting" (Faria, 1999).

Despite this initial challenge, Portugal bought a DMLS machine within the context of the National Network of Rapid Prototyping (RNPR) to explore not only polymer technologies but also metals for rapid tooling applications. The metal machine was installed in Lisbon at INETI, the National Laboratory for Engineering, Technology and Innovation (Interviews 7,8).

Soon after, in the period 1999-2003, INETI joined RAPTIA. In 2003, INETI supplied their DMLS machine for the Rapid Tooling (FRF) project, a follow-up of RNPR. Although the technology was still rudimentary ("we had to spend more time polishing the pieces – which at that time we did manually – than building them"), experts considered the results satisfactory (Interview 8), which suggested the possibility of cost competitiveness of MAM against traditional manufacturing processes in the molds sector (Esperto and Osório, 2008). Between 2004 and 2007, INESC INOV, a research institute in Lisbon, led a European project to study MAM titanium implants (RAMATI, 2007).

Institutional set-backs started in 2005. First, Agiltec, the technology transfer office whose staff had also been working with the machine at INETI and had studied the properties of the parts manufactured by DMLS, was closed due to ongoing problems securing funding. Then INETI closed operations in 2006, following the recommendations of an international working group created to assess the state of the Portuguese system of national laboratories (Contzen et al., 2006; Diários da República, 2006). Thus, within months of each other, the two leading research institutions in MAM, both located in Lisbon, had been shut down. With that move, the creation of new MAM-related know-how at research institutions ceased in the country. Meanwhile, a Portuguese machine manufacturing company[21] played a secondary role in the European project IMPALA, a project for developing MAM applications for high-tech industries such as aeronautics or biomedical (CORDIS, 2013).

[21] One executive of one of this companies had worked at Agiltec (2002-2003) and done research for FRF.

In December of 2012, a DMLS machine was bought at a research institution in Portugal (IPL and SLM, 2012). This DMLS machine was purchased by the Centre for Rapid and Sustainable Product Development (CDRSP), located within the Marinha Grande molds cluster. The purchase ended a six-year gap in MAM research at Portuguese research institutions (Figure 4.2). By this stage, companies in the mold cluster of Marinha Grande had started acquiring their own MAM equipment and experimenting (with mixed results), but without relevant institutional support (Interviews 5,15,16).

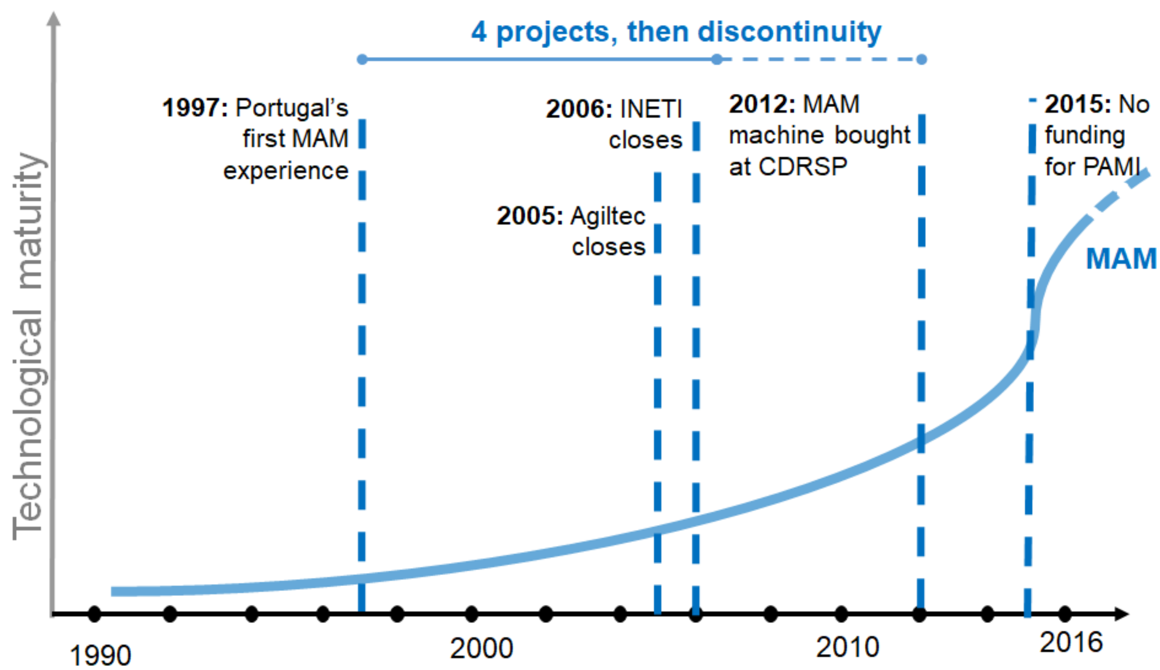

Figure 4.2 MAM research suffered from discontinuities at an early stage of maturation

Until November 2016, the machine at CDRSP was the only operational MAM machine at a Portuguese research institution. Unfortunately, two years after its acquisition, and shortly after the warranty of the MAM machine expired, one of the lasers broke down. This breakdown translated into an additional four-month downtime (Participant Observation, May 5, 2016). Today, the machine is used to supply parts to other universities, which are conducting projects related to MAM, primarily in new material characterization (Interviews 9,11,17). The CDRSP has also received some criticism for not fully utilizing their machine (Interviews 15,16).

In recent years, there has been a new wave of interest towards MAM technology, but, in the case of MAM, the institutional instability caused by the 2009-2010 financial crisis may be creating extra roadblocks for researchers. In 2014, the Portuguese Science Foundation approved the creation of the Additive Manufacturing Initiative (PAMI), a research partnership between CDRSP, CENTIMFE and the University of Coimbra. This partnership has the potential to lead to additional use of the existing DMLS machine. However, PAMI's activities have to-date not started due to delay in the arrival of funding (Interview 18).

Corporate interest may also hold the potential to pave the way for MAM in Portugal, as happened in countries at the technological frontier. For instance, the German automaker Audi reported increases in performance (cycle time) of 20% in their molds with MAM components, and has recently partnered with the equipment manufacturer EOS to "transform the tool manufacturing industry" (Saunders, 2017a). In the USA, the mold-maker Linear AMS owns 17 MAM machines and has started to produce components for other industries such as biomedical and aeronautics (Linear AMS, 2017). In November 2016, a German manufacturing company, Bosch, opened a new research center in Portugal in collaboration with University of Minho. This center is focused on the development of advanced manufacturing techniques (including both PAM and MAM) for automotive applications (Minho, 2016). In June 2016, Addispace, a collaborative project between Portugal, Spain and France, was approved to evaluate the introduction of MAM in the aerospace sector (Interreg, 2016).

As of March 2017, we are aware of at least seven MAM machines in Portugal: two in molds companies, three in engineering companies born in the proximity of the molds cluster, and two in research centers. These numbers contrast with the overall pace of sales of MAM equipment worldwide, which presented an average growth rate of 30% between 2000 and 2015 (Wohlers Associates, 2016). Interestingly, none of the seven MAM machines in Portugal is owned by CENTIMFE, the technology center in charge of developing and disseminating new know-how in the molds industry, which was crucial in the implementation of PAM in the late 1990s and early 2000s. Outside the molds cluster, there is a growing interest in MAM in the Northern region of Porto, where the technology center for the metalworking industry (CATIM) has started a pilot educational project for 11 of their members (CATIM, 2017) and a manufacturer of industrial equipment has developed a prototype of a MAM machine for the construction of large metal parts (3ders.org, 2016).

Most of the large molds firms in Portugal that produce MAM components outsource their production to local or foreign MAM shops (Interviews 1, 3, 4, 16). Due to the undersupply of skilled labor to work with MAM, the few local companies which have acquired MAM equipment are working very secretly so as not to reveal their internal know-how, acquired through months of experimentation and exchanges with other MAM research centers around the globe (Interviews 5,15). This contrasts with the situation in other countries such as the U.S, Germany or the UK, where knowledge is at least to some extent being disseminated through public-private partnerships such as America Makes (The White House, 2012), and higher education institutions are already offering MAM-specific curricula (Guillot, 2017; Saunders, 2017b).

4.5.1.3 Lessons learned from the historical comparison

Two aspects of this history help shed insights into differences between PAM's and MAM's adoption in Portugal.

First, while both PAM and MAM technologies experienced Portugal's periods of institutional and financial instability, including instability in many of the same institutions, the institutional instability occurred at different points of each technology's maturation: PAM enjoyed a more stable institutional environment during the technology's early, immature stage, than MAM (Figure 4.3). This stability during the technology's own instability may have helped set the foundations of a nationwide PAM research infrastructure which brought PAM applications to a higher level. That Portugal's institutional instabilities occurred during MAM's immature phase, in contrast, may have helped contribute to the episodic creation and decay of MAM know-how and likely increased the challenges in the financing of new projects in the area. CENTIMFE, the technology center in charge of technology diffusion across the molds industry, played an important role in the implementation of PAM, but a much more modest role in MAM research, perhaps because MAM was introduced at an earlier maturation stage. Although institutional changes and lack of capital availability have grown worse after the recent financial crisis, they originated well before.

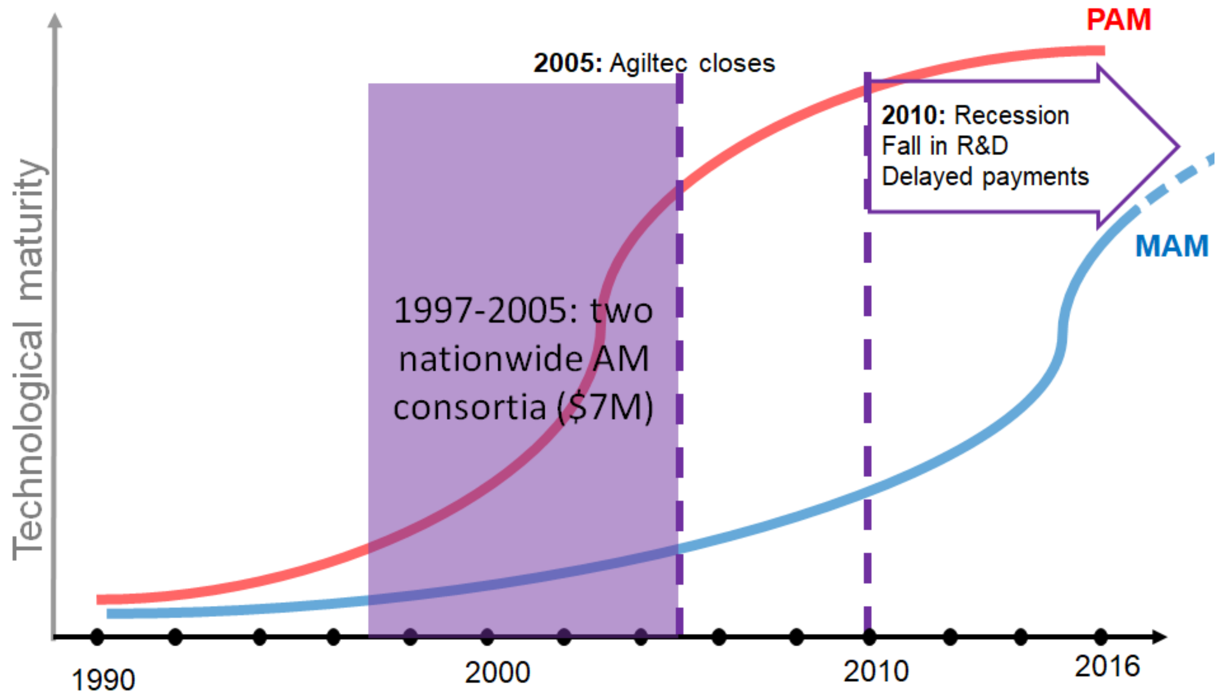

Figure 4.3 Both PAM and MAM encountered institutional instability. However, MAM was less mature than PAM when that instability occurred.

Second, and linked to MAM's ongoing technology immaturity, there is a substantial difference between PAM and MAM in how know-how has spread across the country. PAM know-how has expanded geographically from its origins in Lisbon to the rest of the country. In contrast, for MAM research activities moved geographically from Lisbon, the capital city and main source of engineers, to Leiria, closer to the lead users of the technology in the country but with a much less developed research infrastructure, before MAM technology had become more mature. This move may have helped the process of technology diffusion, but probably also hindered the development of national capabilities due to a much lower exposure to graduate students, researchers and companies outside the molds sector. Furthermore, because most researchers who worked with MAM in the early 2000s have stayed in the Lisbon region (Interviews 7, 8),[22] preexisting know-how has likely largely not supported subsequent adoption.

[22] This claim is supported by the low mobility of Portuguese entrepreneurs and their lack of willingness to move away from their home region (Figueiredo et al., 2002)

Based on these findings, we generate our first proposition, which we later use to build a theoretical framework about why some technologies might be more resilient to institutional instability than others:

Proposition 1: As a technology matures, it becomes more resilient to institutional instability

4.5.2 Instability in funding sources

For a number of reasons, changes in the availability of funding over the last two decades may have affected MAM more than PAM. Such reasons include differences in the acquisition and subsequent marginal production cost of PAM and MAM equipment.

High-end outcomes are expensive for both technologies, but today the price point for entry-level PAM equipment is much lower than for MAM. Currently, a MAM machine costs between half and one million euros (Laureijs et al., 2017), similar to the price of a high-end PAM machine. However, there is a much wider range of PAM machines available with an equivalently wide range of prices. Since 2009, low-end PAM machines can be acquired for less than $1000 (Wohlers and Gornet, 2016), Today, these low-end machines can be acquired at Amazon.com for a couple of hundred dollars.

There is also a difference in price of materials between MAM and PAM: One kilogram of steel powder for MAM may cost between one and two hundred euros, and titanium for MAM costs six or seven hundred euros per kilogram. On the contrary, a kilogram of polymers such as ABS or PLA for a desktop 3D printer costs only around 10 euros per kilogram (BeeVeryCreative, 2016). That said, high-quality resins and polymer powders cost several hundred euros per kilogram, similar to metals (Interviews 6,10).

The ability of Portuguese firms to make multi-million Euro investments is severely limited by their size. In 2012, there were about 450 companies in the Portuguese molds industry, half of which have 10 or fewer employees (Quadros de Pessoal). Only larger corporate groups may feel they have the scale to pool resources to invest in immature technologies, but they, too, can be limited in their ability to do so when their profit margins are low and volatile (Interview 2). This already limited ability worsened with the 2009-2010 financial crisis, during which Portugal experienced a dramatic increase in interest rates (Figure 4.4). At this point in history, there were already low-end PAM printers in the market, three orders of magnitude cheaper than MAM printers[23]. Hence companies did not necessarily have to borrow large amounts of capital to become acquainted with PAM. This leads us to our second proposition:

Proposition 2: Technologies which require lower capital investments might be more resilient to institutional instability.

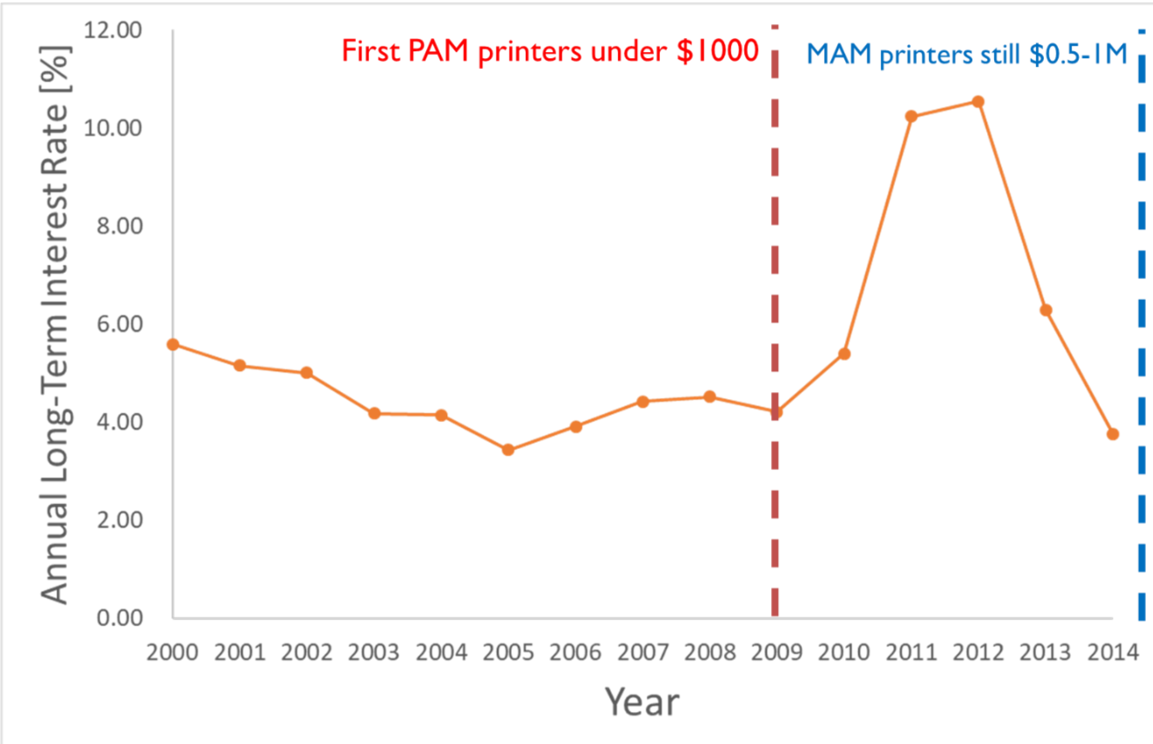

Figure 4.4 The spike in interest rates might have affected PAM less than MAM. By the time interest rates rose, low-cost equipment was available for PAM but not for MAM. It is likely that firms that wanted to enter PAM could do so with low-cost machines, whereas firms that wanted to enter MAM were prevented from financing their purchases of the still-expensive MAM machines.

The Portuguese molds sector has been able to recover from the crisis. However, our evidence suggests that while companies are generating profits again, they are focusing their innovative efforts in less risky, incremental improvements of their production process rather than working with immature technologies like MAM. As one worker explains, "if you have to run the machine 20 times before you get the part right, the boss is not going to be happy" (Interview 5).

[23] Although high-end PAM machines have a similar price to MAM machines, our conversations suggest that, in the case of the molds industry, most applications do not need neither the quality nor the speed offered by such high-end equipment. (Interviews 10, 30)

4.5.2.1 Instability in Portuguese R&D funding

To counteract limitations in their borrowing ability, firms may apply to traditional R&D funds managed either by the Portuguese government or by the European Commission. However, those channels suffered instability during the same period interest rates spiked.

As in most European states (Makkonen, 2013), R&D expenditures in Portugal fell during the crisis, from 1.58% of the GDP in 2009 to 1.28% in 2015 (World Bank, 2016). Due to the adverse macroeconomic conditions, there were not calls for new R&D projects in industry in either 2013 or 2014 (COMPETE, 2016). Portuguese Science Foundation (FCT) also suffered important delays in their payments, which affected a number of projects related to the introduction of PAM and MAM, including the Portuguese Additive Manufacturing Initiative (Interviews 18,23).

Portuguese R&D funding is channeled through two different agencies: the Portuguese Science Foundation (FCT), under the Ministry of Science, Technology and Higher Education, and COMPETE, under the Ministry of Economy. R&D funds from COMPETE come exclusively from the European Union (EU) through three different programs: the European Regional Development Fund (ERDF), the European Social Fund (ESF) and the Cohesion Fund (CF) (COMPETE, 2014). Hence, COMPETE funds are subject to the conditions imposed by the European Union. EU Regions are classified into three groups: "more developed" regions (GDP per capita over 90% of the EU average); "transition" regions (GDP per capita between 75% and 90% of the EU average); and "less developed" regions (GDP per capita lower than 75% of the EU average) ("EUR-Lex - 32013R1303," 2013). The amount of capital available, co-financing rates and the investment priorities differ depending on the nature of the region. For instance, about 50% of the funds are allocated for less developed regions and only 15% go to the most developed regions ("EUR-Lex - 32013R1303," 2013). Regulations establish a co-financing rate of 85% for less developed regions, 60% for transition regions, and 50% for the more developed regions ("EUR-Lex - 32013R1303," 2013).

When Portugal entered the European Union, all its regions fell within the less-developed category. However, as the Lisbon region reached the status of transition and later of more developed, investment started to phase out in the 2000-2006 program (Augusto Mateus & Associados, 2013). While the region of Lisbon received about 30% of the structural funds in the 1994-1999 period, that percentage fell to only about 5% in the 2007-2013 program (Figure 4.5).

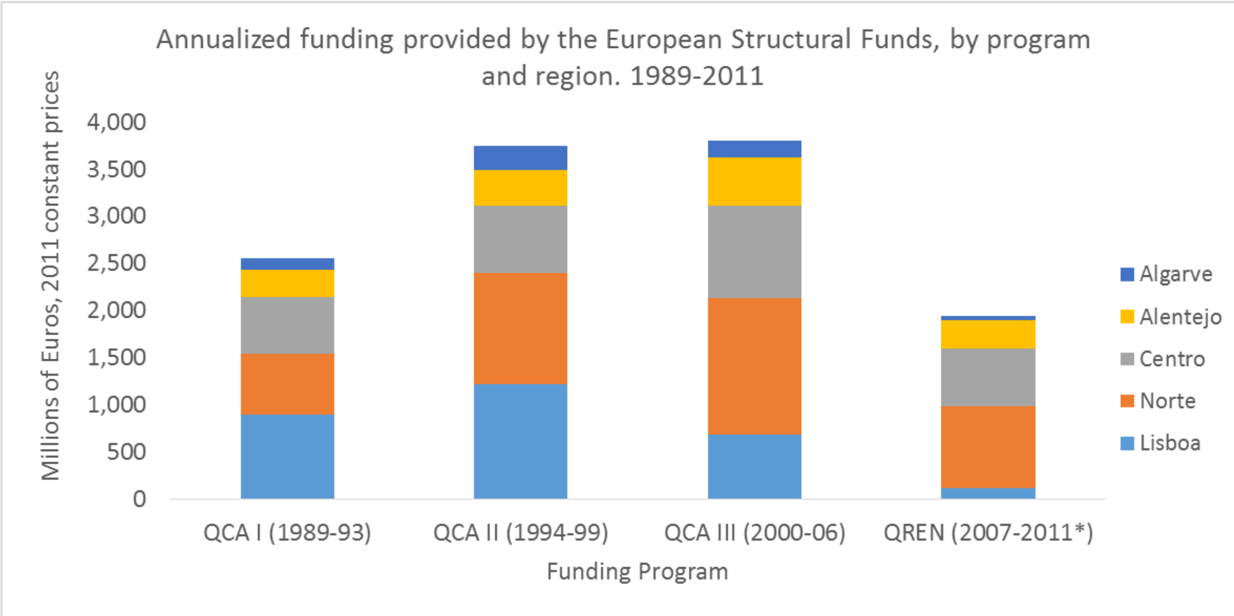

Figure 4.5: Funding from the structural funds has reduced substantially, especially in the Lisbon region. QREN data available only until the end of 2011, although the framework program ended in 2013. Source: (Augusto Mateus & Associados, 2013)

The reduction of funding to the region of Lisbon might have affected MAM more than PAM. In 2006, MAM research was concentrated in Lisbon, while PAM research was much more mature and distributed across the country (CENTIMFE and CDRSP are located in the Centro region). From these facts, we build our third proposition:

Proposition 3: Concentration (geographical and/or institutional) decreases the resilience of a technology to institutional instability.

Interestingly, this geographic concentration in Lisbon may have been associated with the immaturity of MAM in as much as engineers were required to work directly with the technology, and the concentration of such engineers and other expertise in the Lisbon region.

4.5.2.2 Instability in funding from the European Commission

Given the reduced availability of Portuguese R&D funds, some Portuguese research organizations have tried to reduce their dependency on Portuguese R&D funds and started to apply exclusively to EU (i.e. Horizon 2020) funds (Interviews 18,23).

However, several factors have also affected the availability of EU funds for Portuguese research institutions. First, the expansion of the European Union from 15 countries in 1995 to 28 countries in 2013 increased competition. Second, the conditions attached to these funds have changed. Under the ‘Research for SME’ program (2007-2013), projects required the participation of at least three different SMEs, from three different countries, and at least two different “Research and Technology Development” performers such as research centers or technology centers (European Commission, 2007). In the new framework program (2014-2020), the "SME instrument" program is targeted towards “SMEs showing a strong ambition to develop, grow and internationalise”, and any single European company can apply (European Commission, 2016). Thus, European funding for SMEs has shifted its focus away from encouraging research collaborations towards entrepreneurship and rapid growth companies seeking to internationalize. This shift decreases funding available for the Portuguese molds industry, which is characterized by small family businesses feeding a local industry. In fact, success rates for Portuguese projects fell from about 18% in 2007-13 to about 13% in 2014 (European Commission, 2015)[24].

At the same time, with the shift of European funding programs towards entrepreneurship, PAM might have been slightly favored as it is increasingly used by the maker and startup communities to accelerate their product development (de Jong and de Bruijn, 2013; Rayna and Striukova, 2016). In contrast, MAM is predominantly used in components for traditional industries such as aeronautics, automotive or heavy machinery, which are not the focus of the ‘Research for SME’ program. These findings lead us to our fourth proposition:

Proposition 4: Technologies with larger markets might be more resilient to institutional instability.

4.5.3 Technical differences between PAM and MAM

In addition to funding, our findings suggest that the acquisition and development of know-how is a critical factor in the adoption of emerging manufacturing technologies (Interviews 1,3,4,5,20).

PAM and MAM are process-based technologies, this is, technologies where a slight change in the manufacturing conditions may lead to a large change in the final properties of the manufactured component (Linton and Walsh, 2008). Process-based technologies are also often characterized by having a large number of sources of uncertainty which can slow their

[24] The same report shows a decrease of success rates for all member states. Part of this decrease can be explained by a decrease in the total amount of funding available, and by a sudden increase of newcomers, which had a success rate of 38% (European Commission, 2015)

maturation rate (Bonnín Roca et al., 2017b). We use Bonnin Roca et al's (2017b) framework to analyze the differences in the sources of technological uncertainty between PAM and MAM across four dimensions: complexity of the technology, measured through the number of constituents; the need for novel measurement techniques; the testability across intermediate stages of production; and the importance of 'learning by using' (Table 4.2).

In terms of complexity of the technology, measured through the number of constituents, both PAM and MAM are subject to variability in the composition and morphology of the material input, the configuration used in the machines, and the type of post-processing applied. However, melting metal requires operating with much higher temperatures than melting polymers. This creates two additional technical problems: the difference in temperature between the molten and unmolten material is higher, increasing the chances of obtaining undesired microstructures (Frazier, 2014); and metals require specific atmospheric control to avoid contamination and corrosion at high temperatures (Hebert, 2016).

The second and third dimensions are related to testing, and the need for testing depends on the type of component being made. In applications where structural integrity is important, both PAM and MAM need the development of better measurement techniques (Gatto and Harris, 2011; Mani et al., 2015). In the case of MAM, mold inserts need to withstand loads, and quality control is critical. Early applications of PAM in the field of rapid prototyping did not have to withstand such mechanical loads.

Finally, learning by using plays a more important role in metals than in polymers. Metals face problems such as fatigue and corrosion, which only appear after a component has gone through a large number of cycles. MAM materials are particularly sensitive to this issues due to components' porosity (Cabrini et al., 2016; Frazier, 2014). Both fatigue and corrosion are critical problems to avoid in the molds industry, given that the process of injection molding implies working with highly corrosive polymer at high temperature, for hundreds of thousands or even millions of cycles. PAM materials do not experiment these issues and therefore there is less room for uncertainty regarding the final performance of the product.

Table 4.2 From a technical perspective, MAM is subject to a larger uncertainty than PAM

Sources of uncertainty	**PAM**	**MAM**
Number of constituents	Lower	Higher, due to additional process control
New measurement techniques required	Yes, but not necessary for prototypes	Yes
Testability during intermediate phases of production	Not yet, but not critical for prototypes	Not yet
Learning by using	Lower	Higher

In summary, MAM today is less mature as a technology than PAM (e.g. per the art to science definitions in Bohn (2005), even at the technological frontier, engineers are not yet able to define in equations the relationship between process inputs and technological outputs.) This greater uncertainty in MAM may have two implications. First, firms willing to work with MAM need to spend a larger amount of resources, which Portuguese SMEs may not have. Second, we would expect this increased uncertainty to increase the risk aversion of firms towards MAM more than towards PAM, and that the learning period for an industry to make effective use of MAM might be longer.

In addition to the intrinsic technical differences between PAM and MAM, PAM has also benefitted from broader dispersion of knowledge related to at least lower-end applications of the technology. Nowadays there is abundant PAM training material online from the maker community, which serves as a good starting point (Interviews 3,11,24,25). In addition, training is available by PAM equipment and software suppliers (Interview 3,10). In the case of MAM, the technology is not mature enough and sufficient training to reliably produce high-quality outcomes is hard to find (Interview 3).

Building upon our findings related to technological differences between PAM and MAM, we write our fifth proposition:

Proposition 5: Increased technological uncertainty might decrease resilience to institutional instability.

4.6 Discussion and policy implications

Both PAM and MAM in Portugal suffered from severe institutional instability, in the form of the destruction of key research institutions and a sudden decrease of private and public capital availability for R&D activities. However, and despite instability, we find PAM to have achieved greater adoption across Portugal than MAM. We next generate theory about what makes technologies more 'forgiving', this is, more resilient to institutional instability. We develop a generalizable framework for policymakers to analyze how much institutional stability a certain technology may need to be successfully adopted in a specific industry.

4.6.1 A framework of technology forgiveness

Legitimation of a technology – for example by a group of experts or regulators (Bergek et al., 2008), or by a government agency (Fuchs, 2010; Lerner, 1996) – or the establishment of a credible commitment (North and Weingast, 1989) by public institutions may support the adoption of a technology. On the other hand, instability in policy goals and funding can deter private investment (Mowery et al., 2010).

Existing literature studying the effects of institutional instability have been limited to a small group of technologies. One set of studies have focused on technologies which require a large public infrastructure such as energy and electricity (Mowery et al., 2010; Narayanamurti et al., 2011; Schuelke-Leech, 2014) or telecommunications (Henisz and Zelner, 2001). A different group of studies have focused on the effect of instability on technologies which require long-term support for basic research, such as biotechnology (Freeman and van Reenen, 2008; Oakey, 1990). For instance, Lee (2013) makes use of patent data to analyze what contributed to the success of some latecomer countries in their efforts to become high-income countries. Lee's results suggest that latecomers that invested in short-cycle technologies (e.g. South Korea, Taiwan) were more successful than latecomers that invested in long-cycle technologies (e.g. Brazil, Malaysia). However, the existing literature fails to acknowledge that some technologies may more sensitive to institutional instability than others, and why.

Drawing from this literature and from our findings, we propose a framework that explains why some technologies are more 'forgiving' than others, specifically, why some technologies are more resilient to unexpected institutional changes. Our discussion builds most directly upon Bohn's (2005) concept of the transition 'from art to science' and Bonnin Roca et al's (2017b) analysis of how technical and contextual factors affect the uncertainty surrounding a particular technology and its maturation rate. We produce a two-dimensional framework where the forgiveness of a technology depends on both its technological uncertainty, related to our Propositions 1 and 5, and industry-related risks, related to our Propositions 2,3 and 4.

As discussed in Bonnin Roca et al (2017b), the level of technological uncertainty depends on a number of factors such as the number of variables and the interaction among them (Macher, 2006); the number of subcomponents (Singh, 1997); need for complementary innovation (e.g. need for new testing techniques, procedures or process control mechanisms) (Brown and Duguid, 2001; Fleck, 1994; Lécuyer, 2006; Pisano, 1997); or the importance of 'learning by using'(Mowery and Rosenberg, 1981). In our framework, technologies which are less mature (Proposition 1) or that have higher sources of technological uncertainty (Proposition 5) are less forgiving.

In section 5.3, we unpack why technological uncertainty in MAM is larger than in PAM. Because MAM works with higher temperature gradients, it needs additional atmospheric and process control. In addition, MAM components normally perform under higher mechanical stresses than PAM components. Therefore, there is an increased need for the development of new testing and quality control which are specific to MAM. Finally, metals experience problems like corrosion and fatigue which are only observable in the long-term, and which do not affect polymers. Hence 'learning by using' plays a much more important role in MAM than in PAM. From a technical perspective, MAM is less forgiving than PAM.

Industry-related risks depend on four components. The first component is the consequences of part failure, which might be critical in industries such as aeronautics or pharmaceuticals, where errors may lead to the loss of human lives. In our case, the failure of PAM prototypes or small series of plastic components has a much lower impact than the failure of MAM molds inserts, which can paralyze production of large series.

The second component is the existence of barriers to entry, which increase industry-related risks. These barriers might be the existence of stringent regulation and certification procedures which may make the adoption of an emerging technology a slow, costly process (Bonnín Roca et al., 2017b; Stewart, 1981); the presence of an incumbent technology which is cost-competitive in the present (Fuchs and Kirchain, 2010), or the need for a large capital investment (related to Proposition 2), especially in infrastructure industries such as energy or telecommunications (Henisz and Zelner, 2001; Narayanamurti et al., 2011). In the case of Portugal, MAM is replacing reliable machining technologies, while PAM replaced expensive handcrafted prototyping technologies. In addition, since the early 2010s there is low-cost desktop PAM equipment which facilitates opportunities for training, which has not happened for MAM.

The third component to consider is the global market size (related to Proposition 4). Larger market sizes may incentivize firms to increase both product (Acemoglu and Linn, 2004) and process (Desmet and Parente, 2010) innovation, and help overcome cultural distance and country-specific risks (Rothaermel et al., 2006). Thus, increasing market sizes decrease industry-related risks. For additive manufacturing, the BCC Research Group estimated that, in 2015, about 85% of the market of additive manufacturing materials corresponded to polymers, and the remaining 15% to metals, ceramics and other materials (BCC Research, 2016).

Finally, the fourth component is the capabilities of a country's firms and research organizations when compared against the frontrunners (related to Proposition 3). Lee (2013) argues that follower countries need to "build up technological capability and innovation systems at the firm, sector and country level", which requires the establishment of long-term policies to develop technology and higher education. As the gap between the country and the frontrunners increases, the investment needed to catch-up (and therefore the risk of failure) also increases, and firms may not have enough incentives to invest their own resources and try to compete. In the case of Portugal, PAM capabilities seem to be much closer to the leading European countries than MAM capabilities, so private actors may have had higher incentives to invest in PAM, despite the fall of institutional support.

An analysis of both technological uncertainty and industry-related risks allows us to situate a technology and industrial context in a two-dimensional plane (Figure 4.6). On the x-axis is the degree of technological uncertainty inherent to the technology: this stems from factors, described in Table 4.2, such as whether the technology requires new testing methods or the relevance of learning-by-using. On the y-axis is the degree of contextual risks that the technology faces, but which are not inherent to the technology: these include risks associated with change in policy, and market conditions. We contend that, as the degree of contextual or inherent uncertainty associated with the technology falls, it becomes more forgiving of instability in the institutions that seek to foster its growth. We also suggest that, technologies for which both inherent and contextual uncertainties are great are less forgiving than those for which only one of those sources of uncertainty is large. An example of such cases would be MAM in aviation — where the technology is inherently uncertain, and is also subject to contextual uncertainty (e.g., onerous regulatory requirements, possibility of large human losses). Such technologies are the least forgiving to fluctuations in institutional support.

In the case of PAM in the molds industry, both technology uncertainty and industry-related risks are low, and thus forgiveness is high. The case of MAM in the molds industry has a similar technology uncertainty as MAM in aviation (although in the case of aviation it is slightly higher because applications are more demanding), but industry-related risks are much lower given a less stringent regulatory framework, a lower capital intensity and shorter development times. At the same time, and despite being in the same industry, industry-related risks of MAM are higher than PAM in the molds industry, given that applications have completely different consequences of part failure, barriers to entry, market size and national capabilities. Overall, that makes MAM in the molds industry is more forgiving than MAM in aviation, but less forgiving than PAM in the molds industry.

Two cases may have similar levels of forgiveness, but due to different underlying reasons. For instance, the science and engineering behind manufacturing oil tankers is well understood, and therefore technological uncertainty is low. However, the future market for oil tankers is deeply uncertain and manufacturing oil tankers requires important investments in infrastructure, and the preexistence of a strong steelmaking industry and a global demand for oil. In addition, a failure during service may cause extensive environmental losses. Conversely, if 3D displays for smartphones could be developed they would see a strong market given that the smartphone market is mature and the consequences of a single failure in a device are low. However, the technical challenges presented by developing such a display are formidable.

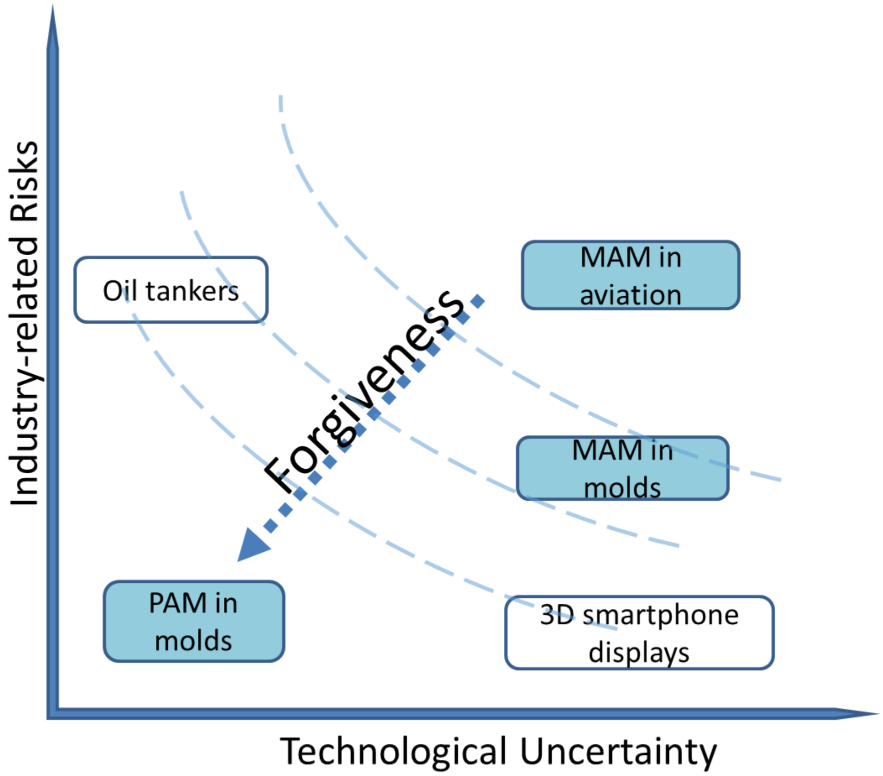

Figure 4.6 In our model, forgiveness depends on technological uncertainty and industry-related risks. In the case of the Portuguese molds industry, MAM would be less forgiving than PAM.

The position of a certain technology-context in Figure 4.6 is not fixed, but moves according to the maturation stage and maturation rate of the technology, and other events such as the development of standards or new regulation. In particular, we expect the forgiveness of a technology to only increase with time along the x-axis. Some industry-related risks such as the consequences of part failure, or the need for large investment in infrastructure, affect forgiveness independently of the maturation state. Therefore, along the y-axis, forgiveness could remain stagnant or, in some cases, even increase (e.g. new legislation more stringent than current).

4.6.2 Policy implications

The case of Portugal provides important insights for the successful adoption of other technologies in other countries. Our proposed framework of technology forgiveness offers an important new lens for understanding past and future cases. For instance, our framework may support Lee's (2013) findings about latecomer countries being more successful catching-up when investing in short-cycle technologies: short-cycle technologies are more forgiving to institutional instability.

Technology followers normally lack the same levels of capital and human resources that technology leaders enjoy (Krugman, 1979; Perez and Soete, 1988). The analysis of a certain technology using our framework may help policymakers estimate the level and duration of support that a technology needs, and prevent waste of scarce public resources in challenges A country is likely not able to afford. As shown in Figure 4.6, some technologies might be more challenging from a technical perspective. In these cases, industrial policies may primarily address the need for a higher capital availability and the development of indigenous know-how. Examples of such policies are the creation of dedicated venture capital pools (Breznitz, 2007); dedicated science parks (Armanios et al., 2017); R&D subsidies for high-risk technologies (Feldman and Kelley, 2006); offshore R&D outposts (Lee, 2005); or the creation of technology-focused intermediaries (Howells, 2006). To help disseminate the existing know-how even more rapidly, especially in the case of material technologies, governments could consider sponsoring the creation of databases with statistically validated material properties, which could be used by the smallest players (Ashforth et al., 2014; Bonnín Roca et al., 2016; NSTC, 2014).

Conversely, other technologies are not so challenging from a technical perspective, but are developed in punishing industrial contexts. In this case, policies may target the creation of a stable market. For instance, governments may want to create public-private partnerships with specific companies to ensure a minimum demand for their products, as happened for instance with SpaceX (C. Anderson, 2013). In addition, the promotion of FDI may help create and further develop a network of suppliers (Reis et al., 2016). Public subsidies, like in the case of solar photovoltaic, may help reduce the difference in cost between the incumbent and the emerging technologies (Morton, 2006). Cases which are both technologically and contextually challenging such as MAM in aeronautics are especially risky, and countries may want to study the possibility of using those technologies in less challenging industrial contexts (Bonnín Roca et al., 2016).

Policies to foster the adoption of less forgiving technologies need the establishment of a long-term public "credible commitment" (North and Weingast, 1989) to attract private investment, in the form of specific regulation, tax policies, or a new long-term direction of the science and technology policy (Bergek et al., 2008). To ensure the continuity of these policies, it is likely that governments would require multi-partisan support (Branscomb, 1997). Otherwise, changes in the political environment may introduce additional instability, such as the introduction of retroactive measures in existing installations in the Spanish energy market, may lead to a market bust (del Río and Mir-Artigues, 2012). After support for a certain technology has been disrupted, it may be very difficult to recover. Our findings suggest that the later acquisition of a MAM machine by CDRSP had little impact on MAM's research or industry's perspective on the potential of the technology. Thus, instability may help create a negative feedback loop, as shown in Figure 4.7. Without institutional support, the leading Portuguese SMEs started experimenting with MAM on their own. Because MAM entailed a large technological uncertainty, and MAM products have stringent specifications, most of these early experiments in the private sector were disappointing, causing firms to lose interest in MAM.

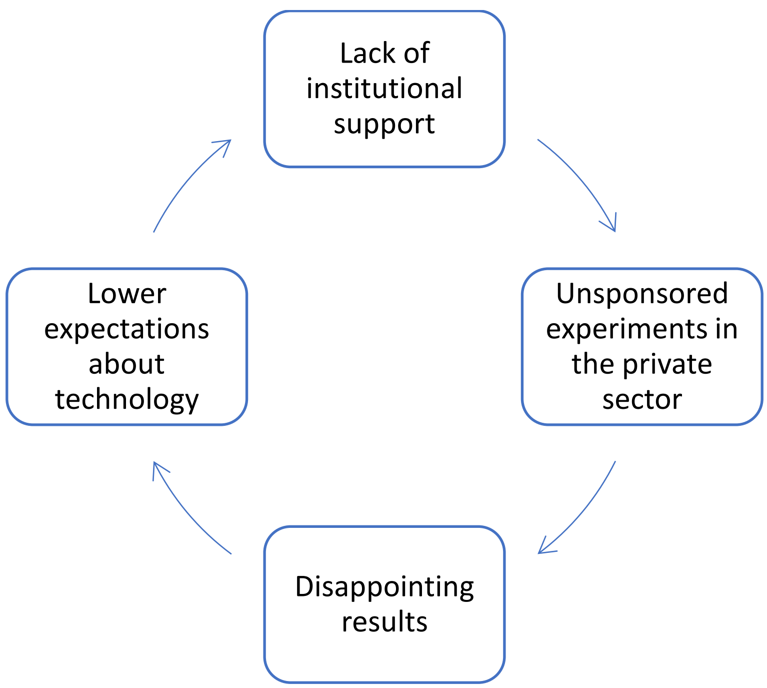

Figure 4.7 The Portuguese industry may have entered a negative feedback loop in the introduction of MAM

The institutional stability we propose should not be confused with institutional rigidity. In fact, existing literature shows that institutions in charge of technology upgrading need to be flexible to adapt to rapid technological changes (Amsden & Chu, 2003; Breznitz, 2007). In addition, regulators may need to periodically revise their policies in order to avoid situations of 'regulatory lock-in', where regulation written while the technology is immature may constrain the long-term potential of a technology (Bonnín Roca et al., 2016; Keith et al., 2010).

4.7 Conclusion

Our work uses a case study of two emerging process-based technologies, polymer and metallic additive manufacturing (PAM and MAM), in Portugal, a resource-constrained technology follower. Although MAM may be instrumental to long-term global competitiveness for the Portuguese molds industry, MAM's adoption has been much lower than PAM's. We shed light on how the different technological characteristics and industrial contexts of both technologies interact with institutional instability during early technology adoption such that one technology (PAM) achieves widespread adoption, while the other (MAM), does not. Based on the case of Portugal and PAM/MAM, we generate theory about how technological uncertainty and industry-related risks, which determine the maturation state and the maturation rate of a technology, influence the 'forgiveness' of a technology, defined as the susceptibility of the adoption of a certain technology to institutional instability. Based on the lessons from our cases, we propose a new framework on how to think about generalizing our findings to other technologies and industrial contexts. One key insights is that latecomer countries willing to invest in less-forgiving technologies may need to create long-term policies to secure private investment and the development of the national know-how, and explore the possibility of applying the same technology in less challenging industrial applications.

5 Recommendations on the development of a Portuguese knowledge base in Metal Additive Manufacturing [25]

One of the purposes of the grant which supported this research is to foster the development of the Portuguese aeronautics industry, motivated in part by the recent investments by the aircraft manufacturer Embraer, which has built two factories in the city of Évora in 2010.

MAM offers the possibility of creating complex and lightweight components, dramatically reducing development times and the need for inventory. These advantages are critical in an industry such as aeronautics, where small weight savings translate into important fuel savings in the long term. In fact, the first MAM parts are already flying. However, the application of MAM in aviation is still limited to a few applications by the major OEMs and a handful of defense contractors. The absence of aircraft-grade standards hinders the adoption of MAM by Portuguese suppliers, which would have to engage in lengthy and costly development program to enter this market. Portuguese companies such as OGMA and TAP hold a strong position in the Maintenance, Repair and Operations (MRO) market. Players in the MRO market see MAM as holding the possibility of reducing their investments in equipment and the need to maintain expensive inventory. However, it is still unclear how MAM will be regulated and, at least in the short term, OEMs are trying to capture the MAM aftermarket.

To date Embraer's investments in MAM have been modest and late, as compared with other industry players such as Boeing and Airbus. Furthermore, Embraer's exploratory MAM projects are localized in Brazil, and to the best of my knowledge there no plans to install MAM technology in the Évora's facilites. However, Portugal offers two advantages over Brazil to develop MAM technology: first, Portuguese firms do not need to pay tariffs to import MAM equipment, while Brazilians do; second, Portugal has access to highly skilled labor from across the EU. Acquiring equipment and creating MAM-focused training programs at the recently opened engineering center in Évora may incentivize Embraer and other companies in the aeronautics cluster (which may also manufacture components for Boeing and Airbus) to gain interest in the technology. At this point, and until Portugal has developed stronger MAM

[25] This chapter has been distributed in the form of a policy brief, with the same title.

capabilities which can compete against the leading countries, the country will likely need to acquire foreign labor to impart the training.

In light of these limitations in the aviation industry, Portugal would be well advise to also expore MAM opportunities in other industries so as to start developing MAM capabilities in application domain that involve higher risk tolerance and lower barriers to entry. For instance, MAM might be instrumental in helping Portugal to retain its global competitiveness in the molds industry. Furthermore, the largest players in the molds industry are already low-tier suppliers in the aeronautics industry. Other players which could exploit MAM advantages are the machinery industry and the manufacturers of tungsten tools. In addition, MAM is becoming a widespread technology in the manufacturing of customized medical implants, a field that also has a more favorable regulatory environment than aviation. Currently, there are no Portuguese companies producing implants (other than dental). Adopting MAM in this area might bring an opportunity to reduce imports.

My findings suggest that there are two important barriers to the development of MAM capabilities in Portugal. The first barrier, and probably the more important, is the lack of MAM-specific formal training. Currently, the Portuguese higher education system is not able to provide graduates with basic MAM skills. Most MAM researchers started their work in the late 1990s or early 2000s within the scope of the Rede Nacional de Prototipagem Rápida (RNPR), but discontinuities in the funding programs and the lack of investment in new equipment led to a situation where there are not formal mechanisms to create a new generation of MAM scientists. Students at engineering schools are barely exposed to a technology which is the center of attention in other European countries such as Germany, the UK or Belgium. MAM is unheard of in professional training centers, while it is already being introduced at community colleges in the USA. Portugal has been a leader in developing graduate programs with some of the world's leading engineering schools, including Carnegie Mellon University. To reduce this gap in education and training, Portugal should give serious consideration to using those associations to leverage those existing international partnerships to access world-class education in the field of MAM. However, doing that will alone will not be enough. If Portugal wants graduates with MAM skills to return to the country after completing their degrees, there the country (and its firms) will need to invest in MAM equipment and the development of MAM-specific curricula.

The opportunity to obtain such top manpower may facilitate the inclusion of Embraer and other leading aero companies in international projects and grants, thus creating job opportunities in Portugal for the new graduates. Furthermore, in order to accelerate the diffusion of MAM knowledge, the Portuguese Science Foundation might want to further promote opportunities for ‘professional’ dual degree PhD programs, in which students develop their dissertation work within the context of a particular sponsoring company.

The Portuguese industrial landscape is dominated by SMEs which have neither the size nor the talent required to perform the type of internal R&D that MAM requires. Industry associations and technology centers, who are theoretically the actors in charge of developing technologies in a pre-competitive stage, have shown until very recently little interest in creating MAM research programs, due to their lack of know-how and the level of uncertainty surrounding MAM technology. To ameliorate these problems, I recommend creating consortiums with members from academia and different industry sectors, where members can share the equipment and thus lower operating and R&D costs. Consortiums such as RNPR have been very successful in the case of Polymer Additive Manufacturing, but they were discontinued before MAM reached a stage of maturity where industry could feel comfortable investing their own funds.

Another barrier which affects not only MAM but any emerging technology, is the structure of Portuguese R&D funding schemes. Currently, funds managed by COMPETE are completely dependent on any changes made at the EU level. Funds also present important different geographic restrictions which restrict the availability of funding in Lisbon, the region which produces the largest number of university graduates, and which lately has become one of the most attractive cities for entrepreneurs. The need for changes in the way how Structural Funds are used for Science and Innovation purposes has recently been brought to scene by the so-called ‘Lamy Report’ (Lamy, 2017), opening a window of opportunity for the Portuguese government to remove geographical restrictions which hurt technological development in the country.

While Portuguese firms may seek funding from Horizon 2020, in the case of MAM they are likely to have a hard time competing against companies in other European countries which have much more developed MAM capabilities. In addition, Portuguese intermediary research institutions have little incentive to work in research projects that offer little immediate financial return. This likely explains why most have remained largely unaware of the details of international development of MAM. To overcome this second barrier, the Portuguese government may want to consider the allocation of a small pool of Portuguese funds, not subject to the restrictions of the EU Structural funds, to the development of technologies which are considered 'strategic' to the competitiveness of the national industry. A portion of these funds could be used to provide base funding to intermediary organizations and incentivize them to participate in long-term projects.

6 Practical implications for managers willing to invest in additive manufacturing[26]

The hope for additive manufacturing is that it will revolutionize manufacturing (D'Aveni, 2013). Although additive manufacturing — also known as 3-D printing — was developed back in the 1980s, it has garnered increased attention in recent years as managers look for ways to improve efficiency and reduce production costs. Much the way GE's new printed nozzle for jet engines has reduced the need for expensive materials and energy, (GE, 2014) 3-D-printed parts will cut lead times and make supply chains more efficient in a wide range of settings, (Marchese et al., 2015) managers hope. Despite the potential of additive manufacturing, we believe that near-term expectations for it are overblown.

In our view, three important myths about additive manufacturing need to be dispelled. The first myth is that additive manufacturing will allow producers to make parts of any complexity as easily and economically as parts that are manufactured in traditional ways (in other words, that it will make complexity essentially "free"). The second myth is that additive manufacturing will prod manufacturing to become local. And the third myth is that additive manufacturing will allow producers to replace mass manufacturing with mass customization. None of these expectations is likely to be realized in the next several decades, especially in the case of 3-D printing in metal.

Additive manufacturing makes it easier to design parts with complex geometries and internal cavities. For instance, a manufacturer using additive manufacturing would be able to make jet engine turbine blades with cooling channels. Cooling channels allow jet engines to operate at very high temperatures—so high that blades without such channels would ordinarily melt. Additive manufacturing would enable manufacturers to produce parts with more complex geometries than is currently feasible, opening the way for engines that are both cleaner and cheaper to run. It could make high quality parts quickly.

[26] This chapter has been published in essentially the same form as:
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Additive manufacturing can also allow companies to produce parts such as engine brackets that are lighter, resulting in increased fuel efficiency. In a competition organized by GE, the winning design using additive manufacturing was 80% lighter than the one it replaced. (Laureijs et al., 2017) Additive manufacturing also enables simpler designs. In developing a new nozzle to inject fuel into the combustion chambers of its jet engines, GE, for example, merged 20 parts into one.(GE, 2014) Colin Chapman, the late founder of Lotus Cars, which manufactures sports and racing cars, once famously encouraged designers to “simplify, then add lightness.” Additive manufacturing makes it possible to do both.

Nevertheless, additive manufacturing has drawbacks and is subject to some restrictions. For one, parts cannot be too thin. They can’t have overhanging sections unless these are properly supported. Knowing the parameters of what’s possible requires skills that are currently scarce. Engineers (including us) have been trained on tools and approaches to design that are tailored toward conventional manufacturing. Training engineers to take advantage of the freedom that additive manufacturing will provide while understanding its limitations will require time. Indeed, limitations are still being discovered. In addition, the software tools that engineers are currently trained on may not be suited for additive manufacturing, and it is difficult to find faculty capable of teaching the new tools. (Gibson et al., 2010)

All this is beginning to change. America Makes, a public-private consortium set up to advance additive manufacturing in the United States, currently has more than 30 academic institutions as members, (AmericaMakes, 2016) many of which are introducing additive manufacturing in their core curricula. The new skills are being built at all levels; for example, two of the America Makes members are community colleges. Relatively inexpensive plastic 3-D printers are also appearing in high schools, thereby introducing students to their possibilities at an impressionable time. (Elrod, 2016) Some of the machines are specifically designed for educational environments.

Contrary to what many people may think, not all additive manufacturing systems and processes are the same. There are fundamental differences in terms of feedstocks, heat sources, and machine configurations. The material science behind plastic additive manufacturing is totally different from the material science of metal additive manufacturing — and expertise in one doesn't easily transfer to another. Each requires a long learning process adapted to the particular application.

In the labor market, there is growing demand for people who have been educated in additive manufacturing processes. In addition to those with bachelor's degrees, there are opportunities for master's degree holders who have the skills to set up, operate, and troubleshoot 3-D printing machines.

In addition to training issues, there are safety issues and technical issues. Some of the safety concerns stem from the fact that the technology is new. In an effort to reduce the possibility that parts will fail, some manufacturers are using parts that are heavier than optimal. Clever new structures such as light-as-air meshes have different vulnerabilities from solid, chunky components; this is especially true in applications where parts need to rotate or are repeatedly loaded and unloaded. Understanding these potential weaknesses, and learning to design parts to avoid them, will take time.

On top of that, more work needs to be done to reduce variability, so that additive manufacturing machines and processes can produce components that are identical given the same set of inputs. (Frazier, 2014) To understand why this is important, it's helpful to recognize a fundamental difference between 3-D printing and other manufacturing technologies. Take machining, for example. Machining involves starting with a block of metal and cutting away the parts you don't need. It's reasonable to expect that after the machining process the material that's left has essentially the same properties as the block you started with. But that is not necessarily the case when a part is made with 3-D printing.

That's because some metallic additive manufacturing involves zapping adjacent microscopic particles of a powder with a powerful laser so that the particles melt and fuse. The process of zapping particles occurs over and over — millions, perhaps billions, of times — until the part is completed. Each particle in the resulting component is rapidly heated and cooled many hundreds of times. What finally emerges depends on a number of factors, including how much each particle was heated, how many particles were heated at one time, how many times the particles were heated, and how quickly they cooled. If the process is not consistent from beginning to end, you can't have consistent results.

To ensure that the process has been properly controlled requires finished part testing. However, some of the necessary testing methods — for example, how to inspect the insides of hollow parts without having to slice them open and destroy them — are still being invented. Ultrasound does not always work well for metals, and another technology, industrial CT scanning, is slow and expensive, and cannot be used for all geometries. (Waller, 2014) Yet unless we can resolve these issues, the savings that might be generated by one-step manufacturing processes, especially for parts critical to product safety, could be swallowed up by the need for additional testing.

Quality control is challenging enough when components are made within the same four walls; working with third-party suppliers makes for even greater difficulty. A part made using additive manufacturing that performs well on tests designed for conventionally produced components may for a variety of reasons perform poorly in service. For example, although the properties at the surface of a part may be the same, they could be different from those a few millimeters deep.

Initiatives are underway to solve these problems. ASTM and the International Organization for Standardization (ISO) are collaborating to develop standards for additive manufacturing. (Bird, 2016) In the United States, the Materials Genome Initiative, an interagency program designed to create public policy and infrastructure for the development of advanced materials, aims to create powerful software simulation tools and create shared material databases. (NSTC, 2014)

Some companies are pushing the boundaries of additive manufacturing with new materials and techniques. For example, Impossible Objects LLC of Northbrook, Illinois, is applying additive manufacturing techniques to composite materials, to produce components that are much stronger than ordinary plastics; these materials can use high-throughput manufacturing techniques that have traditionally been applicable only to plastics. Another startup, XJet, of Rehovot, Israel, is suspending metallic particles in ink so that metallic parts can be printed using fast printing technologies.

While there are a number of innovative startups like Impossible Objects and XJet, the road to the mass market for products and technologies that cater to safety-critical applications can be long. GE recently announced that it would acquire a majority ownership stake in Concept Laser, a supplier of additive manufacturing equipment that is based in Lichtenfels, Germany, and that was founded in 2000. In 2012, GE Aviation purchased Morris Technologies, an additive manufacturing company that was founded in 1994. Indeed, it has taken an amalgamation of GE's own investments and decades of investments by others to bring additive manufacturing to market in the aerospace industry. Smaller companies that seek to master more basic additive manufacturing materials and processes may want to begin by building products where requirements for safety and reliability are less stringent than they are in aerospace.

Many people are anticipating that additive manufacturing will bring manufacturing closer to markets and consumers. (Petrick and Simpson, 2013; The Economist, 2012) But in our opinion, this scenario has been greatly exaggerated. In concept, the idea of sending raw materials, instead of finished products, to a manufacturing location close to the users so the company can produce on demand what's needed makes sense. A company could have machines and raw materials in cities and neighborhoods where its customers are, produce in the right quantities, and thereby reduce lead times while cutting transportation and inventory costs.

However, additive manufacturing, like other methods of production, is subject to economies of scale. Since it takes skilled operators and sophisticated machines to produce reliable and durable products using 3-D printing, having one person in charge of 10 machines would be cheaper than producing at 10 different locations with one person each. Furthermore, additive manufacturing parts often require a number of complex postproduction steps and tests, many of which require specialized machinery of their own. For a simple titanium-alloy aerospace component, such costs would make up 10% to 15% of the total cost of the component. (Laureijs et al., 2017) Clearly, it's better to do the postproduction work at one site to support many different machines than to distribute the capability across multiple locations.

Companies should, however, use additive manufacturing to accelerate and streamline product development. For example, additive manufacturing allows designers to produce and test prototypes for a wide range of concepts, which may not require extensive post-processing or rigid quality control. Early feedback on prototypes avoids expensive surprises later in the product development process. Additive manufacturing also makes it possible to build tools for short production runs. This enables companies to beta test physical products. For example, the automotive molds industry in Portugal uses simple prototype molds to produce sample components.(Onuh and Yusuf, 1999) Because successful product development requires early and frequent engagement with customers, there are clear advantages to being able to do this locally.

Nevertheless, we think many governments would be making a mistake to invest large sums of public money in developing a broad additive manufacturing capability in the hope of "bringing back manufacturing." The United States, China, Singapore, and the European Union are investing hundreds of millions of dollars in national programs to create new or retain existing competitive advantages in manufacturing. (European Commission, 2014) The United States, for its part, has identified additive manufacturing as critical to maintaining its technological superiority in the military and in aerospace. However, the case for public investment in building additive manufacturing capability is less compelling for other countries, particularly when the local market isn't large enough for the economies of scale that a capital-intensive technology needs. For example, our conversations with Portuguese manufacturers revealed that additive manufacturing parts made in Germany had better mechanical properties due to manufacturers' greater know-how and were also cheaper than similar parts manufactured in Portugal by suppliers who catered only to the Portuguese market.

In our view, governments should concentrate on identifying sectors in which their industries are already competitive and support the development of focused additive manufacturing capabilities in those sectors. Portugal's highly successful automotive mold makers, for example, may need to incorporate additive manufacturing into their suite of capabilities in order to meet customer expectations of fast lead times and performance. But the possibilities for a country such as India may be different. Among other things, a country like India would want to examine areas where the ability to respond quickly is critical, such as medicine; for example, additive manufacturing might be a tool for producing customized implants and other medical devices.

Many people have predicted that additive manufacturing will result in a decisive shift from mass manufacturing to mass customization. (Gandhi et al., 2013; Nyman and Sarlin, 2014) But the likelihood that this will occur quickly is slim. Wohlers Associates, a leading additive manufacturing consulting firm, estimates that in the long term additive manufacturing might represent 5% of total manufacturing worldwide.(Wohlers Associates, 2016) Moreover, there are forces other than additive manufacturing that will hasten mass customization. The Spain-based fashion retailer Zara, for example, is able to launch a new collection within weeks. Rather than using additive manufacturing within local markets, it achieves this by managing its supply chain masterfully. (Chow et al., 2008) Manufacturers of IT hardware, for their part, have relied on modularization to assemble bespoke products on demand, and to do so close to their customers. (Feitzinger and Lee, 1997)

We see limits on the extent to which additive manufacturing will be flexible manufacturing. In theory, a good 3-D printer ought to be capable of printing a wide range of designs. In practice — and especially in applications critical to safety — we may see regulations that control how 3-D printers and additive manufacturing equipment in general can be configured. This could mean that every time a machine is reset to produce a part that's different from the one it made before, the system will have to be rechecked. Depending on what this entails and how involved the inspection is, it might turn out to be less costly and safer to have different machines dedicated to the production of different parts.

To be sure, additive manufacturing's flexibility can be, and is being, harnessed to produce products where safety standards are less of an issue — for example, wearable technologies and jewelry. Companies will find the use of additive manufacturing for such products increasingly appealing as production speeds improve and costs decline. For example, last May, HP delivered its first polymer additive manufacturing machine, which it claimed was up to 10 times faster than previous models and cost half as much. (HP, 2016)

In general, additive manufacturing holds great promise, but in many areas the cart has gotten ahead of the horse. Much of the technology is still under development. The history of comparable technologies such as composite materials and high-performance castings shows that the problems may take decades to resolve. For now, additive manufacturing is cost-competitive only in niche applications — for instance, those involving plastics. Businesses that want to plunge into additive manufacturing should be cognizant of the challenges. Determining whether it makes sense to invest in additive manufacturing will require experimentation and learning.

6.1 Should your company move into additive manufacturing?

If you're evaluating 3-D printing technologies, here are some important considerations:

- **Explore whether you could gain competitive advantage in your market by adopting additive manufacturing.** Are customers willing to pay more for such products or for the added speed or flexibility?
- **Evaluate the operating environment for your product.** If it is subject to large or cyclic loads, it may take longer to develop the expertise needed to produce adequate parts.
- **Consider the required production volume and the number of machines (and capital expense) needed to meet that volume.** Consider also the ability of machine manufacturers to supply that number of machines within a reasonable time frame.
- **Check if feedstocks (such as powders or wires) and 3-D printers are available for the material your product is made of.** If not, would it be economic to shift to a different material?
- **Consider the trade-offs between using an expensive material like titanium alloy and the additional value created by a part with higher performance (e.g., lower weight or better corrosion resistance).**
- **If you decide to produce the part using a current material for which feedstocks and machines don't exist, consider the trade-offs between the benefits of doing so and the costs of getting regulatory approval for new materials and processes in your industry.**
- **Consider safety-related limits placed by regulators on manufacturing flexibility.** For example, are there restrictions on producing multiple parts on the same machine, or is it a requirement to design with large safety factors? In applications critical to safety, be aware that what seems technically feasible may not be immediately acceptable to regulators. Start by developing and introducing products where safety is less critical, or where the operating conditions are less demanding.
- **Identify the knowledge and skills you need to make the transition from basic products to more complex ones.** What is the potential for either tapping into or establishing industry or public-private consortia for pre-competitive research collaborations?
- **Consider how your analysis might change as the technology becomes cheaper and faster.** Pay attention to how your customers' needs may change in the future. To what extent do you need to start developing an additive manufacturing capability now in order to satisfy emerging customer appetites? What are your competitors doing? Could additive manufacturing open the door for new competitors to serve your customers in the future?

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8 Appendices

8.1 Referenced Data Sources in Chapter 2

8.1.1 Interviews

Table 8.1 Interviews corresponding to chapter 2

Organization	Position
OEM 1	Senior Manager, Metals
OEM 2	Head, Manufacturing
OEM 2	Type Certificate
OEM 3	Engineer, Additive Manufacturing
OEM 3	Leader, Additive Manufacturing
OEM 4	Director, Manufacturing
OEM 4	Head, Additive Manufacturing
OEM 5	Lead, Additive Manufacturing
OEM 6	Technical Manager
OEM 7	Director, Manufacturing
OEM 8	Manager, Airworthiness
OEM 8	Director, Regulation
Supplier 1	Director, Additive Manufacturing
Supplier 2	Director, Additive Manufacturing
Supplier 3	Director
Supplier 4	Managing Director
Supplier 5	Plant Manager
Supplier 6	Manager, Additive Manufacturing
MAM Equipment supplier	Business Development Manager
Research Center 1	Director, Materials Testing
Research Center 1	Associate Director, Materials Laboratory
Aviation Regulator 1	Additive Manufacturing Team
Aviation Regulator 1	Additive Manufacturing Team
Aviation Regulator 1	Additive Manufacturing Team
Aviation Regulator 1	Advanced Composite Materials
Aviation Regulator 1	Retired
Aviation Regulator 1	Retired
Aviation Regulator 2	Additive Manufacturing Team
Aviation Regulator 3	Director, Aircraft Certification
Aviation Regulator 3	Team Lead, Aircraft Safety
Public Body 1	Additive Manufacturing Team
Public Body 2	Chairman, Additive Manufacturing
Public Body 3	Team Lead, Structural Materials
Public Body 4	Project Leader, Additive Manufacturing
Public Body 5	Senior Technology Manager
Public Body 6	Assistant Director, Advanced Materials
Public Body 7	Chair, Materials & Manufacturing

1, January 6th, 2015. Interview via phone[27].
2, February 2nd, 2015. Interview via phone.
3, January 30th, 2015. Interview via phone.
4, February 2nd, 2015. Interview via phone.
5, June 9th, 2015. Interview via phone.
6, December 15th, 2015. Interview via phone.
7, July 25th, 2015. Interview face-to-face.
8, April 16th, 2015. Interview via phone.
9, February 25th, 2015. Interview via phone.
10, March 3rd, 2015. Interview via phone.
11, February 24th, 2015. Interview via phone.
12, January 29th, 2015. Interview via phone.
13, January 26th, 2015. Interview via phone.
14, June 11th, 2015. Interview via phone.
15, June 15th, 2015. Interview via phone.
16, July 8th, 2015. Interview via phone.
17, August 26th, 2015. Interview via phone.
18, February 17th, 2015. Interview via phone.
19, August 17th, 2015. Interview face-to-face.
20, August 19th, 2015. Interview face-to-face.
21, January 21st, 2015. Interview via phone.
22, September 21st, 2015. Interview via phone.

[27] Due to the sensitive nature of our conversations, we want to avoid revealing the identities of our sources

8.1.2 Archival Data: aviation Industry

8.1.2.1 Title 14 of the Code of Federal Regulations

Airworthiness Certificates - Approval of major changes in type design, 14 C.F.R. § 21.97
Airworthiness Certificates - Changes in Quality Systems, 14 C.F.R. § 21.150
Airworthiness Certificates - Transferability, 14 C.F.R. § 21.179
Airworthiness Standards: Transport Category Airplanes - Materials, 14 C.F.R. § 25.603
Airworthiness Standards: Transport Category Airplanes - Fabrication Methods, 14 C.F.R. § 25.605
Airworthiness Standards: Transport Category Airplanes - Material strength properties and material design values, 14 C.F.R. § 25.613
Airworthiness Standards: Transport Category Airplanes - Casting Factors, 14 C.F.R. § 25.621
Airworthiness Standards: Aircraft Engines - Materials, 14 C.F.R. § 33.15

8.1.2.2 FAA Orders related to certification procedures

Order 8100.15 (2006), *Organization Designation Authorization Procedures*
Order 8120.22 (2013), *Production Approval Procedures*
Order 8110.4C (2007), *Type Certification*
Order 8110.42D (2014), *Parts Manufacturer Approval Procedures*
Order 8120.23 (2013), *Certificate Management of Production Approval Holders*
Order 8130.2H (2015), *Airworthiness Certification of Products and Articles*

8.1.2.3 FAA Advisory Circulars

Advisory Circular 20.163 (DRAFT, 2014), *Material strength properties and material design values*
Advisory Circular 21.43 (2009), *Production Under 14 CFR Part 21, Subparts F, G, K, and O*
Advisory Circular 23.1309-1E (2011), *System Safety Analysis and Assessment for Part 23 Airplanes*

8.1.3 Participant observations

Workshop, 2015. , Certification of Metal Additive Manufacturing Systems and Parts for use in Civil Aviation. Challenges and Opportunities. Carnegie Mellon University, Washington, D.C.

8.2 Referenced Data Sources in Chapter 3

CENTIMFE, 2016. Personal communication (e-mail). September 14th 2016.

8.2.1 Interviews

Table 8.2 Interviews corresponding to chapter 3

Sector/Organization	Position	Date	Cited As
Firms			
Aeronautics-1	R&D Manager	4-Feb-16	26
Aeronautics-1	Metallic Producs	4-Feb-16	
Aeronautics-2	Maintenance	18-Mar-16	
Aeronautics-3	Process Engineer	7-Apr-16	27
Automotive-1	Process Engineer	7-Apr-16	28
Biomedical-1	CEO	17-Feb-16	24
3D-Printing Education	CEO	17-Feb-16	
Engineering and Design-1	General Manager	5-May-16	15
Engineering and Design-2	General Manager	3-Mar-16	16
Engineering and Design-3	General Manager	3-Mar-16	10
Engineering and Design-4	CEO	22-Feb-16	
Engineering and Design-5	Manager	9-Sep-16	
Machinery-1	CTO	12-Jul-16	
Machinery-1	CEO	12-Jul-16	
Machinery-2	Co-Owner	19-Apr-16	
Machinery-3	Managing Director	11-Mar-16	22
Molds and Tooling -1	Technical Manager	10-Mar-16	1
Molds and Tooling -1	CFO	23-Feb-16	2
Molds and Tooling -2	Director, Prototyping	3-Mar-16	3
Molds and Tooling -3	Technical Manager	3/18/2016 and 4/6/2016	4
Molds and Tooling -4	MAM Expert	25-Jul-16	5
Molds and Tooling -5	R&D Engineer	21-Apr-16	14
Industry Organizations			
Industry Association - 1	Technical Director	28-Sep-16	
Industry Association - 2	R&D Head	19-Apr-16	
Industry Association - 3	R&D Coordinator	2-Mar-16	
Technology Center -1	President	December, 2015	
Technology Center -1	R&D Head	Several	20
Technology Center -1	Prototyping	30-Jan-17	6
Technology Center -2	R&D Head	1-Mar-16	21
Technology Center -2	Financial Director	1-Mar-16	
Research institutions			
Research institution-1	R&D Coordinator	1-Mar-16	19
Research institution-1	Head of Prototyping	19-Jul-16	
Research institution-2	Member of Board	28-Sep-16	23
Research institution-3	Adjunct Director	30-Jun-16	18
Research institution-4	PAM Research	4-Mar-16	12

Research institution-5	Member of Board	3/10/2016 and 5/5/2016	9
Research institution-6	Advanced Manufacturing	28-Sep-16	17
Research institution-6	Product Development	2-Mar-16	13
Research institution-7	PAM Research	23-Feb-16	11
Research institution-7	MAM Pioneer	31-Mar-16	7
Research institution-7	MAM Pioneer	1-Apr-16	8
Other			
Training Center-1	Head of Training	6-Apr-16	
Training Center-2	General Manager	28-Sep-16	
Makerspace-1	Director	19-May-16	25
Government-1	Innovation Policy	19-Jul-16	29