Case Study

The Sustainable and Green Engine (SAGE) – Aircraft Engine of the Future?

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Abstract

The case of the EU's Clean Sky initiative and its sustainable and green engine programme (SAGE) focuses on a sector where the implications of climate change are likely to be keenly felt in the coming decades, namely air transport. It is a sector where to date there have been few green or eco innovations. The case focuses on a current EU funded initiative designed to limit the impact of air transport on climate change. The initiative aims to foster innovation through the introduction of open rotor technology to power the next generation of short/medium haul airliners. This technology could potentially cut CO_2 emissions from commercial aircraft by 100 million tonnes per year (Nuttall, 2011). However it may also prove to be a disruptive technology rendering existing aircraft and possibly some of the firms that produce them, obsolete. As well as introducing some of the features of disruptive technologies the case highlights both the drivers for and barriers to the successful adoption of green innovations. Another important aspect of the case is that it also highlights the value of appropriate business strategies, such as the use of technology demonstrator programmes, in supporting and facilitating the adoption and diffusion of green innovations.

Keywords*: Green innovation, climate change, architectural innovation, disruptive technology, technology demonstrator, air transport,*

Introduction

The last half century has witnessed unprecedented growth in air travel around the world. There are currently some 1,400 airline companies operating a total of 25,000 commercial passenger aircraft (Belobaba et al., 2016). In 2013 the world's airlines provided some 36 million flights and transported a total of 3.1 billion passengers. Indeed the airline industry now provides a service to virtually every country on earth. At the same time the industry has played an integral role in globalization and the creation of the global economy (Belobaba et al., 2016).

However commercial airliners operated by the world's airlines contribute to climate change through their emissions, of which the most significant is carbon dioxide (CO_2), a conservative gas that persists in the atmosphere over a long period (Daley, 2012). Perhaps surprisingly given its scale today, air transport has hitherto been a comparatively modest contributor to climate change. Emissions from all forms of transport comprise about 23 per cent of total emissions (Rhoades, 2014), and global aviation emissions amount to about 12 per cent of this, or three per cent of the overall level of emissions (Palmer, 2015). This goes some way to explain why aviation emissions were not included in the Kyoto Protocol.

Lately the perception that aviation missions are relatively modest has begun to change. In part this is because of the increased credibility given to climate change generally, but it also reflects the continued growth of air transport. Since the start of the jet age in the 1960s, air travel has increased dramatically, almost trebling (Vasigh et al. (2013) in the last 20 years (see figure1). This growth has outpaced any specific reductions in emissions that have been achieved through technological advances. The latter have been significant. Over the course of several decades there have been substantial improvements in the fuel efficiency of commercial airliners. The amount of fuel used per mile travelled has dropped by 60% in the last 35 years, and this has been accompanied by lower emissions (Daley, 2012). Most of the improvement has come from advances in engine technology, in particular the use of higher bypass ratios (BPRs) on turbofan engines that have been the product of advances in fan technology associated with new materials and improved aerodynamics.

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After six decades of advances however, gas turbine technology is now relatively mature. Consequently projections for the next 15 years anticipate improvements in fuel consumption to be more modest, and are estimated at no more than one per cent per year (Marais and Waitz, 2016). At the same time commercial market forecasts indicate that sustained growth in air transport of five per cent per year will continue until 2030 (Airbus, 2007; Boeing, 2008). At this rate air transport can be expected to double every 15 years, leading to a sixfold increase by the middle of the century (Palmer, 2015). Given the projected sustained rapid growth of the air transport industry, aircraft emissions are expected to constitute a significant proportion of greenhouse gas emissions by 2050 (Daley, 2012), since emission reductions, assuming turbofan engines continue to be used, are unlikely to be sufficient to offset the continued growth in air travel. Thus while at present CO_2 emissions from commercial aircraft account for about three per cent of total emissions, this proportion is expected to rise by a predicted five per cent per year between now and 2020. Growth on this scale is rapidly transforming aviation from its position as 'a relatively minor polluter' (Daley, 2012: 47) into a significant source of greenhouse gas emissions and in turn climate change.

The Clean Sky Joint Technology Initiative

Given mounting concern about the prospect of rapidly rising levels of emissions from aviation, the European Commission (EC) set up the 'Clean Sky' Joint Technology initiative (Kirby, 2012). This was launched in Brussels in February 2008. This is a large scale EU wide research programme involving a total of 86 organisations from 16 countries. With a budget of €1.6 billion, Clean Sky is the most ambitious aeronautical research programme ever launched in Europe. Its aim is to develop breakthrough technologies that will significantly improve the environmental performance of commercial air transport in the future (SBAC, 2013), through the development of more environmentally friendly aircraft, that are not only quieter but offer significantly lower levels of emissions.

In all Clean Sky comprises six programmes, covering both different categories of commercial aircraft and propulsion systems. One of these programmes is targeted at engine technologies. This is the *Sustainable and Green Engine* programme known as SAGE. The SAGE programme calls for the development of a number of technology demonstrator[1] aero engines covering a range of applications. These include commercial airliners, regional aircraft and rotorcraft (i.e. helicopters). SAGE comprises six technology demonstrator programmes overall covering five different types of engine distinguished by application (e.g. narrow body) and engine architecture (e.g. three shaft). The five are :

- Large 3 shaft turbofan
- Lean burn
- Turboshaft

- Geared turbofan
- Open rotor

Each draws on the competences and facilities of the major European aero engine manufacturers including Britain's Rolls-Royce, France's Snecma and Germany's MTU.

There is a focus within SAGE on innovative product architectures, in particular ones that offer opportunities for step-change reductions in CO_2 emissions, relative to the current generation of turbofan engines powering narrow body and regional aircraft like the Airbus A320 and the Boeing 737. The two most innovative architectures being employed in SAGE are to be found on the geared turbofan (GTF) and open rotor engines.

MTU of Germany is leading SAGE's geared turbofan (GTF) technology demonstrator engine programme. It is based on an already certified engine, Pratt & Whitney's PW1100G geared fan which is just entering service on the Airbus A320NEO aircraft family (A319NEO, A320NEO, A321NEO).

The geared fan engine features a reduction gearbox located between the fan at the front of the engine and the low pressure turbine that drives it. On a conventional turbofan engine the two are directly connect via a shaft. With the addition of a gearbox, the conventional turbofan engine becomes a geared fan engine. The gearbox spins the fan at a much slower speed than the low pressure turbine. The ratio is about 3:1. This allows both sections of the engine to run at their optimum. Although the inclusion of a gearbox produces a weight penalty, the overall result is a much more efficient engine giving lower fuel consumption and lower emissions. The Pratt and Whitney PW1100G engine is expected to be 11per cent more fuel efficient than the engines it replaces.

Developments being carried out as part of SAGE involve principally the high pressure compressor and the low pressure turbine modules. They are designed to improve relevant technologies in order to significantly reduce fuel burn and therefore emissions still further. They will be incorporated into the next generation PW1100G geared fan engine which is slated to enter service in 2022-25.

Open Rotor Technology

While the GTF demonstrator can be integrated into an existing, albeit relatively new and as yet unproven engine design, the open rotor or propfan as it is sometimes termed, provides for a completely different engine architecture. As such it is much the most ambitious of the SAGE technology demonstrator projects. It represents a potential step-change for commercial aviation, because it offers the prospect of a reduction in fuel burn and thence emissions of as much as 40 or even 50 per cent compared to current aircraft (Gunston, 2006). A performance improvement of this magnitude means that the open rotor concept is potentially an example of what Christensen (1997) terms a *disruptive technology*. Disruptive technologies re-define a product's performance trajectory rendering existing technologies obsolete, often leading to the demise of some of the leading firms in the field. These are typically technologies with different attributes compared to existing mainstream products so that they are initially only of value in niche markets, but as the technology develops its performance even on mainstream attributes improves to the point where it displaces existing technologies. If existing firms don't fully embrace the disruptive technology there is a very real prospect that they will exit the industry.

The advent of the 'jet age' in the 1960s with the introduction of the jet engine into civil aviation for example, led to the exit of one of the leading aero engine manufacturers, Wright, because the firm was very slow to develop a jet engine preferring to stick with making increasingly sophisticated piston engines. The same thing happened to the leading manufacturer of piston engined commercial airliners, the California based firm of Douglas. Meanwhile a new entrant to commercial aviation, Boeing, flourished and ultimately came to dominate the industry, that is until wide-bodied jets came on to the scene when another new entrant, Airbus Industrie, appeared.

Over the years engine manufacturers have improved the fuel burn of conventional turbofan engines by steadily increasing the bypass ratio (BPR), that is the proportion of cold air volume driven rearward by the engine's fan in relation to the volume of hot gases coming from the core (i.e. inside the engine). In effect this has meant increasing the size of the fan fitted at the front of the engine and the amount of air ducted around the engine thereby increasing the engine's propulsive efficiency. Consequently as much as 70 per cent of the power of a turbofan engine comes not from the jet but from the fan at the front. The impact of this is very apparent when jets from the 1970s are compared with their modern counterparts like the Boeing 787 Dreamliner. Whereas the former have engines that are long and thin, the latter are equipped with engines that are much broader and more bulbous. General Electric's biggest engine the GE90 has a diameter that is greater than the diameter of the fuselage of a Boeing 737. However there are limits to how much the BPR of an engine can be increased in this way. On a conventional (i.e. unducted) turbofan engine beyond a certain fan diameter the benefits of a higher BPR in terms of fuel consumption will eventually be more than offset by the increased weight and drag of the larger diameter nacelle required to house the fan (Dubois, 2014). Hence the challenge for engine manufacturers is to find technology solutions that will facilitate the use of higher BPR architectures without inducing fuel burn penalties (Dron, 2008).

One way round this is to employ a radically different engine architecture (i.e. an architectural innovation). An open rotor is a concept that employs just such an architecture. Based on the same principles as a modern turbofan engine, an open rotor engine is essentially an engine without the ducting (i.e. the fan containment casing) fitted around the outside of the fan. Instead the fan, in the form of a multi-bladed rotor or propeller, is mounted on the outside of the engine (see figure 2). Using an open rotor in this way means its diameter is not constrained. The increased diameter of the rotor permits a very much higher BPR that allows the engine to work with a larger airflow regardless of aircraft speed and this in turn means that the energy turning the fan will be utilized more efficiently (Hallam, 2009). Combined with the removal of the heavy drag-inducing nacelle this means the fuel burn and hence the CO_2 emissions of an open rotor design will be significantly less than that of an equivalent high BPR turbofan engine. Along with other technological advances associated with new materials and advanced aerodynamics, the gains in terms of reduced emissions (and fuel consumption) become very significant.

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Early Attempts

The open rotor is actually not a new concept. In the 1980s when fuel prices rose dramatically both of the leading American engine manufacturers experimented with open rotor engines. General Electric's open rotor engine was developed as part of a NASA funded demonstrator programme that aimed to develop more fuel efficient engines. Termed the *Unducted Fan (UDF)*, the GE36 engine was based on the core of an existing engine, the F404 that powered the McDonnell-Douglas F-18 Hornet fighter, and featured two rows of eight contra-rotating scimitar-like rotor blades 12 feet in diameter, mounted on the outside of the engine in a '*pusher*' configuration.. Each individual blade was about five feet in length and made of carbon fibre composite, making them both extremely light and strong (Garvin, 1998).

Unveiled at the Paris Air Show in 1985 (Sweetman, 2005), the GE36 engine offered enormous potential but presented equally large risks. It flew for the first time a year later in 1986 and caused a stir when a McDonnell-Douglas MD-80 airliner powered by the revolutionary engine was flown in front of the crowds at the Farnborough Air Show in 1988[2]. It demonstrated outstanding fuel efficiency. However noise levels were problematic. Similarly there were safety issues over the danger of blades breaking free and damaging the fuselage. Despite this, Boeing announced plans to develop a new airliner, the Boeing 7J7 powered by the revolutionary new engine. By then the price of oil had fallen back significantly and airlines were lukewarm about the scale of the investment they would have to make in the new technology. Instead they preferred a much improved conventional turbofan, the CFM 56 developed jointly by General Electric and Snecma,,and as sales of this engine took off, the UDF engine was quietly dropped, although the carbon fibre blades were utilized in the GE90 engine that went on to power the Boeing 777.

SAGE's contra-rotating open rotor (CROR) engine

Thirty years ago aviation emissions really weren't an issue. However today with growing urgency regarding climate change and especially predictions about the future growth of commercial aviation, things have changed dramatically. Engine designers are now looking again at the possibilities offered by the concept of an open rotor engine in terms of delivering a breakthrough not just in fuel burn, but more importantly by delivering radically improved environmental performance through reduced emissions of CO_2.

Consequently, as noted earlier the open rotor concept is making a comeback. It is one of five engine types currently being developed and evaluated as part of the EU's Clean Sky's sustainable green engine (SAGE) programme. Taking the lead is the French engine manufacturer, Snecma, working in collaboration with Airbus. As part of the programme designated SAGE 2 under Clean Sky, the Geared Open Rotor Demonstrator project is evaluating the feasibility and the environmental benefits of an open rotor propulsion system. According to Vincent Garnier, Snecma's director of product strategy and marketing (Dubois, 2014), the technology demonstrator programme they are leading as part of Clean Sky has three main goals:

- to evaluate and validate the open rotor architecture
- to push the science and technology of all the main components of the propulsion system
- to build a team of partners

The open rotor architecture being evaluated is similar to that employed by General Electric during the 1980s. However since then material science has made many advances and among the new technologies now being evaluated is a ceramic-matrix composite (CMC) used for airfoils in the low pressure (LP) turbine. CMC produces airfoils that are 70 per cent lighter than conventional airfoils and yield a lighter disk overall (Dubois, 2014). A feature of technology demonstrator programmes is that they provide an opportunity for firms to work together as partners on a project. To date the partners in this particular SAGE programme include Italy's Avio Aero, Britain's GKN Aerospace and France's Aircelle (part of Safran) along with Snecma (Eshel, 2014) the firm leading the project. Each of these partners is a specialist in its field. For example Avio Aero specializes in gearboxes, while GKN Aerospace which is providing the majority of the engine's rotating module (Reals, 2016) which includes the rotors themselves, specializes in composite aerostructures including things like helicopter blades.

The technology demonstrator programme began with Snecma testing a one fifth scale model of a contra-rotating open rotor (CROR) design. These tests were carried out at the French research agency ONERA's SM1A wind tunnel at its research facility in Modane in the French Alps starting in 2010. They confirmed the open rotor's efficiency (Warwick, 2014) and that a 2030 timeframe for the introduction of open rotor engines into airline service was technically feasible. The aerodynamic performance of the open rotor design also featured in the wind tunnel tests. Three generations of blade design, HERA 1,3 and 5, were evaluated in terms of their aerodynamic performance (Warwick, 2014). Test results indicated that in aerodynamic terms an open rotor had the potential for a saving of around 30 per cent in terms of fuel used over comparable turbofan engines (Gubisch, 2014).

Having successfully completed tests with a scale model, the next stage of the SAGE 2 programme was for Snecma and its partners to construct a full size prototype engine employing an open rotor architecture. Like the earlier General Electric design, this experimental powerplant has two unducted contra-rotating rotors in a '*pusher'* configuration at the rear of the engine. This configuration permits the installation of the engine at the rear of the aircraft, a location that shields the open rotors to reduce noise levels (Warwick, 2014). The advantage of having not one but two rotors and allowing them to contra-rotate is that the rotational component of the velocity of the air leaving the first set of blades (known as the 'swirl') will be corrected by the second set of blades and so increase the engine's effective thrust (Dron, 2008). It also means that a contra-rotating open rotor (CROR) engine can have smaller blades, which offer the benefit of easier integration with the airframe (SBAC, 2012).

The engine itself is based on the core of Snecma's M88 engine which powers the Dassault Rafale fighter (Gubisch, 2012). Unlike General Electric's earlier UDF engine, where a direct drive from the turbine was used to power the rotors, the SAGE 2 demonstrator employs a gearbox to optimize rotational speeds. The contra-rotating pusher with a power gearbox concept is actually slightly lighter than General Electric's UDF engine, because it permits a significant reduction in the number of power turbine stages (Dron, 2008). It is also less noisy thanks to a reduction in the speed of the rotor blades. Like the earlier UDF engine, the SAGE 2 demonstrator features variable pitch technology to control the rotor blades themselves.

Construction of the full size demonstrator engine was virtual complete by mid- 2016, with the first run due to take place later in the year (Reals, 2016). This will be followed by an extensive period of ground testing at Snecma's engine test facility in France. This will not only enable engineers to evaluate the engine's performance it will also be an opportunity to trial variations both in the design and the materials used. This is likely to last at least two years and is scheduled to be carried out on the aft fuselage of an Airbus A340-300. Flight testing will focus on airframe integration and certification issues (Warwick, 2014). Only when the technical and economic viability of the open rotor design has been firmly established through the SAGE 2 demonstrator will work start on the production stage to build a fully commercial open rotor engine. This unlikely to be until 2025, with entry into service taking place after 2030. The production stage will be particularly challenging due to the complexity of the engine's rear assembly comprising as it does a gearbox and a variable pitch system for the rotor blades.

Applications

One weak point of open rotor designs is that they are less suited to long haul wide-bodied aircraft like the Boeing 777 and 787. This arises because the BPR is an important parameter for an aircraft's climb capability. On long haul flights this is a relatively short flight phase, with aircraft spending a much greater proportion of the flight in the cruise phase. On short and medium haul flights in contrast the aircraft spends a much greater proportion of flight time in the climb phase (Dubois, 2014). As a result there is a much bigger gain from a high BPR on short and medium haul flights. This is why Pratt & Whitney's new geared turbofan (GTF) engine the PW1100G, which has a relatively high BPR of 12:1, is fitted to Airbus's new short haul airliner, the narrow body, single aisle A320NEO.

Consequently short and medium haul aircraft are the ones that are most likely to utilize open rotor technology if the outcome of this demonstrator programme is successful. Fortunately this particular market niche is a significant one. The two main protagonists in this market are currently the Airbus A320 and the Boeing.737. These aircraft are each company's best selling models (see table 1), with a combined output in 2015 of almost 1,000 aircraft. Hence if the technology demonstrator programme proves the technology, the market for an environmentally sound, low emission engine is potentially substantial.

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Challenges

While there is a distinct market niche (i.e. short and medium haul aircraft) for an open rotor engine, nonetheless the concept presents considerable technological challenges. This provides much of the rationale behind the use of a technology demonstrator programme, since as Vincent Garnier, Snecma’s director of product strategy and marketing for civil engines noted at a recent conference (Warwick,2014), they provide, ‘a great learning vehicle’. The technological challenges extend to five main aspects of the open rotor design:-

- noise
- safety
- airframe integration
- maintenance
- speed

Noise was an issue on General Electric’s UDF engine back in the 1980s (Gubisch, 2014).Noise levels on an open rotor are higher because the rotating blades are open and not muffled by the fan case and the nacelle as they are on a turbofan engine. However solutions to this appear to be in sight. Using a ‘*pusher*’ configuration for the rotors with the engines mounted at the rear of the fuselage helps to mitigate the noise. In addition Snecma’s wind tunnel tests evaluated a number of aspects of open rotor designs in pursuit of noise reduction. These included: the optimum distance between the two sets of blades; the number of blades on each rotor; and the profile of the blades themselves. The results were sufficiently encouraging for Snecma to conclude that noise was not an insurmountable problem and that an open rotor would be able to meet appropriate noise regulations.

Safety is problematic since certification requirements of bodies like the Federal Aviation Administration (FAA) demand that in the event of a mechanical failure caused by a rotor burst or the release of a blade (Warwick, 2014), pieces from the engine must not be able to penetrate the fuselage and threaten either the passengers themselves or the aircraft's hydraulic systems. On turbofan engines this requirement is met by the fan case which surrounds the fan at the front of the engine. Such protection is clearly absent on an open rotor. Instead aircraft powered by open rotor engines will require the fitting of shielding. Airbus has estimated that this could add as much 1,100 lbs in additional weight (Warwick, 2014). However the use of lightweight carbon fibre composites is likely to offer a solution.

Airframe integration is a potential problem because of the size of the rotor blades which would be too big to fit under the wing as on conventional jets at present. Mounting the engines at the rear of the aircraft instead of under the wings as on most conventional airliners today, avoids this problem but will make maintenance more difficult. Thus as a recent report from the SBAC (2013) noted whichever mounting configuration is selected there will be issues surrounding integration with the airframe.

Maintenance issues are not confined to engine location. Because the SAGE 2 engine utilizes both a reduction gearbox and variable pitch technology, it will require more maintenance as these are complex mechanical systems. This is particularly an issue when it comes to convincing airlines to make the switch to open rotor designs, as airlines that have used turboprop aircraft in the past will be aware of the higher maintenance requirements (compared to conventional turbofan engines) associated with these mechanical systems. Similarly there will also be issues surrounding maintenance.

Finally it is worth noting that open rotor aircraft will be slightly slower than today's jets. This is because while they are capable of travelling at Mach 0.8, for optimum efficiency they need to fly slightly slower at Mach 0.75. However since open rotors are intended for short haul applications the increase in flight times is likely to be minimal.

Thus while an open rotor design like the SAGE 2 engine does present a number of significant technological challenges which will make the new product development process a lengthy one, none of them appears to be insurmountable. In addition given that it isn't planned that open rotor powered aircraft should enter service until 2030 there is sufficient time for the technical issues to be solved. This, combined with the potential contribution to climate change mitigation through much reduced levels of emissions, is part of the rationale for the EU funding technology demonstrator projects like the sustainable and green engine (SAGE).

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Note

1. A technology demonstrator is a prototype of a new product incorporating new technologies and built as a *proof of concept* design, with the primary purpose of showcasing the feasibility, performance and possible applications of the new technology. They aim to demonstrate to potential investors, partners and potential customers the viability of the new technology. They are used in high tech sectors like aerospace where they are often publicly funded.

2. A video clip showing a demonstration flight of this aircraft powered by General Electric's GE36 open rotor engine at Farnborough in 1988 is available at: https://www.youtube.com/watch?v=1BMNaXc1rL8

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TEACHING NOTE

1. Synopsis

According to Dogannis (2009) in the last 50 years technological innovations in air transport have far outstripped any other transport mode. Open rotor technology embodied in propfan engines like SAGE 2 potentially represents another important leap forward. However while this technology is highly attractive in terms of cutting emissions from commercial aircraft, the success of this green innovation is by no means certain. The case study provides an opportunity to explore some of the barriers and other factors that contribute to this uncertainty, while also exploring how initiatives such as technology demonstrators can help to convince potential customers (i.e. airlines) of the value of this technology, not just for those who are flying but for society as a whole. At the same time it provides scope for considering the possible impact of this new technology through the concept of disruptive technologies. A key feature of the case study is that it deals with a topic, air travel, which most students will have experienced and provides an opportunity to appreciate that green innovations, while they are clearly highly desirable in terms of creating a sustainable environment, often face complex issues when it comes to successful adoption and diffusion.

2. Learning objectives

The case study’s primary learning objectives for students are:

a) Analyse the range of drivers that can induce green innovations.
b) Evaluate the business strategies, such as demonstrator programmes and targeting of niche markets, that can help to facilitate the successful adoption and take-up of green innovations.
c) Analyse the concept of a disruptive technology and be aware of both its potential impact and the factors that can lead to its acceptance or rejection in commercial markets.
d) Assess the various barriers that can impede the successful introduction of green innovations.

2. Suggested questions

Q1: Identify and assess: a.) the drivers and b.) the barriers to the successful introduction of green innovations in the field of air transport.

See Rennings (2000) and Smith (2015) for discussion of the drivers and barriers associated with green innovations.

Drivers: According to Rennings (2000) there are potentially three types of driver for green innovations, namely technology push, market pull and regulatory push. It is likely that the drivers in this case will be a combination of regulatory push and technological push factors, although students might well want to discuss the possibility that market pull would also be a driver. Perhaps surprisingly there is at present no real regulatory push in the sense that there are only limited requirements for the airlines or the manufacturers to reduce their emissions from aircraft. However significant changes are on the way. For example, the International Civil Aviation Organisation (ICAO), the agency that oversees civil aviation, recently put forward the first efficiency standard for aircraft for the United Nations to approve (Reals (2016) in February 2016. Given the rapidly rising level of emissions from aircraft and increasing concerns about climate change, further regulations covering aircraft emissions are likely. Certainly by 2030 one could expect to see regulations requiring significant reductions in emissions. There is also an element of technology push. This is associated with improvements in design, especially in the field of aerodynamics, which have led to improvements in fan blade design. (It can be useful to get students to look at modern passenger aircraft and compare them with those of the 1960s – fan blades look different and one rarely sees large amounts of smoke being produced on take-off today). The other technological change is in the area of new materials. The introduction of carbon fibre has permitted the development of much more efficient and safer fan blades.

Barriers: These are likely to be technological, economic, and institutional. As with most technological innovations one would expect the technological barriers to be the main ones. While these are undoubtedly important, and include aspects such as safety, noise and maintenance requirements, students should be encouraged to explore possible economic and institutional barriers. The economic barriers include the enormous cost of developing both new engines and new aircraft and the problem of 'sunk costs', such as the large sums airlines have invested in maintenance facilities for jet engines. However institutional barriers are also likely to be important (see Scott, 2013). The institutional barriers are likely to be ones associated with the structure of the airline industry. It is highly competitive and very cyclical. Consequently major investment decisions like switching to a new type of aircraft fitted with a new propulsion system involve issues surrounding legitimacy and isomorphism. Airline managers may be very wary of new technologies, if they are different and not used by other airlines. Given its highly competitive nature there is likely to be a collective wariness within the industry about the legitimacy of committing massive resources to investing in a new technology. One might well see the airlines and others in the industry as *'vested interests'*. Having invested in the current technology for air travel they may be reluctant to write this off and invest in something new. The key thing is that students appreciate that innovations, especially green ones, are about much more than developing new technologies.

Q2: What is an architectural innovation and is the concept relevant in this case?

Essential reading for this question is the paper by Henderson and Clarke (1990) on architectural innovation (alternatively there is a summary in Smith (2015)). According to Henderson and Clarke (1990) the essence of an architectural innovation is that it involves the re-configuration of a system to link together existing components in a different way. That is pretty much what was has happened in the case of the SAGE 2 open rotor engine. The 'core' of the SAGE 2 is from an existing engine, similarly gearboxes and variable pitch systems are used on turboprop engines and the rotor blades are very like those now being used on the most advanced turbofans. What is different is the way they are configured. An open rotor engine has a different architecture and that's what makes it an architectural innovation. This is a good opportunity to get students to think about the nature of innovation. Innovations aren't just about new technologies. Design is also very important and an open rotor is a design that differs markedly from conventional turbofan engines.

Q3: Why is it possible that the open rotor may prove to be an example of a disruptive technology?

This is an opportunity to explore the concept of disruptive technologies in greater depth (see Christensen, 1997) and ensure that students thoroughly understand it by considering examples where a new technology has proved destructive in the past. According to Christensen (1997) a disruptive technology typically brings forward a different value proposition compared to an existing technology. Quite often this new value proposition or aspects of it will not be valued by most mainstream consumers. Thus the first jet airliners were faster and could fly much higher than conventional airliners but were much more expensive to purchase and to operate. Initially this made them an unattractive proposition for most airlines, who assumed that higher operating costs would mean higher fares that would deter people from flying. But for some travellers, such as business people and celebrities, the benefits of a more comfortable flight and shorter journey times outweighed the additional cost. In time jet engines became more fuel efficient and jet travel began to appeal to mainstream customers. The technology proved disruptive because piston engined airliners (i.e. with propellers), like the Douglas DC7C and the Lockheed Constellation quickly became obsolete. As a result engine makers like Wright who were slow to adopt jet engine technology exited the industry.

With the open rotor the new value proposition will be significantly lower emissions. At present this does not appear to be highly valued either by passengers or airlines. But in time this may well change. If emissions are much more tightly regulated either directly or through something like a carbon trading scheme, then this could well change dramatically and open rotor technology could come into its own. If it does then conventional jet powered airliners in use today will become obsolete. This in turn may lead to some existing makers of aircraft and engines going out of business, to be replaced by new entrants who are quicker at adopting open rotor technology. However students need to appreciate there is much uncertainty surrounding this and this makes decisions about developing and adopting such a technology particularly difficult.

Q4: Identify and analyse the business strategies employed in this case to facilitate the successful adoption of green innovations.

This is a great opportunity to get students to think about the adoption and diffusion of green innovations. To that end students should be directed to the classic text on innovation diffusion by Rogers (1995). Students need to appreciate that especially with green innovations its quite easy to sell an innovation to *'early adopters'* those individuals and firms that are interested in and enthusiastic about sustainability and efforts to mitigate climate change. Persuading the rest of us is a more difficult task, especially where huge investments in time and money are concerned.

Two business strategies that can help are technology demonstrator programmes and niche markets and these are both being used in this case. The SAGE 2 engine is a technology demonstrator programme, where the European Union is putting up much of the money to enable a commercial enterprise, in this case the French engine manufacturer Snecma, to build a prototype open rotor engine. The value of this is that manufacturers can then trial new technologies, test their feasibility and collect valuable performance data through extensive testing of the prototype. At the same time technology demonstrators provide a valuable opportunity to showcase the new technology especially for potential customers, who in this case include both the airlines and the travelling public. They can then hopefully be convinced of the value of this green innovation. Students need to appreciate that building a prototype aero engine is enormously expensive, which is why bodies like the EU fund this kind of activity.

Similarly niche markets can be a very effective way of introducing an innovation. A good example is the construction equipment manufacturer JCB, where they initially sold the first hydraulic excavators not to existing users of cable operated excavators such as mining companies, but to house builders and utility companies, who had always dug trenches by hand in the past. The latter were a specific group (i.e. niche) that valued the flexibility and mobility of the new hydraulic excavators whereas existing customers did not. So too with propfan engines using open rotors where the market niche is short haul aircraft where the gain will be greatest.

Concluding remarks

The SAGE 2 project is on-going. By mid-2016 Snecma was reporting that most of the manufacturing of the technology demonstrator had been carried out and it, along with its partners was at the engine assembly stage. Ground testing of the engine was due to start towards the end of 2016. Flight testing on an Airbus A340 isn’t due to start until 2019. A key feature of ground testing will be validating the mechanical integrity of the powerplant and identifying potential applications (i.e. the types of aircraft for which it would be suitable). Open rotor engines are expected to enter commercial service by 2030-35, but this will be dependent on the development of an all-new airframe which according to Henrick Runnemalm, director of advanced engineering at GKN Aerospace (Reals, 2016), is likely to be a smaller, short range regional airliner. It will also be dependent on oil prices rising from their current low levels and persuading airline managers that passengers will accept a return to aircraft with propellers – albeit of a very different design!

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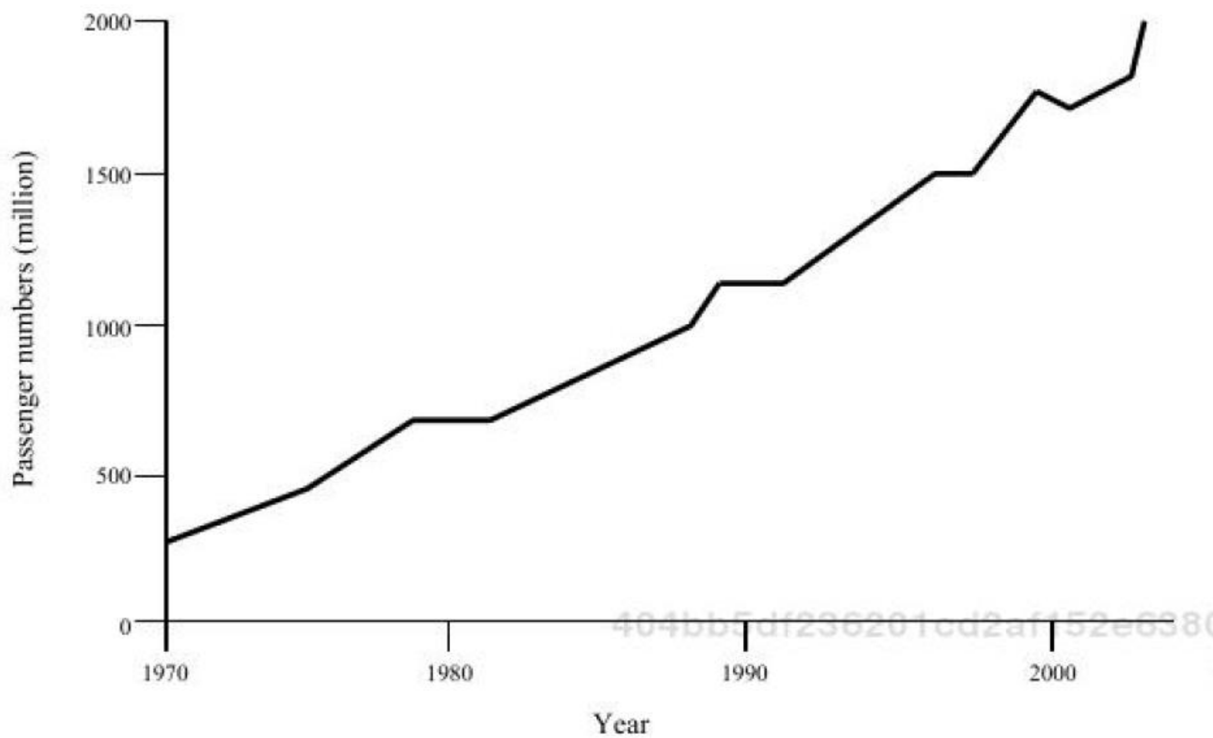
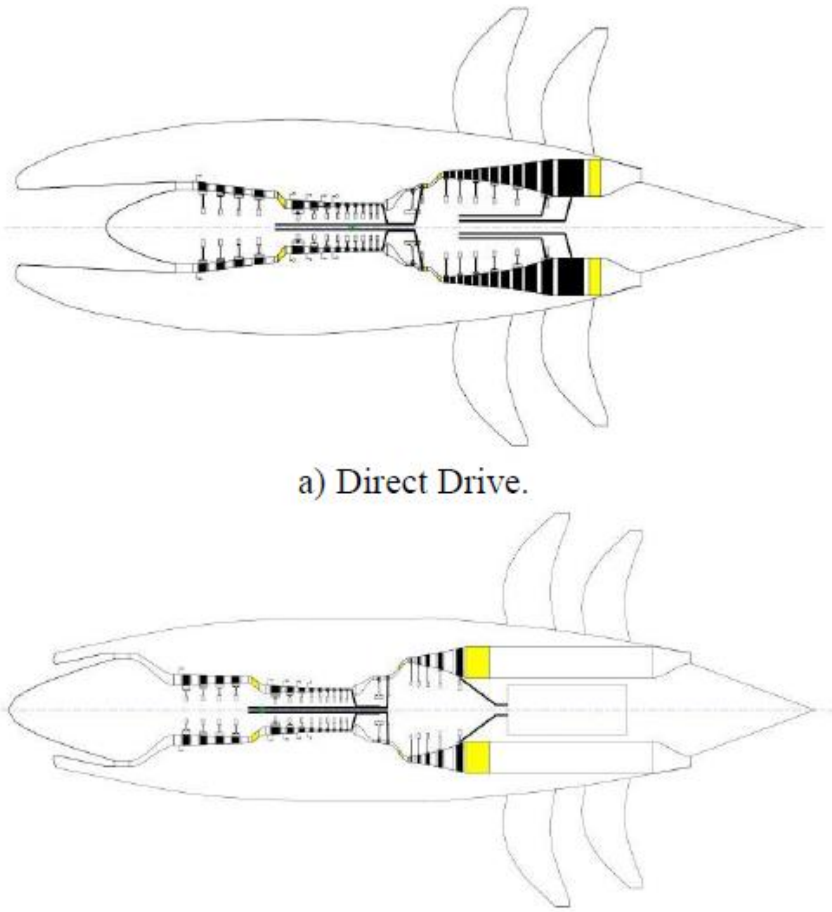
Figure 1
The Growth of Air Transport in Passenger Numbers 1970-2005



Source: Daley (2012)

Figure 2
Contra-Rotating Open Rotor Pusher configurations



a) Direct Drive.

b) Geared.

Source: Guynn et al. (2011)

Table 1
Orders and output of Airbus and Boeing aircraft 2014-15

	2014		2015	
Airbus *short/medium haul (single aisle)*	Orders	Deliveries	Orders	Deliveries
A320	1321	490	897	491
Long haul (twin aisle)				
A330	154	108	140	103
A350	-32	1	-3	14
A380	13	30	2	27
Total	1456	629	1036	635
Boeing				
Short/medium haul (single aisle)				
737	1104	485	588	495
Long haul (twin aisle)				
747	0	19	2	18
767	4	6	49	16
777	283	99	58	98
787	41	114	71	135
Total	1432	723	768	762
Grand Total	2888	1352	1804	1397

Source: Kingsley-Jones, M. (2016)