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ORIGINAL ARTICLE

Multi-level perspectives with technology readiness measures for aviation innovation

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Abstract Sustainability science requires the development of a theoretical framework to understand, analyze, and design innovation to solve social, economic, and environmental issues. This paper extends the framework of multi-level perspectives (MLP) by introducing a technology readiness level (TRL), and analyzes the innovation of the advanced turboprop (ATP) engine in the aviation industry, also known as a propfan or an open rotor engine, which is one of the most promising engine innovations expected to mitigate climate change. The concept of TRL was introduced to explain the mechanisms of ATP failure in the late 1980s as well as the transition of the geared turbofan (GTF). In this paper, we discuss why ATP and GTF faced different fates although both were developed under the same landscape in the aviation industry. We also discuss the different roles of the socio-technical regime, such as uneven and dynamic opportunity windows, technological readiness, niche stock, institutional support of export products, and the risk of a 'launch' customer, at different TRLs. As illustrated in this paper, MLP with TRL is expected to facilitate future interdisciplinary collaboration between social scientists and engineers, and also transdisciplinary expertise between academia and practitioners by supporting analysis and design of the industry's transition toward a more environmentally friendly regime as well as its effective management.

Keywords Multi-level perspective · Strategic niche management · Technology readiness level · Transition path · Innovation · Advanced turboprop · Open rotor · Propfan

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Introduction

The term 'sustainability' spread widely after the United Nations Conference on the Environment and Development (UNCED), also known as the Earth Summit, in Rio de Janeiro, in June 1992. Innovation for sustainability is a challenging issue in both industry and academia. In the academic area, researchers from a variety of disciplines have begun to join sustainability science and interdisciplinary research with transdisciplinary expertise and are expected to offer an effective way to explore the root causes of issues relating to sustainability and design as well as to offer plausible solutions for society to realize sustainability (Kajikawa 2008). However, the movement toward sustainability has not proceeded at a quick pace. Many innovative technologies for sustainability are being invented or are under active investigation, but most are not competitive enough against conventional technologies and do not become dominant. Such new and immature technologies are often very expensive, have little compatibility with existing regulations, or, find difficulty being accepted by conservative societies or markets. Therefore, scientific inquiry and a systematic framework to comprehend the evolutionary process of invention, innovation, and diffusion are necessary (Jaffe et al. 2002). But factors affecting the process are obscure, while a number of techniques to mimic diffusion processes with an S-curve are well studied (Geroski 2000). Sustainability science requires the development of a theoretical framework to understand, analyze, and design how new technological, economic, and social systems interact and co-evolve with various factors of socio-technical regimes in the context of sustainability.

To understand the transition process toward sustainability, we must understand interactions among stakeholders with different normative structures and incentives, which are embedded in, influenced by, and exploited in innovation systems (Geels 2010). The socio-technical regimes in innovation systems have a dominant role in accelerating but also obstructing niche technology in its progress from invention to innovation (Kemp et al. 2001; Smith 2006). Transformation of the socio-technical regimes can work as a tipping point in the evolutionary process of innovation.

Literature about multi-level perspectives (MLP) has emerged and has been developed intensively for two decades, by trying to model innovation based on evolutionary transition. MLP is a simple, but flexible, framework to comprehend dynamic innovation. The MLP approach has attracted enormous academic attention in science, technology and innovation studies fields (Kern 2012). The nature of this framework is multi- and inter-disciplinary and requires a repertoire of empirical and theoretical approaches both application and generalization (Grin et al. 2010). This paper analyzes empirically the uncompleted transition path of the advanced turboprop (ATP)[1] in the aviation industry through MLP and then extends the theoretical approach of MLP by introducing the concept of a technology readiness level (TRL). How socio-technical regimes affect the transition process at different TRLs is also discussed in this research.

This paper is organized as follows: The next section reviews the previous literature and discusses the theoretical background to this paper. The "Scope and methodology" section explains the scope and approach used in this paper. The "Analysis" section analyzes an innovation path of ATP that is expected to appear in the aviation industry in the near future within the MLP framework. This section also introduces TRL into MLP framework and explores the transition process of the geared turbofan (GTF), which was derived from a core technology developed in ATP projects, to understand the promising innovation path of GTF in contrast with other ATP technologies. The "Discussion" section, discusses the different roles of socio-technical regimes at different TRLs. The final section concludes this paper with our findings.

Literature review

Modeling innovation

In the 1980s, many firms faced the need to manage globalized and increased competition, but these firms showed innovation not in R&D strategy, but in the strategy of the company (Van Lente 1997). In the same period, many innovation researchers criticized past literature for over-emphasizing the technological aspects of a system and claimed broader views were necessary to see the whole picture. For example, in science and technology studies, Linstone (1999) claimed that past science and technology literature studied "a system in terms of a very limited number of elements (or variables) and the interactions among them" so that the set of subsystems studied in such a manner would not represent the characteristics of the entire system. He proposed organizational and individual perspectives in addition to traditional technological perspectives used in the technology assessment process.

In economic studies, evolutionary theories were introduced to model innovation in the disequilibrium dynamics observed in the process of economic growth driven by technological change (e.g., Nelson and Winter 1977; Dosi 1982; Freeman 1974). Evolutionary economics developed the concept of socio-technological regime that is the socio-technical mainstream and creates stability, and disseminated the importance for the regime of cognitive rules, routines and corporation with a comprehensive perspective that is beyond the firm or sectoral level (Weber et al. 1999; Kemp et al. 1998; Raven 2006; Geels 2006b; Verbong and Geels 2007; Jones and Miller 2007; Grin et al. 2010).

[1] In this paper, ATP is defined as an innovative turbofan engine with a fan uncovered by a duct, and propfan, unducted fan (UDF) and open rotor are all included in this term. The original engineering concept of ATP was an innovation from a turboprop, aimed at bringing the speed of a fuel-efficient turboprop to a competitive level with the turbofan engine. NASA first developed a single rotation tractor ATP system in the ATP project at the Aircraft Energy Efficiency Program (ACEE) launched in the late 1970s. When NASA's investigated passengers' acceptance of ATP technology with United Airlines in the late 1970s, the term "propfan" was used in order to avoid passengers conjuring up images of the old troublesome propeller from the term of turbo-"prop". In the early 1980s, General Electric (GE) revealed the concept of the UDF, i.e., a dual rotation pusher system with neither a gearbox nor a duct. The engineering concept of dual rotation systems without a duct such as GE's UDF or DX-578 was rather an innovation from a turbofan, aimed at bringing the fuel-efficiency of a turbofan to a competitive level with the turboprop engine. (DX-578 was with reduction-gear and developed by Pratt, Whitney and Allison, who originally developed a single rotation ATP at NASA's ATP project.) NASA's original ATP and UDF might be different in the strict in terms of the engineering concept but are same in the purpose to achieve the best features of turboprop and turbofan. A brief explanation of turboprop and turbofan will appear in the "Scope and methodology" section. A dual rotation system has recently been called an open rotor.

Diffusion of innovation, which is the "selection" stage in the evolutionary process, is a vitally important dimension of the transition between different regimes (Metcalfe 1981), and many researchers were challenged to measure the speed of diffusion. However, Brown (1981) criticized past diffusion research as overemphasizing demand and modeled the diffusion research with adopters having equal opportunity. Brown also emphasized the importance of considering socio-economic conditions such as the existence and type of infrastructures that support the diffusion of innovation. In recent studies of diffusion of innovation, user acceptance (Venkatesh et al. 2003), knowledge and capability (Attewell 1992), culture (Straub 1994), network (Abrahamson and Rosenkopf 1997), demand factors and conditions (Popp et al. 2011), market competition (Chrysovalantou and Petrakis 2011), international trade barriers (Eaton and Kortum 2006), strategic and psychological factors (Abrahamson and Rosenkopf 1993), and organizational structure (Abrahamson 1991) are investigated and analyzed as important factors controlling adaptation and the diffusion process of innovation.

While research on diffusion of innovation focuses on the "selection" stage in the evolutionary process, research on strategic niche management (SNM) studies the development processes of an emerging innovation system (i.e., a niche), which is vulnerable in its infancy. Previous research of SNM has emphasized the necessity for a protected experimental space with strategic factors such as broad and deep social networks, robust expectations shared between actors of the niche, and learning processes at multiple stages where the actors related to the niche learn about the design, user needs, cultural and political acceptability, and other aspects of the niche (Hoogma et al. 2002). Case studies of SNM can be seen in various domains, for example, products such as organic food and eco-efficient houses, public services such as biogas energy plants and wastewater plants, and even policies such as road access charges (e.g., Smith 2007; Raven and Geels 2010; Hegger et al. 2007; Ieromonachou et al. 2004).

MLP framework

MLP has been developed as a model to grasp technical change by synthesizing the factors affecting innovation process. MLP introduced the idea of a "landscape"—the macro-level and historical momentum of society as a whole—to past studies on socio-technical regimes (Grin et al. 2010). MLP emphasizes the importance of interaction with externalities for niche development. Specifically, MLP explores the innovation process of three levels (and interactions among them): niche innovations, the socio-technical regime, the socio-technical landscape. Here, a socio-technical regime illustrates the dynamics of stable dimensions of society in science, technology, industry, policy, market-user preference, and culture. The stable nature of the regime often causes "lock-in" (Unruh 2000). Niche innovations come from internal momentum, but destabilization of the regime opens a window of opportunity for niches to come into the regime level. Destabilization of the regimes is often caused by changes in the landscape. Transitions are not caused by a change in a single aspect and level, but by the interplay of many aspects, actors and levels (Schot and Geels 2008; Markard and Truffer 2008; Raven 2007). MLP offers a comprehensive perspective for analyzing and understanding the process whereby the niche becomes part of the mainstream of a regime, which is then affected by the existing regime and landscape. The number of papers reinforcing and using MLP are increasing rapidly (e.g., Späth and Rohracher 2010; Lauridsen and Jørgensen 2010; Hodson and Marvin 2010; Kern 2012). For example, Späth and Rohracher (2010) developed the MLP approach by analyzing the regional dynamics toward an energy-safe future. Lauridsen and Jørgensen (2010) highlighted problems resulting from conflicting interpretations between regimes in their study on the waste policy of the European Union.

Regarding the aviation industry, which is the focus of this paper, several literature reports (e.g., Haan and de Mulder 2002; Geels 2006a) have analyzed the transition to the jet age. However, there is little research on innovation transition after the jet age. Cohen (2010) and Kivits et al. (2010) are two of the few papers to address this issue. Kivits et al. (2010) assessed aviation energy alternatives and concluded that consensus and perceived needs among the aviation industry are important, but very difficult due to the long product lifecycle and huge sunken costs (Kivits et al. 2010). Innovation in aviation sustainability after the mature jet regime is expected through research on plausible technologies beyond the jet regime.

MLP can be utilized to analyze dynamic and interactive processes among landscape, regime, and focal niche technology, but MLP is not used for depicting the dynamic evolution of technology itself. In MLP, a technology is regarded as static, thus MLP cannot explain the different status of innovation diffusion among different technologies in the same industrial domain governed by the same landscape and regime (Fig. 1a).

Technology readiness level

One of the ideas used to resolve these issues is to assume that each technology has a different influence according to the technology development phase even when they occur under the same landscape and regime. For any engineering project, a measurement is needed to monitor a project for control and implementation (Tan et al. 2011). TRL is a

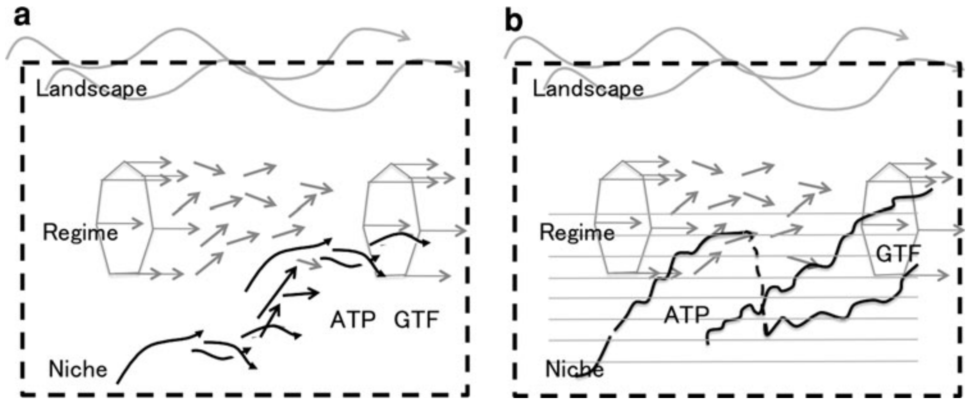

Fig. 1 Conceptual diagram of socio-technical transition. **a** Existing multi-level perspective (MLP) framework. **b** MLP with technology readiness levels (TRL)

Table 1 Technology readiness level (TRL) (NASA definition)

TRL	Definition
TRL 9	Actual system “mission proven” through successful mission operations (ground or space)
TRL 8	Actual system completed and “mission qualified” through test and demonstration in an operational environment (ground or space)
TRL 7	System prototyping demonstration in an operational environment (ground or space)
TRL 6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)
TRL 5	System/subsystem/component validation in a relevant environment
TRL 4	Component/subsystem validation in a laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof-of- concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

measurement of technology used globally in the aviation and other high technology industries for various purposes such as procurements and risk-analysis in system development (Ramirez-Marques and Sauser 2009; Khan et al. 2011) and has several definitions. Table 1 shows NASA’s definition, which is also used in this paper. Mankins (1995) provided a descriptive discussion of each TRL as follows, which are used widely to understand NASA’s TRL (Conrow 2011):

> “TRL 1 […] is the lowest “level” of technology maturation. At this level, scientific research begins to be translated into applied research and development.
>
> TRL 2 […] occurs when basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be ‘invented’ or identified. (A)t this level, the application is still speculative.
>
> TRL 3 […] (A)t this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory based studies to physically validate that the analytical predictions are correct.
>
> (At) TRL 4 (F)ollowing successful “proof-of-concept” (validation at TRL 3), basic technological elements must be integrated to establish that the “pieces” will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications.
>
> (At) TRL 5, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a ‘simulated’ or somewhat realistic environment.
>
> TRL 6, (A) major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system—which would go well beyond ad hoc, ‘patch-cord’ or discrete component level breadboarding—would be tested in a relevant environment.

TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space.

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true 'system development' for most technological elements.

And by definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, TRL9 represents the end of a long line of last 'bug fixing' aspects of true 'system development'.

Figure 1 shows the concept of the introduction of TRL to this paper and illuminates the difference of innovations in the same technology domain.

Scope and methodology

This paper extends the empirical work of MLP to the civil aviation industry. The civil aviation industry was chosen because it is embedded in complex socio-technical system where a variety of stakeholders from government, industry, and society exist, and collaboration and interaction among these stakeholders are imperative for transition toward a sustainable society that mitigates climate control. In the aviation industry, realizing sustainability[2] requires not only technological challenges, but also many severe social challenges such as large investments from different stakeholders as well a change in their behavior in some cases. Research on innovation transitions in the aviation industry is also useful for other industries with similar industrial characteristics such as transportation, and information and communication.

Design of an innovation pathway for aviation sustainability is not a rudimentary task. There is not much dialogue between researchers of MLP and practitioners in the aviation industry. According to recent conversations with project managers for environment sustainability in aviation research institutes including the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), such transition research approaches appear only rarely in the sustainability discourse in their institutes and governments. On the other hand, managers in NASA and JAXA often emphasize that the aviation industry needs a theory to support the industry transition towards a more environment friendly regime. Therefore, further research combined with industry interaction is required not only for conducting reliable academic research, but also for designing salient solutions for aviation sustainability[3].

Among environment challenges in the aviation industry, the mitigation of climate change is the newest big issue, but it has the least accumulated knowledge, while noise and local air pollution were recognized as far back as the 1960s (Lee et al. 2010). The impact of the aviation industry on the effect of greenhouse gases (GHG) was estimated to be 3.5–4.9 % of current anthropogenic radiative forcing (Lee et al. 2010). Both worldwide passenger traffic and cargo traffic markets are forecast to grow continuously by more than 5 % per year over the next 20 years[4] (IATA 2009a; Boeing 2010). To mitigate aviation-induced emissions, in 2010, the International Civil Aviation Organization (ICAO) achieved a global consensus to put forth more effort in improving fuel efficiency than today, i.e., 2 % annual fuel efficiency improvement, and are now trying to set more ambitious goals such as carbon neutral growth by 2020 relative to the baseline of 2005 among its member states, including developing countries (ICAO 2010). The number of projects and investments with technologies to deal with emissions mitigation has been increasing in this context. For example, the European joint technology initiatives for aeronautics and air transport CLEAN SKY, and the NASA Environmentally Responsible Aviation (ERA) project have been working in this direction (Nakamura et al. 2011).

The engine is the source of GHG and fuel consumption in aviation operation and therefore technology innovation in engines is very important. The thrust power of the first jet engines, known as a pure jet, was all gained from the exhaust jet gas. Letting the hot, very high-speed, air of the exhaust jet into the relatively very low-speed air behind

[2] Aviation sustainability depends largely on whether the industry can accommodate forecasted strong traffic increase to severe transport market competitions and mitigation of noise, local air pollution and greenhouse gas (GHG) emissions. Please see Nakamura et al. (2011) for further discussion.

[3] The idea of using TRL as a measure of niche development came from our conversation with engineers in the aviation industry during this research. They considered that the analysis shown in this paper was not enough to explain failure of ATP in 1980s and current promising transition of GTF, while part of the reason might be that they are engineers and are not familiar with sociological qualitative discourse with socio-technical transition frameworks. They preferred to discuss detailed level of the technology's progress rather than the generalized picture of transition.

[4] Shocks to aviation such as the severe acute respiratory syndrome (SARS) epidemic, the September 11 terrorist attacks and the Asian financial downturn, which caused the bankruptcy of many airlines and accelerated the reorganization of manufacturers, also increased global discussions about the security and health problems associated with air transport. However, the industrial perspective of a strong increase of traffic has not been rewritten because the market has shown resiliency by recovering from shocks within a relatively short period.

the engine and the aircraft causes a critical waste of kinetic energy so that pure jet was very fuel inefficient initially. On the contrary, turboprop engines used jet power to rotate the blades. Rotating propellers push the air behind the engine to obtain the thrust power. Turboprop engines are very fuel-efficient. However, it is difficult to operate turboprops at high speeds. When the tips of the blades reach supersonic velocity, shock waves are formed, increase the drag and dramatically reducing thrust and efficiency (Fig. 2b). Turbofan engines are a hybrid of 'pure jet' and turboprop engines. Turbofan engines use jet power partly as the thrust power from the exhaust jet and partly as mechanical power to rotate the fan. One of the efficient measurements of a turbofan is the bypass ratio, which is a ratio of the secondary air flow drawn in by the fan bypassing the engine core to the primary air flow passing through the engine core (Fig. 2c). Higher bypass ratios generally mean higher fuel efficiency. The bypass ratio of the first commercial turbofans in the 1960s was five, while the latest turbofan has a 7.5–11 bypass ratio.

The ATP engine, whose uncompleted transition path this paper investigates, is an innovative aviation engine that achieves a 40 bypass ratio by removing the duct covering the fan (Fig. 2a). This engine is a hybrid of the best features of both a turboprop and a turbofan engine, overcoming the tip supersonic velocity problem by using a swept blade. On the other hand, GTF, whose promising transition path this paper also investigates, has a modest bypass ratio such as 12. For a fuel-efficient high bypass turbofan engine, not only increasing the fan diameter but also increasing the rotation speed of relatively smaller low-pressure compressor (LPC) and low-pressure turbine (LPT) are necessary to maintain mechanical efficiency. However, the fan, LPC and LPT, are all connected with shafts so that increasing the diameter and rotation speed of LPC and LPT causes shock waves from the fan tips and therefore noise and inefficiency. To optimize the rotational speed of the fan, GTF is an innovative way to introduce a reduction gear on the low spool of a two-shaft engine between the fan and LPC/LPT. The reduction gear technology has its roots in NASA's ATP project. ATP and GTF engines are both innovative and promising engines in terms of fuel-efficiency for short- and mid-haul aircraft.

ATP is now considered a mid-term engine innovation for short and mid-haul aircraft that are expected to mitigate climate change in the aviation industry (IATA 2009a). For example, ATP engine demonstrations are planned in the Sustainable and Green Engines (SAGA) research project and the Smart Fixed Wing Aircraft (SFWA) research project in CLEAN SKY. GE and NASA also tested a new generation of ATP concepts for aircraft engines from 2009 to 2011. ATP was chosen because the failure of NASA's ATP project in the 1980s is still a big concern for those in the industry who have just started new ATP projects.

The aim of this paper is two-fold. One goal is to analyze factors affecting the development of the ATP project including GTF within an MLP framework. What does MLP tell us about NASA's development? Even though the engine concept itself is very attractive in terms of fuel-efficiency, mounting an innovative engine to an aircraft is not simple and does not guarantee the same level of fuel-efficiency as the whole aircraft system due to technical and social problems, such as trade-off between noise and fuel-efficiency. ATP engines are generally nosier than turbofan engines. The MLP analysis will derive useful implications to understand and transform social-technical regimes

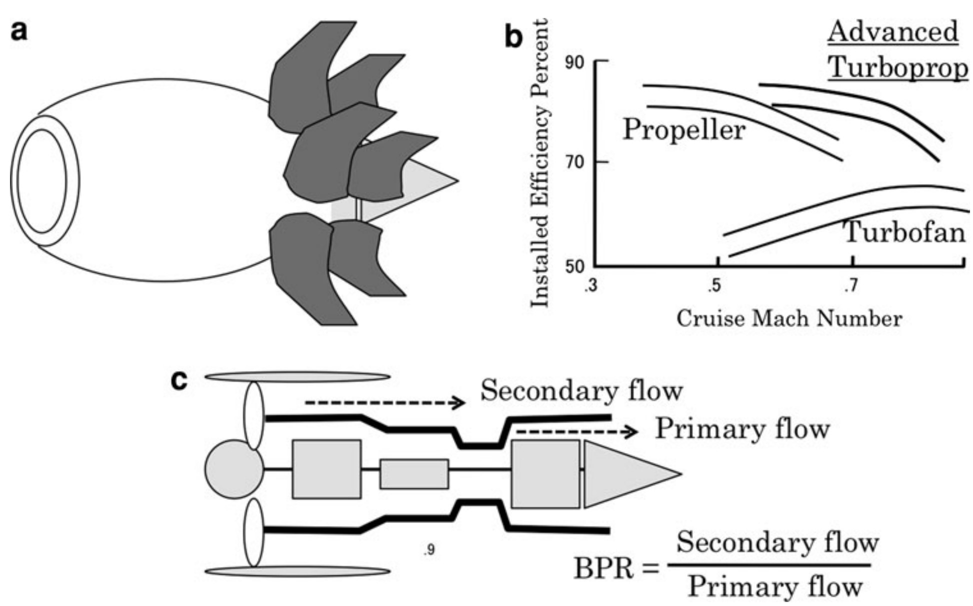

Fig. 2 Advanced turboprop (ATP) engines. Schematic images of **a** an unducted fan (UDF) engine, a type of ATP; **b** ATP total propulsive efficiency advantage; and **c** bypass ratio

toward aviation sustainability. The second goal of this paper is to elucidate mechanisms that differentiate GTF from other ATP technologies in terms of MLP. Does MLP help illuminate the fact that ATP did not make it to market in the 1980s and was not ready by 2000? What does MLP tell us about the development of GTF, which was derived from a core technology developed in ATP projects, and which will soon be introduced onto the market? To answer these questions, we introduce the concept of TRL, and discuss the mechanism of GTF development.

The MLP literature mainly reflects qualitative analysis based on historical materials (Bennett and Pearson 2009). This paper also consulted historical materials related to NASA ATP projects from 1973 to 1992, which include materials archived at the library in the History Division of NASA Headquarters and from newspapers, books, reports, and journals[5]. The authors also conducted two face-to-face 1-h interviews in 2010 and 2011 with engineers to check the reliability of the archives used in this research and the validity of our investigations of ATP history. One engineer we spoke with works for Boeing as a noise specialist and participated in 7J7 development, which was planned with an ATP engine. Another worked for Fokker as an aircraft designer and participated in aircraft development with ATP until Fokker went bankrupt. The authors also consulted the interviewees on their perceptions of the technology readiness of GE's ATP engine because there were several articles specifically discussing GE. The interviewees reported that engine manufacturers were confident about the realization of their ATP engines in 1980s. However, they also said that weight problems due to additional insulators needed in the integration of engines to aircrafts were challenging even at the end of their projects. The Boeing engineer added, "open rotor (ATP) is one of the most efficient engines. We still investigate it every time we have a project with small aircraft".

Analysis

We analyzed factors affecting development of the ATP project including both fuel price and other factors based on the existing MLP framework from the perspectives of niche development, landscape change, and socio-technical regime interaction. The 1973 oil embargo caused some US senators and the 94th Congress in 1975 to examine how NASA's aeronautics division could save airlines and related services. Airlines were the national status industry and suffered badly from the energy crisis. "Jet fuel prices jumped from twelve cents to over one dollar per gallon", and "during the crisis, fuel represented over half of the airlines' operating costs" while "prior to 1972, fuel accounted for one-quarter of the commercial airlines' total direct operating costs" (Ziemianski and Whitlow 1988).

Niche development

The concept of sweeping propeller blades came from continuous efforts by engineers to ease the problem of supersonic tip velocity and to extend the use of fuel-efficient propellers at the high speeds required in the jet age. Unlike five other projects launched at NASA's Aircraft Energy Efficiency Program (ACEE), which ran from to 1986 with six projects: The Energy Component Improvement, the Energy Efficient Engines and the Advanced Turboprop Project at the Lewis Research Center, the Energy Efficient Transport, the Composite Primary Aircraft Structure, and the Laminar Flow Control at the Langley Research Center (details of those projects can be seen in Bowles and Dawson 1998), the ATP with sweeping propellers failed to launch officially in 1977. Because many people were skeptical about ATP technology feasibility, early work of the assigned engineers in NASA was devoted to project management jobs. NASA engineers conducted surveys such as an investigation of whether civil aircraft passengers would accept engines with old-fashion images of propellers in the jet age in order to remove negative concerns about the ATP project. Working closely with external people such as policy makers, the engineers succeeded in an official launch of ATP projects in 1978.

The ATP project had a number of technical and social challenges. Technical concerns included propeller efficiency at the targeted cruise speed, which was around 0.8 Mach, cabin noise, installation aerodynamics, drive systems such as the gearbox, and maintenance costs. Social concerns included the perception of turboprops as old-fashioned, troublesome devices that were unsafe, and the risk that airlines and passengers would not accept the changes in traffic management because ATP aircraft would need to fly slower and lower than a jet.

To challenge these issues, NASA took over the administrative role and created over 40 industry contracts and 15 institute grants through the following four stages of the NASA ATP project: concept development (1976–1978), enabling technology (1978–1980), large-scale integration (1981–1987) and flight research (1987) (Bowles and Dawson 1998; Ziemianski and Whitlow 1988).

At the stage of large-scale integration, the competition between engine manufacturers and acceptance of the niche was recognized. NASA originally developed a single rotation tractor ATP system with a reduction gearbox with

[5] These include "From engineering science to big science" (Bowles and Dawson 1998), an article by Ziemianski and Whitlow (1988), and *Flight International*, *Aviation Week & Space Technology* (AW&ST), *Journal of Aircraft Engineering*, and The *Journal of Turbomachinery Society of Japan*.

contractors such as Hamilton Standard and Allison Gas Turbine at the Division of General Motors. Then, to NASA's surprise, GE released a dual rotation pusher ATP system without a gearbox, known as an unducted fan (UDF). NASA later tested both GE's UDF type ATP, GE36, and a counter rotation with a reduction gearbox, Model 578-DX, that Allison and Pratt & Whitney (P&W) developed after GE revealed their UDF engine. Special reports appeared in aviation journals about the Paris Air Show and the Farnborough Air Show, both of which are held biennially on different years. These special reports told of the progress of the GE36 and 578-DX every year in the mid-1980s.

The development of ATP technology was not limited to NASA and its contract companies and institutes. For example, France revealed their plans to build an ATP model with sponsorship from the Ministry of Defense in 1982. Rolls Royce in the UK launched 3 years of ATP engine research from 1984–1986. Many aircraft manufacturers initiated studies of a new aircraft model with ATP engines in the late 1980s[6].

While ATP projects achieved technological progress and spread around the world, many challenges for ATP engine aircrafts still remained into the late 1980s. The main problem was noise and fatigue caused by the vibration of the propellers in engine–airframe integration. The uncertainty of noise and fatigue by the vibration prolonged the airworthiness certification process. Furthermore, to keep the fuselage and engine free from noise and the risk of blade destruction, the weight of the insulator offset the fuel efficiency achieved by the engine itself.

Boeing announced delaying the certification process of the 7J7 in 1987 and officially canceled the 7J7 project in 1993. In 1989, a few months after offering executive customers the experience of an ATP demonstrator to convince them of lower noise than expected, McDonnell Douglas started to study the V2500 turbofan engine as a possible replacement for the planned ATP engines of the MD-90. GE froze the development of the UDF type ATP engine in 1989. Many other projects were cancelled. In the late 1990s, there were few articles about ATP, and only a few aircraft projects with ATP engines existed.

In the meantime, in the early 1990s, P&W started the development of GTF, a turbofan with reduction gear, which had its roots in the ATP project. GTF has a modest bypass ratio from 10 to 12 and is able to save 8–10 % on operating costs. P&W has kept GTF in their technology portfolio for 20 years and has accumulated hours of gearbox tests to respond to the skepticism on high-maintenance risks of the gearbox.

Recently, ATP and GTF have been given another window of opportunity. In the aviation industrial technology roadmap, the ATP engine is expected to be in new aircraft design before 2020 and to reduce fuel consumption to 15–20 % (IATA 2009b). On the other hand, Bombardier and Mitsubishi selected GTF engines, whose commercial product development P&W launched in 1998, in the new Canada Regional Jet (CRJ) aircraft project, and the Mitsubishi Regional Jet (MRJ) project in 2007. Lufthansa and All Nippon Airlines (ANA) signed as launch customers of CRJ and MRJ, respectively, in 2009. These aircrafts will be delivered in 2013. The Boeing 737 series and Airbus A320 are also in the segment of ATP and GTF engines. Airbus announced a new generation A320 with a new GTF engine in 2010, and Boeing is now considering a new generation 737 rather than creating a new aircraft.

Landscape change

Several landscape changes influenced the aviation regime and ATP and GTF. The first (1973–1974) and second (1979–1980) oil embargo worked as the window of opportunity for ATP technology by changing the priority of activities of the US, NASA, and the airlines. Even though fuel increases due to the oil shocks ended after several years, these experiences implanted the fear that fuel prices would once again increase some day. On the other hand, the oil shocks experience did not change the regime of the airlines in terms of business. At that time, when fuel costs were the most dominant costs in the airlines' overall costs, the first priority was to reduce fuel costs, but the overall principle of the airline business is to make a profit.

Another significant landscape change, for example, was the end of the Cold War. In the 1970s, the fact that Russia was advanced in terms of turboprop speed also put pressure on the US to advance the preparation of the NASA ATP project. When the Cold War ended, the military budget, which was an important source for the US aviation industry, decreased gradually so that the number of projects for new technology in the aviation industry decreased.

The increasing world attention on the responsibility of the aviation industry to climate change such as the Kyoto protocol acted as a new opportunity for ATP and GFT technology. However, soaring fuel prices in the early 2000s acted as the greatest opportunity. During the oil shocks, for example, the average paid price for a gallon was 3.07 dollars in 2008 and 1.05 dollars in 1981 according to data released by the US Energy Information Administration and Department of Labor (Fig. 3). Fuel-efficient technology was needed in this context, and ATP needed to be

[6] For example, McDonnell Douglas's MD88, MD91 and 92; Boeing's 7J7; the ATRA90 from a joint venture of Boeing, Messerschmitt-Bolkow-Blohm (MBB) of Germany, Fokker B.V. of Holland and Nusantara Aircraft Co. (IPTN) of Indonesia; the Fokker P376, the Russian Tupolev Tu-34 and Antonov An-70 were all planned to fly with ATP engines.

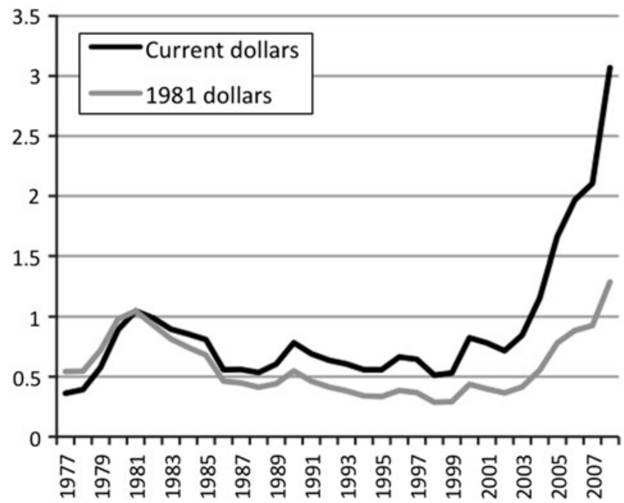

Fig. 3 Spot kerosene prices (Source: US EIA and Department of Labor, http://www.eia.gov/)

re-introduced and developed because ATP was a strong candidate for the next leap in fuel-efficient technology.

Socio-technical regime interaction

Next, changes in the socio-technical regime in civil aviation were analyzed. Many changes that have worked as supporters and interrupters to the niches exist. A socio-technical regime has drivers. Smith (2007) summarized various important characteristics suggested from previous literature such as Geels (2002), Schot (1998), and Rip and Kemp (1998) into seven dimensions. The seven dimensions include the following, but not necessarily in this order: (1) guiding principles, (2) technologies and infrastructures, (3) industrial structure, (4) user relations and markets, (5) policy and regulations, (6) the knowledge base for the regime, and (7) cultural and symbolic meanings underpinning practices. These dimensions are useful for unraveling the complex nature of the aviation regime, and are interrelated. For each dimension, we explain its current nature and find changes and interactions that have affected ATP and GTF transition.

Guiding principles

Among the key guiding principles in civil aviation, which are to transport passengers and cargo faster, safer, farther, and with more comfort than trains, ships, and vehicles, safety is paramount. For the safety and security of passengers and governments, there is an array of regulations and certifications such as the Chicago Conventions of ICAO, the Federal Aviation Administration (FAA) Standard, the European Aviation Safety Agency (EASA) Standards, and bilateral agreements that regulate the airline business including the flight route as well as aircraft manufacturing activities including small specification changes in the certificated products or supply chain. Therefore any innovative technology will require additional costs and time in the aircraft certification process for airworthiness. The long and costly certification process was, and is always, a big constraint for manufacturers and airlines in adopting an ATP aircraft. Even though GTF is not as innovative as ATP technology, GTF is no exception and it took GTF technology two decades to clear the barriers of the transition by convincing stakeholders of their safety feasibility since the early 1990s through P&W's accumulated knowledge and tests about blades.

Technologies and infrastructures

In the late 1980s, insulation of the fuselage to reduce the noise of ATP weighed a lot and offset the fuel efficiency in the aircraft configuration. The feasibility of light materials such as carbon fiber reinforced plastics (CFRP) has advanced greatly over the decades since then. In terms of infrastructure, both in the past and today, there are still the problems of how to support traffic route changes because ATP aircraft must still fly lower and slower than jet aircraft.

Industrial structure

The four major civil aircraft manufacturers are Boeing, Airbus, Bombardier, and Embraer. The three major engine manufacturers are Rolls Royce, GE, and P&W. Some jet engines are produced under inter-company collaboration. The rise of the Airbus drove US support to ATP technology and NASA ATP projects when President Reagan tried to cancel the NASA budget for ATP technology in the early 1980s. GE and P&W competition in ATP development also accelerated the development of ATP in the 1980s. Recently, aircraft and engine development have become even more complex and require more human and financial resources than before. Manufacturers tend to hedge risks and investment and develop projects by contracting with other companies. ATP was, and GTF might have been, abandoned during such a trend. However, in the 1990s, by trying to win the competition among engine manufactures, P&W kept GTF-related technologies, including reduction gears, in the technology portfolio. In the 2000s, the GTF engine became a unique product of P&W. Recently, both GE and Rolls Royce have announced ATP projects.

User relations and markets

Airlines, which are operators of aircraft and often the owners of aircraft, have a strong need to reduce their operational costs, such as fuel costs, airport charges and maintenance costs, and various financial costs, because of the highly competitive business of airlines. Global commercial airlines made a profit only twice in the 2000s, once in 2006, and once in 2007 according to IATA world carrier financial data. Therefore, when fuel prices calmed down, airlines addressed the risk of increased maintenance costs by using high-speed propellers. Fuel prices became lower compared to the time of the oil shocks. The average paid price for a gallon was US $1.05 in 1981, and US $0.56 in 1986, according to the US Energy Information Administration (EIA; http://www.eia.gov/) (Fig. 3). This highlighted the cost of ownership. A 30 % higher fuel efficiency of the new aircraft with ATP engines that aircraft manufactures announced should have interested government, NASA, and manufacturers even after considering the initial costs in the tens of millions of dollars and the low fuel price in the late 1980s. However, the risk of having aircraft that were newer, nosier, and slower than conventional aircraft outweighed the interest. This landscape change accompanying the oil shocks drove the direction of government, NASA, and manufacturers toward the ATP project, but airlines did not want to change their basic preferences in the selection of a fleet.

Policy and regulations

Big regulation changes in the airline business occurred in 1987, the Airline Deregulation Act. Before the Act, the Civil Aeronautics Board (CAB) controlled the fare, routes, profits, and market entry of flights over states. Control on fare and profit resulted in non-price competitions and promoted the airline's introduction of new equipment for service differentiation (Jordan 1978), which might have been favorable for a new technology such as ATP. However, non-price competition resulted in excessive equity stock, cost increases, and inefficiency of operation (Cherington 1958). The Act promoted market entry and competition and drove numbers of mergers and acquisitions. In recent severe competition, the risk for buying an innovative technology is high and thus, a very difficult decision. There were other regulation changes that influenced the transition of ATP. Some airports have their own regulations and charges for reducing noise. When aircraft manufacturers tried to sell aircraft with ATPs in the late 1980s and the early 1990s, strengthening of the noise standard was forecast; thus, many airlines were unwilling to consider the ATP engine, which was noisier than the conventional turbofan engine. Noise regulation is currently much stricter than in the 1980s and is a disadvantage for the ATP. On the other hand, there is a movement within the ICAO to set a GHG emission standard that may regulate airlines to operate aircraft only with a fuel-efficiency above the standard. Such a standard is expected to guide manufacturers and airlines to invest in environmentally friendly technology. Europe, under the EU Emission Trade System (EU-ETS) is currently proceeding with a positive economic measure to promote CO_2 reduction. EU-ETS reflects the strong driving force of Europe towards sustainability, which includes its ambitions to become a leader in sustainability development. However, as airline networks go beyond single governments and become global, setting political and economic measures is difficult[7]. However, if collaboration between regulators and industries toward implementation of innovation for sustainability is developed widely without jeopardizing safety, the ATP transition path will be a lot smoother[8].

Knowledge base

An aircraft is a highly complex system, which integrates a fuselage, engines, and various equipment such as electric flight control. Computer performance is a very important part of the infrastructure for the design of each component, and for the integration of components and equipment. Computer performance in the 1970s enabled the examination of high-speed propellers, which was impossible in the 1960s (Ziemianski and Whitlow 1988). Furthermore, the performance of computers is much better than in the epoch of the NASA ATP project. While high computer performance and new materials enabled advanced detailed research on ATP and GTF and pushed the ATP and GTF project towards realization, the computers and materials used in ATP development in the 1980s were so different that the current ATP project cannot use much of the research accumulated in the 1970s and the 1980s for the NASA ATP project in a practical way.

Cultural, symbolic meanings

Even though the rise of low cost carriers (LCC) is now changing part of the culture of flying, aviation, as a highly technological, complex system still has status for both employees and for passengers as a service. Safety, security and reliability are paramount. Both production and operation are very important for a country's economic and military strategy. Current aviation is heavily locked in to using jet fuel. Throughout the NASA ATP project, it was

[7] In 2009, the US Air Transport Association of America (ATA) sued the EU-ETS and in 2012, some airlines in China refused to finalize orders of aircrafts from the European aircraft manufacture, Airbus.

[8] For example, regarding the problems of cost and time consumption associated with the certification for airworthiness, as discussed in "Guiding principles", a collective action for accelerating the certification process for innovative technology for sustainability was recently found in the certification of biofuel produced through the Fischer–Tropsch process (ASTM D7566).

uncertain whether current flying and national cultures would accept going ‘backwards’ to using a propeller instead of a modern jet.

Introduction of TRL to MLP

In the previous sub-sections, we summarized the situation faced by ATP and the aviation industry and analyzed factors affecting the development of ATP projects. While general understanding about the ATP failure in the 1980s hinges on the end of soaring fuel prices, our analysis using MLP shows additional interrelated changes of the different levels of promoting the ATP project, such as relationships with policy makers, competition among engine manufacturers, improved feasibility of light materials, and progress of computer technology. We also discuss factors interrupting the transition of niche ATP, such as the end of the Cold War, safety as the guiding principle, the low profitability of airlines, and noise regulation. This means that analysis with MLP can extract both supporting and interrupting factors of a niche’s development, depending upon the timing of the window of opportunity. However, these factors are common to both ATP and GTF, because GTF is in the same technology domain as ATP. The fate of the ATP project and the current promising transition of GTF cannot be explained.

Figure 4 visualizes the transition of niches described in the previous section, based on TRL measurements. Evaluations of TRL at each period are based on engineers’ inspections. TRL 9 is the stage where a niche system has matured enough to be on the market. ATP technology was at its early TRL stages when the first opportunity window opened. Roche and his colleague filed a US Patent, US4171183A, for a “multi-bladed, high speed prop-fan” in September 1976. The concept of a multi-bladed high-speed propfan, therefore, must have been created before the ACEE’s ATP project. Otherwise, the ATP concept would not have been a candidate for ACEE when the window of opportunity opened.

The industrial expectation of fuel-efficient technologies, industrial competition, and development of computers and materials accelerated the development of ATP engines. However, ATP did not close the gap between TRL 7 and 8 while the window was open. After closure of the window, ATP was abandoned. The success of the current ATP projects in GE and NASA and in CLEEN SKY is not assured even when opportunity knocks. TRL lost out when the opportunity closed due to the change in design processes and materials, which used to be the driver of ATP. On the other hand, P&W kept the GTF project in its technology portfolio just after the NASA ATP projects. After the opportunity for green technology reopened in the early twenty-first century, GTF is now on the way to TRL 9. Two aircraft manufacturers selected this engine in 2007, and airlines selected the aircraft in 2009. Figure 4 shows the importance of continuous engineering efforts between opportunity windows for GTF transition.

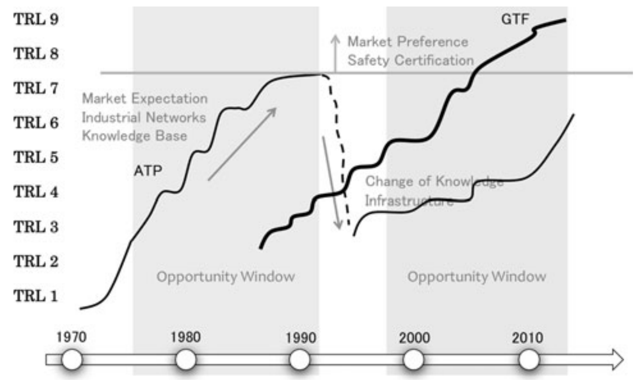

Fig. 4 Schematic image of ATP and GTF transition in TRL measurement. *Gray background* Opportunity window, *white background* closed window

Discussion

Socio-technical regime and TRLs

TRL—originally a tool of technology measurement—can be controversial when applied to MLP because of the risk of focusing too much on the technological aspects of a socio-technical transition. However, Fig. 4 highlights the interaction of social factors. In ATP, as in most cases in the aviation industry nowadays, a niche cannot progress to such high stages without both a market and social feasibility due to the large investment required for stepping to a next TRL stage. Therefore, interactions between technology and diverse social factors in each TRL are essential in developing and implementing technology in society.

Technological readiness and niche stock

Discussions about how to manage technology until a niche matures enough to be seen in a market are few. Stages of TRL 2–6 are now often well managed by institutes such as NASA ERA and CLEEN SKY after the rise of aviation responsibility toward sustainability. And SNM covers mainly TRL 2–3 to TRL 6. The aviation industry seeks theoretical support for phases TRL 1–3 and TRL 7 to TRL 9. The stages from TRL 7–9, which require high costs, used to be covered by military applications during the Cold War. The stages from TRL 7 to TRL 9 are very important for innovative technology to acquire enough safety reliance required from the civil aviation regime. Current discourse on SNM and MLP assumes the pre-existence of candidates of niche technology, but in reality this is not so. The stages from TRL 1 to TRL 3 are important for accumulating niche stocks as future candidates of niche technology. Technology at these earlier TRLs are usually invented and investigated in academia rather than in industry. Therefore, in future SNM research, the principle of academic discovery and research development and also academia-industry collaboration has become an important research topic for the technology classified into these TRLs.

A dynamic and uneven opportunity window

MLP and SNM have shown how a niche interacts with other factors of socio-technical regimes and landscapes. The socio-technical regimes and landscapes can open a channel for a niche technology to become a mainstream technology. However, as shown in Fig. 4, TRL should be at a certain level before the window of opportunity opens, and these options must mature before the window closes. The window of opportunity is not static and uniform. The window opens and closes depending on the landscape and regime change at that time. Different organizations face different widths of window, which depend on the conditions that each organization faces and the capability of each organization to adopt to the change of the landscape and regime. MLP and SNM usually downplay technological progress itself, rather than downplaying other social, institutional, and organizational factors, but how to support people in the field to manage the dynamic and uneven opportunity window should be discussed.

Risk of launch customer

The MLP approach emphasizes that the transition path is made of multiple dimensions. However, for the aviation industry, the dimension of the market is the most important. While SNM covers the stages from TRL 2 to TRL 6, the transition after TRL 7 depends highly on the manufacturers and the airlines. Furthermore, manufacturers will stop development at a certain stage if the airline does not sign as a launch customer. In the 1980s, no airline took the risk of being a launch customer for the Boeing 7J7 and MD-90 series so that these new aircraft projects were canceled. In 2007, two airlines signed for CRJ and MRJ with GTF. For airlines, to be a launch customer of a new aircraft has both advantages and risks. One of the advantages is that many demands from the launch customer can be integrated into the final specification of the product. The effect of advertising on airline brand awareness is large. However, there are also many risks, such as, whether the manufacturer achieves the committed operational and maintenance performance, safety, and schedule. Airlines know from their experience that a new engine will be troublesome. How to reduce the perceived risk, which delays an airline's decision to be the launch customer should be discussed in future research.

Institutional supports of export products

MLP accounts for policy and regulation issues, but focuses on these factors from the point of view of adaptation of innovation. However, even in the research and development phase, policy and regulation issues are important in the aviation industry. When we discussed institutional strategic support for the stages from TRL 7–9 in the previous section, we had to be especially careful in considering World Trade Organization (WTO) issues. The WTO Subsidies and Countervailing Measures Agreement (SCM Agreement) is an international agreement to discipline government subsidies. Here, all export subsidies are prohibited because they distort the market. Although the ambiguities in the interpretation of "import subsidy" and the SCM Agreement are crucial problems, many types of government assistance provided to the civil aircraft industry are likely to fall under the SCM Agreement definition of subsidies (Cunningham and Lichtenbaum 2005). Europe, the US, Canada, and Brazil were all accused of supporting the export of Airbus, Boeing, the Bombardier, and the Embraer, respectively, by the government of the competing company. According to several people in the public relations department of CLEEN SKY, CLEEN SKY does not go above a TRL 6 to avoid the WTO dispute. Perhaps this problem may be overcome by promoting collaboration among industries rather than governments. If so, then problems regarding expectations arise again.

Interaction of niches

Both ATP and GTF are being developed in 2012. However, the success of GTF will delay the transition of ATP to the market. Many specialists are worried that ATP cannot be on the market before 2020. ATP engines are suitable for short- and mid-haul aircraft, but are not yet ready yet to be mounted in a real aircraft project. On the other hand, GTF engines, which are also suitable for short- and mid-haul aircraft, and whose commercial product development P&W launched in 1998, were selected by Bombardier and Mitsubishi in the new Canada Regional Jet (CRJ) aircraft project, and the Mitsubishi Regional Jet (MRJ) project in 2007. Lufthansa and All Nippon Airlines (ANA) signed as the launch customer of CRJ and MRJ, respectively, in 2009. These aircraft will be delivered in 2013. The Boeing 737 series and the Airbus A320 are also in the segment of ATP and GTF engines and both companies have announced a new generation 737 and A320 with a new high bypass turbofan engine (and GTF engine for A320)

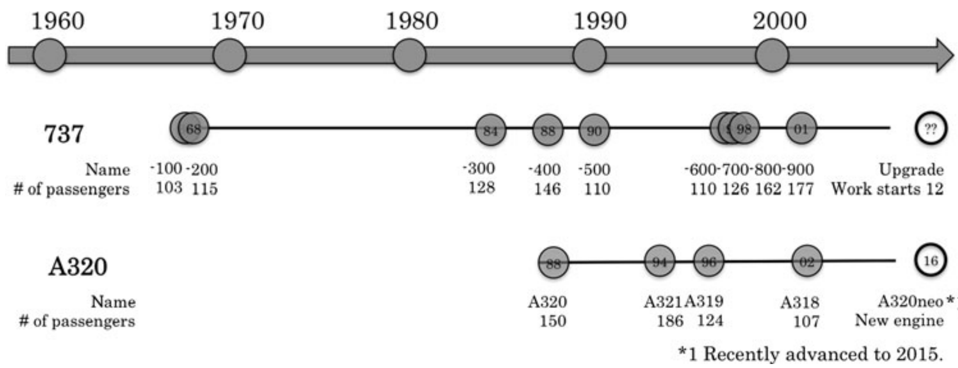

Fig. 5 The long product life cycle of an aircraft

rather than creating a new aircraft with ATP. Considering the long product life cycle of an aircraft (Fig. 5), it is very unlikely that a new aircraft project in this segment with the ATP engine will be launched before 2020 due to the spread of GTF. Visualization of such niche interaction is important in understanding innovation transition and is part of our future research.

Concluding remarks

This paper analyzed innovation in the aviation industry, which is locked stiffly into the current regime and faces sustainability issues. The paper also extends the framework of MLP to TRL. The authors believe that a scientific theory created by a generalized process of individual phenomena should be tested by repetitive application of theory to a certain domain, in this case, the aviation industry, which will contribute to the sophistication and improvement of the theory.

The aviation industry has started renewed ATP development as one of its most promising sustainability innovations. ATP failure in the late 1980s was generally considered the end of an opportunity window first opened during the 1973–1974 and 1979–1980 oil embargos. MLP analysis on ATP's unfinished transition illuminated the factors in a multi-level perspective that have supported and interrupted ATP transition from the early 1970s until now. MLP illuminated interrelated changes of factors promoting the ATP project including relations with policy makers, competition among engine manufactures, improved feasibility of lighter materials, and progress of computer technology. MLP also extracted factors interrupting the transition of niche ATP, such as the end of Cold War, safety as the guiding principle, low profitability of airlines, and noise regulation.

Stiff market preference, and safety certification, which were recognized as factors interrupting the 1980s ATP transition, and a change in knowledge infrastructure, which was recognized as a support factor of the 1980s ATP transition, are now hindering the current ATP transition. The authors observed that the same type of changes in a dimension of the socio-technical regime could both support and interrupt a niche, depending on the timing of the window of opportunity.

The difficulty in investigating details of the transition of two niches in the same technology domain was undertaken with a new measurement of niche development. As discussed in this paper, while MLP offers a comprehensive perspective for analyzing and understanding an innovation transition process, we believe that MLP analysis cannot explain the detailed transition of several innovations in the same technology domain. GTF is a niche in the same technology domain as ATP, and therefore, concluding that GTF and ATP should have different transition paths under the influence of the socio-technical regime and landscape within the existing MLP framework is difficult. In this paper, ATP and GTF analysis in MLP frameworks were facilitated by introducing TRL, a globally used measure of technology readiness in the aviation and other high technology industries. MLP with TRL should now provide greater information to study the deeper mechanisms of the innovation process. In addition, even though TRL is a technology measurement, TRL when combined with MLP analysis highlighted the interaction of social factors. This is because a niche cannot progress to higher stages without a market and social feasibility due to the large investment required in going to the next step. Therefore, interactions between technology and diverse social factors in each TRL are essential for the development and implementation of technology in society. We discussed the different roles of socio-technical regime at different TRLs. The introduction of TRL into MLP enables us to discuss functions of regime and landscape in transition paths such as technology readiness and niche stock, dynamic and uneven opportunity windows, institutional support of export products, and the risk of a 'launch' customer. The introduction of TRL to the framework of MLP can be beneficial for showing the complex structure of transitions, and to comprehend factors affecting technology and R&D projects in each TRL.

TRL not only supports academic research and theoretical development, but also collaboration among scholars of these theories, as well as practitioners and engineers, by elucidating the tacit knowledge of experts. Therefore, the application of TRL measurements to cases will appear soon in other industrial sectors with similar characteristics such as transportation, and information and communication technologies.

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