"Learning-by-using" as systems integration:
The case of aircraft maintenance

Luis Araujo* and João Mota**

*Department of Marketing
Lancaster University Management School
Lancaster LA1 4YX
U.K.
e-mail: **L.Araujo@lancaster.ac.uk**

**Departamento de Gestão
ISEG
Universidade Técnica de Lisboa
Rua Miguel Lupi 20, 1200-725 Lisboa, Portugal
e-mail: **joaomota@iseg.utl.pt**

Abstract

The purpose of this paper is to explore Rosenberg's (1982) notion of "learning-as-using" as form of systems integration. In the recent past, there has been a surge of interest in the interaction between product and organisational architectures at the level of design and to a lesser extent production. We take these insights further by studying a case on the interaction of product and organisational architectures at the level of maintenance activities. The maintenance of complex systems such as civilian airliners is characterised by extensive interaction between different types of actors involved in monitoring the performance of that system over time. These interactions lead to important learning opportunities regarding the scheduling of maintenance activities themselves as well as the performance of particular subsystems and components. Our study followed the activities of an aircraft repair and maintenance station attached to an airline over an 18 month period. We elaborate on Rosenberg's notion of "learning-by-using" by showing how this form of learning is both connected to the architecture of the airliner as a complex, decomposable system and embedded within intricate patterns of relationships between the various actors involved in the design, operation and maintenance of these aircraft.

Keywords: product architecture; organisational architecture; systems integration; "learning-bu-using"

Introduction

In the industrial networks literature, following the seminal contribution of Richardson (1972), products have been seen as outcomes of activities and their underlying capabilities. However, the link between products and their interconnection with the organisation of activities and capabilities has been less well researched (but see Håkansson and Waluszewski, 2002 for a recent exception).

The connection between product and organisational architectures has focused on how the architecture of products influences the division of labour and leaves imprints on the structures of organisations which, in turn, influences how new product architectures come to reflect extant structures (Henderson and Clarke, 1990; Sanchez and Mahoney, 1996; Langlois, 2002; von Corswant, 2003). The assumption is that the type of architecture at one level determines the architecture at other levels (Fine, 1998; Sanchez, 1999). Thus modular product architectures should lead to modular organisational structures and modular production networks (Sturgeon, 2002). Pre-existing structures and capabilities in turn, embody particular architectural preference and will influence product design activities (Sako, 2003).

An alternative view suggests that the interaction of architectures at different levels (e.g. products, organisations, supply and production networks) is more subtle and complex than previously imagined and implies significant systems integration capabilities (Brusoni and Prencipe, 2001). Rather than isomorphic mapping across levels, we should expect important asymmetries of architectures at different levels. Thus modular product designs for example, may require strong relational links between firms rather than thin, market interfaces (Pavitt, 2003),

The problems of interaction between different architectures are compounded when a variety of organisations are involved in design, production and service activities and the interdependencies between these activities are high. For example, if there is a high interdependency between design and use, there is a strong incentive to design products with specific maintenance philosophies in mind.

This paper revisits these arguments in a particularly relevant context: the maintenance of civilian aircraft. Civilian aircraft can be regarded as complex systems in their own right which are continuously evolving as their operation and maintenance feed back lessons into the design of particular components or subsystems – or "learning-by-using" in Rosenberg's (1982) felicitous expression. The network of actors involved in the design, operation and maintenance of these aircraft is often highly distributed and encapsulates divisions of capabilities embodied in the architecture of the product. But when looked at a finer level of detail, the architecture of the system is not uniformly understood and shared across the network of actors. Different parts of these complex systems may have different failure rates and require different regimes of inspection whilst the underlying technologies of modules may change at different rates. These changes may cause the need for adjustments to the patterns of interaction between different actors as the understanding of how the system works and is to be maintained evolves through it lifecycle.

The paper is structured as follows: in the first two sections we will review the literature on the interaction between product and organisational architectures and systems integration. In the third section, we will introduce the case of an aircraft maintenance and repair station we have followed over an 18-month period, focusing on the division of labour and coordination patterns employed to deal with routine and non-routine problems. The paper concludes with reflections on the nature of systems integration in the case of maintenance of complex systems over time.

The Interaction between Product and Organisational Architectures

Ulrich (1995) provides a useful introduction to product architectures. A product's architecture is defined by: 1) functional elements describing features necessary for a product to operate successfully; 2) the mapping of functional elements into physical components; 3) interacting components connected by a physical interface. Integral and modular design architectures lie at the opposite ends of a continuum. A modular architecture involves a one-to-one mapping of functional elements onto physical components. By contrast, an integral architecture implies a complex (one-to-many or many-to-one) mapping of functions into physical components.

Henderson and Clarke (1990, p. 16) propose a connection between product architecture knowledge and an organisation's product development strategies, communication channels and information filters:

"The strategies designers use, their channels for communication, and their information filters emerge in an organisation to help it cope with complexity. [..] Since architectural knowledge is stable once a dominant design has been accepted it can be encoded in these forms and thus becomes implicit."

Architectural innovation often depends on introducing new linkages in the way components interface with each other and these can be a source of unexpected interdependencies. The transition from propeller to jet engine initially appeared to have little impact on airframe technology. However, established airframe firms failed to appreciate that technical interdependencies between the engine and the airframe changed in complex ways when the jet engine was introduced.

Sanchez and Mahoney (1996) view of the interaction between product and organisational architectures was that: "…although organisations design products, it can also be argued that *products design organisations*, because the coordination tasks implicit in specific product designs largely determine the feasible organisational designs for developing and producing those products" (*ibid*, p. 64). Fine (1998) went further and argued that consistency amongst product, process and supply chain architectures improves performance, a claim supported by some empirical studies (e.g. Randall and Ulrich, 2001). Takeishi and Fujimoto (2003) study of modularisation in the car industry concludes that changes at the product, production and supply network levels evolve gradually through dynamic interactions between development, production and purchasing activities across multiple levels of the inter-firm system.

In summary, a number of authors have assumed that the architecture at one level determines the architecture at other levels. The dissemination of visible design rules (e.g. standard interfaces) within an industrial system permits a clear-cut division of labour associated with the definition of modules and their coordination through market-based interfaces (Baldwin and Clark, 2003).

Another stream of research has questioned this argument. Instead, it suggests that the interaction of architectures at different levels introduces some important asymmetries in these connections. Kogut and Bowman (1995, p. 251) regard the notion of isomorphism between levels as misguided: "In product design, it is nonsensical to think of one module 'teaching' another. Teaching, cooperation, and joint problem solving are distinctively human activities".

In the aircraft engine industry, the adoption of modular approaches to product development underpins the development of product families based on common platforms (Brusoni and Prencipe, 2001). However, companies maintain and continuously try to improve "…their technological capabilities related to several of the outsourced components, and certainly well beyond what we have labelled the 'inner core' of the engine" (*ibid*, p. 196). Even if visible information or codified knowledge may be widely shared by several actors, "…modular product architectures do not define clear 'information structures' capable of coordinating actors via smooth, arm's-length market relationships" (*ibid*, p. 202). Thus product and knowledge boundaries of the firm are likely to differ (Fine and Whitney, 1996; Dubois, 1998; Araujo et al, 2003).

The ability to sustain and integrate these multiple technological specialisms constitutes a capability in its own right – a systems integration capability (Granstrand et al, 1997). Brusoni and Prencipe (2001) use the examples of the aircraft engine and chemical industries to discuss the role of lead manufacturers as systems integrators. Architectural knowledge cannot necessarily be embedded into the standardised interfaces that connect these modules. Simon (1981) argued that boundedly rational agents could at best achieve near-decompositions that

---

[1] For example, in a desktop PC system visible design parameters are apparent in the multitude of ports, plugs and sockets that allow the system to be powered and connected together. A parameter such as the amount of CPU RAM is "hidden" and can be changed independently without impacting upon other elements.

[2] Sosa et al (2004) introduce the notion of product ambiguity "…defined as the absence of knowledge about design variables and/or their interfaces, some design interfaces are not foreseen at the outset of the project and are only discovered after design teams work on the systems themselves" (p. 1677).

identify key interdependencies and partition the system accordingly. Systems integrators must thus "know more than they do".

Brusoni *et al* (2001) see these systems integration firms as coordinators of loosely coupled networks of suppliers of equipment, components and specialised knowledge that rely on other mechanisms for accumulating and developing new knowledge other than productive activities. As Pavitt (2003, p. 81) noted, in complex product fields it is important to have capabilities to deal with unforeseen interactions amongst system components and to deal with uneven rates of development amongst components with potential implications for the stability of architectures.

In summary, the systems integration view is put forward as the Chandlerian, visible hand counterpart to the Smithian, invisible hand mechanism of modularisation and markets (Dosi et al, 2003). In the next section, we will argue that to understand the operation of complex systems over their life cycle, we need to move beyond design and production issues.

Complex systems and "learning-by-using"

Sako and Murray (1999) make a useful distinction between three different types of modularity: modularity-in-design, modularity-in-process and modularity-in-use. Their argument is that modularity can be regarded from multiple and not necessarily convergent perspectives. For example, good decomposability of a system from a design or process angle may not coincide with good decomposability from a service perspective. Failures in minor components of large modules may lead to costly replacement of whole modules. Compatibility may become an issue when customers find themselves forced to upgrade their products in order to keep pace with developments in complementary modules (e.g. computers and software). Product upgradeability may be an attractive feature of modular construction but enabling this option may require a great deal of coordination between different module producers. Sako (2003) argued that there may be a variety of perspectives regarding the most appropriate architecture from a design, production and use perspective. For example, modularity can be identified at different levels of analysis (e.g. subsystems, components, parts of components) and it may be a characteristic of one or multiple levels. What may be relevant from one perspective or level may be inconvenient from another and the nature of these debates is likely to evolve through the system's life cycle.

Much of the literature reviewed so far has focus on product development activities coordinated by a single firm and the interaction between product and organisational architectures at the level of design and to a lesser degree production (e.g. Salvador et al, 2002; Sosa et al, 2004). The role of users and after-sales service in improving knowledge of complex systems as they evolve over time has largely been ignored.

The role of systems integrators is seen as smoothing over differences and conflicts as far as design and production tasks are concerned, but when the role of users and service over the lifecycle of the system are introduced the literature has little to offer. As Rosenberg (1982, p. 122) points out, the performance characteristics of durable and complex systems cannot be understood until after prolonged experience with it. As a result, the only way to determine the optimal performance characteristics of this type of system is to learn through extensive use ("learning-by-using"), namely through servicing and maintenance activities whose schedule is also subject to evolution through cumulative experience.

In these circumstances, knowledge about the system becomes dispersed amongst a variety of actors who will develop different types of expertise as they monitor the behaviour of the system over time. Maintenance activities assume a particularly important role in this regard. On one hand, these activities have to reflect well-established systems decomposition patterns at the product level. On the other hand, as experience with the system grows, there is often a need to redefine existing interfaces to say, accommodate technological changes in upgraded components or readjust maintenance schedules to take into account unexpected interactions between different subsystems.

Rosenberg (1982) distinguishes between disembodied and embodied "learning-by-using". In the first form of "learning-by-using", prolonged experience with hardware leads to better understanding of its performance and operating characteristics. This type of learning leads to new practices for increasing the productivity or lengthening the life of hardware as well as fine-tune maintenance schedules. Embodied learning, describes a situation when early experience with a complex system leads to a better understanding of the relationship between the characteristics of components and their performance. In this case, the result is design modifications and improvements embodied in later generations of components and subsystems.

Aircraft maintenance and repair activities are prime examples of "learning-by-using" due to the long life of airliners and the strong emphasis on safety and reliability in the industry. Maintenance involves a variety of actors from flight crews, maintenance and repair stations, airframe manufacturers, airline associations and regulatory agencies at the national and international level.

At the level of a repair station, maintenance activities are decomposed according to different units embodying expertise on different subsystems of the aircraft (e.g. engines, avionics). In this context, what constitutes a module for some can be a decomposable system for others. The interdependence between different subsystems of an aircraft requires some degree of integration amongst these different specialisms to ensure the performance of the system as a whole. Furthermore, maintenance problems can shed light on hitherto unsuspected interactions between subsystems, which may require new liaisons across specialisms as well as involve broader interactions with a variety of actors (e.g. airline operator, airframe manufacturer, subsystem supplier). Thus knowledge on how to operate and maintain an aircraft requires both stable routines that promote the division of knowledge and link up systematically interdependent activities as well as mechanisms to deal with the effects of disembodied and embodied "learning-by-using". In summary, "learning-by-using" can be seen as a form of systems integration in that it requires the integration of multiple specialisms around maintenance and repair problems.

The aircraft maintenance case

In the following three subsections we will attempt to illustrate the interaction between product and organisational architectures in the context of an aircraft maintenance operation we studied over a period of 18 months. During this time we conducted a number of observations *in situ*, interviews and informal conversations with senior managers, engineers and technicians. Our interviews followed a semi-structured format, were taped in the near totality of cases and transcribed verbatim. Our interpretations of these texts were cross-checked with respondents and clarifications were sought and obtained in a number of cases. In addition, we have consulted a number of publications and internal and external documents from industry magazine reports to manuals on maintenance philosophies.

In the first of the following subsections we give a brief overview of the framework within which maintenance practices operate. In the second subsection, we explain the organisation of maintenance activities of the repair station we studied. In particular, we focus on the routines that coordinate activities of the various units involved in these activities. In the third section, we focus on examples that illustrate how "learning-by-using" occurs in non-routine situations.

Our starting point is that the functional architecture of an aircraft is reflected in the division of maintenance specialisms (e.g. engines, airframe, aircraft controls) with virtually no overlap in specialist know-how. The counterpart to this fragmentation is the creation of coordination routines and relationships that attempt to bridge over the necessarily myopic specialisation embodied in the operational routines of each of these specialisms. These coordination routines and relationships are pivotal to deal with a complex system like an aircraft. Airframe manufacturers, operators, repair stations and regulators value the generation and access to knowledge on the performance of an aircraft as whole and its various subsystems through its life cycle.

The evolution of maintenance philosophies in civilian airliners

Civilian aircraft maintenance stands at the junction of a network of relationships that define how maintenance operations have to be performed and how they evolve over time. A civilian airliner is a complex system comprising many subsystems and components (e.g. propulsion system, avionics, landing gear) and has a long useful life.

The companies that operate in the civilian airline industry (e.g. airliners, airframe and engine manufacturers, repair stations) face a highly regulated context. Different regulatory authorities[3] construct a set of rules establishing what is acceptable, desirable or mandatory in what concerns all activities and resources involved in the operation and maintenance of aircraft. Safety and reliability issues are paramount in the design of for aircraft maintenance schedules.

---

[3]For example, the Federal Aviation Administration (FAA) in the US, the Civil Aviation Authority (CAA) in the UK, the Association of European Airlines (AEA).

Maintenance rules emanate from a process of codification of distributed knowledge and experiences generated by the whole network of actors involved in the design, assembly, operation and use of aircraft and are subject to evolution over time.

Maintenance programmes have evolved in recent years and became more flexible in order to reflect the different technical and economic requirements faced by aircraft operators. It is common to distinguish between the traditional approaches based on "hard time" and modern approaches, less rigid in terms of the frequency of inspection, repair or replacement of aircraft parts. The traditional "hard time" approach was based on the principle of preventative maintenance, where structures, systems and components were overhauled at set intervals. This approach, dominant until the 1960s, began to be regarded as uneconomical as well as having an adverse effect on reliability and safety[4]. Not only could "hard time" inspections lead to maintenance-induced faults, but new evidence was also pushing towards a new framework for maintenance. In a bid to increase the length of service intervals, airlines and airframe manufacturers submitted to regulatory authorities selected samples of components with longer life cycles than originally forecasted. The planning of inspections, removal and repair of a variety of parts and systems operating under different maintenance regimes proved harder than expected in practice whilst the emergence of self-diagnostic kits made planned some planned maintenance tasks obsolete.

In the early 1960s, the FAA formed an industry committee to look at alternatives methods to ensure reliability. These efforts eventually led to the formation of a team designated as Maintenance Steering Group (MSG), including airframe and engine manufacturers, airline operators and regulatory authorities. The MSG documents produced by the Air Transport Association (ATA) set up a framework of decision rules, which served as a platform for developing maintenance programmes for specific aircraft.[5] The current version of MSG-3 contains a system of rules intended to act as guidelines for the setup of maintenance schedules for four areas: systems/ power plant, aircraft structure, zonal inspections and lightning/ high intensity radiated fields. For example, as far as systems/ power plant are concerned, the construction of a maintenance schedule must start by defining the systems, subsystems and components that comprise the systems/ power plant area. Once this is done for each of these elements, based on technical information and experience, maintenance significant items (MSI) are identified and schedules constructed.[6]

Additionally, to the extent that airline operators differ in the pattern of usage of aircraft, the intervals for scheduled maintenance are defined taking into account the dominant parameters for different systems or components (e.g. calendar time, flight hours / cycles, engine / auxiliary power unit hours/ cycles). The initial definition of these parameters is usually unavailable before the equipment enters service. Previous experience with similar systems or components may serve as an initial guide and revisions to these parameters will be ongoing through the operating life of the equipment.

The MSG document establishes only a generic framework that need to be adapted to specific contexts, namely for particular aircraft models. A steering group constituted by airframe manufacturers, component suppliers, airline operators and regulatory authorities may use the MSG-3 framework for the development of a Maintenance Review Board (MRB) report concerning the initial maintenance requirements for a specific aircraft or even the redesign of maintenance schedules for older aircraft. The MRB is, in turn, used to construct the Maintenance Planning Document (MPD) for a specific type of aircraft. The MPD is then used to construct the maintenance programme of a particular aircraft adapted to its operating context, which has to be approved by the respective national authorities.

Two aspects need highlighting at the end of this section. First, both specific maintenance programmes and the generic rules underpinning their construction evolve over time. The initial

---

[4] Rosenberg (1982, p. 136, footnote 26) remarks: "It is known that taking complex things apart creates some nontrivial likelihood of putting them together incorrectly. Thus, the possibility of identifying a defect by more frequent maintenance is offset by the possibility of doing something wrong and therefore of creating new hazards as well as reducing existing ones".

[5] The first version of this document the MSG-1, was first developed with the Boeing 747-100 in mind and the publication of the MSG-2 in the early 1970s was applied to the two rivals of the B747, the Lockheed Tri-Star L-1011 and the McDonnell-Douglas DC-10. A European version (EMSG-2) was applied to the Concorde and the Airbus A300.

[6] Based on a flowchart method featuring steps such as ease of detection of failures, the impact of failures on safety, as well as other technical and economic criteria.

version of an MRB is built on generic assumptions, projected operational conditions and past experience. Secondly, cumulative experience in maintenance, including non-programmed maintenance, may constitute a platform not just to improve maintenance schedules but also the design of systems, subsystems and components. The FAA and other regulatory authorities issue airworthiness directives every time problems are discovered and corrective action (e.g. redesign of a specific part) is required. The number of airworthiness directives issued against a particular aircraft type is an indication of the degree of problems experienced with that aircraft type.[7]

The organisational architecture of maintenance activities

In this section, we briefly describe the organisation of maintenance of activities in the repair station we studied. The division of labour at the station is embodied in three units: airframe, engine and components maintenance, including in addition to avionics a variety of mechanical and hydraulics components (e.g. landing gear).

The inspection and maintenance of these systems, subsystems and components is based on letter checks according to their periodicity and scheduled downtime. Type A inspections are carried out frequently and in some cases do not even require hangar time. Type B inspections can be done every 400 to 500 flight hours, type C every 12 to 18 months and type D may be done every 8 to 10 years. In the latter case, scheduled downtime may be as long as 4 to 5 weeks and requires major structural checks. The differentiation of tasks and capabilities required for different type inspections is institutionalised in the organisational structure of the repair station, namely operational and heavy maintenance. In contrast with operational maintenance which usually involves the performance of visual inspections, lubrications and repair of small faults, in heavy maintenance a large number of components can be taken off the aircraft, sent to specialised units, and subsequently put back on and tested on the aircraft.

In addition, the division of maintenance tasks also takes place between the heavy maintenance and the engine and components maintenance units (see figure 1)

---
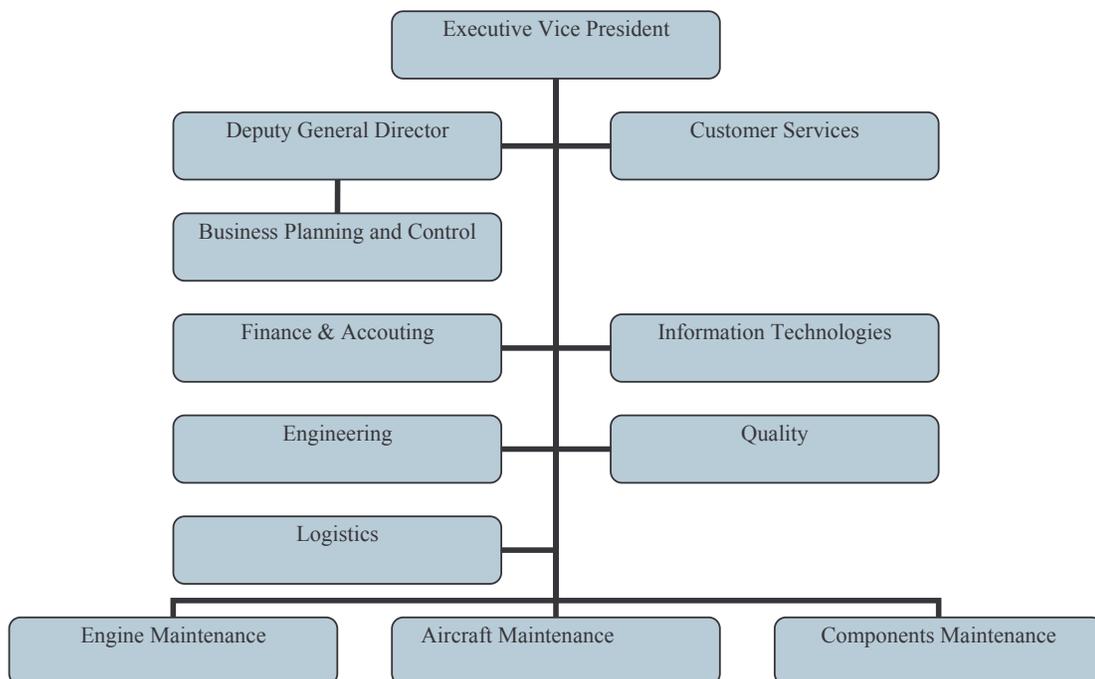
[7] As recognised in the ATA MSG-3 (2002, p. 13) document: "…scheduled maintenance, as such, cannot correct deficiencies in the inherent safety and reliability levels of the aircraft. The scheduled maintenance can only prevent deterioration of such inherent levels. If the inherent levels are found to be unsatisfactory, design modification is necessary to obtain improvement".

Figure 1: Organisational chart of the repair station

These two units take responsibility for the removal, testing and re-mounting of all the components that fall under the remit of the aircraft maintenance unit. This set of activities which often involves the diagnostic and repair of faults requires knowledge on how these subsystems and components fit into a broader and more complex system. Practitioners label these components rotables - i.e. black-boxed physical modules whose functionality must be checked by other units before being reinserted and tested with the broader system and are interchangeable. For example, a generator is a rotable from the perspective of an aircraft maintenance unit. A spare generator can be picked off the shelf and inserted in an aircraft system whilst the original one is repaired.

Finally, and due to the increasing variety of technologies and number of components and subsystems that populate modern aircraft, the activities of heavy maintenance are divided amongst several teams. The division of competencies amongst teams is clear for some systems but in other cases, the interfaces amongst different systems are more complex and knowledge domains overlap. For example, flight commands and engine knowledge interact "... not just because the flight commands system interacts with other systems but also because a technician in flight command is going to work with mechanical movements, hydraulic components, etc"[8]. In some cases, a technician needs to know something about a variety of interrelated systems in order to diagnose a fault – e.g. a problem with cabin pressurisation can arise from in the engine system (air generated by the engines) or in the air conditioning system.

The need for overlapping knowledge domains also varies substantially with the type of aircraft with reflexes on the need for coordination amongst different teams. For example, in the older generation of aircraft such as the Lockheed Tri-Star L1011, the complexity of the flight systems maintenance is associated with the existence of a variety of interfaces, mechanical, electromechanical or electronic amongst different components. In between the command unit and the controlled unit there are a chain of links including levers, straps, etc. The technicians specialised in the maintenance of these systems have to know a great deal about an aircraft as a system.

On the other hand, a large part of these activities has to be performed on the aircraft since the maintenance technicians have to "...have the whole system on view so that they can act on different sections". [9] Furthermore, the variety of components can also mean a variety of test units for each subsystem or component (e.g. ILS[10] or VOR[11]). In contrast, in more recent airliners, testing of subsystems and components is performed on systems installed in the aircraft (e.g. CFDS[12]) and the repair of faults is often done by replacing the faulty module with a new one.

As mentioned earlier, the implementation of letter checks maintenance requires a fine division labour and competencies in a repair station. The functional architecture of an aircraft is reflected in the division of maintenance specialisms (e.g. engines, airframe, aircraft controls). The counterpart to this fragmentation is the creation of coordination routines and relationships that attempt to bridge over the specialisation embodied in operational routines. Beyond the section heads who partly act as "systems integrators", the organisation of regular meetings between work planning, maintenance workshop and logistics teams is another key coordination mechanism.

As engines have their own maintenance and monitoring programmes, there are parallel meetings with the engine maintenance units. Generally these meetings are dominated by the organisation of previously scheduled activities but they also constitute a forum for the discussion of unexpected problems that span various teams.

When the maintenance interventions on an aircraft or fleet are seen as non-routine or particularly complex, the coordination of these activities is undertaken by specific teams. For example, in cases where aircraft are subject to extensive maintenance schedules that have to do the replacement of various subsystems (e.g. navigation) a special team is assembled to ensure that potential interdependencies are addressed. The same happens when third parties

---

[8] Head of Heavy Maintenance.
[9] Head of Engineering unit.
[10] Instrument Landing System – provides lateral, along-course and vertical guidance to aircraft attempting a landing
[11] VOR – VHF Omnidirectional Radio Range – provides bearing information to an aircraft.
[12] CFDS – Centralised Fault Diagonistics System

draw up the execution of a maintenance schedule. When an aircraft is not being followed and maintained by the same repair station there is inevitably a degree of uncertainty about the history of the aircraft and its maintenance as well as uncertainty concerning the requirements of the operator.[13]

But even in these situations, the coordination effort can vary substantially between those customers with whom there is a long-standing relationship and those whom the station knows less well. One of our respondents commenting on this situation remarked:

"As far as maintenance of Boeing 727 is concerned, we worked on almost two hundred only for Fedex. The Fedex aircraft were still on their way to us and we were already programming non-routines. We knew that a particular component was broken or that a bearing was corroded and we were requesting replacement parts before the aircraft reached us."

Finally, we should note that the functionality of subsystems maintained by specific units usually have to be tested when it is mounted back on the plane. And, as we will see in the next section, the functionality of an individual component is not assured once it is reinserted back in the aircraft. Often unexpected problems appear during scheduled maintenance or intermediary inspections. In these cases, more interactive organisational interfaces are required to deal with these problems and initiate changes in either the maintenance schedules or the redesign of components and subsystems.

Embodied and disembodied "learning-by-using"

The provisional nature of maintenance solutions is highlighted when unexpected problems call upon capabilities that are otherwise kept apart in repair stations. The existence of coordination routines to deal with these interdependencies does not exclude the possibility of making changes either in those activities or in the artefacts themselves - the disembodied and embodied categories of "learning-by-using" defined by Rosenberg (1982).

Every aircraft has its own biography (e.g. different maintenance regimes, faults, upgrades) that is reflected in its maintenance schedule. As a result, this schedule mirrors the aircraft operational history and the pattern of "learning-by-using" associated with it. For example, the type of operational history determines if the maintenance of say engines or airframe is dictated by hours or operational cycles (i.e. take-off and landings). The seasonality of operations often implies adaptations in the letter check inspections (e.g. more stoppages but for shorter periods). Climatic conditions in which aircraft operate (e.g. dry or humid) can also place different requirements on the nature and timing of inspections. In this context, the repair station can have a key role not only in the initial design and implementation of maintenance schedules but also on how these schedules evolve over time.

The diagnostics and troubleshooting activities can involve a variety of capabilities internal and external to the repair station. Even in the simplest case of replacement of one subsystem for another (e.g. the replacement of an engine), unexpected problems can appear (e.g. an engine can fail once mounted on the wing). These problems have often to do with the software programme of the engine's control unit. They are usually solved by combining capabilities from the aircraft and a specialist team from the engine maintenance units. Even if technicians of the aircraft maintenance unit do the programming of the software of the engine's control unit, it may not be clear that the fault resides in the software. It is the combination and confrontation of knowledge from aircraft and engine maintenance that helps determine the origin of the problem – usually involving a detailed investigation of the engine's history (e.g. part number of components, type of maintenance undergone).

The mounting of an engine on the wing can also reveal unexpected problems after a short period of operation. In one case, the trend monitoring of an engine type (i.e. the daily reading of its operational parameters) revealed an abnormal degradation of these parameters. These engines, equipping Airbus A340 aircraft, started to show abnormal temperatures of the exhaust gases much earlier than expected. As a result the engine blades showed early damages leading to more frequent inspections and longer periods on the ground for the aircraft involved. In this particular case, the early degradation of the reactor blades were identified as a shorter

---

[13] This uncertainty derives in large measure from structural aspects of the aircraft, its vulnerability to climatic conditions, its ageing pattern and its maintenance history.

power to wingspan ratio than normal, leading to changes in the maintenance schedules to deal with that particular combination of engine/ aircraft usage.

The effects of "learning-by-using" and the combination of capabilities required to address them can also lead to the redesign of components and their interfaces. In another example, periodic inspections of a landing gear revealed a fracture in the central section of the landing gear. In this case, the joint work of repair station technicians from the aircraft and components maintenance units, airframe and landing gear manufacturers, concluded that the abnormal break had to do the use of the aircraft in landing strips with very sharp turning curves. The first solution involved the placement of a component acting as a fuse, early warning of an impending problem, and onboard software to collect data on turning circle parameters. Subsequently, the definitive solution to the problem involved structural specialists and a way of increasing flexibility in the interface between the airframe and the landing gear.

The association between a repair station and an operator has other significant advantages over stand-alone repair stations, namely in access to a range of capabilities including airframe manufacturers and aircrews. As far as the first aspect is concerned, the combination of a repair station/ operator allowed a closer relationship with airframe and engine manufacturers. In our case, both manufacturers have resident engineers at the repair station site. In addition to dealing with routine questions, their presence is viewed as particularly important to search for novel solutions for unexpected problems, as illustrated by the landing gear episode.

On the other hand, the large inspections constitute a privileged time to generate new knowledge on the operation of the aircraft and it is usual for manufacturers to send technicians to collect new data particularly on the airframe's behaviour. The repair station-airline operator combination can also be very useful when launching new models. In our case the airline operator was one of the first users of the Airbus A340 and that lead to the creation of a group of engineers and pilots that worked together and shared learning during the development and assembly of the aircraft up to its delivery to the operator.

Furthermore, the spatial proximity of the maintenance and operational areas is seen as beneficial. As one of our respondents put it:

"We are only 600 metres away from the pilots, flight crews and route planning personnel. This proximity can have benefits as we can influence them or let know of specific concerns. For example, the pilots tell us about specific events and their perceptions of an aircraft's behaviour. Often, we supply them with explanations about events they have lived through. We are referring to anomalous events, not included in the MPD. This is constitutes a rich source of knowledge that other companies do not have access to."

This learning can be incorporated in new procedures such as the Flight Crew Operation Manual. For example, the usual procedure for using the parking brake when the aircraft is immobilised on the ground was altered after noticing an excessive deterioration of the braking discs.

Conclusions

In this paper we have addressed the interaction between technical and organisational interfaces in a hitherto neglected context, the maintenance of complex systems over time. Perhaps unsurprisingly, our study demonstrates that the organisational architecture of maintenance activities reflects the architecture of the system they have to deal with. But, as we have shown, neither the modules nor the interfaces in such a complex as a modern airliner can be regarded as fixed and stable throughout the life of the system. Processes of gradual improvement both at the level of maintenance procedures and design of components are the norm as far as civilian airliners are concerned. These gradual changes often involve a variety of actors in interaction with each other and a number of distributed processes.

In short, a repair station's routines and organisational architecture faces the task of mirroring the modular architecture of the systems it deals with whilst being able to provide a non-modular response to complex interfaces and interdependencies that transcend narrow specialisms based on the system's architecture. The degree of stability in the architecture of the various subsystems and components that constitute a modern aircraft suggests the need for tight routines and clear division of responsibilities in maintenance activities. On the other hand, the need for both disembodied and embodied "learning-by-using" suggests open-ended organisational interfaces and patterns of interaction amongst actors which allow the connection

of capabilities dispersed amongst many actors (e.g. airframe manufacturers, operators, repair stations).

"Learning-by-using" reinforces the view there can be no symmetry between product and organisational architectures in contexts where we are dealing with evolving, complex systems and uneven rates of changes in underlying technologies. The stability in the definition of modules and interfaces can be seen as manifestations of provisional solutions and as constituting a reliable baseline against which incremental changes can take place (e.g. partial retrofit of a system). In these circumstances, the stability of operational routines is more apparent than real.

"Learning-by-using" lead to a continuous questioning of that stability as new knowledge is accumulated by a variety of distributed processes taking place in the network involved in the design, operation and use of an aircraft (e.g. airframe manufacturers, subsystems suppliers, maintenance and repair stations). This is still a form of systems integration bridging over specialisms and combining specialist knowledge at the component and subsystem with architectural knowledge, as highlighted by Granstrand et al (1997) and Brusoni and Prencipe (2001) amongst others. But unlike design and production activities, there is no single centre, no visible hand coordinating the activities of a loosely coupled network of specialists. "Learning-by-using" as a form of systems integration relies on a more fluid, dynamic, interactive and multi-centred set of activities embedded in a tight institutional framework acting as the ultimate guardian of reliability and safety in the whole industrial system. The fact that the network of connections that comprises this system is able to combine tightly defined routines at the micro level with flexible and responsive adjustments at the systemic level is a remarkable tribute to the power of interactive interfaces and distributed systems integration.

References

Araujo, L., A. Dubois. and L.-E Gadde (2003), "The Multiple Boundaries of the Firm", <u>Journal of Management Studies</u>, **40**(5), 1255-1277.

Baldwin, C. and K. Clark (2003), Where do Transactions Come From? A Perspective from Engineering Design, Working Paper No. 03-031, Harvard Business School.

Brusoni, S. and A. Prencipe (2001). "Unpacking the Black Box of Modularity: Technologies, Products and Organizations." <u>Industrial and Corporate Change</u> **10**(1): 179-205.

Brusoni, S., Prencipe, A. and K. Pavitt (2001). Knowledge Specialisation, Organisational Coupling and the Boundaries of the Firm: Why do Firms Know more than they do? <u>Administrative Science Quarterly</u>, **46**, 4, 597-621.

von Corswant, F. (2003), <u>Organising Interactive Product Development</u>, PhD thesis, Department of Operations Management and Work Organisation, School of Technology Management and Economics, Chalmers University of Technology, Gothenburg, Sweden.

Dosi, G., M. Hobday, L. Marengo and A Prencipe. (2003). The Economics of Systems Integration: Towards an Evolutionary Interpretation. In <u>The Business of Systems Integration,</u> edited by A. Prencipe, A. Davies and M. Hobday. Oxford, Oxford University Press**:** 95-113.

Dubois, A. (1998). <u>Organizing Activities Across Firm Boundaries</u>. London, Routledge.

Fine, C. (1998). <u>Clockspeed. Winning Industry Control in the Age of Temporary Advantage</u>. Reading, MA., Perseus Press

Fine, C. H. and Whitney, D. E., (1996), Is the Make-Buy Decision Process a Core Competence, Paper presented at the MIT IMVP Sponsors' Meeting in São Paulo, Brazil.

Granstrand, O., Patel, P. and K. Pavitt (1997). "Multi-technology Corporations: Why they have "distributed" rather than "distinctive core" competencies." <u>California Management Review</u> **39**, 4, 8-27.

Håkansson, H. and A. Waluszewski (2002). <u>Managing Technological Development. IKEA, the environment and technology</u>. London, Routledge.

Henderson, R. M. and K. Clark (1990). "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." <u>Administrative Science Quarterly</u> **35**(1): 9-30

Kogut, B. and E. Bowman (1995). Modularity and Permeability as Principles of Design. In <u>Redesigning the Firm</u>, edited by E. Bowman and B. Kogut. New York, Oxford University Press**:** 243-260.

Langlois, R. N. (2002). "Modularity in technology and organization." <u>Journal of Economic Behavior & Organization</u> **49**(1): 19-37

Pavitt, K. (2003). Specialization and Systems Integration: Where Manufacture and Services Still Meet. In <u>The Business of Systems Integration</u>. edited by A. Prencipe, A. Davies and M. Hobday. Oxford, Oxford University Press**:** 78-91.

Randall, T. and K. Ulrich (2001). "Product variety, supply chain structure, and firm performance: Analysis of the US bicycle industry." <u>Management Science</u> **47**(12): 1588-1604.

Richardson, G. B. (1972). "The Organisation of Industry." <u>The Economic Journal</u>, **82**, September, 883-896.

Rosenberg, N. (1982). <u>Inside the Black Box. Technology and Economics</u>. Cambridge, Cambridge University Press.

Sako, M. and F. Murray (1999), Modularity in Design, Production and Use: Implications for the Global Automotive Industry, Paper presented at the International Motor Vehicle Program (IMVP) Annual Sponsors Meeting, 5-9 October, Cambridge, MA

Sako, M. (2003). Modularity and Outsourcing. The Nature of Co-evolution of Product Architecture and Organization Architecture in the Global Automotive Industry. In <u>The Business</u>

of Systems Integration, edited by A. Prencipe, A. Davies and M. Hobday. Oxford, Oxford University Press**:** 229-253.

Salvador, F., C. Forza, and M. Rungtusanatham (2002). "Modularity, Product Variety, Production Volume, and Component Sourcing: Theorizing Beyond Generic Prescriptions." Journal of Operations Management **20**(5): 549-575

Sanchez, R. and J. T. Mahoney (1996). "Modularity, Flexibility, and Knowledge Management in Product and Organization Design." Strategic Management Journal **17**(SISI): 63-76

Sanchez, R. (1999). "Modular architectures in the marketing process." Journal of Marketing **63**(SISI): 92-111

Simon, H. A. (1981). The Sciences of the Artificial. MIT Press, Cambridge, MA.

Sosa, M., Eppinger, S. and Rowles, C., "The Misalignment of Product Architecture and Organizational Structure in Complex Product Development", Management Science, **50** (2): 1674-1689.

Sturgeon, T. J. (2002). "Modular production networks: a new American model of industrial organization." Industrial and Corporate Change **11**(1): 451-496

Takeishi, A. and T. Fujimoto (2003). Modularization in the Car Industry: Interlinked Multiple Hierarchies of Product, Production and Supplier Systems. In The Business of Systems Integration, edited by A. Prencipe, A. Davies and M. Hobday. Oxford, Oxford University Press**:** 254-274.

Ulrich, K. (1995). "The Role of Product Architecture in the Manufacturing Firm." *Research Policy* , **24**, 3, 419-440.