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Citation for published version:

Slayton, R & Spinardi, G 2016, 'Radical innovation in scaling up: Boeing's Dreamliner and the challenge of socio-technical transitions', *Technovation*, vol. 47, pp. 47-58.
<https://doi.org/10.1016/j.technovation.2015.08.004>

Digital Object Identifier (DOI):

[10.1016/j.technovation.2015.08.004](https://doi.org/10.1016/j.technovation.2015.08.004)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Technovation

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Contents lists available at ScienceDirect

Technovation

journal homepage: www.elsevier.com/locate/technovation

Radical innovation in scaling up: Boeing's Dreamliner and the challenge of socio-technical transitions

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ARTICLE INFO

Article history:

Received 5 November 2014

Received in revised form

16 August 2015

Accepted 23 August 2015

Keywords:

Sociotechnical transitions
Strategic niche management
Multi-level perspective
Radical innovation
Process innovation
Product innovation
Learning curve
Sustainability

ABSTRACT

Radical technological innovations are needed to achieve sustainability, but such innovations confront unusually high barriers, as they often require sociotechnical transitions. Here we use the theoretical perspectives and methods of Science and Technology Studies (STS) to demonstrate ways that existing theories of innovation and sociotechnical transitions, such as the Multi-Level Perspective (MLP), can be expanded. We test the MLP by applying STS methods and concepts to analyze the history of aircraft composites (lightweight materials that can reduce fuel consumption and greenhouse gas emissions), and use this case to develop a better understanding of barriers to radical innovation. In the MLP, "radical innovation" occurs in local niches—protected spaces for experimentation—and is then selected by a sociotechnical regime. The history of composite materials demonstrates that radical innovation could not be confined to "niches," but that the process of scaling up to a wholly new product itself required radical innovation in composites. Scaling up a process innovation to make a new product itself required radical innovation. These findings suggest a need to refine sociotechnical transitions theories to account for technologies that require radical innovation in the process of scaling up from the level of sociotechnical niche to regime.

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1. Introduction

On October 26 2011, the Boeing 787 made its first commercial flight on a route from Tokyo to Hong Kong, and set a new standard for fuel efficiency. The 787 "Dreamliner" achieves the highest efficiency among mid-sized airliners by using several innovative technologies, including lightweight composite materials that account for approximately 50% of the aircraft's weight. Launch customer All Nippon Airlines reported that the aircraft is 21% more fuel-efficient than its predecessor. More significantly, Boeing's decision to build the Dreamliner has triggered a broader shift in aircraft manufacturing. As orders for the Dreamliner began pouring in, Boeing's arch rival, Airbus, promised that its direct competitor to the 787, the A350, would boast 53% composite construction (Wall, 2008).

The industry's shift towards composite construction is good news for advocates of energy efficiency, but it also raises a key question: why did the industry not fully embrace these innovative materials earlier? As Fig. 1 shows, airliners have used composite

components for decades. Indeed, one business aircraft, the Beechcraft Starship, was built entirely from composites in 1985, and remains operational today, a decade after the manufacturer decided to decommission it (Scherer, 2010). Why has commercial aviation adopted composite materials so slowly, and what policies might enable greater use of weight-saving materials?

By addressing these questions, this paper aims to clarify theories of how technological innovations cross the "valley of death" to enter wide-spread use. As innovation scholars have noted, new innovations may struggle to enter markets, both because they initially have relatively poor performance (Mokyr, 1990 calls them hopeful monstrosities) and because they must be compatible with a broader *sociotechnical regime*—a complex, heterogeneous, and interdependent network of organizations, artifacts, engineering practices, skilled workers, government policies, financing systems and consumers. Such regimes encourage incremental innovations, which improve price and performance of technologies already in the market, while discouraging radical innovations, which are discontinuous and can cause regime change (Freeman and Perez, 1988).

Evolutionary economists initially coined the "regime" concept to describe the rule-sets that govern decisions about how to develop and produce new technologies (Nelson and Winter, 1977, 1982; Dosi, 1982). Regimes encourage what engineer-historian

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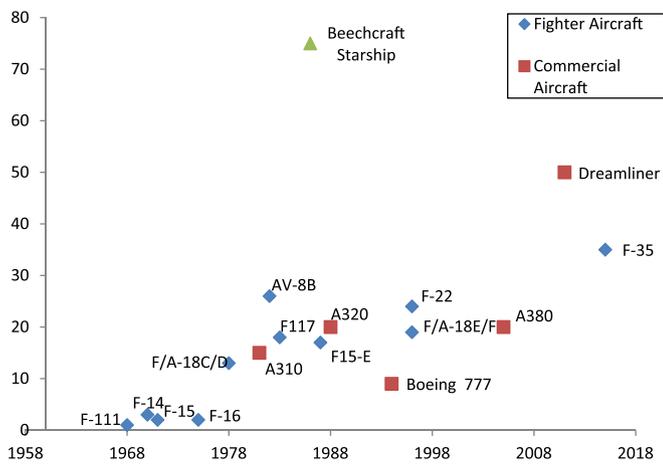


Fig. 1. Percentage of aircraft mass comprised of composite materials (initial configuration).

Walter Vincenti (1993) termed “incremental design,” which is based upon known concepts and technologies, rather than “radical design,” in which engineers must develop new knowledge as well as new artifacts. Rip and Kemp (1998) expanded the notion of regime to include the rules shared by technology’s “selection environment.” Geels coined the notion of “sociotechnical regime” to describe a larger set of rules—those held by policymakers, user groups, financiers, and so on (Geels, 2002). This paper defines sociotechnical regimes broadly to include artifacts and organizations, a usage that is common in the literature (see e.g. (Kemp et al., 1998)), and explicit in Gabrielle Hecht’s notion of “technopolitical regimes” (Hecht, 2001; Allen & Hecht, 2001).

Regimes can create interdependencies that cause “technological lock-in,” a situation in which new innovations are unable to succeed, even if they are superior to established technology (Unruh, 2000; David, 1985; Arthur, 1989). Radical innovations often depend on the integration of many interdependent systems to succeed; although they may be “generic” in their ability to transform many industries and applications, radical innovations can rarely slot into a modular framework in a “plug-and-play” manner (Christensen et al., 2015; Maine and Garnsey, 2006). In particular, downstream obstacles in the value chain often need resolving before adoption can take off (Musso, 2009). Future improvements in such radical innovations are hard to predict when those innovations are still immature, and may not follow the traditional ‘learning curve’ seen in more mature technologies (Linton and Walsh, 2004).

Scholars have developed several frameworks for analyzing how such innovations can be successfully introduced into regimes. Kemp, Schot, and Hoogma proposed creating “strategic niches,” protected spaces for technological innovation and experimentation by a broad range of stakeholders, including researchers, companies, policymakers, and end-users of technology (Kemp, Schot and Hoogma, 1998). Rotmans, Kemp, and van Asselt broadened the notion of niche management to overall transition management (Rotmans et al., 2001).

Thinking about transitions has also been heavily influenced by the multi-level perspective (MLP), which treats sociotechnical regimes as an intermediate level between local niches and overarching landscapes (Geels, 2002, 2005a, 2006b, 2011, 2014; Elzen and Geels, 2004; Geels and Schot, 2007; Raven and Geels, 2010; Sutherland et al., 2015; Fuenschilling and Truffer, 2014). According to Geels and Schot (2007, p. 400), “transitions come about through interactions between processes at these three levels: (a) niche-innovations build up internal momentum, through learning processes, price/performance improvements, and support

from powerful groups, (b) changes at the landscape level create pressure on the regime and (c) destabilization of the regime creates windows of opportunity for niche innovations.”

Conceptual frameworks such as strategic niche management and the MLP helpfully broaden evolutionary economic approaches to sociotechnical transitions by emphasizing social and cognitive dimensions of innovation and selection (Geels 2006a, b; Raven and Geels, 2010; Klerkx and Leeuwis, 2008). However, most of the literature focuses on what innovation scholars have dubbed “product innovations,” which are associated with new end-products, rather than “process innovations,” which improve the performance of existing products (Tornatzky and Fleischer, 1990; Abernathy and Utterback, 1978). Advanced materials, such as the composites discussed here, are examples of process innovations, which have been shown to confront unique challenges for value creation (Maine and Garnsey, 2006; Maine, Lubik and Garnsey, 2012; Linton and Walsh, 2008, 2004)

Furthermore, we argue that transition theories in general, and the MLP in particular, could be refined by more systematically applying methods drawn from science and technology studies (STS). In what follows, we briefly outline three ways in which transition theories could benefit from STS insights. We then use these methods to analyze the development of a “niche” for composite aircraft components, and efforts to scale up that niche to a potentially regime-changing aircraft—the Dreamliner. Whereas the sociotechnical transitions literature generally argues that radical innovations are developed in niches, and subsequently selected by the dominant regime, this case study shows that some technologies must undergo radical innovation in the process of scaling up from the niche to regime level. We argue that STS methods and concepts can help the transitions literature to accommodate the need to take radical innovation beyond the niche.

2. Methods and theoretical perspective

Like many studies of sociotechnical transitions, we adopt a case study method, using the history of composites development and Boeing’s Dreamliner experience to extend and refine existing theories. However, our approach is different than most existing studies in three ways which reflect the theoretical perspective and methods of STS.

First, while sociotechnical transitions theory has primarily been developed through case studies of innovations that successfully effected transitions, we focus on a partial or incomplete transition. This contributes to a theoretical perspective that follows the STS ‘symmetry principle,’ in which success and failure both require sociological explanation (Pinch and Bijker, 1987). Although there are a few case studies of innovations that have yet to cause transitions (Hofman and Elzen, 2010; Elzen et al., 2011; Grünewald et al., 2012; Raven and Geels, 2010; Geels, 2014), frameworks such as the MLP have primarily been used to study successful transitions (Bunduchi et al., 2011; Turnheim and Geels, 2012; Hall et al., 2014; Geels, 2005b, 2002, 2006a; Geels and Schot, 2007; Berggren et al., 2015; Rosenbloom and Meadowcroft, 2014). Geels and Schot (2010, p. 79) note that theorization would be improved by correcting ‘the bias towards winners and novelty’. Similarly, Wells and Nieuwenhuis (2012) argue that the literature focuses on causes of change at the cost of understanding “transition failure.”

Second, rather than pre-defining composite aircraft components as either “incremental” or “radical” innovations, we focus on how different types of actors in the commercial aviation regime have conceptualized these innovations. This methodological choice reflects the STS emphasis on the interpretive flexibility of technology (Pinch and Bijker, 1984). Different actors could view the same innovation as relatively radical or conservative,

depending on their perspective. Indeed, in our case study the very conception of an incremental (and therefore low-risk) innovation was a resource for Boeing executives in the debate about whether the 787 was too risky. This analysis of what counts as conservative or radical contrasts with the approach of many innovation studies, which tend to adopt a structural rather than a “micro-level” view. As Geels and Schot have noted, the global theory of the MLP ‘needs to be complemented by local theories which help to analyze how actors navigate, struggle and negotiate on specific alternatives’ (2010, 101).

Third, we take seriously the injunction of STS to “open the black box” of technology, by considering how specific technical challenges affect the process of regime change. Our results suggest the need to broaden existing frameworks to account for aspects of technological design. In particular, we find that significant innovation (and according to many observers, radical innovation) in composite manufacturing was needed in order to scale up from niche applications of composites (e.g. tail pieces) to regime-changing applications (e.g. fuselage and wings). This finding complicates the dominant framework for sociotechnical transitions, in which radical innovation is confined to protected niches, and scaling-up requires only incremental adjustments to the new technology. We argue the composites case illustrates a type of innovation-driven transition that merits further study. Furthermore, we suggest that closer attention to technological specificity can address the MLP’s acknowledged need for a more complete understanding of how niches and regimes interact to cause sociotechnical transitions (Schot and Geels, 2008).

We draw our empirical data from primary sources, including industry journals, government reports, and mainstream media. One reason for relying on primary sources is the dearth of secondary literature about the evolution of composites in aviation. Another reason is that primary sources are better suited for gaining a micro-level understanding. *Aviation Week & Space Technology (AW&ST)*, a major industry journal reporting international news on both civil and military aviation, served as one significant source of data. The Lexis-Nexis database, which contains all *AW&ST* articles from 1975 to the present, was searched using keywords such as “composites,” “carbon fiber” (the type of composite most commonly used in aircraft components), “Boeing” and “787”. These searches produced thousands of pages of documents. We also studied industry, academic, and government reports on composites manufacture, as well as popular news articles about the use of composites in commercial aviation. These reports provided a consensus view of the state-of-the-art in composites manufacture, and how the state-of-the-art changed over time. Finally, we examined articles about the Dreamliner in the popular media to incorporate public perceptions and stakeholders into the analysis.

In the remainder of this paper, we first describe how the composites niche was established in commercial aviation, and outline specific lessons learned. We then discuss why Boeing decided to develop a plane with an all-composite wing and fuselage, and the difficulties the company faced in scaling up composite components. As we will see, Boeing was forced to undertake radical innovation in the process of increasing the size and complexity of components, which could not have been accomplished in the niche of small aircraft components.

3. Understanding the niche for composite aircraft components

In this section we describe how aerospace use of composite materials developed, and how significant use of composites in primary structural elements of aircraft required advances in knowledge with regard to both manufacturing processes and

operational safety.

3.1. Landscape pressure and niche creation

Composite aircraft components typically consist of reinforcing fibers (most commonly carbon) embedded in a resin (most commonly an epoxy). High strength carbon fiber was first developed at Union Carbide in the late 1950s, with efficient manufacturing processes developed in both the UK and Japan in the early 1960s (Spinardi, 2002). Several properties of carbon fiber drew special attention. Its strength was comparable to that of metal but at a much lighter weight, a property that would enable military aircraft to enhance their speed, range, and performance.

Unfortunately, composites such as carbon fiber also came with significant disadvantages: high production cost, uncertainties about methods for maintenance and long-term costs, and new risks to safety. Thus, they were used only in niche applications in the aerospace industry. Military forces were willing to pay the extra cost of composites in order to reduce weight and improve the performance of fighter aircraft. Composites’ ability to withstand high temperatures also made them very valuable for applications in missiles and space vehicles. “Landscape” pressures, specifically the Cold War arms race and space race, nurtured this early niche, and use of composites grew rapidly in the 1970s and early 1980s (Fig. 1). For example, in the late 1970s, British Aerospace Corp and the German Messerschmitt-Boelkow-Blohm began replacing tailerons in the Tornado—a fighter plane jointly produced by Great Britain, West Germany, and Italy—with carbon fiber components. The companies aimed to gain experience that would enable greater use of carbon fiber in future fighters (Staff, 1979b).

In the 1970s, new landscape pressures—the energy crisis and the rising price of oil—encouraged commercial aircraft manufacturers to use lighter weight materials. Airlines became more willing to shoulder higher production costs in order to save on operating costs. Aluminum manufacturers responded to the oil crisis and competition from composite components by developing lighter weight aluminum alloys, but even the lightest weight aluminum alloys were heavier than carbon fiber. In 1982, Airbus manufactured one of the first airliners to contain composites, the A310, with a carbon fiber vertical tail fin and carbon brakes. The carbon brakes alone saved 1100 pounds, more than any other component (Lenorovitz, 1985). Airbus went further with its A320, the first commercial aircraft to use an all-composite tail, making the plane approximately 20% composite by weight (Younossi et al., 2001).

These developments gave composites manufacturers cause for optimism. In 1981, one production engineer predicted that aircraft would be more than 50% composite construction by the end of the 1990s (King, 1981). British, German, and French companies were all planning to design and manufacture fighter aircraft that would use 40% composites by weight, and the proposed British P-110 fighter was to include a wing that was 80% composites by weight (Staff, 1980). Lockheed bolstered its carbon fiber manufacturing capabilities, predicting that composites would comprise 40% of fighter/attack aircraft weight by 1990 (Kolcum, 1986). Similarly, in 1983, the Dutch aircraft company Fokker announced that its next commercial aircraft, to be introduced in 1992, would consist of 50–65% composite materials by weight (Feazel, 1983).

Although fuel prices dropped in the mid-1980s, returning airlines to their traditional focus on initial cost of production rather than potential fuel savings (Feazel, 1985), both airlines and manufacturers remained optimistic about composites. Ernst Simon, Lufthansa’s general manager of engineering, noted that a 10% reduction in weight would increase Lufthansa’s profits by \$20 million/year, and predicted that manufacturers would introduce an

all-composite wing by 1992 (Staff, 1985). In the early 1990s, composite suppliers predicted that sales of non-metallic materials would grow at a rate of 15–18% over the decade (Velocci, 1991). An economic downturn encouraged commercial manufacturers to again seek ways of improving fuel efficiency, and composites saw growing use in cabin design as a result (Ott, 1993). An interest in fuel efficiency also drove Fokker and the Netherlands' National Aerospace Laboratory to launch a 5 year research program to reduce the costs of producing composites, aiming to produce an all-composite wing by the late 1990s (Staff, 1994).

In the 1990s commercial aircraft increasingly used composites for relatively small components, such as tail fins, horizontal stabilizers, and landing gear. But they did not use composites for the largest and most high-risk parts of the aircraft: the fuselage and wings. By the turn of the millennium, no airliner had more than 20% composite construction. To understand why aircraft manufacturers did not attempt an all-composite wing or fuselage earlier, we must consider what carbon fiber's market niche did, and did not, enable manufacturers to learn.

3.2. Learning about manufacturing

The key point to understand about composite materials is that they are produced at one and the same time as the composite structure. Thus, the final properties of the material are strongly influenced by the shape of the component itself. Additionally, the process of manufacturing composite aircraft components is highly labor-intensive and specific to the particular component. This meant that knowledge of how to manufacture small components (the focus of the composite niche) could only partially be applied to efforts to manufacture much larger components. This section briefly summarizes some of the learning that took place in the niche of small composites.

Most composite component manufacturers begin with sheets of pre-impregnated carbon fiber, consisting of bundles of fiber pressed into a resin. This “pre-preg” or “pre-form” must then be molded into the appropriate shape. By the turn of the new millennium, the two most common ways of producing composite components for aircraft were resin transfer molding (RTM) and fiber (or tape) layup. In the RTM process, carbon fiber preform is placed within a mold, the mold is closed, and resin is injected into the mold. The part is then cured under high temperature and pressure. The primary advantage of RTM is its ability to produce complex shapes reproducibly and precisely. Unfortunately the mold must be made of expensive materials to withstand high temperatures and pressures (Younossi et al., 2001). Nonetheless, because RTM could be highly automated, for large production runs it was competitive with aluminum by the early 1990s (Staff, 1990).

The layup process is much more difficult to automate. It begins with designing and building a tool that will be used as a substrate for the carbon fiber or tape, thereby giving the final component its shape. For each part, plies are cut by hand or with automated cutting equipment. Next, workers place the plies on the tool by hand, using Mylar templates or optical projection systems as a guide. Since the directional strength and stiffness of the parts comes from the alignment of these fibers, it is crucial that workers lay the plies in the correct order and direction. Parts can have up to 80 plies that must be properly stacked and aligned. After laying the plies, the workers apply pressure to compact the pile and remove any voids.

After the plies are laid and compressed, workers place additional materials over the part to ensure that the plies lay flat while also allowing excess resin to bleed out of the assembly while it is curing. Workers then enclose the entire assembly in a heat-proof plastic bag and place it in an autoclave, which applies heat and pressure to cure the part. Depending on the type of resin being

used, the curing process can range from 5–11 hours, at temperatures ranging from 350–600 °F, and pressures of 100–200 psi (Hughes, 1990). The parts sometimes also go through a postcure cycle. After curing is complete, workers inspect and trim the part. At the turn of the millennium, a review concluded that the laying up and compacting the plies accounted for over 40% of the labor required for part fabrication, while compressing, bagging, inspecting and trimming comprised another 40% (Younossi et al., 2001).

Tacit knowledge—non-codified knowledge residing in the hands of workers and organizational arrangements of companies (see e.g. MacKenzie and Spinardi, 1995)—was thus critical to producing composite components reliably. Nonetheless, manufacturers were able to reduce costs by developing techniques for automating some tasks. For example, automated tape laying machines, which cut and place tape from a spool, came into widespread use in the 1980s. However, they were only suitable for large skins with minimal contours (Younossi et al., 2001).

By the early 1980s, automated processes enabled manufacturers to produce some components less expensively with carbon fiber than metal. Although composite materials remained much more expensive than metal, the complex process of cutting and assembling many metal parts was labor intensive and generated significant amounts of scrap. Raw materials accounted for about 20% of the cost of a fighter aircraft, with the complex manufacturing and assembly process accounting for the rest (King, 1981). Since composite components generated little scrap and were fabricated as seamless wholes, they reduced assembly costs and were a promising alternative.

Nonetheless, metal retained advantages for components that could be fabricated with relatively little scrap metal and few subassemblies. Metal components could also be more easily assembled because they could be slightly reshaped as needed to mate with other parts. By contrast, since most composites cannot be reshaped after curing, composite components required more precise manufacturing to ensure a good fit. Assembling composite components also required special tools and fasteners that could be very expensive. For example, in the mid-1990s, an automatic fastener could cost as much as \$100 per hole because of the time required to drill, measure, and inspect the hole, as well as the cost of special fasteners (Vosteen and Hadcock, 1994).

Perhaps most significantly, automation could not eliminate the need for tacit knowledge. Even the most automated composite construction processes require skilled workers to intervene at key moments, such as manually debulking, bagging, and inspecting parts. The need for tacit knowledge also prevented the easy transfer of skills from one project to another. In 1994 a NASA-commissioned study noted that technology transfer rarely occurred “via technical reports, presentations, lectures and courses,” but “was best accomplished by having experienced and inexperienced people working together” (Vosteen and Hadcock, 1994). Additionally, because composite components could not be readily reshaped after fabrication, design and production teams could not be readily separated: the “close involvement of manufacturing/assembly personnel in the design process is essential to strike the proper balance between design requirements and the need for producibility” (Vosteen and Hadcock, 1994).

The composites niche thus provided valuable lessons about automation and the organization of manufacturing and assembly teams. But it also made clear that experience with small components was a limited guide for dealing with larger components. Throughout the 1990s, concerns about the high cost of production discouraged airline manufacturers from pursuing large composite components. For example, in October 1991 Airbus announced that its new extra-large, 600 seat airplane would not use a composite fuselage or wing because of concerns that such structures would

be too expensive to manufacture (Lenorovitz, 1991).

3.3. Learning about safety and maintenance

In addition to higher production costs, composite components raised concerns about safety and maintenance costs. For example, in the late 1970s NASA expressed concern that fibers released in a fire might interfere with electronic signals (Staff, 1979a). An extensive testing program put these concerns to rest, but composites continued to raise questions about lightning strikes. Because aluminum airframes conduct electricity easily, current from a lightning strike flows readily on the aircraft skin and dissipates into the air without compromising internal electronics. However, because electricity cannot flow easily through composites, charge from a lightning strike could build up at the point of contact, and arc to other points of the plane, destroying electronics. To protect against such lightning strikes, manufacturers built electrically conductive layers into composite plies and developed other techniques for protecting electronics (Tocknell, 2009).

Composites also raised concerns about structural integrity. The risks of using new materials for aircraft were tragically demonstrated with the de Havilland Comet, the first airliner to use a pressurized aluminum fuselage at high altitudes. On three separate occasions in the mid-1950s, Comet aircraft broke up in mid-flight as the pressurized fuselage underwent an explosive decompression (Marks, 2009). Although the Comet had been subjected to the most rigorous safety testing available to that time, engineers did not fully understand how the process of pressurization and depressurization would fatigue the metal, leading to cracks around the plane's square windows, and eventually structural failure. Although engineers learned to make oval windows and use structural reinforcements to make aluminum safe, the lesson was clear: a new material came with unknown risks.

Even if airlines assumed that composites could be made structurally safe, they worried that maintenance costs might skyrocket. Niche applications of composites provided some opportunity for learning. For example, in 1979 Airbus added various composite components to four A300s in operation with Lufthansa, in order to study maintenance costs (Bassett, 1979). Unfortunately, by the mid-1980s Lufthansa concluded that the costs of maintaining composite components were twice those of their aluminum equivalents. Without easy and non-destructive methods for testing the integrity of a part, technicians were forced to spend days on inspection. Unlike aluminum, composites could not be reshaped, so extensive damage typically required replacing the entire part (Staff, 1990). This in turn meant that airlines lost additional revenue as aircraft were taken out of operation (Staff, 1985). Airlines argued that aircraft manufacturers had not provided adequate non-destructive testing techniques or worker training to ensure the safety of composite components (Staff, 1985).

Concerns about the costs and risks of maintenance continued, especially after the explosive decompression of a Boeing 737 over Hawaii in 1988 demonstrated that a cracked fuselage could hide beneath the painted surface of aircraft. Military organizations had special concerns about how to repair battle-damaged aircraft in the field, and often modified initial aircraft configurations to include less composites as time went on (Younossi et al., 2001, p. 10).

Since the U.S. Defense Department needed lightweight components to meet performance goals, it invested in better techniques for inspecting aircraft. For example, in the early 1980s, the Air Force began developing a facility for robotic inspection, which would eliminate the need for the airplanes to be disassembled for inspection. It aimed to cut the inspection time from 3 months to 3 days for a military aircraft, saving at least 50% on inspection costs (Henderson, 1989). Similar work continued throughout the 1990s

(McKenna, 1998).

Niche applications thus provided important lessons about detection and repair of composites. Unfortunately, by the late 1990s, airlines concluded that composites often demonstrated a better service record than their metal counterparts during the early period of adoption, but that they were less resistant to impact damage (McKenna, 1998). While impacts on metal structures would cause immediately visible damage, impacts to composites could cause a slow delamination process that was difficult to detect, but could cause a long-term failure (Staff, 2001). The need for better methods of detecting and repairing damage remained.

4. Scaling up composites

We now turn to describing Boeing's decision to make large aircraft structural components such as the fuselage and wings, and the challenges of scaling up composite production; challenges that in this case demonstrate that establishment of a successful "niche" does not necessarily mean that an innovation is sufficiently mature to effect regime change.

4.1. The decision to scale up

In short, ongoing concerns about the high costs of production and maintenance limited the development of large composite components through the late 1990s. Using MLP concepts, we can say that landscape pressures (high fuel prices and the Cold War arms race) nurtured the composites niche (in the form of a market for small components). Niche innovations (such as improved inspection technology and automated tape-laying machines) helped expand use of composites, but did not enable aircraft manufacturers to scale up composite components to a potentially regime-changing size (i.e. fuselage and wing).

Indeed, Boeing's decision to declare composites mature enough to create fuselage and wing structures was prompted neither by a technological breakthrough, nor by landscape pressures such as rising fuel costs. Instead the initial decision was fueled by a much more company-specific problem: Boeing was losing market share to Airbus.

In the late 1990s, Boeing's orders were falling while Airbus's orders rose, and in 1999 Airbus won more orders than Boeing for the first time. As Boeing felt its incumbency threatened, it became more willing to take on risks. In March 2001, not long after Airbus unveiled its A380—to be the world's largest commercial aircraft—Boeing announced its new Sonic Cruiser. A radical deviation from the classic airliner aerodynamic design, this was to be a mid-sized plane that would fly 15–20% faster than conventional aircraft and at higher altitudes to enable more direct point-to-point routing. After the September 2001 attacks on the world trade center, Boeing abandoned the Sonic Cruiser concept for a more conventional, but very fuel-efficient design, which eventually became the Dreamliner. On April 26, 2004 Boeing formally launched the Dreamliner production program based upon 50 firm orders with All Nippon Airlines (Staff, 2004).

Even before the Sonic Cruiser became the Dreamliner, Boeing planned to use composites extensively. More fuel efficient engines and lighter weight materials were essential to making a faster plane fly economically, and plans for the Sonic Cruiser included 60% composite structures by weight (Wallace, 2001; Smith, 2002, 2001; Staff, 2001). Although Boeing considered lightweight aluminum alloys, it preferred composites for several reasons. Composites enabled the more complex fuselage design that was needed to increase speed without sacrificing fuel efficiency, and resisted corrosion better than aluminum (Barrie, 2003; Dornheim, 2002). Composite structures, unlike aluminum, were strong

enough to enable larger windows (Wallace, 2001). Composite construction could reduce the number of fasteners, thereby reducing noise from fastener-induced turbulence (Staff, 2009).

Some leaders at Boeing also came to see composites as ideal for a new manufacturing strategy that might reduce costs and time of producing new aircraft. Mike Bair, a marketing specialist who became the manager of Boeing's new aircraft project, argued that composites would help reduce manufacturing times because composite components could be cured as seamless wholes (Barrie, 2003; Mecham, 2003a). By avoiding labor-intensive assembly, Boeing would reduce the total number of U.S. assembly workers from thousands to 800–1200. As we have seen, composite component manufacture was labor-intensive, but Bair aimed to outsource this part of the job to countries with lower wages. *AW&ST* explained: "Relying on large modular assemblies will shift more jobs down the supply chain (and off Boeing's payroll, so that bad-times layoffs happen elsewhere)" (Mecham, 2003b).

Bair was part of a broader shift in Boeing management, which in the late 1990s established reduced manufacturing times and costs as a principal goal. Similarly, the head of engineering, manufacturing and partner alignment for the new project, Walt Gillette, directed the Airplane Creation Process Strategy Team in the late 1990s, aimed at reducing manufacturing times (Wallace, 2001). When Boeing unveiled a first prototype fuselage section in 2004, Gillette emphasized that the challenge of the 787 was "not technical viability, but how to manufacture it at commercial cost" (Mecham and Sparaco, 2004, p 46).

Gillette's assurances minimized the safety and manufacturing risks, implying that composite wings and fuselage were not too radical for risk-averse airlines. Boeing had an obvious stake in portraying the Dreamliner as innovative, but not too radical. However, the question of whether or not scaling up composites to the size of wings and fuselage constituted "radical" or "incremental" engineering was far from settled, and was contested by individuals and companies with a clear stake in the outcome.

4.2. Incremental or radical engineering?

Having committed to use of large composite components, Boeing worked hard to reframe many of the associated risks. For example, Boeing acknowledged concerns that composites might not survive "rump rash"—from careless treatment of aircraft by ground crews—but also highlighted tests showing that some composite parts, such as door frames, could better withstand impact than their aluminum counterparts. To prove it, Boeing gave engineers at All Nippon Airlines (ANA) hammers and invited them to try denting a composite aircraft door. They could not (Mecham and Sparaco, 2004).

Boeing promised that composites would cut maintenance costs by 9% and lifecycle costs by 5–6% (Mecham, 2005). Because each composite component was created as a seamless whole, aircraft would have fewer parts, both reducing assembly time and maintenance. Boeing promised that more durable composites and improved electronic systems would enable 59% fewer cancellations than the A330—though it also rolled out its most comprehensive maintenance service ever to support the 787 (Mecham, 2006a, b, 2010).

Some knowledgeable industry insiders viewed Boeing's optimism skeptically. Early on, Boeing's manufacturing partner Vought Aircraft Industries noted that making the parts affordably would "require major breakthroughs in materials technologies and manufacturing processes that currently do not exist" (Phillips, 2002). *AW&ST* noted that despite Boeing's "breezy attitude that carbon fiber is old hat," the manufacturing difficulties were immense: "Notwithstanding carbon fiber's earlier use in the tail fins, Boeing's radical application makes it essentially a new material for

airliners" (Staff, 2005, 58).

Indeed, because composite materials and components are created at one and the same time, large composite components raised new questions about safety. These concerns erupted publicly in 2007 when a Boeing engineer, Vincent A. Weldon, claimed he was fired because he raised legitimate questions about the crashworthiness of the 787. Weldon claimed that Boeing was covering-up problems and filed a whistleblower complaint with the U.S. Occupational Safety and Health Administration. He also wrote and publicized a long letter to the Federal Aviation Administration (FAA) (Weldon, 2007). Boeing denied the accusation and claimed that Weldon was fired for threatening and racist comments made towards an African-American executive. Weldon's whistleblower complaint was denied on the grounds that Boeing was complying with all FAA regulations, but his concerns attracted broad media attention, including an interview with Dan Rather on 60 minutes (Gates, 2007).

Were carbon fiber fuselages and wings radical departures or incremental advancements from the established niche? Far from being obvious categories of analysis, the notions of "radical" or "mature" technologies were actively contested by stakeholders. Nonetheless, Boeing's tribulations with the development of composite aircraft suggest that some aspects of the 787 did indeed require radical engineering.

4.3. In pursuit of the dreamliner

Boeing's project began auspiciously. In 2003, Boeing began contracting for specific parts of the 787. The Japanese firms Mitsubishi, Kawasaki, and Fuji provided the wing box, forward portions of the fuselage, landing gear, wing fixed trailing edge, center wing box, and wheel well for the main landing gear. The Italian firm Alenia teamed with the U.S. Vought to build the horizontal stabilizer and portions of the fuselage (Mecham, 2003c). To streamline production, Boeing created a tiered supply chain that would deliver parts pre-integrated. For example, Spirit Aero-systems would deliver the forward portion of the fuselage to Everett with the cockpit fully "stuffed" with electronics and controls (Tang and Zimmerman, 2009). Boeing would then rapidly "snap together" each aircraft from just seven parts—two wings, three fuselage sections, the horizontal stabilizer, and the vertical fin—and complete the systems integration in just two to three days (Mecham, 2003b).

In spring 2007, as parts began arriving for final assembly, Boeing publicized its streamlined factory in Everett, Washington. The fully stuffed aircraft sections would pause at station zero for 24 hours so that they could equilibrate to the ambient temperatures. At the first station (also called the "big bang" station), a massive machine—the Mother of All Tools Tower (MOATT)—would lift the rear fuselage sections, horizontal stabilizers and vertical fin and attach them to the airplane (Mecham, 2007b). At the second position, workers would add engines and main landing gear, connect electrical systems between each of the sections, and turn on power. The aircraft could then roll itself forward, and the third station would be used to finish testing (Wallace, 2007).

Boeing promised ANA that the first airplane would be delivered in May 2008 (Mecham, 2011; Schofield, 2010b). But in 2007, the schedule began to slip. Because several suppliers were behind schedule, composite components were shipped with "traveled work" to be completed at Boeing's factory in Everett, Washington (Norris, 2007). Boeing chose a splashy date, 7/8/07, to roll out the 787 for the first time, but the plane that rolled out on July 8 was a "Potemkin 787"—it had no interior (Staff, 2008). Managers nonetheless promised that Dreamliner's first flight would come in late August or mid-September (Mecham, 2007a; Staff, 2007a). On September 5 program manager Mike Blair acknowledged that first

flight might be as late as December, but aimed to make up the time by compressing flight testing to even less than the originally planned eight months—already the shortest flight testing program in Boeing's history (Staff, 2007b). On October 10, Boeing was forced to acknowledge a six month schedule slip (Mecham, 2008a). More bad news was forthcoming; by 2011, Boeing had changed the schedule eight times (Schofield, 2010a; Mecham, 2011). Boeing finally gained FAA and European aviation safety agency approval in August 2011, and delivered the first airplane to ANA in September 2011.

Why did Boeing struggle to build the Dreamliner? Industry observers and management scholars criticized Boeing's supply chain management for failing to create appropriate incentives for suppliers, and for making it difficult to anticipate problems (Tang and Zimmerman, 2009; Peterson, 2011; Madslie, 2010). Boeing's management team had no experience with supply chain management (although that changed when program manager Mike Bair was replaced with Pat Shanahan in 2007). Outsourcing contributed to labor unrest which further slowed the program (Tang and Zimmerman, 2009).

Yet the Dreamliner's woes were not solely a result of poor management. They also stemmed from the intrinsic challenges of scaling up composite components to unprecedented sizes. As the following section shows, the radical innovations required to overcome these challenges could not be happen in the market niche of small components.

4.4. Innovations in the process of scaling up

Despite decades of experience with composites manufacture, Boeing's suppliers needed to develop new equipment and techniques to manufacture composite fuselages and wings. For example, manufacturers built unprecedentedly large autoclaves to carefully control pressure and temperatures. Kawasaki built a 17 meter autoclave to cure fuselage sections that were 9 or 10 meters long, while Mitsubishi built an autoclave with an interior length of 36 meters in order to cure wingboxes (Norris, 2010b).

More problematically, integral stringers—supporting structures that are bonded to the skins they support, forming a single piece—proved to be very difficult to work into the complex wing and fuselage shapes (Perrett and Mecham, 2007). In August 2009, Boeing discovered wrinkles in the fuselage sections produced by Alenia, which were caused by limitations in the stringer trimming machine. The stringer edges were supposed to be reduced in steps of 0.015 in., but the machine was unable to achieve this precise trimming, causing wrinkles during the curing process. Boeing and Alenia planned to fix the problem by patching the pieces with extra plies (Norris, 2009a).

Similarly, because manufacturers struggled to build huge parts to extremely precise tolerances, shims were used to fill some of the inevitable gaps between parts. However, in 2010, engineers discovered that Alenia had applied pressure improperly to shims intended to fill gaps between the horizontal stabilizers and the center box joining them. The gaps were particularly troubling because they were “deeply embedded” in the tail piece, and had passed undetected into the final assembly. The resulting stresses threatened the structural integrity of the tail piece, forcing a temporary stop to flight tests in 2010 (Norris, 2010a).

Boeing addressed renewed concerns about the effects of lightning strikes on composite structures by developing a proprietary bronze-phosphor mesh system to protect against such risks. But during the manufacturing process, Boeing became concerned that gaps between metal fasteners and composite components developed by Mitsubishi might cause electrical arcing in the event of a lightning strike. Boeing and Mitsubishi worked together to redesign special-purpose fasteners that would seal more

tightly and thus reduce the risk of arcing, but the resulting fastener shortage put the project behind schedule (Mecham and Norris, 2007). Boeing was forced to use 10,000 temporary fasteners, each circled in red, in order to assemble its first aircraft (Mecham, 2008b).

The process of finding and refastening each fastener created considerable stress for the leaned-down workforce at Everett. Attaching fasteners to composites is more challenging than with metal, because it is easy to apply stresses that damage the material. Making matters worse, technicians were forced to replace fasteners twice because removal of the temporary fasteners created metal swarf, which prevented the first set of replacement fasteners from sealing close to the composite material (Marshall, 2009). In 2008, industry observers noted that Boeing's once-impressive assembly line looked like a “hospital emergency room,” covered with scaffolding that the more streamlined process should have rendered obsolete (Mecham and Norris, 2008).

Most alarmingly, the process of scaling up revealed erroneous knowledge about how large composite structures would respond to stress. One week before the already-delayed first flight test in June 2009, ground tests revealed unexpected structural weaknesses. When pressure was applied to the wings of the test aircraft, titanium fasteners did not transfer the load properly, causing delamination of the carbon fiber plies and deflection inside the fuselage. The failure was especially troubling because computer models had not predicted it. The data which had been sent from Boeing headquarters to suppliers around the world, and was the basis for engineering the entire aircraft, suddenly appeared to be flawed (Mecham, 2009). The 787's first flight was pushed back to December 2009 (Norris, 2009b).

Finally, the development of the first commercial all-composite fuselage and wings entailed new techniques and routines for maintenance. Boeing developed a new training curriculum, composite patches that could be bonded to surfaces to fix minor damage, and hand-held scanners for testing structural integrity (Norris, 2010c). While the FAA authorized 787 repairs using composite patches fused to the surface, the European Aviation Safety Agency (EASA) rejected this type of repair, insisting that repairs entail bolted metal patches (Kingsley-Jones, 2010). Non-standard fabrication methods for different aircraft components, combined with different maintenance guidelines from Boeing and Airbus, and the proprietary status of structural data, raised concerns about expensive maintenance routines (Chandler, 2012a, b; Wall, 2011a).

In short, even after decades of experience in the carbon fiber niche, the process of scaling up composite components required massive levels of innovation: new technologies for mitigating lightning strikes; new types of fasteners; new knowledge about how large composite structures respond to stress; and new manufacturing techniques requiring unprecedentedly large equipment. The fact that some structural knowledge could not be extrapolated from small composite components to larger components, suggests that Boeing did go beyond incremental engineering to what Vincenti terms “radical design”. Boeing's supply chain strategy amplified these difficulties by separating manufacturing teams from final assembly teams (a separation that experience with composites should have cautioned against), but it did not create the challenges associated with scaling up.

5. Discussion

In this section we return to the question of whether the multi-level perspective (MLP) provides an adequate heuristic for understanding transitions. We draw on our case study of Boeing's development of composite materials to highlight some limitations

in the MLP framework.

5.1. Niches and the challenge of scaling up

As the foregoing account suggests, the MLP and niche management frameworks can partially account for the development of carbon fiber aircraft components. Military aviation and small components of commercial aircraft both provided niches for experimentation, learning, innovation, and developing a social network surrounding composite manufacture and use. Landscape developments—first Cold War aerospace competition, and then concerns about rising fuel costs—encouraged adoption of niche innovations in composites.

However, the Dreamliner experience also suggests the need for revisions to sociotechnical transitions theories such as the MLP. In such theories, radical innovation only occurs in niches, and is subsequently “selected” or “adopted” by the dominant regime. However, this was not possible for composites. Innovations which many stakeholders regarded as “radical” were needed to make composite components of a scale that could potentially effect regime change.

Carbon fiber is just one example of how “opening the black box” of technology may help to refine and expand theories of innovation and sociotechnical transitions. Existing frameworks effectively “black box” technical design in explaining how transitions occur. In perhaps the most detailed discussion of different transition pathways, Geels and Schot (2007) argue that transitions vary depending on whether the niche innovation is disruptive or symbiotic with the existing regime, and upon whether the niche is mature when landscape pressures for change emerge. The resulting typology of transitions (shown in Box 1) makes no reference to specific technological features of the innovation. In other words, existing frameworks for transitions treat new technological innovations as a kind of black box. There is no a-priori reason to expect that innovations in, for example, information technology, cause transitions any differently than innovations in other areas, such as automobiles.

However, the case presented here suggests that aspects of technological design do affect the ways in which transitions occur. The Dreamliner experience shows that one specific aspect of niche innovation is particularly relevant: the degree to which additional radical innovation is required in the process of scaling up from niche to regime levels.

Box 1—Typology of transition pathways, with examples (Geels and Schot, 2007)

- Transformation: When there are moderate landscape pressures, but niche innovations are too immature to compete with regime technologies, transitions occur as regime actors slowly nurture and then adopt niche innovations. Geels and Schot (2007) provide the example of a transition in Dutch sanitation, in which the dominant regime slowly adopted niche innovations associated with sewer systems. The transition required only an “add-on to existing knowledge” rather than “disruptive” innovation (Geels and Schot 2007, p. 408).
- Dealignment and realignment: When there are sudden landscape pressures, but niche innovations are too immature to compete, several niche innovations emerge and co-exist until one becomes dominant. Geels and Schot (2007) provide the example of the late 19th century horse-based transportation regime in the U.S., which faced challenges that created opportunities for multiple niche innovations. An innovation in mass production—the Ford factory—was needed for automobiles to become the basis

of a new transportation regime, and adjustments in the socio-technical system (such as drive-through restaurants and theaters) supported this transition. However, in Geels and Schot’s account, few changes to the automobile itself were required; the auto was adopted more or less “as-is.”

- Technological substitution. When there are sudden landscape pressures, and niche innovations are mature enough to compete with regime technologies, transitions come about as regime actors adopt economically superior niche technologies. Geels and Schot (2007) provide the example of the transition from sailing ships to steamships. Several niche applications of steamships (e.g. inland waterways and ports) provided opportunities for innovations that incrementally improved steamship performance. These innovations eventually enabled steamboats to become economically competitive with, and thereby to replace, sailing ships. While “many adjustments in the socio-technical regime followed the breakthrough of steamships,” (Geels and Schot 2007, p. 411) this regime change did not require radical innovations in steamships. Rather, scaling up from niche to regime required incremental improvements in economic competitiveness, and the production of more steamships.
- Reconfiguration: When there is no landscape pressure, niche innovations may nonetheless be slowly adopted for economic reasons. Geels and Schot (2007) give the example of the transition from traditional to mass-production factories, which was enabled by multiple innovations in multiple niches, such as small battery-driven electric motors and conveyor belts. These niche technologies were initially adopted by the traditional factory regime to solve small problems, and eventually Henry Ford integrated them into a new kind of factory regime. This transition required innovation in the form of “new combinations of existing elements,” (Geels and Schot 2007, p. 413) not a radical innovation in the elements themselves.

The MLP has not acknowledged this aspect of technological design previously, not only because it does not encourage analysts to open the black box of technology, but also because it has generally been applied to a specific type of scaling up, which we provisionally refer to as “modular scaling up.” In modular scaling up, mass production of a niche “product innovation” enables regime change by multiplying the number of artifacts in use. Since technology is more than just an artifact, modular scaling up also requires increases in the size of systems for production, financing, and other supporting components, and such increases may entail “process innovations,” such as improvements in materials. However, in modular scaling up, the final product delivered to the sociotechnical system does not change radically; rather, its instances are multiplied. Most if not all accounts using the MLP perspective focus on transitions that require only modular scaling up. For example, in each of the cases used to exemplify the MLP typology of transition pathways, transitions are portrayed as occurring when niche or regime actors multiplied the number of technologies in use, and thus do not require radical innovation after niche development (see Box 1).

Modular scaling up may require incremental adjustments in the socio-technical regime; as Geels notes, the selection of new technologies by regimes is “more than adoption” because users “also have to integrate new technologies in their practices, organisations and routines, something which involves learning, adjustments and ‘domestication’...” (Geels, 2002, p. 1259). In other words, the sociotechnical regime may need to change in order to fully allow the integration of niche technologies. However, modular scaling up does not require additional radical innovation in

the new technology itself.

By contrast, the scaling up of composite components required much more innovation in the niche technology itself. In such “systemic scaling up,” niche or regime actors must increase the size and complexity of the technology itself in order to effect a regime change. In such cases, we might say that “process innovations” are themselves scaled up. Although the development of large and complex systems is an incremental process in some ways, it can require radical innovations in others. For example, the Facebook social networking site could not have expanded from a college campus to a world-wide user base without innovations in managing massive amounts of data and network traffic (Pingdom, 2010). Most large software systems confront similar challenges (Slayton, 2013; Brooks, 1995). Similarly, Grünewald et al. (2012) have noted that distributed energy storage does not fit neatly into existing paradigms for sociotechnical transitions, because it supports a larger system and does not aim to replace an existing technology. While niche applications of distributed storage (such as electric vehicles) are crucial, the systemic nature of this technology means that additional radical innovation is likely to be necessary to scale up distributed storage to a regime-changing scale. These are all examples of technologies that can only effect regime change by increasing the scale and not simply the number of artifacts in existence. Transitions that require systemic scaling up confront unique challenges, and merit further attention.

5.2. Broadening sociotechnical transitions theory with STS

The case presented here also illustrates three methodological points that may help sociotechnical transitions theory more fully account for transition processes such as systemic up scaling. First, accounts of sociotechnical transitions would do well to “open the black box” and consider how the detailed workings of technology influence transitions. Without looking closely at the processes of manufacturing composites and developing new aircraft, it would be impossible to understand the kinds of innovation needed to enable a transition.

Second, this account reinforces the point that the structural, global theory of the MLP “needs to be complemented by local theories which help to analyze how actors navigate, struggle and negotiate on specific alternatives” (Geels and Schot 2010, p. 101). As we have seen, far from representing a stable analysts’ category, the “radical” nature of the innovations required to scale up composites was contested by organizations and actors with an interest in how those innovations were portrayed. Boeing wanted to appear innovative, but not too radical for a risk-averse industry. Some engineers and industry observers contested Boeing’s portrayal of composite fuselages and wings as a safe and incremental innovation. Government regulators entered into the fray, and while they ruled that composites are safe, nobody can yet predict how composites will hold up in the long term. Perhaps the greatest indication that something “radical” was at work is the fact that the process of scaling up produced new knowledge; consistent with Walter Vincenti’s (1993) notion of “radical design,” structural failures demonstrated that knowledge extrapolated from small composite components was inadequate for purposes of scaling up. Nonetheless, the radical nature of the Dreamliner is very much a matter of perspective. From a consumer perspective, the use of carbon fiber does not appear radical at all; aside from enabling larger windows, carbon fiber does not look much different than aluminum. Operators, however, face radical maintenance challenges in comparison with aluminum.

Third, this study illustrates how accounts of incomplete, partial, or failed transitions can help refine theories of sociotechnical transitions, by calling attention to previously neglected challenges in scaling up from niche to regime levels. With regard to their

long-term success, the jury is still out on composite airliners. In 2010, Boeing began a three-year process of fatigue testing the 787, putting a prototype in a cage and applying frequent pressures to simulate the process of aging (Norris, 2010d). It has yet to announce the results. Furthermore, problems with composite manufacturing have continued to surface since the 787 entered service. For example, in February 2012, Boeing discovered that workers had failed to put shims in place between the aft fuselage and its internal structure, creating stresses that could increase the long-term risks of delamination (Mecham, 2012). In July 2012, cracks developed in the fan case of a General Electric GENx engine, a lightweight design unique for its all composite case and composite blades (Barnett, 2012). Just two months later, maintenance crews discovered cracks in the fan mid-shaft (George, 2012). In March 2014, Boeing reported hairline cracks in the wings of 40 aircraft still in the manufacturing phase, which emerged after Mitsubishi modified its manufacturing process (Scott and Hepher, 2014).

Some observers remain hesitant about composites. As the CEO of GKN Aerospace and Land Systems, Marcus Bryson, explained:

Fifty percent of our business still includes metallics. ... There is still a view [at GKN] that composites are not the be-all-and-end-all. Airbus and Boeing are also nervous about whether you can industrialize for production of 50 composite narrowbodies per month. The metals story is not over (Wall, 2011b).

Nonetheless, Boeing’s decision to embrace large-scale composites production has encouraged a shift towards lighter, more fuel-efficient aircraft. After initially criticizing Boeing’s use of composites, Airbus began emphasizing that its 2010–2012 generation aircraft would sport all-composite wings and fuselage (Wall, 2005). Louis Gallois, the CEO of Airbus’s parent company, explained that airlines had come to associate composites with modern aircraft: “it’s partly fashion” (Wall, 2008).

Fashion or not, the Dreamliner entailed billions of dollars of investment in manufacturing infrastructure which is likely to see increasing use (for representative investments, see (Sekigawa, 2004; Nativi, 2007; Parmalee 2004)). Boeing has developed technological and management capabilities that can be applied to future aircraft. In 2007 analysts predicted aerospace industry demand for composites to quadruple in 20 years (Phillips, 2007).

6. Conclusions and policy implications

This paper has used the history of composite aircraft components to examine theories of innovation and sociotechnical transitions. As we have seen, the multi-level perspective offers a helpful, but limited heuristic for understanding technological transitions. Niche applications of composites did provide useful experience for developing all-composite wings and fuselage. However, the process of scaling up from niche to regime level required that composites undergo additional “radical” innovation which could not be accomplished in the niche alone. This case does not fit neatly within existing paradigms for sociotechnical transitions, which acknowledge that the sociotechnical regime may need to adapt to niche technologies, but assume that the niche innovation can be “selected” or “adopted” by the regime with very little additional change once it is mature. Indeed, the purpose of a niche is to allow radical innovation that is unlikely to thrive in the existing regime. Experience with the Dreamliner suggests the need to modify this paradigm to account for technologies that may require considerable innovation to scale up from the niche to regime level.

Our findings are particularly relevant to understanding the challenges facing commercialization of radical innovations (for example, in materials, nanotechnology, and biotechnology). The classic distinction between process and product innovations may be

misleading in such emerging areas. Scaling up promising process technologies may require significant further process innovation to enable the development of products customized to a particular market requirement. While production techniques may eventually become “black-boxed,” initial value creation is challenging because it requires both process and product innovation.

Two broad policy implications follow from the methods and findings of this paper. First, policies should not be directed towards nurturing niches in general, but should target the types of niches that will allow the most needed kinds of innovation. An understanding of what types of niches are most needed can only be achieved by opening the black box of technology to understand how the content of technological design affects barriers to adoption. In the case of composites, policies which nurtured the market niche of small components were insufficient to produce the radical innovation needed to scale up to large components. A research and development niche that focused on the producibility and maintainability of large components more specifically would have been more effective.

Second, policies should not target niche innovation alone, on the assumption that the market will select or adopt niche innovations when they are sufficiently mature. Some kinds of radical innovation cannot take place in niches alone; thus policies should sustain the ongoing innovation that is needed to scale up from niche to regime level. We argue that this is especially likely to be the case when the process of scaling up is systemic rather than modular; in such cases, unexpected interactions are likely to attend the growth of complexity, and will require significant innovation beyond the niche.

In the case of composites, policies might include the continued exertion of pressures for the adoption of lighter weight materials (e.g. a carbon tax); investing in maintenance technologies; formulating standards for maintenance; and providing financial backing for companies that take on risky production jobs. However, such policies are likely to be controversial. One reason that Japanese companies were able to compete favorably for 787 contracts was that the Japanese government provided backing for the companies, and many observers object to such support as a violation of international competitiveness rules. Boeing and Airbus are currently in a WTO dispute about whether their respective governments have given the companies unfair economic assistance (Pritchard and MacPherson, 2009).

These recommendations stem from an approach to analyzing transitions that acknowledges the heuristic value of socio-technical transitions theory, but seeks to go further by unpicking the particularities of specific technological developments. The same factors that have made theories such as the MLP so successful—its clear conceptualization of the overarching structural interactions involved in transitions—can also be a weakness if the framework is adopted unthinkingly as a template for understanding all types of technological transitions. As the composites case shows, transitions can come about in different ways. If sociotechnical transitions theory is to be a truly useful tool for analysis and policy advice then further investigation is needed into how transition pathways vary across different types of innovation.

Acknowledgments

This work was supported by UK Economic and Social Research Council, Grant no. RES-062-23-2379.

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