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Seeking coherence between barriers to manufacturing technology adoption and innovation policy

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ABSTRACT

Manufacturing-enabling technologies (MET) play a key role in increasing the reliability of manufacturing processes, and help accelerate new product development and testing. Manufacturing firms are, however, often reluctant to develop MET themselves, as these may not be part of their core competencies nor easily appropriable. Government support can play a vital role in overcoming these barriers for firms. Ideally, this support should be tailored to the barriers associated with a specific technology. Existing studies do not provide insight into how these barriers differ across types of MET. Based on 26 interviews and approximately a hundred sources of archival data, we study the adoption of four types of MET for advanced composite materials in the aviation industry. We analyze what technology-level and market factors affect the adoption of each type of MET, and whether government programs have responded to industry's needs. We find significant heterogeneity in barriers to the adoption of different METs, and that government programs designed to foster manufacturing innovation do not readily adapt to these variations. In particular, they often do not account for factors such as MET technological interdependence, nature of learning (scientific versus trial-and-error), and the heterogeneity of the technology development community. Our findings, and recommendations for policymakers, can improve the alignment between the public support programs for MET and barriers to adoption.

1. Introduction

Our study analyses the coherence between government policy programs aiming to foster manufacturing innovation, and the barriers to adopting manufacturing-enabling technologies (MET). We define MET as those physical or virtual tools that help enhance the stability and reliability of a manufacturing process. Examples of MET are measurement tools, testing equipment, and material characterization data. MET are essential for accelerating R&D processes and reducing production costs.

MET present two characteristic features. First, the knowledge base required to develop MET typically falls outside the traditional boundaries of the manufacturing firm (Tassey, 1982). Second, MET are quasi-public and infrastructural, given that they may be used across industries, and are often embodied in technical standards (Link and Metcalfe, 2008). These two features raise significant barriers for the development and adoption of MET. R&D activities are expensive and usually not appropriable as MET are applied in multiple sectors (Link and Scott, 2010a). The knowledge to develop MET is highly tacit, and user-based innovation is highly relevant, creating a need for strong relationships between technology users and producers (Fleck, 1994; Gertler, 1995; Riggs and von Hippel, 1994; Rosenberg, 1992; Rothaermel and Thursby, 2007). The quasi-public good character of MET increases network effects, hinders private investment, and heightens the need for inter-industry coordination (Bresnahan and Trajtenberg, 1995; Featherston and O'Sullivan, 2017; Tassey, 2004).

Academics and government officials alike have argued that specific public support could overcome these barriers to the development and diffusion of MET (Link and Scott, 2010b; Tassey, 1982; Wengel and Shapira, 2004; Youtie et al., 2008). Examples of public support are the establishment of public research programs, venture capital and technology transfer funds, demonstration platforms, demand-side policies, and technology-specific regulation (Edler and Georghiou, 2007; Masson, 2005; Shapiro and McGarity, 1991a; White, 2012; Woodcock and Woosley, 2008).

The nature of MET is quite diverse. MET encompass tooling and

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process technologies, measurement instruments, simulation tools, platforms for data science, and technical standards (Featherston and O'Sullivan, 2017; Höyssä and Hyysalo, 2009; Nightingale, 2000; Tassey, 2000). While government should ideally adapt its support to match the characteristics of each technology (Martin and Scott, 2000; Metcalfe, 1995), the literature is not able to explain how that adaptation could occur. It lacks a description of how barriers to adoption across types of MET differ. This paper intends to fill that gap.

We study the case of MET for the manufacture of advanced composite materials in aviation. We obtain information by conducting 26 interviews and analyzing approximately a hundred sources of archival data. For our study we select four categories of MET: manufacturing and repair methods; virtual design and modelling; quality control and damage evaluation; and material characterization methods and standards. For each category, we apply the diffusion of innovations theory to study the factors affecting their adoption. We analyze how public programs have historically tried to help industry address these factors.

We find there is great variability across the types of MET in terms of firms' incentives and barriers to invest in a technology. Our data suggests that the MET least successful in the market are those where the barriers to adopting them are pre-eminently cultural and social, rather than technical. From the comparison across our four categories of MET, we discover the main technology and market characteristics behind their diversity, and to what extent this affects the required public support.

2. Theoretical background

2.1. *Incentives and barriers to the adoption of METs*

Mastering an emerging manufacturing technology is typically a slow process, and a major barrier to the commercialization of new products (Hatch and Mowery, 1998; Pisano, 1997a). In the early stages of process technology, it is often complicated to match certain configurations of production equipment with the final product's characteristics, increasing the interdependence between manufacturing and R&D activities (Gray et al., 2015). Tolerances are high, and production yields are usually low, resulting in additional rework costs and waste of materials, to the point that rework costs can exceed labor costs in high-tech industries (Bohn and Terwiesch, 1999). Moreover, engineers often have to visit the shop floor to troubleshoot, increasing the process downtime and lowering production rates (Fuchs and Kirchain, 2010).

MET are essential to reduce variability in production, accelerate product development, allow for the design of products with more stringent tolerances, and reduce material waste, all of which improve productivity (Bohn, 2005; Jaikumar, 2005; Lécuyer, 2006; Pisano, 1996). Different types of METs have different advantages. For instance, better tools and automated processes can increase the reliability of the technology and enable the production of higher volumes at lower cost (Featherston and O'Sullivan, 2017; Fuchs et al., 2008); new sensors and measurement instruments speed up the ability to find potential flaws in firms' products which could otherwise not be detected (Höyssä and Hyysalo, 2009; Lécuyer, 2006); new software modelling tools allow for rapid pre-evaluation of different design choices without the cost of extensive prototyping and mechanical testing (Nightingale, 2000); shared data platforms and standardized interfaces can accelerate the learning speed of the research community, and allow for supplier specialization (Fosso Wamba et al., 2015; Jain et al., 2013; Tassey, 2000).

Despite their benefits, MET face significant barriers to being adopted. Adoption costs are a major factor. Managers need to evaluate whether the increased financial burden compensates a potential strategic advantage (Krinski and Miltenburg, 1991). Early adopters may seek first-mover advantages which confer them market dominance and the option to sell their products at a higher price (Kakati, 1997; Lieberman and Montgomery, 1988). However, because some of the benefits from MET are indirect and difficult to quantify, managers may see their investments in MET as an 'act of faith' (Small and Chen, 1995). Retraining employees in charge of product development, manufacturing, quality control, and maintenance, can incur non-negligible reskilling costs (Agnew et al., 1997; Koh et al., 2009; Machin, 2001).

In addition, the adoption of MET depends on an industry's structure and social relationships. MET need to be compatible with pre-existing manufacturing processes and routines (Link and Scott, 2010a); they are often subject to network externalities, and need to become an industry standard before experiencing wide adoption (Farrell and Saloner, 1985a; Tassey, 2000; Thoma, 2009). Furthermore, in highly regulated industries, MET also have to be endorsed by the corresponding regulatory agency, as existing industry standards might not be good enough to ensure product safety (Bonnín Roca et al., 2017; Woodcock and Woosley, 2008). As innovation of MET requires the involvement of a large number of stakeholders, coordination problems may arise (Bresnahan and Trajtenberg, 1995). Consequently, the outcomes of R&D activities are often not appropriable (Featherston and O'Sullivan, 2017; Tassey, 2004) which in turn deters private investment.

The adoption of MET is also subject to high levels of technical uncertainty. The scientific community might not be aware of the key parameters that determine whether a certain production batch is successful or not (Bohn, 2005). Moreover, the process of unraveling such parameters is usually slow and acquired through trial-and-error (Balconi, 2002; Terwiesch and Bohn, 2001). The knowledge about what works, and what does not, becomes highly tacit and precious, kept by a small community of early adopters and not shared with the rest of the community (Balconi, 2002; Collins, 1974; Koskinen and Vanharanta, 2002). Tacitness exacerbates information asymmetries between MET producers and users, who may steer MET development efforts towards their individual needs (Fleck, 1994; Gertler, 1995; Riggs and von Hippel, 1994; Rosenberg, 1992; Rothaermel and Thursby, 2007). Thus companies may not have enough information to make informed decisions about which MET to use, and the optimal way to use them.

2.2. *Public support for adopting of MET*

Government intervention to foster R&D is typically justified in cases where expected social benefits exceed private returns, and innovators might not be able to appropriate all the benefits from their R&D investments (Audretsch et al., 2019; Choi and Lee, 2017; Martin and Scott, 2000). MET are a typical example of this innovation market failure, due to their infrastructure hampering the appropriability of R&D activities, and the impact of network externalities (Link and Scott, 2010a; Tassey, 2004).

Governments have several mechanisms to incentivize private R&D. If development costs are a major concern, tax credits can reduce the marginal costs of private R&D, although their effectiveness may depend on a firm's size (Koga, 2003; Rao, 2016). Venture capital programs such as Small Business Innovation Research (SBIR), foster investment in high-risk technology applications at small, innovative firms (Audretsch et al., 2019; Ceulemans and Kolls, 2013). Agencies use such programs to signal their priorities and incentivize the development of MET which would hardly happen without support (Cooper, 2003; Masson, 2005). In addition to these supply side measures, demand-side policies such as procurement contracts can extend the market, enabling producers to more easily reach economies of scale (Edler and Georghiou, 2007). In cases where costs related to achieving regulatory compliance are high, agencies can work with industry members to streamline their certification processes (Kesselheim et al., 2015), or endorse technology-based regulation (Shapiro and McGarity, 1991b).

In addition, governments can provide resources to increase coordination among a large pool of stakeholders. Efforts are usually channeled through public-private partnerships in the form of bridging institutions such as the Fraunhofer Institutes, which act as a neutral party for pre-competitive R&D (Intarakumnerd and Goto, 2018). When a certain technology is considered strategic, governments can also promote the creation of mission-oriented consortia, such as SEMATECH in semiconductors (Irwin and Klenow, 1996), or the Materials Genome Initiative (White, 2012). Government agents can also bring their knowledge to standardization committees, increasing their legitimacy (Wiegmann et al., 2017).

Public support can also help to generate technical knowledge and reduce information asymmetries among industry members. Besides direct funding of research activities, governments can use their institutions to sign cooperative research contracts with firms, and make their innovations available for licensing (Link et al., 2011; Roessner and Bean, 1994; Rogers et al., 1998). In some cases, publicly-funded research, like databases with material properties (Bonnín Roca et al., 2016) or promising avenues for the development of new medical treatments (Wagner et al., 2010), can become available to the public to promote innovation.

Given the wide variety of barriers to technology adoption and public support mechanisms, ideally the selected mechanisms should tackle the specific barriers of each technology (Martin and Scott, 2000). The literature does not recognize any granularity or differentiate at the technology-level. It is therefore unclear which type of public support might be most effective to support the adoption of a given MET. We try to fill this gap by studying four different groups of MET used in the production of components with advanced composite materials: manufacturing and repair methods; virtual design and modelling; quality control and damage evaluation; and material characterization methods and standards. We expect that our findings can be generalized to suit other process-based manufacturing processes in fields such as semiconductors (Holbrook et al., 2000), optoelectronics (Fuchs and Kirchain, 2010), biotechnology (Rothaermel and Thursby, 2007), pharmaceuticals (Pisano, 1997a) or additive manufacturing (Bonnín Roca et al., 2017).

2.3. *Theoretical lens: diffusion of innovation theory*

This paper analyzes the barriers to the adoption of MET through the lens of Diffusion of Innovation (DOI) theory (Rogers, 2003). While other theories of technology adoption, such as the technology acceptance Model (Davis, 1989; Szajna, 1996), social cognitive theory (Bandura, 1989; Compeau et al., 1999) or the theory of planned behavior (Ajzen, 1991; Lynne et al., 1995); are more suitable for explaining technology adoption at the individual level, DOI is particularly appropriate for collective adoption and diffusion processes (Straub, 2009). Within manufacturing contexts, scholars have used DOI to study for instance Industry 4.0 technologies (Dalenogare et al., 2018), electronic collaborative tools (Chong et al., 2009), and the diffusion of innovations across the supply chain (Kim and Chai, 2017).

In the original DOI formulation, Rogers (2003) defined five factors that affect the adoption and diffusion of an innovation: its relative advantage compared to the incumbent technology; its compatibility with pre-existing norms and values; its complexity of use and understanding; its trialability or degree to which the innovation can be tested and modified; and observability, or how visible the effects of an innovation are to others. These technology-level characteristics interact with the norms of the social system where the technology is diffused (Rogers, 2003).

Hall (2004) matched the five factors defined by Rogers (2003) with traditionally sociological factors and empirical analyses in the economics literature, which emphasize economic aspects such as profits and economies of scale (Caselli and Coleman, 2001; Griliches, 1957; Nelson et al., 2004; Rosenberg, 1972; Saloner and Shepard, 1995). Hall (2004) concluded that Rogers' model was compatible with the empirical evidence, and that the factors impacting technology diffusion come under four groups: those that affect the benefits gained, those that affect the costs of adoption, those related to the industry or social environment, and those that occur due to uncertainty and information problems (Hall, 2004, p.12). Table 1 indicates the correlation between Hall's and Rogers' categories, and examples relating to the introduction of MET, as mentioned in sections 2.1 and 2.2.

We use Hall (2004) taxonomy to build a theoretical model (Fig. 1). In our model, industry adoption decisions are influenced by the four categories Hall defined. Government action affects the magnitude of each of these factors. Our paper contributes to the literature by adding (arrows in bold) 1) how each type of MET differs in the factors affecting adoption decisions; and 2) how the type of MET may moderate the effect of government support.

3. Industrial background: advanced composite materials in the aeronautics industry

Advanced composite materials are a family of high-performance materials where two or more materials are combined to produce a third material with better properties than its constituents (Hahn and Tsai, 1980). A high-strength reinforcement (typically fiber) transmitting the loads is introduced inside a matrix which maintains structural integrity and protects the fiber. This matrix can be a polymer, a metal or a ceramic, creating possibilities for countless potential fiber-matrix combinations, all with different physical properties (Hull and Clyne, 1996). For the sake of simplicity, we focus on a specific type of composite: carbon fiber reinforced polymers (CFRP). In CFRP, a carbon fiber is usually embedded in an epoxy resin matrix.

Carbon fiber has a strength-to-weight ratio approximately double that of aluminum, and is less susceptible to problems of corrosion and fatigue (Soutis, 2005). One of the sectors that benefits the most from those characteristics is the aerospace industry. This is due to the aircraft's exposure to harsh environmental conditions, the cyclical loads that can cause metal fatigue, and the benefits that light-weighting brings to fuel economy (Slayton and Spinardi, 2015). In fact, the aerospace and defense market is the highest consumer of carbon fiber, representing about 30 percent of the tonnage, and 50% of the revenue (Holmes, 2014). In the latest generation of commercial aircraft, namely the Boeing 787 and the Airbus 350, approximately half of the weight of their structure corresponds to CFRP (Slayton and Spinardi, 2015).

Despite being around for about 50 years, the behavior of CFRP components is not well understood and there are still significant technical and market barriers limiting a more widespread adoption (Composites UK, 2017; Sloan, 2017, 2014). Nowadays, two of the major policy initiatives to lower those barriers are the Institute for Advanced Composites Manufacturing Innovation in the USA (IACMI, 2017); and the National Composites Center (NCC) in the UK, a product of the 2009 "UK Composites Strategy" (BSI, 2009). IACMI's initial funding model was a federal funding matching private investment 1:1, but aims to become financially self-sustainable within the first decade (Manufacturing USA, 2017). NCC is part of the UK network of Catapult Centers, which have a 'thirds' funding model: one third of core funding from the government; one third from private sector contracts; and one third from collaborative public-private R&D projects (Hepburn and Wolfe, 2014).

4. Methods

To analyze the coherence between policy programs and the barriers to adoption of METs, we used a qualitative case study (Eisenhardt, 1989; Yin, 2013) on the introduction of manufacturing-enabling technologies (MET) in the aeronautics industry. The case study is based on 26 interviews (Table 6), approximately a hundred sources of archival data, and participant observations during three visits to aircraft manufacturing plants.

We started our analysis by creating a list of MET which had been, or are, considered important for adopting carbon fiber reinforced polymers (CFRP). This list, containing more than 70 ME T, is based on various national strategies and technology roadmaps from organizations in

Table 1
Hall's taxonomy of factors affecting technology diffusion can be mapped to Rogers' original taxonomy. Based on the literature, we provide examples of factors relating to the adoption of MET, and public support programs which may incentivize private R&D by lowering barriers to adoption.

Hall's categories	Rogers' categories	Factors relating to MET adoption	Examples of supporting public policy
Benefits from adoption	Relative advantage Complexity	• Reduce variability (Fuchs et al., 2008; Terwiesch and Bohn, 2001) • Tighten tolerances (Jaikumar, 2005) • Improve flaw detection (Höyssä and Hyysalo, 2009; Lécuyer, 2006) • Accelerate product development (Nightingale, 2000; Pisano, 1997b) • Increase learning rate (Fosso Wamba et al., 2015; Jain et al., 2013)	N/A
Adoption costs	Relative advantage Complexity	• Capital costs (Fuchs and Kirchain, 2010; Krinski and Miltenburg, 1991) • R&D costs and time (Hatch and Mowery, 1998; Pisano, 1997b) • Retraining costs (Agnew et al., 1997; Koh et al., 2009; Machin, 2001)	• R&D subsidies (Rao, 2016) • SBIR/STTR (Cooper, 2003) • Procurement contracts (Edler and Georghiou, 2007) • Streamlined regulatory processes (Kesselheim et al., 2015)
Industry and social environment	Compatibility	• Preexisting norms (Link and Scott, 2010a) • Network externalities (Farrell and Saloner, 1985b; Thoma, 2009) • Regulation and certification (Bonnín Roca et al., 2017; Woodcock and Woosley, 2008)	• Public-private bridging institutions (Intarakumnerd and Goto, 2018) • Mission-oriented consortia (Foray et al., 2012) • Legitimize standardization (Wiegmann et al., 2017)
Information and uncertainty	Trialability Observability	• Knowledge tacitness (Balconi, 2002; Koskinen and Vanharanta, 2002) • Lack of scientific knowledge (Bohn, 2005; Collins, 1974) • User-producer asymmetries (Gertler, 1995; Rosenberg, 1992; von Hippel, 1976)	• Cooperative research agreements and licensing (Rogers et al., 1998) • Publicly available databases (Bonnín Roca et al., 2016)

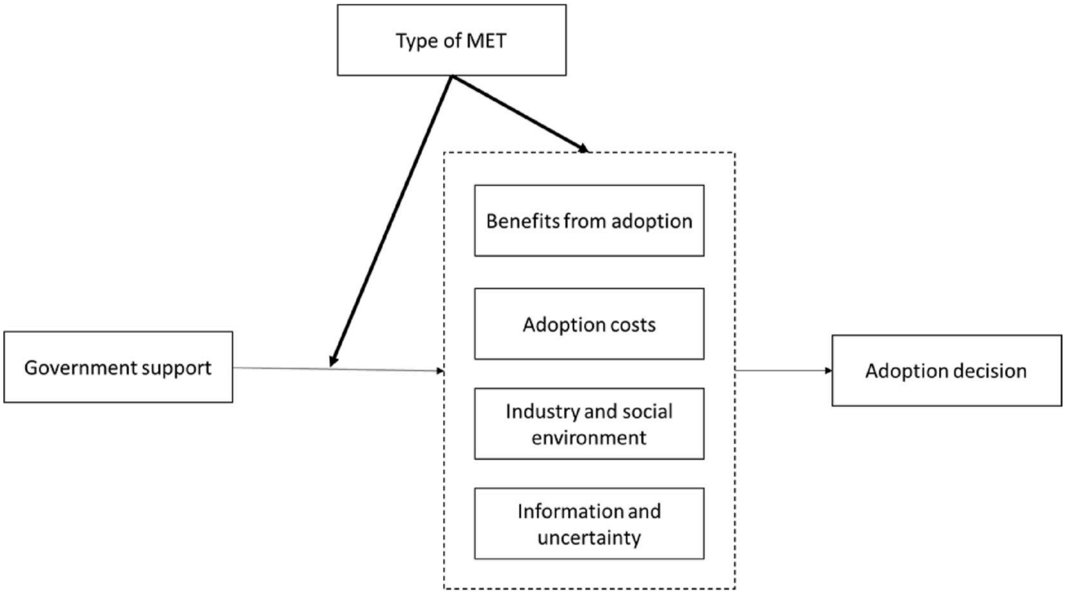

Fig. 1. This paper analyzes how barriers to adoption differ across types of MET, and how those technology-level differences affect the effectiveness of public support.

Japan, the U.K, and the U.S. (BSI, 2009; Davis, 1993; IACMI, 2015; NRC, 2005, 1993; OTA, 1995, 1988; Tenney et al., 2009, 2011). Using government reports and specialized press, we identified the major R&D programs devoted to the development of MET. We engaged in an iterative process between data collection and data analysis, to assess the most relevant barriers to adoption of each MET type, and the public program efforts to tackle them. We assessed the level of alignment between barriers to adoption and policy programs qualitatively according to: 1) the existing literature on innovation policy, as shown in Table 1; 2) the documentation corresponding to each public program; and 3) our interviewees' perceptions. Table 2 is a summary of the research process, further explained in sections 4.2 and 4.3.

5. Data analysis

- Constant comparison across data sources for validation purposes
- Axial coding according to the dimensions of our framework (Table 1)
- Assessment of the alignment between barriers to the adoption of MET, and public programs, based on the innovation policy literature, archival data, and interviewees' perceptions

5.1. Case selection

We chose the case of advanced composites for several reasons: first, they have been available in the market for more than half a century, compensating the relatively slow pace of adoption that emerging manufacturing technologies typically experience. Second, advanced composites have been considered strategic by various industries and governments, which till this day, are still creating new institutions for their promotion. Third, many of the technologies considered strategic by current government programs, such as nanotechnology, tissue engineering, and additive manufacturing, are also process-based; we therefore expect our findings to be applicable to topical matters. Aviation has

Table 2
Summary of our research process.

Stage and objectives	Data sources
1- Case selection • Identification and classification of relevant MET • Identification of major public support programs	• National manufacturing strategies and consortia documentation • Technology roadmaps
2- Data collection and initial coding Stage 1: • Learn about the socioeconomic context leading to program creation • Clarify program goals and members' incentives to join	• Interviews with program managers • Government and industry reports • Funding agencies' documentation • Evaluation reports • Interviews with former members outside government
Stage 2: • Assess alignment between government and other stakeholders	• Government and industry reports • Interviews with technical managers at firms and research institutes
Stage 3: • Understand missing technical details • Analyze trade-offs in cost-performance when choosing MET • Observe real-life implementation	• Participant observations at manufacturing plants • Technical journal articles

been one of the leading users of CFRP since their inception, and as such was the focus of most research programs and commercialization efforts. In addition, manufacturers are subject to stringent safety levels, and therefore may have additional incentives to adopt reliable MET to ensure any new component is safe to fly.

The existing literature does not provide any detailed categorization of MET. To decide which types of MET to consider in our analysis, we observed how public organizations have structured their investments in MET for composite materials. For instance, in the 2007 Small Business Innovation Research (SBIR) solicitations, NASA stated that "advanced composite material systems and their corresponding manufacturing, processing and verification techniques are desired." In the 2009 SBIR solicitations, under the Advanced Composite Technology (X5) category, the areas of interest included "materials; manufacturing; nondestructive evaluation/structural health monitoring; and structural concepts." A public-private partnership such as the National Composites Center (UK), has four different R&D working groups: Manufacture, Design and Simulation, Automation and Tooling, and Materials and Processes (including testing). These structures are similar to organizations in charge of promoting other manufacturing technologies. For instance, the America Makes Additive Manufacturing Technology Roadmap (2018) is broken down into the following five technical focus areas: Design, Process, Material, Value Chain (which includes quality control) and AM Genome. Based on the overall level of overlap across these existing organizations, we classified our initial list of MET into four categories: manufacturing and repair methods; virtual design and modelling tools; quality control and damage evaluation; and material characterization methods. Table 3 presents examples of the various MET for composite materials.

Table 3
Examples of the various MET included in our study.

Quality control and damage evaluation	Manufacturing and repair methods	Virtual design and modelling tools	Material characterization methods
Ultrasounds	Filament winding	NASTRAN/ PATRAN	MIL-HDBK-17
Eddy currents	Resin Transfer Molding	ABAQUS	CMH-17
Shearography	Automated Fiber Placement	STAGS	CMI, Inc
Thermography	Automated Tape Laying	MARC	AGATE
Radiography	Textile processes	StressCheck	NCAMP

5.2. Data sources

We conducted 26 1 h-long interviews, which we recorded and transcribed within 48 h. Our selection of interviewees encompassed a balanced representation of stakeholders across government, industry, and academia, covering the four types of MET as evenly as possible. We conducted interviews in three phases. In the first phase, we approached former program managers of the major public programs identified in the archival data. They provided their perspectives on the socio-economic context behind the creation of the program, key goals, stakeholder participation, and relative success. They helped us snowball sample (Noy, 2008) our second group of interviewees. In this second phase, we targeted the main corporate and academic members in those development programs, such as managers of collaborating research institutes. They helped us better understand the level of alignment between government and other members of programs focusing on the development of MET. After the second round, having extensively analyzed the rationale behind public support for MET, we discovered that there was a lack of technical details about what makes each type of MET different. We used the third round of interviews to reach out to technical managers at firms and research institutes, to learn more about their R&D programs, and the trade-offs that companies face when adopting each type of MET. Overall, all our interviewees had at least ten years of experience, and seven interviewees had spent more than fifteen years in the private sector.

To overcome potential cognitive biases, which can be misleading when dealing with long-term memories and historical events (Coyle, 1997), we validated the insights from the interviews with archival data. We used government and industry reports to obtain historical information on the major development programs, their objectives, and outcomes. We searched for articles in specialized press in the field of composite materials and aviation, such as the magazine Composites-World, to compare information on technological developments and the players involved. Our interviewees provided us with key reports and technical documentation which might not be publicly available, or difficult to find. Finally, we used technical documents and journal articles in the fields of material science and engineering, to validate our interpretation of the technical challenges with MET.

We visited three aircraft manufacturing plants, one exclusively dedicated to the production of composite components. The visits lasted half a day and enabled us to observe at first-hand how MET are implemented (or not) in a real setting. During our visits, we had informal conversations with the plant managers about their challenges in their production processes, and the rationale for selecting their preferred MET. Thanks to their insights, we were better able to distinguish the technical and economic requirements between R&D and production activities.

5.3. Data analysis

We performed data coding iteratively between archival data and interviews throughout data collection, following the guidelines provided by Charmaz (2014). The first author did the coding initially manually, and conducted all the interviews; the second author, who provided a less biased perspective, continued with the coding.

We started by coding, paragraph-by-paragraph, our first sample of archival data containing information on the objectives of the major public programs in the area of CFRP. We used this initial coding to build interview protocols for the first set of interviews.

We coded the interviews line-by-line, applying constant comparison across interviewees, sectors (corporate, academic, or government), regions (America vs Europe), and data sources (archival data vs interviews). Overall, we found notable conformity among our diverse pool of data sources. The results of this constant comparison informed our search for additional archival data, and added questions to our interview protocols to deepen our understanding of the issues considered key by our data sources. We continued iterating between archival data and interviews until we reached theoretical saturation.

Axial coding (Corbin and Strauss, 1990) provided structure for our initial codes. In particular, we matched our codes to the various factors affecting technology adoption and diffusion as stated in Table 1. Axial coding allowed us to distinguish between the conditions under which public programs to provide support for MET were created; the actions and interactions of the various stakeholders involved in those programs; and the programs' outcomes (Charmaz, 2014).

6. Findings

6.1. ME T's critical role in adopting composites

Despite the potential advantages and associated commercial potential offered by CFRP, the adoption of composites has been slower than expected (OTA, 1988). This is due to the difficulties in establishing a robust control to reduce variability in manufacturing, and high production costs (Cheung and Gershenfeld, 2013; Mair, 2002; Veitch, 1997). New MET have played a pivotal role in lowering development production costs, shortening development times, and ensuring a higher reliability, which have broadened the scope of potential applications (Ashforth et al., 2014; Lukaszewicz et al., 2012; Slayton and Spinardi, 2015; Tenney et al., 2009).

The manufacturing process of composites is very sensitive to changes in process parameters. As one expert commented, "*we had what we thought was the most innocuous change come through the system, and suddenly the part was no longer good*" (Interview 14). The exact composition of the chemical precursors is rarely known, given that it is the material supplier companies' most valuable competitive advantage. Internal defects are also difficult to observe (Cantwell and Morton, 1992). Composites are therefore considerably more complex than the metallic structures they typically replace (Scott and Scala, 1982). This increased technical complexity is also an important barrier for creating reliable scientific models of the process (Interviews 5,9,14). Most knowledge about process configuration is gathered through expensive trial-and-error, becoming firms' most valuable intellectual property (Interviews 7,8,12).

Manufacturing costs are high for several reasons: the need for large equipment, expensive molds and tooling, and the low throughputs which make it difficult to achieve economies of scale (NRC, 1993). In addition, the manufacturing process is labor-intensive (Das, 2001). In aviation, manufacturers are responsible for paying the certification costs. For each non-standard material, manufacturers need to generate their own data to show that the material can achieve the specifications in the aircraft's design (Bonnín Roca et al., 2017). Given that composites are used in aircraft components (from stabilizers to wing boxes) that are safety-critical, generating such databases may entail testing thousands of samples (RAND, 2001). In a project where several suppliers are involved in the production of components, each of these suppliers would have to go through this process, even if they were all using exactly the same material (OTA, 1988).

MET can help increase reliability and reduce both the production and qualification costs of CFRP components. However, MET face several technological and market barriers to their widespread adoption. In sections 5.2 to 5.5, we present how those barriers differ across the four types of MET.

6.2. Quality control and damage evaluation tools

Non-destructive testing (NDT) technologies are critical for ensuring that manufactured components do not present significant structural flaws (Scott and Scala, 1982). NDTs are used at the manufacturing plant during production activities, and at airports by maintenance personnel. During maintenance, NDTs determine whether a certain component needs to be replaced or repaired. Having better NDTs may enable manufacturers to implement lower safety factors in their designs, and increase the time between maintenance inspections (Interview 26).

Some of the NDTs for composites, such as ultrasound (Hitt and Ramsey, 1963) and eddy currents (Armour, 1948), were already used to inspect metallic structures before composites existed. For these 'conventional' NDTs, the main task was to adapt the pre-existing solutions, or knowledge in other sectors such as biomedical, to the particular problems of composites. However, the failure modes of composites are more challenging than those of metals. While metals are mostly isotropic (that is their properties are similar along the three spatial directions), composites are highly anisotropic, which makes it difficult to inspect components along the direction of the fibers (Scott and Scala, 1982). Not detecting a defect does not necessarily mean that there is no defect, and therefore it is hard to ensure components' structural integrity (Interviews 1,3,14). 'Emerging' NDTs had to prove they were better than conventional solutions. Examples of emerging NDTs are: infrared thermography, used for industrial applications since the 1960s (Vavilov, 2014); computer tomography scans, invented in 1972 b y Hounsfield, who worked at British corporation EMI Ltd (Hounsfield, 1973); and shearography (or speckle pattern shearing), based on work by British (Leendertz and Butters, 1973), Japanese (Nakadate et al., 1980) and American (Hung and Grant, 1977) academics in the 1970s.

Public support for NDT focused on the creation of basic scientific knowledge (Ilcewicz and Murphy, 2005; Tenney et al., 2009), as industry needed critical data about all the ways composites could fail, and the assessment of the various NDTs' validity in detecting those flaws (Galella, 2002). Much of the seminal work to understand and develop NDTs for composites was performed by NASA Langley and made publicly available (Tenney et al., 2009, 2011). NASA scientists analyzed the applicability of existing technologies to composites (Vary, 1979; Vary and Sorg, 1975), built experimental testing facilities (Roberts and Vary, 1976), and studied the 'effects of defects' in composites (Sendeckyj, 1983). This information would be later used by officers to certify new aircraft and create guidelines for industry (Interview 6). In the 1990s, the Federal Aviation Administration (FAA) took over the responsibility of evaluating emerging NDTs (Perry, 1999). Because FAA did not have its own scientific facilities, they funded two Centers of Excellence: in 1990, the Center for Systems Reliability at Iowa State University; in 1991, the Airworthiness Assurance NDI Validation Center at Sandia National Laboratories (Galella, 2002). FAA's work has focused on efforts to determine the probability of detection of flaws, and compare the accuracy of traditional versus emerging NDTs (Roach and Rice, 2016). In addition, FAA-NASA funded demonstrator programs to facilitate the deployment of NDT in production and maintenance environments (Galella, 2002; Roach and Rice, 2016). They also instigated SBIR grants to help commercialize new NDT (AFRL, 1999; Bogue, 2010; Russell, 2007).

Despite all these efforts, the introduction of emerging NDTs in commercial aviation has been modest. In the factories we visited, ultrasound was the most widely used equipment. This lack of penetration appears to have several causes. Shearography and thermography equipment is considerably more expensive than ultrasound (Interview 3), and it is still not clear they have a substantially better probability of detection (Roach and Rice, 2016). Radiography equipment has significant limitations in terms of the size of the components which can be analyzed, and limited portability (Beattie, 1994). Often, firms do not believe that the new technologies are 'sufficiently better' to switch (Interview 26). In addition, emerging NDTs usually require skilled labor, which most airlines may not have (Galella, 2002; Roach and Rice, 2016). And as Roach and Rice (2016) argue: "*More specialized training, beyond Level I, II, and III certification, needs to be developed to specifically address composite inspections [...] The majority (86%) of the industry does not have additional, special inspector qualification/certification to qualify personnel to conduct composite inspections*." Because the requisite NDT to inspect a certain component is determined by the aircraft Original Equipment Manufacturer (OEM), the fear is that promoting emerging NDTs meant additional investment and training, which would discourage potential customers (Interview 3).

6.3. Manufacturing and repair methods

New manufacturing equipment offers the potential for manufacturers to reduce not only their production costs, and their reliance on manual labor, but also the variability in their end products' properties (Bader, 2002). However, the knowledge about how to use the new machines to produce high-quality components is mainly tacit, and extensive trial-and-error learning is required to improve and properly configure new machines (Interviews 8,20,21). In addition, new equipment is usually capital intensive, up to several millions of dollars (McPherson, 2013), which is hard to justify if production volumes are low (Interviews 20,21). Hence, in a situation where initial costs are high and profitability is highly uncertain, firms might be reluctant to invest their time and money.

Due to the need for tinkering with existing equipment, and constant refinement of the tools, "*most machines are born out of a company which has some element of knowledge about the machine platform. For a university, there are too many unknowns … For [company name] … it's easy, they only have to recycle their existing designs*" (Interview 20). For instance, automated tape laying (ATL) machines are based on the same principles as computer numerical control (CNC) mills, working additively instead of subtractively (Lukaszewicz et al., 2012). Automated fiber placement (AFP) is a result of combining ATL machines with filament winding (Lukaszewicz et al., 2012), a process invented in the 1970s to manufacture pipes and tanks (Black, 2016). Resin transfer molding (RTM) presents many similarities with injection molding (Mitchell, 1980), a technique to mass produce polymer products.

The challenge for machine manufacturers is therefore how to adapt the technologies to their users' particular needs and reduce the risks for early-adopters. Early government efforts to support novel manufacturing processes were spearheaded by the U.S Air Force (USAF) and NASA, with the industry participation of the largest American OEMs such as Boeing, Douglas or Lockheed (Amaoka and Taki, 1997). Probably the most important initiative was NASA's Air Craft Energy and Efficiency (ACEE) program (1976–85), where 350 components were put into service in real commercial aircraft, completing more than 4 million flight-hours (Bowles, 2010; Dow, 1987). In the 1990s, the main programs were USAF's Design and Manufacture of Low-Cost Composites (Anderson and Holzwarth, 1998); NASA's Advanced Composite Technology Program (Davis, 1993; Jackson, 1991) and Advanced Technology Composite Aircraft Structure (Ilcewicz et al., 1991); and DARPA's Affordable Polymer Matrix Composites Programs, which ended abruptly in 1995 after the management decided to cut its funding (Veitch, 1997). As a result of those programs, numerous parts for military and commercial uses were created to prove the efficacy of low-cost manufacturing technologies (Amaoka and Taki, 1997), but at a much lower scale than for ACEE. In 2015, renewed industry interest in composites fostered the creation of a new consortium, NASA's Advanced Composites Project (Allen, 2017).

Despite all these efforts, the introduction of these process technologies has been slow, as global demand took several decades to reach the point of making automation cost-effective (Black, 2003). An expert commented that nowadays, AFP is only clearly cost-effective for those players with a demand of more than 15,000 parts per year; below that threshold it depends on each firm's specific context (Interview 20). In fact, Boeing only introduced these automated processes in the late 2000s, when the firm needed to ramp up the production of composite components for the new B787 (Brosius, 2007). As an equipment salesperson told us, "*in the last 10 years it has been mostly the demand side, machines have become better but are not that important*" (Interview 25). For smaller market demands, low-cost solutions such as RTM might promise important productivity increases, and have enabled considerable advances in industries like automotive, which has less stringent technical requirements than aviation (NRC, 1993). However, RTM typically leads to undesirable thermal gradients and residual stresses (Michaud et al., 1998), which in some aircraft components mean unacceptable risks.

6.4. Virtual design and modelling tools

Simulation software has many advantages: it enables early experimentation with many technological alternatives before engaging in costly physical prototyping and testing (Barbero, 2017); it helps explain the behavior of the manufactured components, from the material to the system level (LLorca et al., 2011); it also contributes to optimizing production parameters, providing a basis for technical decision-making (Degenhardt et al., 2006). Overall, simulation tools accelerate the speed of iteration at all stages of technological development, thus increasing the speed and the efficiency of the innovation process.

Many of today's software companies owe their existence to university spinoffs. For instance, NASTRAN, probably the most important code for structural analysis using finite element methods, was created thanks to a grant awarded by NASA to MSC Software, a company funded by two CalTech PhDs (MacNeal, 2003). STAGS, the software used to analyze shell structures, was developed at Lockheed Palo Alto Research Laboratory with continuous funding from NASA covering at least three decades (Almroth, 1978; Knight and Rankin, 2006). MARC Corporation was funded by a former lecturer at the Imperial College in London who moved to Rhode Island to work with another group of researchers at Brown University (Öchsner and Öchsner, 2017).

The creation of algorithms which accurately represent the behavior of materials and components requires a thorough scientific understanding (Interview 11). Given that composites' properties are highly dependent on the manufacturing process, and aviation is an industry producing complex products, it is hard to build meaningful models. In addition, until very recently, computing power was not good enough to run realistic cases in a reasonable amount of time (Interviews 11,16). Because there is little publicly available material data, "… *simulations and experiments are intertwined, developed together, not like the textbooks models. All models need to be validated. You start with coupon size and need to start with simulation activities because those allowables are the inputs for the next steps of the simulation*" (Interview 17).

Furthermore, manufacturing firms might be reluctant to culturally accept simulation tools, as they see software packages as 'black boxes' where it is not exactly clear what is happening inside (Interviews 17,18,19). "*The manufacturing sector works on the premise of trial-and-error. It is very hard to go to a company and try to embed process modelling because engineers don't trust it*" (Interview 18). This problem might be solved through workforce development efforts, given that there is an important undersupply of skilled labor with technical knowledge of composite materials, even at the largest manufacturing firms (Interviews 5,16,18,19). Thus, the translation of those new algorithms to firms is not always straightforward, because of differences in the software infrastructures between firms and research centers, or simply because it just takes time for firms to re-educate their employees and change their daily routines (Interview 17). Firms may sign a contract with a University to create a new algorithm, but afterwards they might not use it, or it could take a decade until they finally implement it (Interview 17,18). In addition, not all firms (especially SMEs) may have enough internal expertise to cope easily with generic algorithms (Interview 16).

Public programs can help firms analyze the validity of new software tools, by building small systems in real life and providing comparisons between the computational and mechanical testing results. Usually these validation programs are run under a cost-sharing structure, where firms gain important insights about the cases they want to study (a real case is required in order to match the software specifications to their expected use) in exchange for a membership fee (Interviews 11,15,17,18). Such funding structures have been successfully adopted by diverse actors such as the University of Delaware's Center for Composite Materials, one of the pioneers in computer simulation technologies (Interviews 1,8,15); NIST, as part of the Advanced Technology program in the 1990s, pioneered work on the simulation of RTM processes (NIST, 2004; Wang and Fitting, 1995); and more recently, the Advanced Manufacturing Research Center at the University of Sheffield (AMRC, 2017).

6.5. *Material characterization methods and databases*

The creation of standards and databases with statistically significant material properties helps homogenize manufacturing practices across firms, reduces redundancies in the development of material data, and significantly cuts certification costs, allowing for the entry of new players (Ashforth et al., 2014; OTA, 1988; Tenney et al., 2009; Tomblin et al., 2002). Risk mitigation strategies might become easier to implement, as regulators deal with a lower variety of technological solutions and are able to gather more data (Ilcewicz and Murphy, 2005). In particular, standards inform manufacturers about the typical steps to follow in the manufacturing process, the number of parameters which need to be controlled, the range of values which are acceptable for those parameters, and the range of expected properties of the final components (CMH-17, 2012; MIL-HDBK-17, 2002).

Typically, these standards are linked to a number of "measurement and test methods, interface standards, scientific and engineering databases, and artifacts such as standard reference materials" (Tassey, 2000, p.592). Thus, the creation of this technological infrastructure usually requires the integration of knowledge created at leading firms (Blind and Mangelsdorf, 2013). These firms, however, are usually unwilling to share knowledge which has been very costly to acquire, and is seen as a competitive advantage, especially in the early stages of the technology (Blind and Thumm, 2004; Bonnín Roca et al., 2016). "*Technology like composites is very much tribal knowledge and company-specific … it takes a long time [for others] to take into the learning curve … And that all comes because people can't go [to university] and take the practical aspects of composites they learn in the industry because the industry hasn't passed that proprietary knowledge on*" (Interview 5).

Given the knowledge asymmetries across players in the aviation industry, and the lack of appropriability, public support was needed to create technical infrastructure, bring industry players together, and validate material and process data. Early standardization efforts were led by the Army Research Laboratory and the FAA, which published the MIL-HDBK-17 handbook (Feraboli, 2006). As advanced composites gained more acceptance in civilian applications, leadership was transferred to FAA, and the handbook renamed as the Composite Materials Handbook 17 (CMH-17) (Foedinger and Andrulonis, 2010). The information gathered to create the CMH-17 comes from a variety of industry sources, and committee chairs organize regular meetings and workshops to discuss potential changes and additions (Interview 4,5,14). FAA officials are crucial in these informal interactions. First, most FAA officials have long industry experience before joining the public body, so they are aware of industry practices. Second, they interact with the major manufacturers on a daily basis for certification purposes, so they keep their knowledge up to date and develop trust relationships (Downer, 2010). These interactions allow them to aggregate all the different pieces of firm-level information to build a larger picture of what industry is doing, and what it needs (Bonnín Roca et al., 2017).

The purpose of these handbooks was to lend consistency to the methods characterizing polymer matrix composite materials, report their properties, and provide guidance about design, repair, and quality control. However, neither the MIL-HDBK-17 nor the CMH-17 offered data which could be directly used by manufacturers in their designs, and certification costs remained high (Ng, 2010).

One solution was developed in the late 1990s, also under the strong leadership of public agencies. The U.S. general aviation (small and business aircraft) industry was in decline, and FAA and NASA were tasked by the Federal government to create a revitalization program (Grenville and Kleiner, 2004; Metz and Bowen, 2005). They both public-funded the Advanced General Aviation Transport Experiments (AGATE), a public-private consortia including 40 principal members from industry, 10 universities, and 30 supporting members (NASA, 1996). One of the projects undertaken under AGATE was creating a materials database for composite materials. This enabled general aviation players, who face much greater financial constraints than larger companies such as Boeing or Lockheed, to save money, time, and effort in their certification processes, and take advantage of the latest generation of materials (Tomblin et al., 2002). Because general aviation has a higher risk tolerance than commercial aviation, there was also more room for experimentation. The revolution with the AGATE project was the creation of a 'canned process' which could be applied to any composite material (Interviews 5,15). The specific materials to include in the database are chosen by industry, according to their priorities (Interview 15). Manufacturers in turn would only need to perform a limited number of tests to show that they were able to replicate the properties in the database (Ashforth et al., 2014; Tomblin et al., 2002). Certification costs for general aviation were cut from $300 k to less than $50 k, and certification time reduced from 24 months to just 6 months (Tomblin et al., 2002).

The experiment was so successful, that commercial aviation manufacturers soon became interested in creating a similar database for their own applications (CompositesWorld, 2010, 2008). Such a database is currently being developed and maintained in the National Center for Advanced Materials Performance (NCAMP), at Wichita State University (Ng, 2010; WSU, 2014). To legitimize these efforts, both FAA and the European Aviation Safety Agency (EASA) agreed to make NCAMP data valid for certification purposes on both sides of the Atlantic (EASA, 2014; FAA, 2010).

6.6. *Summary comparison*

We presented the potential benefits of each type of MET, the perceived barriers to their adoption and diffusion, and the major public support programs (sections 5.2–5.5). Our findings suggest that there is substantial heterogeneity across the four types of MET (Table 4).

- Adoption of process technologies appears to be driven almost exclusively by cost-performance metrics, and each firm makes its own decisions independently. The challenge is stimulating demand for new MET to achieve economies of scale.
- NDT experience strong network effects, as the same technologies need to be used by players with heterogeneous capabilities across the supply chain. Path dependency is exacerbated if emerging NDT are based on different scientific principles than the incumbent NDT, for instance between ultrasounds and infrared equipment.
- In the case of simulation tools, we observe that both cultural and knowledge factors are important drivers of adoption decisions. Technology users possess a quite different software infrastructure than technology developers. Notably, manufacturers appear not to trust the content of the simulation packages, which are often seen as a black box due to their complexity and lack of transparency.
- Material databases do have a strong infrastructural character, as they are typically publicly available. Their creation requires the coordination of a large number of players across sectors. However, leading firms might be reluctant to share their knowledge, seen as a source of competitive advantage.

7. Discussion

7.1. *Factors behind differences in adoption barriers*

Proponents of specific public support for the development of MET argue that markets tend to underinvest in MET due to their infrastructural character, lack of appropriability of R&D, and the type of knowledge required to develop them, which tends to fall outside the

Table 4
Comparison across the four types of MET in the factors affecting their diffusion, and how public programs have tried to lower obstacles.

Case	Factors affecting technology diffusion, and scope of major public support programs			
	Benefits from adoption	Adoption costs	Industry and social environment	Information and uncertainty
NDT	Detecting flaws faster and more reliably allows improved component design and optimal maintenance scheduling.	Emerging technologies are more expensive and use completely different scientific principles than incumbents, requiring extensive retraining. Consortia to help automate and combine NDT, to reduce labor costs. SBIR grants to create more effective NDT.	Important resource and cultural gap between manufacturers and airlines. If new aircraft require new NDT, airlines may not buy it, favoring technology lock-in. Demonstrator programs to introduce emerging NDT to existing maintenance environments. Lack of trained personnel identified as key deterrent.	A flaw may exist and not be detected. Differences in failure modes between polymers and metals. Lack of scientific knowledge about which NDT is best. NASA research on basic material behavior. FAA funded Centers of Excellence to compare performance of traditional vs emerging NDT. Information publicly available
Process Technologies	Increase productivity and reduce variability in production	High fixed costs but lower marginal cost, require high production volumes to compete with manual labor. While some programs like ACEE induced the manufacture of hundreds of components, demand was not large enough	Generic machines need to be applicable to the specific context of each industry. Several consortia devoted to assessing the feasibility of lower-cost manufacturing processes.	Optimal process configuration achieved through trial-and-error, important source of competitive advantage.
Simulation	Accelerate product design, and reduce need for physical testing	Initial setup costs are high, as companies perform physical tests to obtain the right value for simulation parameters, but at high volumes it is cheaper than physical testing	Differences in culture and infrastructure between academic spinouts and manufacturing firms. Undersupply of skilled labor. Consortia to select industry-specific case studies to check compatibility between physical and digital testing.	Models show a simplified version of reality, and it is unclear what happens inside the 'black box'. Firms might not trust them. Use of public infrastructure to validate simulation models. R&D funding for basic materials research
Material databases	Reduce qualification costs and harmonize practices, allow for supplier specialization, reduce risks	Social benefits much larger than individual costs, but leading firms may lose strategic advantages if their knowledge becomes standardized Public funding to create shared testing and data infrastructure, in collaboration with academia	Material design data needs to be approved by regulators International regulatory bodies formally endorsed the new qualification.	Knowledge asymmetries across players. It is difficult to create rules valid for more than one material or component. AGATE/NCAMP process provides a 'canned' process applicable to any material combined with small sample testing. Data made available to the public.

traditional boundaries of the manufacturing firm (Link and Metcalfe, 2008; Link and Scott, 2010a; Tassey, 2004). Existing studies miss any granularity across types of MET. However, our findings suggest that this granularity is essential to designing efficient public support.

The impact of factors such as technology complexity (Macher, 2006; Rogers, 2003; Singh, 1997), market size (Acemoglu and Linn, 2004; Fuchs et al., 2011; Peças et al., 2009), or network effects (Choi and Thum, 1998; Saloner and Shepard, 1995) on technology adoption, have been extensively studied by economists and management scholars. While previous studies do not necessarily focus on MET, we find considerable alignment between our findings and existing theory. More complex MET, such as simulation software, may reduce interorganizational trust (Bruneel et al., 2017) and hinder knowledge transfer. MET which require large production volumes to become cost-competitive, such as production technologies, are sensitive to changes in demand. Network effects are strong in cases such as NDT or material databases, where industry-wide consensus is required to become standardized.

In addition, our data suggests that other factors greatly influence adoption decisions, which may have attracted less attention from scholars, but are essential for designing effective policy programs. These factors are technological interdependence, nature of learning, and stakeholders' heterogeneity.

The first factor is MET interdependence. By this, we mean that each type of MET cannot be developed and introduced independently, without a holistic perspective of the entire R&D, production, and aftermarket stages. For instance, a certain process technology might be prone to introducing one type of defect in the manufactured component. The right NDT should therefore be chosen that is good at detecting that type of flaw. Similarly, conducting realistic simulation needs testing and monitoring equipment that can provide the required input for the simulations. As a result of this interdependence, efforts to introduce a single MET without taking the entire production context into account, probably have a lower chance of success. Furthermore, standardization relies heavily on having a technologically consistent production process across firms. Overall, we would expect that MET interdependency raises the social barriers to technology adoption, as it increases the need for industry-wide consensus, and encourages incremental innovation which does not require the rest of the pre-existing technology infrastructure to change.

The second factor is the nature of learning involved in MET adoption. Developing process technologies, or generating material databases, requires extensive (and costly) trial-and-error. Such experimental trials lead to the development of a wealth of tacit knowledge about the manufacturing process. Tacit knowledge may become a strategic advantage (Teece and Pisano, 1994), discouraging cooperation with other industry members and the research community. Conversely, technologies such as NDT or simulation software depend largely on the development of scientific models to make sure we maintain the properties of the manufactured product. Developing scientific models typically falls outside the traditional boundaries of the manufacturing firm. On the one hand, this constitutes a barrier, as technology users need to ensure the underlying science is accurate, which may generate a feeling of mistrust towards new models, especially in the early stages. On the other hand, once scientific models are validated, knowledge may become publicly available, reducing information asymmetries.

The third factor is the number and heterogeneity of stakeholders in technology development. Policy scholars have devoted considerable efforts to study university-industry technology transfer (Etzkowitz and Leydesdorff, 2000; Link and Siegel, 2005; Mowery et al., 2015). While university-industry interactions might be important, like in the case of simulation software, our findings suggest that we need to consider a considerably larger diversity of actors. We observe that friction may arise between on the one hand developers of MET, who want to create solutions that can be applied across multiple sectors, and users who need MET tailored to their needs. Furthermore, we observe that even within the same industry, there is great heterogeneity in terms of knowledge and financial resources available to companies across the supply chain. This diversity fosters conflict between technology leaders and followers, manufacturers and service providers, further hindering consensus.

The effect and magnitude of each of these factors on technology adoption can only be measured through large-scale theory-testing research. In addition to other standard metrics, quantitative researchers may consider the use of patent data to construct variables similar to the concept of technological distance (Aharonson and Schilling, 2016; Bar and Leiponen, 2012). The nature of learning can be evaluated through surveys or participant observations at the firm level (Chaston et al., 2001; Nonaka and von Krogh, 2009). An analysis of the participants in public private partnerships and business innovation grants may generate insights into the number and heterogeneity of stakeholders; however, it might only be possible to evaluate the role of final users such as airlines, and the effect of potential cultural differences, through surveys (e.g. Cui et al., 2006).

7.2. *Practical implications*

Our findings provide insights relevant to both policymakers and managers at manufacturing firms. Currently, governments around the world are focusing most of their efforts to foster manufacturing innovation through large public private partnerships such as the National Network of Manufacturing Innovation in the U.S., the Fraunhofer Institute in Germany, or the Catapult Network in the U.K. R&D contracts are typically run under cost sharing structures which are expected to become financially sustainable in the long term. We would expect such contracts to be suitable for developing the MET that can be translated into measurable productivity gains. However, consortia participants might tend to avoid co-investing in those MET where network effects are high and generated knowledge is hardly appropriable. Furthermore, MET may be mature in the eyes of government programs (e.g. reached the highest Technology Readiness Level), but still face important social barriers to their adoption, such as the need for sustained workforce development. If this misalignment between public and private interests is not resolved, industry's MET infrastructure may become unbalanced and never achieve the full potential of a manufacturing process. Composite materials in aviation represent a clear example of these limitations, as designers still tend to design composite structures as if they were metallic (Chatzimichali and Potter, 2015).

Due to the salient diversity of MET, and their barriers to adoption, there is not a one-fits-all solution. Policy mixes should be adapted to the socioeconomic reality of each industry, and not be merely copied from elsewhere (Breznitz, 2007; Zeitlin and Herrigel, 2000). Policymakers could use Tables 1 and 4 as a basic tool to map the perceived barriers to adoption against the policy mechanisms more likely to challenge them. Technology foresight exercises such as roadmapping (European Commission, 2013; Phaal et al., 2004) or expert elicitation (Morgan, 2014) may help to reveal the most relevant sources of uncertainty and project interdependencies, fostering coordination across public and private stakeholders. A potential mechanism to manage interdependencies is to shift the focus of the research contracts from specific technologies to final products. An example of such program is AGATE, a consortium 'to develop the technology to create a single-engine, four-passenger aircraft with improved avionics and crashworthiness features that will sell for approximately US$100,000' (Cole, 2001, p.ii). Public agencies might also provide industry with platforms for experimentation in the real world, such as the Air Craft Energy and Efficiency program (ACEE) in the late 1970s (Bowles, 2010; Tenney et al., 2011).

We find that the origins of MET used in aviation are quite diverse, including the metallurgy, mining, and textile industries. Given this potential to be used across a variety of industries, suppliers of MET ought to consider the trade-offs between designing a flexible MET which can be translated relatively easily to any production environment, or cater to the needs of one relevant industry or customer. While focusing flexibility may require a higher initial investment and a change in organizational culture, it would allow MET suppliers to adapt to unexpected market opportunities (Thomke, 1997). To reduce cultural barriers to adoption, MET users may want to establish MET co-development partnerships with MET suppliers. Through these partnerships, MET users can also ensure that novel MET satisfy their needs with the least amount of adaptation possible.

7.3. *Limitations and future work*

This paper suffers from the typical limitations of qualitative research. "In journal articles, multi-case researchers face a particularly difficult trade-off between theory and empirical richness," (Eisenhardt and Graebner, 2007). Within the scope of this paper, the data we present does not aim to convey the full picture of the history of advanced composite materials, and the (intensive) government intervention in composite technology development. Instead, we have highlighted characteristics of the technology and accompanying development programs which might be more identifiable by decision makers. We have focused mostly on efforts in the U.S., as the American aviation industry, led by USAF, NASA and FAA, spearheaded the application of composites in the late twentieth century (RAND, 1992). Information gathered through interviews might be subject to temporal biases, especially when recalling historical events. Although we expect our findings to be applicable to other process-based manufacturing fields, the external validity of our findings can only be assessed through quantitative theory-testing research.

Further research is needed to improve our understanding of how the barriers to adoption across types of MET evolve in time, and how public support may need to adapt to such evolutionary processes. Policy adaptation might prove particularly difficult in fast-evolving fields, or in the presence of sudden exogenous shocks. In addition, it remains unclear whether tighter collaboration between government and the private sector, which may increase industry's innovative performance, might also increase the risk of agency capture and a deviation from government's objectives.

8. Conclusion

This paper explores the alignment between public support for manufacturing innovation, and the barriers to adopting four categories of manufacturing-enabling technologies (MET). Using the diffusion of innovations theory, we examine the case of those MET used to support the introduction of advanced composite materials in aviation. Our findings highlight the essential diversity in the forces influencing technology adoption of different families of MET. We unravel what market and technology-level characteristics affect the adoption of MET. Current government programs oriented towards fostering manufacturing innovation might be unfit to develop certain MET, especially those which are a lower priority for the private sector, or where there are significant cultural barriers between MET developers and users. We provide policymakers with guidelines on how to tailor public support to each type of MET.

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Appendix A. Interviews

Table 6
Brief description of our 26 interviewees and their area of expertise

#	Short description of interviewee's expertise	NDT	Process	Simulation	Databases	Policy
1	Pioneer in the analysis of structural integrity of composites		X			
2	Director of a research center, expert in composite structures					x
3	Expert in the evaluation of NDT efficacy in the aeronautics industry	x				x
4	Longstanding member of composite standardization committees			x	x	x
5	Expert in risk mitigation and certification of composite structures	x	X	x	x	x
6	Co-developer of first-ever guide for inspecting composites	x				
7	Industry leader in the certification of all-composite aircraft	x	X	x	x	x
8	Program manager, 30+ years of experience in composite research	x	X	x		
9	Leader of composites research at a public agency	x	X	x		
10	Expert in composites aging	x	X	x		
11	Founder of a composite research team at a public agency		X	x		x
12	Project coordinator at standards agency				x	
13	Retired, industry expert in the application of composites since the 1960s		X			
14	40 years of experience in design and certification of composite structures		x		x	
15	Expert in the characterization and certification of advanced materials				x	
16	Pioneer, creating consortia for civilian composites technology transfer		x			x
17	Technology strategist, consortium devoted to the advancement of composite materials			x		
18	Project manager, development and implementation of simulation tools			x		
19	15+ years of experience in the simulation of composite structures			x		
20	Project manager, digitalization of composites manufacturing		x			x
21	Project manager, co-development of process technologies		x			x
22	Leader, laboratory devoted to the characterization of composites	x				x
23	Leader and strategist of a consortium for technology transfer in aviation					x
24	Design and project evaluation, technology transfer consortium					x
25	20 years of experience, business development of process technologies		x			
26	30 years of experience, NDT research and development	x				

Appendix B. Sample of interview questions

Questions for program managers:

- What was the industry context which led to the creation of this program?
- What type of technologies did the program aim to develop? What are their main advantages and disadvantages?
- Who were the most important/active members? How were members selected?
- How were costs split among program members?
- What were the main outcomes of the program?
- How was intellectual property managed? Who owns the data generated during the program?
- To what extent have the technologies developed in the program been adopted by industry? What have been the main barriers?

Questions for research institutes:

- How do you choose which R&D projects to pursue?
- How are costs split among the membership?
- What types of technologies are members usually interested in developing?
- What is your membership's attitude towards this (specific type of MET)?
- How do companies balance cost and performance when choosing their MET?
- What are the major factors that determine when to move a technology from R&D to production?
- To what extent are the developed technologies generic? How much adjustment do they need to fulfil each firm's needs?

Questions for academics:

- How did you get involved in (a certain public program)? Have you continued doing research in areas related to the program?
- What were the main outcomes of the program? Can we see those technologies being used today?
- What are the main challenges when working with this technology?
- What are the major advances in scientific knowledge in this area?
- Does the material behave in a way that we can still not explain?
- Which do you believe are the most useful MET when trying to tackle (a certain issue in the manufacturing of composites)?

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