

IMPROVING COMMONALITY IMPLEMENTATION IN THE COCKPITS OF COMMERCIAL AIRCRAFT

by

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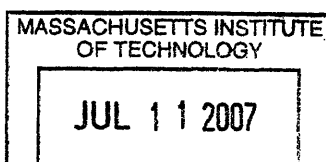
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IMPROVING COMMONALITY IMPLEMENTATION

ABSTRACT

Product development is a major source of competitive advantage in the commercial aircraft business. Judiciously implementing commonality across a range of products yields important benefits in this area. Thus, measuring the quality of commonality implementation is extremely beneficial for aircraft manufacturers. This thesis analyses the concept of commonality and divides it into three constructs that can help understand all of its aspects: standardization, reusability and modularity. This work then presents a set of metrics measuring each of these aspects, from the point of view of the manufacturer and of the customer.

The appropriateness of this set of metrics is then tested in a case study analyzing the efficiency of commonality implementation in the cockpit of two well-known commercial aircraft families: the Airbus A320 family and the Boeing 737 family. This thesis further describes what additional analysis should be performed to validate the set of metrics for broader applications. After documenting the efficiency of the set of metrics, this thesis analyses the current practices of commonality management in commercial aviation. It finally explores some of the limitations of the concept of commonality and sketches solutions to overcome them.

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FOREWORD

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The history of technology understanding is integrative. From the time of Adam Smith, people have tried to understand and improve the production process. They began analyzing the part manufacturing. Then, they aimed to optimize the assembly steps, and Henry Ford built cathedrals of steel and glass to house his vision of an integrated, scientific enterprise. Once the concept of product flow entered the mind of engineers, we realized that the entire enterprise had to be architected and designed as the manufacturing process was yesterday. The task is enormous, and so are the challenges waiting for us ahead. And each of us who participates in the work will *integrate* yet another part of the model, and lighten a new part of the puzzle that was in the shadows until now.

On this road, numerous are those who encouraged me, helped me or gave me valuable advice. Naming all of them here would be as hopeless as counting the grains of sand on the beach. Still, I will mention a few who were particularly influential in this period of my life. The names of the others are written in my heart even if they do not appear here. I feel especially indebted to Jacques-Jean Picard, Jean-Claude Hubert and Richard Adenis whose help was essential for preparing my application to MIT. I also have to thank the kindness of the staff of the department of Aeronautics and Astronautics and of the Engineering Systems Division, which saved me many hours and thus contributed to the success of this research. Among them should be mentioned Barbara Lechner, Marie Stuppard, Beth Marois and Elisabeth Milnes. I further recognize the many efforts of the

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ABBREVIATIONS AND ACRONYMS

ATC:	Air Traffic Control
CCQ:	Cross-Crew Qualifications
CoE:	Center of Excellence (Airbus)
DSM:	Design Structure Matrix
EASA:	European Aviation Safety Agency
ECAM:	Electronic Centralized Aircraft Monitor
EFIS:	Electronic Flight Instrument System
ETRC:	Estimated Total Relevant Costs
E/WD:	Primary ECAM
FAA:	Federal Aviation Administration
FCU:	Flight Control Unit
GPS:	Global Positioning System
JIT:	Just-In-Time
LAI:	Lean Aerospace Initiative
LCD:	Liquid Crystal Display
MCDU:	Multi-function Control and Display Unit
Md_a :	Degree of modularity (customer)
Me_m :	Efficiency of modularity (manufacturer)
MFD:	Modular Function Deployment
ND:	Navigation Display
PED:	Primary Engine Display
PFD:	Primary Flight Display

ABBREVIATIONS AND ACRONYMS

Rd _a :	Degree of reusability (customer)
Rd _m :	Degree of reusability (manufacturer)
Re _a :	Efficiency of reusability (customer)
RMP:	Radio Management Panel
SED:	Secondary Engine Display
SMED:	Single-Minute Exchange of Dies
Sd _m :	Degree of standardization (manufacturer)
TCAS:	Traffic and Collision Avoidance System
TDPC:	Total Development and Production Costs
TPS:	Toyota Production System
UAV:	Unmanned Aerial Vehicle
VSM:	Value Stream Mapping
WX:	Weather

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IMPROVING COMMONALITY IMPLEMENTATION IN THE COCKPIT OF COMMERCIAL AIRCRAFT

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DAMIEN BADOR

I. Introduction

I.1 Lean Engineering and the Aerospace Industry

Eliminating waste with the goal of creating value for all stakeholders in an enterprise is the root concept of Lean (Womack & Jones, 2003). Yet, improving separately each part of the lifecycle of a product, or each product in isolation from the others is less likely to produce lasting results. It will rather create some islands of success within the enterprise, which will not integrate together. As a result, such a strategy can only result in a general suboptimization of the enterprise value flow and a lower productivity (Murman *et al.*). Improvement must focus at the enterprise level. In the automotive industry, multi-project management and concurrent technology transfers have long proved to increase the efficiency of product development. Such techniques have been reproduced in other industries working on complex engineered products. In the commercial aeronautics world, one of the main ingredients for success is the product development phase. This phase represents huge upfront investments, with very long payback periods. Even for medium-haul commercial aircraft, the average development lead-time is currently around 49

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months¹. Even after the aircraft certification, additional validation flights usually take place before the first delivery. One program failure can determine the fate of the commercial division of an aircraft manufacturer (United States of America, 2006). This actually happened for Lockheed, whose L-1011 TriStar did not reach the break-even point and caused the manufacturer to withdraw from the commercial aircraft business.

Aircraft manufacturing companies tried to mitigate the risks of aircraft development programs. From the beginning of the commercial aircraft age, they widely reused the design of older models to minimize the development costs. For instance, when Boeing launched the original 737-100 in the 1960s, the company reused about 60% of the structure of the 727 model in order to shorten the development lead-time. Many variants of the 737 were successively developed until the 737-900ER, whose first airplane flew in 2006. Later on, aircraft manufacturing companies decided to increase the level of commonality between models of the same generation or even between product families covering different segments of the market. The first example of an integrated product family planned as such from the beginning was the Airbus Industrie A320, whose variants range from 107 to 221 seats capacity. Design for commonality has allowed important reduction of the development lead-time of new aircraft and similar reductions of development costs, while rationalizing the manufacturing departments.

Yet, measuring all aspects of commonality remains a challenge. There currently exists no precise measurement method for determining the effects of commonality on the efficiency of aircraft cockpit development. Thus, determining the ideal level of commonality for an aircraft belongs as much to art as to science. Rigorously identifying the potential drawbacks of an excess of commonality in the cockpit is even more difficult.

¹ Have been taken into account the development lead-time of the A320 family and of the 737NG sub-family, which are the only two medium-haul narrow-body aircraft families still produced in 2007.

I.2 Research Objectives

Globalization has increased competition between commercial aircraft companies. New entrants, such as the Canadian Bombardier or the Brazilian Embraer, are likely to reinforce the importance of shortening product development lead-time as a competitive advantage. In this context, optimizing the implementation of commonality is of the utmost importance. Thus, this research has three fundamental objectives:

- By studying the various aspects of commonality and investigating its consequences on the pilots and on the other aircraft customers, I intend to identify the metrics that could be used to measure the quality of commonality implementation.
- After validating the metrics identified, the most effective ones will be regrouped in a set, which will constitute the basis of a measurement and decision tool for the aircraft manufacturers and for the airline companies.
- With the help of this set of metrics, I will perform an in-depth analysis of the current industrial practices with respect to commonality implementation and suggest paths for improvement for the aircraft manufacturers.

I.3 Commercial Aircraft Cockpits

In a commercial aircraft, the cockpit is an adequate section for the purpose of this study. It is a strategic part of the aircraft, as it has a high value added and as it concentrates all the command systems of the aircraft. In the Boeing 787 project, Boeing subcontracted 65% of the work share. Still, the cockpit is the largest section of the aircraft that was not subcontracted. It is also a section where commonality advantages are considered to be particularly important. Most hindrances linked with the size of the aircraft or the necessity of product differentiation are removed. Digital fly-by-wire now allows for using almost the same hardware instruments for any type of aircraft. The only major architectural differences needed in the cockpit come from differences in the propulsion system. As an illustration, Figure I-1 is a photograph taken in an Airbus A318 cockpit (107 passengers in

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a typical 2-classes configuration) and Figure I-2 is a photograph taken in an Airbus A340-600 (passengers in a typical 2-classes configuration). The two aircraft are respectively the smallest and largest Airbus currently in service.

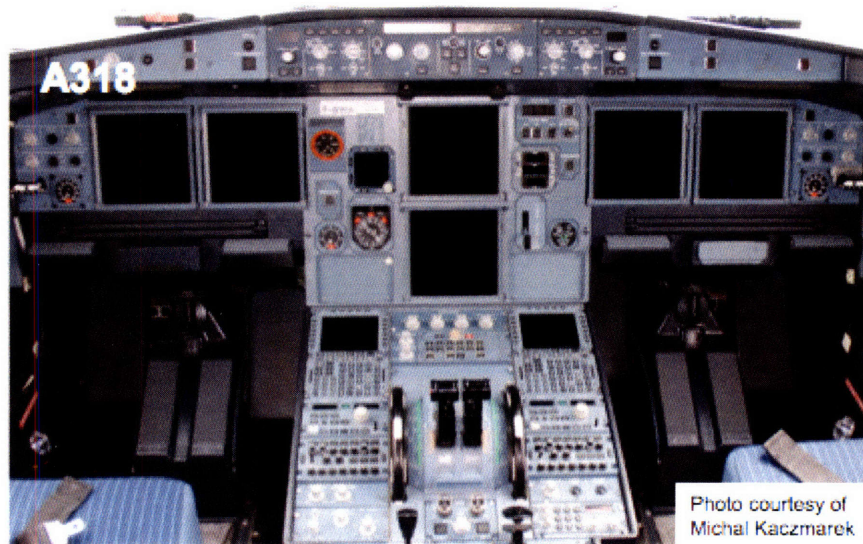


Figure I-1: Close view of the instruments panel of an Airbus A318.

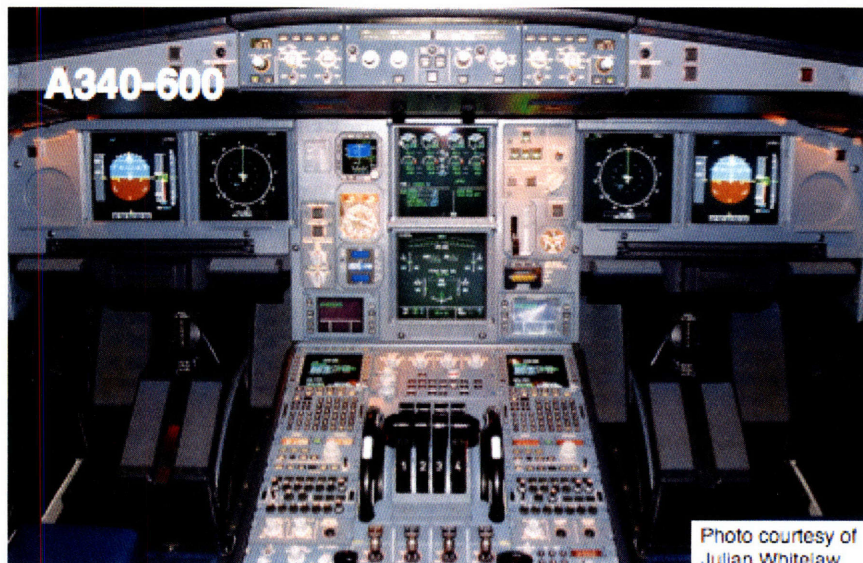


Figure I-2: Close view of the instruments panel of an Airbus A340-600.

A high level of commonality in the cockpit is a selling argument as well. The aircraft manufacturers claim that it contributes to maximizing benefits for the airline

INTRODUCTION

companies by increasing the flexibility of their fleet. As functional differences in the cockpit lessen, the pilots can be licensed on more types of aircraft. As a consequence, it is possible for the airline companies to change the type of aircraft deserving a destination even after the crew for this destination has been chosen. Thus, it will permit the company to keep fewer standby pilots in its major hubs, a major labor cost for an airline company. Less functional differences between the cockpits of different models of aircraft also means a reduction in the time needed to train a pilot to transfer from one to the other. Consequences are multiple and often amount to further reducing the training costs of the pilots, as well as some overhead costs for the airline company. For example, it will allow for a decrease in the total number of flight simulators needed by the company and pilots' training will require fewer ground instructors.

1.4 Commonality Implementation in the Commercial Aircraft Industry

American aircraft manufacturers began to focus on Lean engineering at the end of the Cold War (Murman *et al.*, 2002). At that time, military support to research and development programs rapidly dwindled. The surviving commercial aircraft manufacturers, which ultimately coalesced into The Boeing Company, found themselves with a massive infrastructure unadapted to the emerging market. The European manufacturers had missed most of the commercial aircraft market boom following the end of the Second World War. They had a far smaller infrastructure and thus were constrained to manage flexibility from the beginning. Yet, their size made it impossible for them to catch up with their American counterparts and they had to regroup at the European level. This effort finally gave birth to Airbus Industrie. On both sides of the Atlantic, adapting to the new situation was a major challenge. The customers' priorities shifted from technical performances (the famous Higher, Faster, Farther) to economic ones (which can be summarized as Better, Faster, Cheaper). Similarly, the liberalization of the aerospace market implied that airline companies could no more accommodate long, careful development projects and slow, revolutionary improvements. Instead, they would need

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manufacturers adaptable to their needs and able to react with flexibility to the market changes. The goal would not be to cram as much new technology as possible in an aircraft, but rather to constantly decrease its exploitation costs. Safety is the only criterion that was unchanged.

As competition increased, managers looked for best practices in related industries. The success of Japanese automobile manufacturers (and particularly of Toyota) in the United States demonstrated the strength of Lean practices. In 1993, the foundation of the Lean Aircraft Initiative (later Lean Aerospace Initiative or LAI) acted as a catalyst in the American aerospace industry. Lean concepts were adopted and the industry reorganization was accelerated. Among these concepts, commonality. Yet, no uniform practice has yet emerged regarding the implementation of this later concept. Since the development of the A320 in the 1980s, Airbus advertises product commonality as one of the key factors of its strategy. Pilots usually see Airbus as the aircraft manufacturer that went farthest in making common the cockpit of its entire range of aircraft. On the other hand Boeing sees commonality as one of the aspects of its general Lean transformation program. It aims to optimize this aspect simultaneously with other development and manufacturing techniques (such as Just-In-Time, moving assembly line, reduction of the number of suppliers, etc). These approach differences demonstrate the need for a comprehensive analysis of this concept, in a way that can translate to the industry. My present goal is thus to bring a new stone to contribute to this edifice.

II. Literature Review

There is substantial literature dealing with Lean and with product development. Attempting to list all relevant books and papers would be a Herculean task. I will simply attempt to discuss highlights of relevant work that will help provide an understanding of the current state of Lean product development in aerospace and a firm theoretical basis for the study of commonality in this context. Appropriate literature is quoted throughout the research, *cela va sans dire*.

The literature reviewed in this chapter can be divided into three categories. The first one concerns the development of Lean theory, from Lean Manufacturing as it originated at Toyota to the present understanding of Lean as a holistic concept permeating the entire enterprise. I will put a special emphasis on the consequences of Lean upon the product development of complex assembled products. In the second category, I will review literature pertaining to design issues in product development and on the emergence of the concept of product families. The third category will deal with the various aspects of commonality in product development and in manufacturing.

II.1 From Lean Manufacturing to Lean Enterprises

The Toyota Production System (TPS) is the origin of the philosophy known under the term of Lean in the United States. It was invented by Mr. Ōno Taiichi (whose name is often spelled Taiichi Ohno in the Western world) when he was working for the Toyota Motor Company. It developed out of a need for Japanese automobile manufacturers to catch up with more efficient American manufacturers. Japan had a small and diversified automobile market, which prevented Japanese automakers to benefit from scale economies. Therefore, the original goal of TPS was to uncover the root causes of

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waste in a production plant, in order to reduce the lead time between orders and deliveries (Ohno, 1988). Lean Manufacturing has often been reduced to a collection of tools such as Just-In-Time (JIT), andon and kanban (visual controls) or Single-Minute Exchange of Dies (SMED). It is however an integrated production system aiming at reducing all types of waste. Dr. Shingo Shigeo identifies seven types of waste in manufacturing operations: overproduction, inventory, useless motion, useless material transportation, waiting time, overprocessing, and defects (Shingo, 1981).

Lean theory was further refined by several authors, among whom the most famous are indisputably James P. Womack and Daniel T. Jones. Their first book, *The Machine That Changed the World* (1990), co-authored by Daniel Roos, exposed the reasons of Toyota success in the post-oil crisis area. In *Lean Thinking* (1996), they detailed the practices behind TPS, and summarized Lean philosophy as continuous improvement to reduce waste and make the value flow across the enterprise. They exposed additional tools to measure the degree of leanness of the enterprise, such as Value Stream Mapping (VSM), which was further detailed by Mike Rother and John Shook in *Learning to See* (2003). Womack and Jones expanded the Lean concepts to apply them to the entire enterprise, and especially to product development.

Lean was soon applied in other fields than the automobile. In the aerospace industry, the most important contribution to Lean was *Lean Enterprise Value* (2002), authored by Murman *et al.* This book gathered the first findings of the Lean Aerospace Initiative (LAI). LAI is a research community established by MIT with the collaboration of the US government and of the major US aerospace companies to provide answers to the crisis that struck the US aerospace industry at the end of the Cold War. *Lean Enterprise Value* established the context in which Lean was applied in aeronautics, and why most Lean initiatives ultimately failed. The authors demonstrated that Lean methods had to be applied throughout the enterprise and be supported by the highest level of the hierarchy. If these two criteria were not respected, early benefits would remain confined in the unit where they initiated, would not benefit to the enterprise as a whole, and would ultimately disappear, as discouragement prompted to go back to business as usual.

LITERATURE REVIEW

Lean Enterprise Value proposed a framework to enable Lean transformation in the enterprise. Key is value identification, which requires involving all stakeholders to determine where their interests lay and propose a plan acceptable by all parties involved. Empowering all stakeholders is particularly important in the aerospace industry, since all aerospace markets can be considered as oligopsonies. Many further works at LAI have contributed to Lean transformation theory in the context of the aerospace industry (McManus, 2005; McManus & Millard, 2002; Stanke, 2006). Some focused more on the manufacturing aspect of Lean (Vaughn & Shields, 2002), whereas others focused more on the value delivery to the customer (Cohen, 2005).

LAI also focused on specificities of Lean product development. It coined the concept of lifecycle value, a balance of performance with cost and other attributes. In *A Framework for Achieving Lifecycle Value in Aerospace Product Development* (2002), Alexis Stanke and Earll Murman developed value creation attributes to characterize the maturity of the product development process.

An analysis of successful product engineering was performed by Beckert (2000). A comparative study of four organizations showed that success was correlated with well-defined plans and metrics for product line engineering. Senior management involvement in enforcing product line strategies is seen as crucial for success. Additionally, this research confirmed that success was dependent on product development methods: most successful organizations adopted modular product architecture and developed few all-new projects.

II.2 Product Development of Complex Assembled Products

Kim B. Clark and Fujimoto Takahiro (1991) stressed the importance of product development rapidity and efficiency. They identified this as a critical source of competitive advantage that explained the rise of Toyota among the automobile manufacturers. Four themes were central in their analysis. Superior performances in time, productivity and quality were the driver that allowed the enterprise to respond timely and

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adequately to changes in their environment. Clark and Fujimoto found the source of such performance in the integration of the development process. Determining the right team size, encouraging multi-disciplinary expertise and flattening the enterprise hierarchy allows for more flexibility in the development process.

The two other sources of performance identified in this book were integrating customer and product and manufacturing for design. Product integration can be best achieved through a process organization with heavyweight product managers overlooking all aspect of the development and production process. This also enables more customer implication during the development phase, which brings feedback for the developed concept. Manufacturing for design implies constant interactions between design and manufacturing. Fast prototyping and efficient building of tools and dies are two activities on the critical path of development programs for complex engineered products, such as automobile – or aircraft.

Within the product development function, a more recently recognized source of competitive advantage was identified by Michael A. Cusumano and Nobeoka Kentaro in their book *Thinking Beyond Lean* (1998). They analyzed the reorganization of Toyota in vehicle development centers, which permitted higher knowledge sharing, faster technology improvement and an increase in the level of component commonality. They also demonstrated that it had given Toyota a better ability to manage more complex and more numerous automobile programs, without requiring a comparable increase in management overhead and costs. They predicted that reorganizing the enterprise around product families would allow increased horizontal resource sharing, and cut development lead time and costs.

In 2002, James Morgan further detailed Toyota product development process, and related it to the superior performance of Toyota in organizational learning. He demonstrated how simultaneous design practices, *obeya* team system and staggered design strategies contributed to higher product quality and a diminished number of problems in the industrialization phase. He particularly stressed that the early involvement of all

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departments in the definition and design of a new product was one of the sources of Toyota competitive edge.

Timely adaptation to changes in one of the main characteristics identified for the successful enterprise. Therefore, many authors concentrated on establishing flexible processes in product development. One of the most interesting papers on this subject was written by Konstantinos C. Kalligeros and Olivier de Weck in 2004. It combined classic real option theory with stakeholder value analysis. Recognizing uncertainty and addressing it explicitly led to significant improvement of the design solution. Other papers investigated the value of systems engineering with respect to product development (Honour, 2004).

Further analysis of product development considered its integration in the product lifecycle and stressed a systems engineering approach. Bozdogan *et al.* (1998) advocated that early supplier integration would improve design innovation in product development. The systems engineering approach has received particular attention in the commercial aircraft field (Gartz, 1996). Numerous analyses were performed to determine the influence of logistics on the efficiency of product development (Langford, 1995; Silver, Pyke & Peterson, 1998).

Jaeil Park and Timothy W. Simpson particularly focused on lifecycle optimization through development of product families. Their paper *Production Cost Modeling to Support Product Family Design Optimization* (2003) presented a framework for measuring product development costs incurred by common components and variants in a product family. They established rules for component sharing based on production volume and on design efficiency for manufacturing. However, this paper mainly concerned relatively simple, mass-produced items and the authors did not test their framework against products built in a batch mode.

Due to lack of published data, estimating the costs of product development in aeronautics is often difficult. Markish (2002) created a valuation tool to measure the program value of a family of aircraft. The tool integrates a performance model, a development and manufacturing cost model and a revenue model. It accounts for market

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uncertainty. The usefulness of this model is however reduced by two drawbacks: it does not account properly for commonality effects on development costs and on revenues, and it considers future demand as a stochastic, unpredictable process. The consequences of commonality are approximated through a simplistic model giving standard costs reductions for different parts of the aircraft body. The commonality implementation is not analyzed. Other authors developed cost model estimations for commercial aircraft (Tirovolis & Serghides, 2005), without significantly improving the value estimation of commonality.

Specific issues linked with product development in aeronautics have been until recently mainly studied by governmental or para-governmental agencies. These reports most frequently deal with market-specific issues such as the state of the competition, the sources of capital in aerospace product development, the number of competitors and their strategies (U.S. International Trade Commission, 1998). Human-machine interaction is also another axe for research in aeronautics product development. Of particular interest is the influence of automation in cockpits on commercial aircraft crew errors. Sanjay S. Vakil (2000) identified the relation between complexity of cockpit instruments layout and misrepresentation of automation by the pilots. He also uncovered the failings of pilots' training to address the issues of complexity management. He particularly demonstrated that one of the main causes of crew errors was the lack of a common model for automation processes. This prevented pilots to create a consistent mental model that would allow them a correct understanding of the system.

In 2006, Barry C. Smith and Ellis L. Johnson showed that imposing restrictions on the types of aircraft allowed to serve a given airport (i.e. imposing station purity) was a sound decision for airline companies. It particularly contributes to improve crew planning, as well as maintenance planning and operation management. Since such a change was likely to alter computational efficiency, they also developed a new system, called station decomposition, which takes into account the new network structure.

II.3 Aspects of Commonality

Timothy W. Simpson, Zahed Siddique and Jianxin Jiao contributed to develop the concept of product platform. The book they edited, *Product Platform and Product Family Design* (2006), aims to create an integrated theory for designing product families. This book defined existing types of product families: product platform, process platform and customer platform. It also stressed the risks and tradeoffs linked with adopting a product platform strategy, such as lack of differentiation, decreased functionality and increased development and production costs. The book proposed a tool for evaluating platform concepts and detailed market segmentation and positioning methods for product families. It finally described various optimization methods for product families and a methodology to translate strategic objectives in product specifications.

Additional research on product family variety was undertaken by Fujun Wang *et al.* (2003). In their paper, the authors used the example of the CFM-56 aircraft engine family to illustrate their product family evolution model. This tool captures the relationship between all members of the product family and the evolution rationales behind every component changes. The model is designed to determine opportunities for optimizing the number of product variants with regard to the target markets. Olivier de Weck, Eun Suk Suh and David Chang (2003; 2005) pursued this approach and developed a methodology to determine the optimum number of product families for an enterprise. They identified the target market segments and compared product performance and price position for the market leaders in order to maximize product family profitability. They used a simultaneous optimization algorithm to determine the ideal number of product families and of variants within each family. Other authors developed similar methods (Nidamarthi, Mechler and Karandikar, 2003). A different approach was followed by Michael J Carone *et al.* (2003). They determined the ideal number of variants by solving a problem of optimization of access in a geometric space.

A separate aspect of product family was studied by Brian P. Corbett and David W. Rosen (2003). They analyzed the case of an existing set of product that may not form a

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product family. They determined how components should be chosen to be part of the product platform, through the use of design spaces that help identifying connections between modules. This relates to portfolio analysis methods and real options with regard the product platforms, as advocated by Konstantinos Kalligeros in 2006. He found that standardization could increase program flexibility if the criteria of design choice did not rely on market uncertainties. Several optimization methods were developed on this approach. Eun Suk Suh *et al.* (2004) used a Monte Carlo simulation to evaluate the economic profitability of a flexible design.

In the aeronautics field, Karen Willcox and Sean Wakayama (2003) created a framework for optimizing the design of a multiple aircraft family whose models share common parts. They based their results on an optimization algorithm taking into account numerous design conditions to address issues linked with performance and physical constraints. They used trade studies to determine the desired level of commonality that should be attained and divided the aircraft into four main structural components, which were allowed to vary independently one from the other (the interfaces between components staying the same). Each aircraft variant was then tested through the same algorithm as before. Their results showed that a high degree of commonality was attainable, even when the mission objectives of the various models of an aircraft family varied widely.

One of the first researchers to take into account the entire lifecycle of the aircraft model to determine the right level of commonality in an aircraft family was Matthew R. Nuffort (2001). He applied most specifically his efforts on the aerospace defense sector. He found that a judicious use of commonality could reduce costs of ownership by reducing both acquisition costs and costs of operations and support. Acquisition costs could be reduced, because commonality would also reduce the design, manufacturing and subcontracting costs of the prime suppliers. The costs of operations and support could be reduced, because commonality helped reducing maintenance cycle time and operators training costs, improving both reliability and availability of the aircraft. He also found that having a common organization charged to manage all aircraft having common subsystems greatly contributed to reduce the complexity of commonality management at the enterprise

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level. While being centered on military systems, Nuffort's work is also applicable to airline companies, which sometimes find themselves in need of maintenance operations for some of their aircraft on an airport far from their logistic hub.

Modularity is the most often studied aspect of commonality. Authors proposed various definitions of this concept, often coupled with a particular product decomposition method. One of the most interesting benchmarking of modularity was performed by Ishii Kosuke and Tae G. Yang (2003). They reviewed the utilization of the concept in several industries representing very diverse markets. They used the resulting definition to identify the areas where modularity impact the performance of the enterprises. They divided the research on modularity in three phases, depending on whether it occurs before, during or after the product modularization. The first phase concerns strategic decisions driven by market positioning, the second concerns the implementation of modularity, and the last deals with measuring the results and optimizing the solutions obtained.

Determining whether the product should be modular is the first step before undertaking this process. Tian-Li Yu, Ali A. Yassine and David E. Goldberg (2003) use the Design Structure Matrix (DSM) to capture the architecture of a product. They developed a genetic algorithm to determine automatically the ideal number of modules in the product. This allowed for decomposing more complex product architectures than what is possible with manual decomposition. Many authors proposed their own methodologies for determining the optimal number of modules in a product, depending on the level of commonality they aimed to achieve (Simpson & D'Souza, 2002), or on the minimum level of performance that the modular product should be able to achieve, compared with an integral architecture (Rai & Allada, 2003). Some authors also proposed an optimization method based on a combination of these two factors (Fujita & Yoshioka, 2003). One of the most common methods to separate types of modularity was to separate them according to the type of interfaces existing between two modules. Slot-modular, bus-modular and sectional-modular are the three main types obtained with such a decomposition (Ulrich & Eppinger, 2000). Some authors recognize additional types (Otto & Wood, 2001).

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Determining the tradeoffs between modularity and performance was undertaken by Katja Hölttä, Eun Suk Suh and Olivier de Weck (2005). They determined that physical constraints such as mass, volumetric and power efficiency led to a high level of coupling between elements of form and functional elements. This physically translated by a higher number of functions per component, and a higher connectivity both within and between modules. More specifically, they discovered that products having to comply with high physical constraints tended toward a modularity ratio closer to the bus-modular architecture than to a fully integral architecture. Also, the elements and subsystems more specifically concerned by the physical constraints displayed a lower modularity than non-critical elements. They used three different metrics for measuring modularity and obtained comparable results for all of them.

The multiplication of the concepts related to modularity created a need for a classification of modularity concepts. Timothy W. Simpson (2003) provided an overview of the research in this area. He separated the studies into two groups: the first concerned platform leveraging strategies, the second dealt with optimizing the modular decomposition of the product. Numerous modularity measures were compared and analyzed by F. Guo and J. K. Gershenson (2003). They found these measures to be tightly related but of varying sensitivity. Most of them were not easily applicable to complex engineered products. Matthew B. Strong, Spencer P. Magleby and Alan R. Parkinson (2003) standardized several classification methods through a set of metrics allow for better concept screening.

Katja M. M. Hölttä and Mikko P. Salonen (2003) compared the three main modularization methods used in the industry: the heuristic method, the DSM and the Modular Function Deployment (MFD). They noticed that modularization methods that may be efficient for single products did not necessarily perform well for an entire product family. They compared the three methods results for various products and noticed the differences between the resulting modular decompositions. The function structure heuristic method takes into account the functionality of the product and interface simplicity. It is also the only method specifically designed to handle modular

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decomposition of a product family. The DSM considers only interface simplicity and has to be combined with other strategic matrixes to take into account company-level issues. At the other extremity of the spectrum is the MFD, which focuses on strategic issues and let the interface definition and the functionality tradeoffs undecided. Repeatability of the method varies between 68% (MFD) and 100% (DSM), the function structure heuristics having repeatability results varying between 70% and 90%.

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III. Research Methodology

III.1 Research Questions

From the literature review, it is possible to identify several questions that deserve further study. It is clear that development methods are key to economic success in the aeronautics industry, and that product families hold a central place in this respect. However, no unified approach has been attempted to assess the costs and benefits of product commonality in the context of commercial aircraft. Such an analysis would help airline companies to optimize their purchase strategies with regard to the aircraft manufacturers, while aircraft manufacturers would be able to reduce development lead-time of new aircraft as well as production costs. But before being able to accomplish this goal, it is necessary to determine which metrics could be used to measure commonality efficiently and without bias. Such a set of metrics will then have to be tested against examples of modern aircraft families, whose technical and economic performance is well known. After validation, it will be possible to lead an in-depth analysis of commonality trade-offs, and to assess the limits of this concept.

This research consists of an in-depth study of the metrics measuring the quality of commonality implementation for commercial aircraft. Analysis of these metrics will be made in relation with the cockpit of these aircraft. This research will then validate a set of metrics providing an efficient and unbiased measure for all aspects of commonality. This research is primarily based on a series of interviews with professionals from the aviation and aircraft manufacturing industries. On-site visits have been performed whenever possible: one has been made in the headquarters of the Air France airline company, and another in a French plant of Airbus. The methods of this research are grounded in a tradition of qualitative and quantitative research.

III.2 Research Methods

Qualitative research has been used in the social sciences as well as in organizational studies. As product development becomes more complex and involves more stakeholders, it has to take into account this qualitative aspect, which is particularly useful for understanding interaction issues, complex environments and changing priorities. Qualitative data is usually obtained through face-to-face or phone interviews, and direct observation. Face-to-face interviews and direct observation bring more interesting results, but the convenience of phone interviews allows for additional input that would not have been taken into account otherwise. Additional documentation can also provide more insight to interviews and observation. Quantitative analysis methods strengthen the results obtained by qualitative research. However, discernment is required on the part of the researcher for an adequate understanding of the answers obtained.

III.3 Data Collection and Analysis

Data collection focuses on two families of medium-haul, large capacity commercial aircraft: the Airbus A320 family and the Boeing 737 family. These families have been used to gather information on commonality implementation and its consequences throughout the lifecycle of a commercial aircraft. They have been selected for several reasons, of which the main is comparison easiness: the A320 (the baseline aircraft of the A320 family) was developed at the same period as the 737-300, a major redesign of the 737 model, which was developed more than ten years after the preceding version. In addition, both aircraft families fulfill the same needs, as they have roughly the same range at maximum payload and the same typical passenger seating¹, as shown in Table III-1 and Table III-2:

¹ The typical passenger seating corresponds to the number of passenger seats for the most common seating arrangements proposed. In this case, it corresponds to a two-class arrangement

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Model	A318	A319	A320	A321
Program start date	April 1999	June 1993	March 1982	Nov. 1989
Certification date	May 2003	April 1996	Feb. 1988	Dec. 1993
Typical passenger seating	107	124	150	186
Max. take-off weight (kg)	68,000	75,500	77,000	96,000
Range at max. payload (km)	3705	6845	5676	4907

Table III-1: Characteristics of the Airbus A320 family.

Model	737-300	737-400	737-500	737-600	737-700	737-800	737-900
Program start date	Mar. 81	June 86	May 87	Nov. 93	Nov. 93	Sept. 94	Sept. 97
Certification date	Nov. 84	Sept. 88	Feb. 90	Aug. 98	Nov. 97	Mar. 98	April 01
Typical pass. seating	128	146	108	110	126	162	177
Max. take-off wgt. (kg)	62,823	68,040	60,555	65,090	70,080	79,015	79,015
Range at max. pld. (km)	6300	3850	4444	5648	6037	5445	5083

Table III-2: Characteristics of the Boeing 737 family.

Additional reasons for using these two families for the purpose of validating the set of metrics is the fact that both of these families belong to an aircraft manufacturer which produces an entire range of large-capacity aircraft. Both of these families are among the most successful commercial programs of Airbus and Boeing, respectively, despite major differences in philosophy and in industrial production organization between the two companies. A direct consequence is that a lot of technical and economic data is available concerning both families of aircraft (and especially the A320 family, which is usually held to have been instrumental in the rise of Airbus in the 1990s).

Data and information was mainly gathered through interviews with pilots and aircraft manufacturing professionals (*cf.* Appendix 1), and through on-site visits. The visits of the headquarters of Air France in the Aéroport Roissy – Charles-de-Gaulle and of the Airbus site of Méaulte were particularly important in this respect. Pilots participating in the interviews had a variety of background and experience (trainee, pilot, captain, instructor). Aircraft manufacturing professional included mechanical and industrial engineers, team leaders, mid-level managers and researchers. A list of standardized questions was used for the interviews (*cf.* Appendix 2). These questions were organized in

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different categories and tailored according to the industry to which belonged the interviewee. As interviewees were not necessarily knowledgeable on all questions, interviews were correspondingly tailored. Follow-up questions were used to investigate a topic further and explore related topics. Interviews were preferentially set at the interviewee workplace, but phone interviews were used when physically meeting the interviewee was not an option.

Data collection and data analysis periods significantly overlapped. Analyses of available data led to further rounds of interviews and triggered additional data collection for validation purposes. It was far more effective to analyze small batches of data while performing other data collection activities than trying to group the entire analysis afterwards. This was also a safer process in a research like this one, where data collection is dependent on the availability of the interviewees, especially when time constraints do not allow delays for the data gathering activities. Data analysis could be divided into four types of activity:

- 1) Identify concepts in the data
- 2) Group data into categories based on these concepts
- 3) Classify data according to the categories defined
- 4) Develop categories with additional inquiries and perform comparisons within each category

This iterative framework was used for the present research and is explicitly advocated when axes for future investigations are outlined in this thesis.

IV. Metrics for Measuring the Efficiency of Commonality

IV.1 Definitions

Two types of commonality have to be distinguished: the first, which can be called *transverse commonality*, describes the common aspects of a subsystem accomplishing the same type of functions in a range of products. Here, this refers to the common aspects of a cockpit subsystem across an aircraft family or across all aircraft families of a manufacturer. The other type can be called *temporal commonality*. It deals with the common aspects of a subsystem evolving over a period of time. In commercial aviation, this type is particularly important, since an aircraft model has a very long lifecycle, compared to most electronic subsystems found in the cockpit. Each aircraft model is periodically upgraded to stay up-to-date with the evolution of cockpit instruments, commands and other aircraft subsystems.

From these two types of commonality, it is possible to derive three constructs: *standardization*, *reusability*, and *modularity*. These constructs have already been identified in the literature and studied for their potential to measure common characteristics across a range of products. However, their relation with commonality and with each other is rarely recognized. Standardization characterizes the common aspects of a subsystem performing identical or analogue roles in products fulfilling different needs. For instance, the Multi-function Control and Display Unit (MCDU) plays the same role in all aircraft: it serves as a common terminal for all cockpit subsystems. Therefore, when we consider a family of aircraft having different ranges or different sizes, the standardization of the MCDU subsystem will depend on how many pieces are common across all MCDU units installed in all the models of the aircraft family (*cf.* Figure IV-1).

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Figure IV-1: Pairs of MCDU units in the Airbus A320 & A340-600 models.

Lee and Tang (1997) detail the consequences of standardization on the manufacturing process while calling it *delayed product differentiation*. Yahiaoui and Boujut (2005) assimilate it to commonality itself and compare its consequences with the consequences of modularity upon design and manufacturing. However, since they consider the organization of a production system at a given point in time, they fail to identify the third construct, reusability.

Reusability characterizes the common aspects of a subsystem accomplishing identical or analogue functions across a line of products fulfilling the same needs but having been developed at different period. For instance, the landing gear control system fulfills the same role for all aircraft. In the case of a succession of aircraft having similar range and number of passengers, the degree of reusability of the landing gear control system will depend on how many pieces of the subsystem are common to all aircraft considered (*cf.* Figure IV-2).

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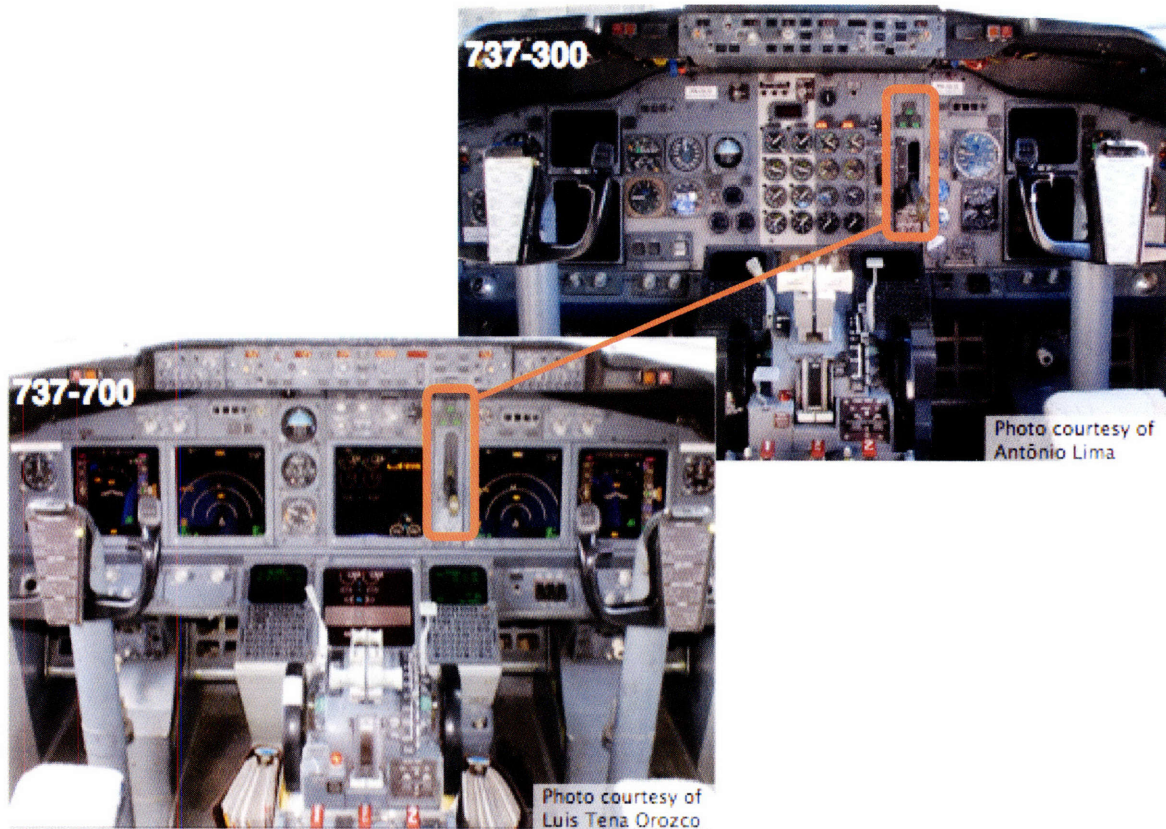


Figure IV-2: Landing gear control systems in the Boeing 737-300 & 737-700 models.

Sivaloganathan and Sahin (1999) reviewed the influence of design reuse on product development and identified its relations with standardization, which they described as a particular aspect of reusability. They briefly mentioned some research (Inns & Neville, 1998) linking reusability with modularity, but failed to subsume the three constructs under the concept of commonality.

Modularity characterizes the degree to which a subsystem can be maintained and its design modified without altering its environment. For instance, the standby horizon indicator (or attitude indicator) is a mechanical instrument used to inform the pilot of the orientation of the aircraft relative to the ground. In commercial aircraft, it is mainly used to verify the indications given by the Primary Flight Display (PFD). While there are a variety of models of standby horizon indicators, their dimensions are generally uniform, and their interactions with other cockpit subsystems are limited. When we consider a

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family of aircraft or a succession of aircraft fulfilling the same needs, the modularity degree of the standby horizon indicator will depend on how much it is possible to maintain or alter it without affecting its environment (*cf.* Figure IV-3).

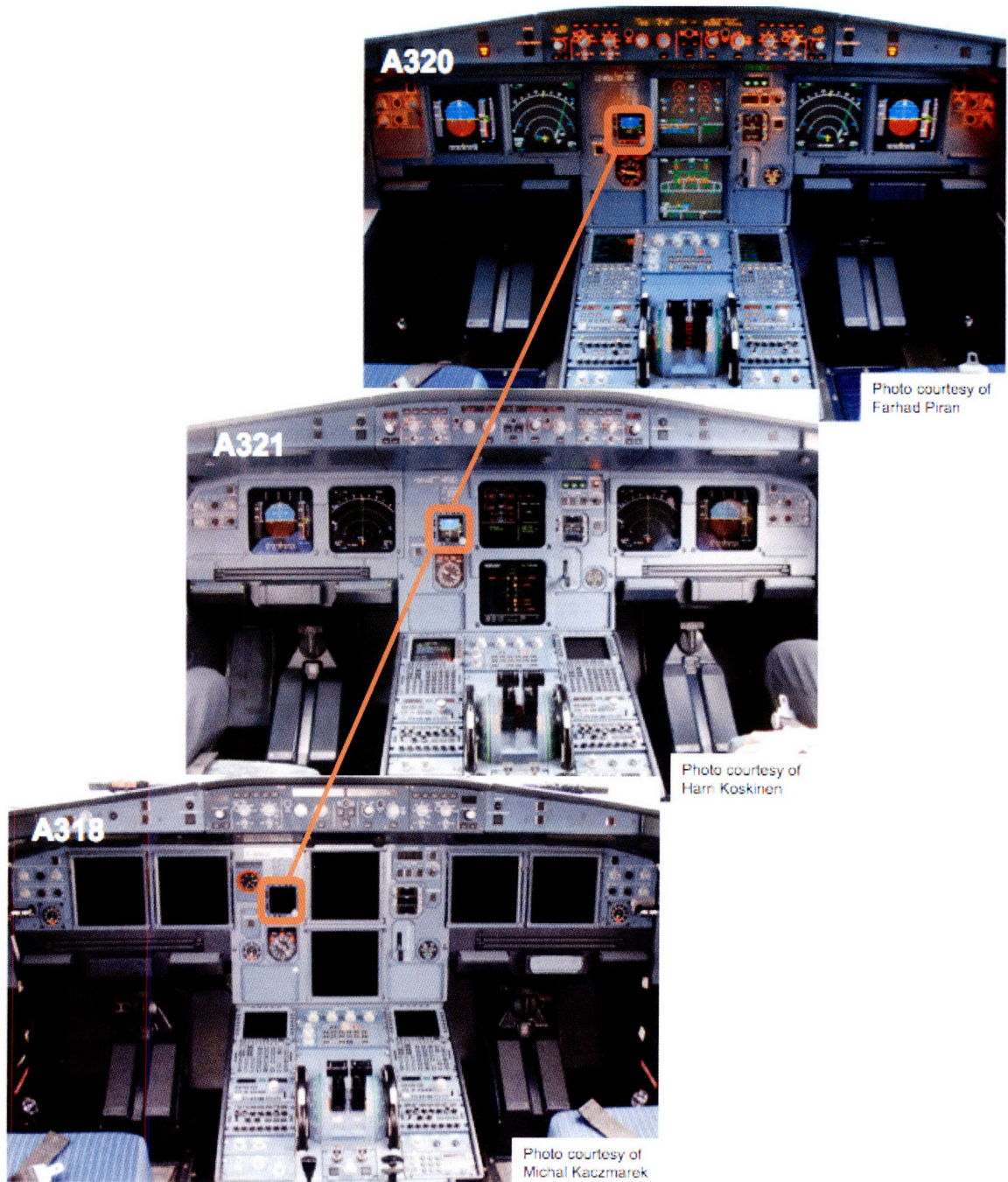


Figure IV-3: Standby horizon indicators in the Airbus A320, A321 & A318 models.

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While many authors recognized the advantages of modularity for product architecture reuse and analyzed the trade-offs between level of modularity and performance, few studies compared modularity with the other aspects of commonality. Interestingly, no study seems to focus on identifying the subsystems that are most likely to be reused or standardized across a family of products before proceeding to the module decomposition. Before establishing a framework for optimizing the implementation of commonality, it is therefore necessary to compare the three concepts and determine unbiased and efficient metrics to measure them in the context of the commercial aircraft industry.

From the definitions of the three constructs, we may notice that the first one is related to transverse commonality, the second to temporal commonality and the last to both types of commonality. Each of these constructs can then be observed from the point of view of the manufacturer or from the point of view of the customer¹. The denomination of customer can be further decomposed in two categories: primary and secondary customers, the first one is the main user of the product in the usual sense of the term (i.e. the pilots, in the case of the cockpit of an aircraft), the second one deals with the maintenance of the product. But in the commercial aviation case, as the airline companies are most often in charge of the maintenance of the airplanes they use, it is not necessary to maintain this distinction.

The set of metrics proposed here will have to measure each of the six aspects of commonality previously exposed in an accurate manner. Its goal will be to determine the quality of commonality implementation in a cockpit. First, this requires determining which variables should be measured to obtain at the same time the level and the quality of the commonality implementation. As the example of the Boeing 757 and 767 families shows, increasing commonality too much is not necessarily beneficial. Hence, for each

¹ I do not take into account in this analysis the various intermediaries between the aircraft manufacturers and the airline companies. For instance, I assume that the parameters upon which the airline companies rely on before committing to use a new airplane do not change whether the airline company chooses to buy or to lease it.

construct, we need to maintain the distinction between the degree of commonality and the quality of commonality implementation. The first one determines how much two aircraft models take advantage of standardization, reusability or modularity. The second aspect measures whether taking advantage of this construct is beneficial for the specific aircraft models that are studied.

IV.2 Variables

IV.2.1 Standardization

From the point of view of the manufacturer, standardization impacts both the design and the manufacturing departments. Considering the entire aircraft or any well-defined subset thereof (such as the cockpit), the degree of standardization will be a function of the ratio between the sum of the engineering development costs of all derivatives over the engineering development costs of the baseline model, divided by the number of derivatives of the product family. Thus, the degree of standardization (Sd_m) will be given by Equation IV-1:

$$Sd_m = 1 - \frac{\sum_{i=1}^k Dd_i}{k \times Db} \quad (IV-1)$$

With k the number of derivatives in the aircraft product family, Db the engineering development costs of the baseline aircraft, and Dd_i the engineering incremental development costs of the derivative i .

Sd_m is normally comprised between 0 and 1. A value of Sd_m smaller than 0 denotes a failure to achieve any savings over the engineering development costs of the derivatives. If this ratio is used to evaluate the degree of standardization of a family of aircraft that will be expanded in the future, the engineering development costs will have to be estimated. In such a case, taking into account the uncertainty linked with product development seems wiser than relying on point estimates and allow for a sensitivity analysis. Furthermore, if engineering techniques or governmental regulations sensibly

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change during the expansion of the product family, it might become necessary to normalize the engineering development costs of each model to take into account these parameters in an adequate manner.

In Table IV-1, my preliminary results show the following values for evaluating the degree of standardization of a modern commercial aircraft. These results have been compiled by determining the degree of standardization for all large commercial aircraft currently produced and in exploitation. The results obtained were compared with existing analyses concerning the application of standardization in the commercial aircraft industry (de Melo, 2000; Rogers & Nazzaro, 2006; Sandholtz & Love, 2001), which were in most cases backed by the opinions of aircraft industry professionals. These results displayed a great consistency:

Degree of standardization	Sd_m
High	> 0.8
Moderate	$0.7 < Sd_m < 0.8$
Low	< 0.7

Table IV-1: Evaluation of the degree of standardization of a commercial aircraft.

However, it is easy to see that this metric, taken alone, would be biased: if the engineering development costs of the baseline model were higher than the industry standard, the level of standardization would likely be higher as well. The optimal standardization level will then have to minimize the development and production costs of the entire set of aircraft that will occupy the target market segment (Martin & Ishii, 1996). The total development and production costs of the set of aircraft considered (*TDPC*), which is used to determine the efficiency of commonality implementation, can thus be expressed as in Equation IV-2:

$$TDPC(l) = \sum_{g=1}^l \left(Db_g + \sum_{i=1}^k Dd_{g,i} \right) + \sum_{g=1}^l \left(n_g \times Pb_g + \sum_{i=1}^k n_{g,i} \times Pd_{g,i} \right) \quad (IV-2)$$

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With l the number of product families, k the number of derivatives in the aircraft product family, Db_g the development costs of the baseline aircraft of the g^{th} product family, $Dd_{g,i}$ the development costs of a derivative, n_g the number of aircraft of the g^{th} model produced, Pb_g the production costs of the baseline aircraft of the g^{th} product family, and $Pd_{g,i}$ the development costs of a derivative.

This number is not normalized. It should be noticed that a set of aircraft does not necessarily correspond to a single aircraft product family. The main criteria to define a set of aircraft concerned are the effective range and the maximum number of passengers for a given configuration (usually 2 classes of passengers). If several aircraft families overlap, all derivatives corresponding to the definition of the set of aircraft should be taken into account to evaluate the *TDPC*.

For the customer, standardization will be considered from a functional point of view. Technical standardization (i.e. the standardization of the physical components) depends on the same parameters as modularity and will be discussed in the corresponding section. Functional standardization concerns the pilots and characterizes the degree of similarity between the training required to fly two types of aircraft. Functional standardization needs consequently to be measured by the airline companies with two variables: the cost of pilots training and the cost of crew errors. The evaluated cost of the latter variable being considered as proprietary information by most airline companies, I will approximate it with the number of crew errors occurring during the flight phase².

The cost of training for an airline company is a direct function of the length of the specific training of the pilot. Since almost all pilots qualify on more than one aircraft during the course of their career, a major driver of the cost of training will be the length of the additional training needed to be qualified on a new model. This will of course depend on the functional commonality between the two types of aircraft. To a large extent, each airline company decides how long the initial training and the transition periods for being qualified on a model of aircraft should be, but minima are fixed by the commercial

² An aircraft is considered in a flight phase as long as it moves under its own power. Consequently, the flight phase also covers most aircraft moves on the ground.

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aviation authorities. Most authorities base their regulations on the decisions of the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA). The Figure IV-4 below shows the length of the required Cross-Crew Qualifications (CCQ) for the major Airbus aircraft currently produced:

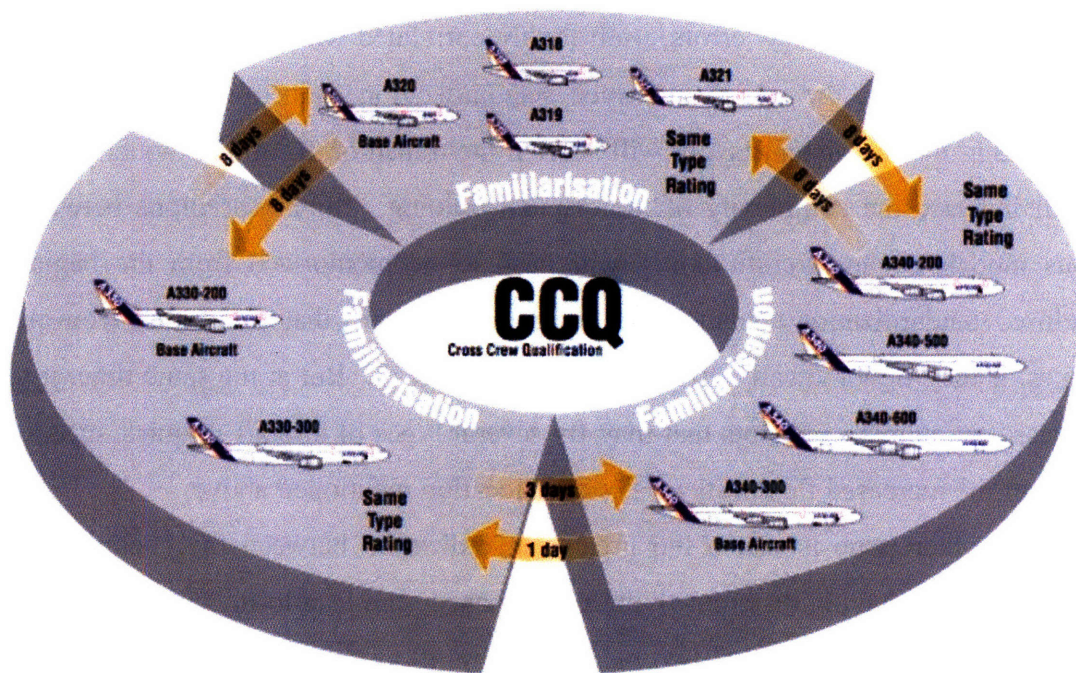


Figure IV-4: Length of Cross Crew Qualifications for three Airbus aircraft families³.

For the airline companies, another major advantage of cockpit standardization is an increased flexibility for allocating aircraft among the destinations they serve. As CCQ decrease, it becomes easier to change the type of aircraft that will serve a given destination, even after the airplane crew has been designated. This permit companies to optimize their airplane allocations with respect to demand, meteorological conditions and technical factors (such as the sudden unavailability of a given airplane). However, a high standardization may also have negative consequences, especially upon the frequency of aircraft incidents. Hence, the length of CCQ does not completely describe standardization, and it becomes necessary to introduce a new metric.

³ These CCQ correspond to the FAA Advisory Circular 120-53 (Vadrot *et al.*, 2003).

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The majority of aircraft accidents can be related to wrong decisions taken by the crew (Green, 1990; Kővári, 2005). The wrong reading of the cockpit instruments, which leads to inappropriate action from the pilots, is one of the major causes of crew errors. The number of crew errors is then directly linked with the complexity of the instruments layout (Cranfield University, 2005). Standardization of the cockpit layout therefore directly impact the frequency of crew errors, itself highly correlated with the frequency of aircraft accidents. However, the relation between standardization and crew errors is complex. Standardizing the instrument layout will shorten the transition from one model to another but will increase the complexity of the original training. Slight variations between the various models of an aircraft family will need to be memorized from the beginning. Therefore, standardization tends to eliminate major mistakes that could arise from pilots' mistakes, if they flew radically different models of aircraft. But at the same time, it tends to increase the number of pilots that may fly several types of aircraft in quick succession, because of the increased flexibility of aircraft allocation mentioned above.

Another issue is that a too great standardization between the cockpits of two models of aircraft having different flying performances can lead to inappropriate handling of a situation. If the cockpits of two models of aircraft are highly similar, pilots may not remember which model they are currently flying, and act as if their airplane were more maneuverable or less heavy than it actually is. Such a mistake is rare, but mainly occur under stress, during the most complex maneuvers, like take-off or landing, especially when exterior factors complicate the situation (Interviews with Air France pilots, 2006). Thus, standardization may have a negative impact on the frequency of crew errors. At this point, there seems to be no *a priori* way of determining the degree of standardization that will minimize crew errors, and only a backward estimation through historical crew error reports is possible.

Having examined the points of view of the manufacturer and of the customer for this construct, I can now summarize the metrics used to measure the degree and the efficiency of standardization in Table IV-2:

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Metrics User	Metrics Type	Expression
<i>Manufacturer</i>	Standardization degree	$Sd_m = 1 - \frac{\sum_{i=1}^k Dd_i}{k \cdot Db}$
	Standardization efficiency	$TDPC(l) = \sum_{k=1}^l \left(Db_k + \sum_{i=1}^k Dd_{k,i} \right) + \sum_{k=1}^l \left(n_l \cdot Pb_k + \sum_{i=1}^k n_{k,i} \cdot Pd_{k,i} \right)$
<i>Customer</i>	Standardization degree	Length of CCQ
	Standardization efficiency	Number of crew errors

Table IV-2: Metrics – Standardization.

IV.2.2 Reusability

For the manufacturer, reusability can concern the subsystems, the production tools and methods. Subsystems reusability is relatively straightforward. It is the capacity of a given subsystem to be reused in another model of aircraft. But, depending on the definition used, subsystems may greatly differ in size, complexity and cost. Consequently, the question is not to measure how many such subsystems can be reused but rather how much development time they represent for the enterprise, since development lead-time is directly proportional to costs. Therefore, Equation IV-3 can be used to measure the degree of reusability of the cockpit subsystems for the manufacturer (Rd_m). Since the formulation of Equation IV-3 is not product-dependent, this result may also be used for measuring the degree of reusability for the entire airplane:

$$Rd_m = 1 - \frac{Dn}{Dt} \tag{IV-3}$$

With Dn the amount of time spent in developing the new subsystems in the cockpit (*alt.* the new subsystems in the aircraft) and Dt the total development time spent in developing the cockpit (*alt.* the aircraft).

It may be noticed that this metric will become biased if we do not make the assumption that no gain in product development productivity is made over the years between the development of the baseline model and the time when the derivative is

developed. If productivity increase occurs, it becomes necessary to take it into account and create a normalized value for this metric.

Determining the reusability of the production tools is somewhat more complicated by the fact that it refers at the same time to *intrinsic reusability* (inherent capability of the production tools to be used for specified purposes after their initial installation) and to *extrinsic reusability* (degree of reuse determined by the effectiveness of a system intrinsic reusability with respect to the required capability introduced by the change of the system extrinsic environment). From a practical standpoint, it is only the extrinsic reusability that impacts the amount of investment required by the development of a new aircraft, so I will solely focus on it. Ko *et al.* (2005) have shown that extrinsic reusability is a probabilistic assessment. It depends on the probability of having to perform a set of n tasks at a given time t . In Equation IV-4, the extrinsic reusability is expressed under the form of a weighted sum of conditional probability $R(t,F,K(t))$, given n tasks, having a probability $Pr(t,n)$ of requiring to be carried out at a time t :

$$R(t,F,K(t)) = \sum_n R(t,F | n) \cdot Pr(t,n)$$

$$R(t,F,K(t)) : (t,F,K(t)) \mapsto \mathfrak{R} / \begin{cases} K(t) = \{k | Pr(t,k) > 0\} \\ R(t,F,K(t)) \in [0,1] \end{cases} \quad (IV-4)$$

With F a set of functionalities that the system has at period t and $K(t)$ a set of possibly required tasks at period t .

Reusing development methods is possibly one of the areas that yield the maximum room for improvement in product research and development. It is related to the wider question of knowledge management in the enterprise. As such, it is penalized by the lack of accurate measurement that characterizes the management of intangible assets. Numerous frameworks have been developed, but none of them appear to measure all possible aspects of development reuse. Developing metrics to measure the efficiency of product development methods is beyond the scope of the present research, but can certainly be viewed as a future extension of this set of metrics.

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The reusability construct is also a capital factor for the customer. It will determine the homogeneity of the airline fleet, which directly impacts the airplane maintenance costs. Using the same subsystem to accomplish a given task on several versions of an airplane allows the airline company to store fewer spare parts than if each aircraft version had its dedicated subsystem version. In this respect, reusability has a similar impact on maintenance as standardization. Consequently, the degree of reusability of a given subsystem from the airline point of view (Rd_a) can be measured by the following expression in Equation IV-5:

$$Rd_a = 1 - \frac{\sum_{i=1}^l \left(\frac{St_i - 1}{n_i} \right)}{l} \quad (IV-5)$$

With l the number of aircraft models in the airline fleet, n_i the number of aircraft of model i and St_i the number of variants of the subsystem considered that are installed on the aircraft of model i .

Contrary to the previous construct, there is few negative consequences on reusability in the cockpit of a commercial aircraft. A too high reusability may perpetuate an inefficient design, but since the transition to glass cockpits (i.e. cockpits with LCD screens replacing a multitude of analog indicators), pilots do not seem concerned with this issue. However, when reusability is considered with respect to the entire aircraft, it must face a trade-off with flight performances. These performances (speed, maximum altitude, useful range, maximum take-off weight, etc) translate into consumption efficiency, which is the main driver of costs during the flight phase. Keeping older subsystems can affect the weight of the airplane or decrease its aerodynamic qualities. The case of the engines is particularly important, as each generation of engine yields a consumption efficiency increase on the order of 5%. As a consequence, the efficiency of reusability (Re_a) will be measured in Equation IV-6 by a function of the fuel consumption gains of the derivatives, compared with the baseline model:

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$$Re_a = 1 - \frac{Cd_i}{Cb} \tag{IV-6}$$

With Cd_i the average unit consumption of the derivative i , and Cb the average unit consumption of the baseline aircraft.

Table IV-3 summarizes the metrics related to the reusability construct:

Metrics User	Metrics Type	Expression
Manufacturer	Reusability degree	$Rd_m = 1 - \frac{Dn}{Dt}$
	Reusability efficiency	$R(t, F, K(t)) = \sum_n R(t, F n) \cdot \Pr(t, n)$ $R(t, F, K(t)) : (t, F, K(t)) \mapsto \mathfrak{R} / \left\{ \begin{array}{l} K(t) = \{k \Pr(t, k) > 0\} \\ R(t, F, K(t)) \in [0, 1] \end{array} \right.$
Customer	Reusability degree	$Rd_a = 1 - \frac{\sum_{i=1}^l \left(\frac{St_i - 1}{n_i} \right)}{l}$
	Reusability efficiency	$Re_a = 1 - \frac{Cd_i}{Cb}$

Table IV-3: Metrics – Reusability.

IV.2.3 Modularity

There is no unquestionable way of defining the degree of modularity of a product from the manufacturing point of view. Several metrics have already been proposed to measure it, but they strongly depend on the variables considered as relevant. Thus, for a given product, the results will vary according to the method chosen. As I mentioned in the literature review, Sosa *et al.* (2003) have defined a method that determines whether a product is integral or modular. This method is based on component interactions matched against each other in the DSM. The binary DSM is a matrix where each line (and the corresponding column) represents one component. The diagonal terms of the matrix are set to zero, and the off-diagonal terms depend on the relations between the two components concerned. An off-diagonal term is set to unity if there is a connection between the two components, else it is set to zero. A connection can be a physical link

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between the two components, or a transmission of power or information. Figure IV-5 represents idealized examples of product structure for a number of modules equal to 7:

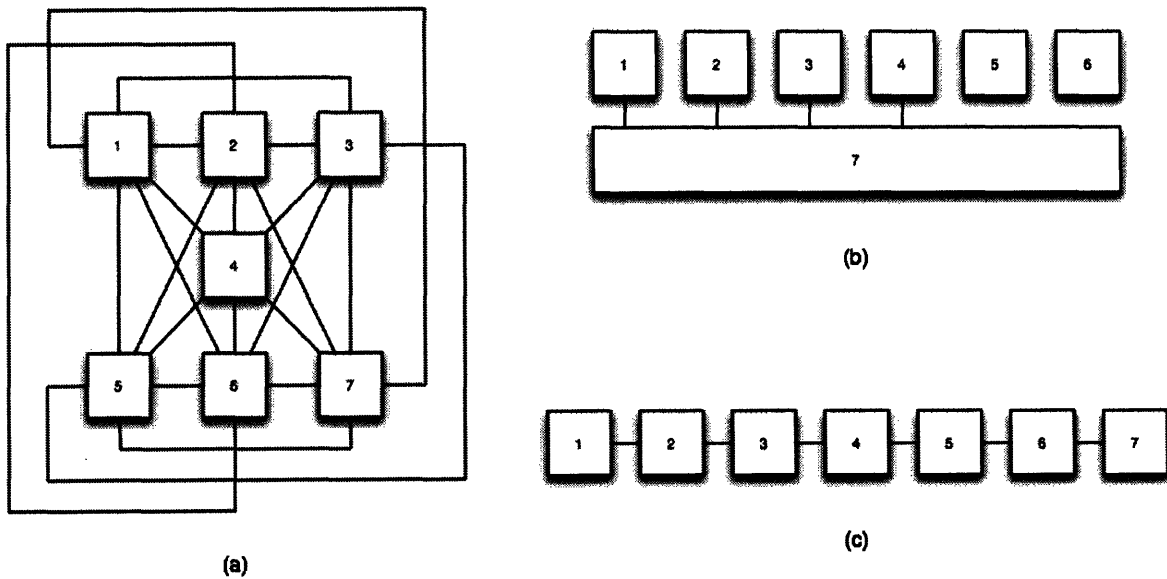


Figure IV-5: Idealized examples of various product structures⁴: (a) Fully integral system. (b) Bus-modular system. (c) Fully modular system.

The sparsity pattern of the Design Structure Matrixes representing these systems are given by Figure IV-6:

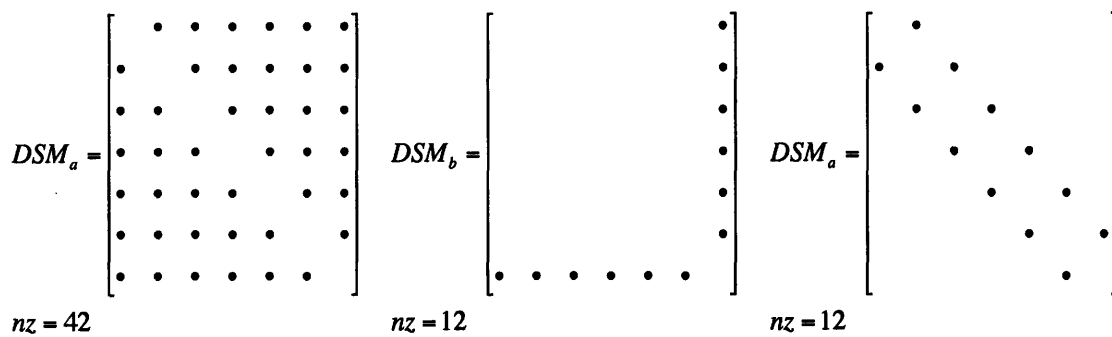


Figure IV-6: Sparsity pattern for idealized DSMs: (a) Fully integral system. (b) Bus-modular system. (c) Fully modular system.

⁴ This example, and the following sparsity patterns are taken from Hölttä, Suk Suh & de Weck, 2005

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Stone *et al.* (2000) developed the function structure heuristic method, based on the function structures created by Pahl and Beitz (1999). This method decomposes the product functions in a bloc diagram and analyses the resulting function structure. Modules are separated by isolating the various functional flows in the product. Product, energy and information flows are represented as arrows linking the modules. The level-0 decomposition describes the role of the product and its inputs and outputs. Each successive level gives more details on how the subsystems constituting the product function. Thus, it creates layers of functional modules. Figure IV-7 describes the level 0 of a turbofan:

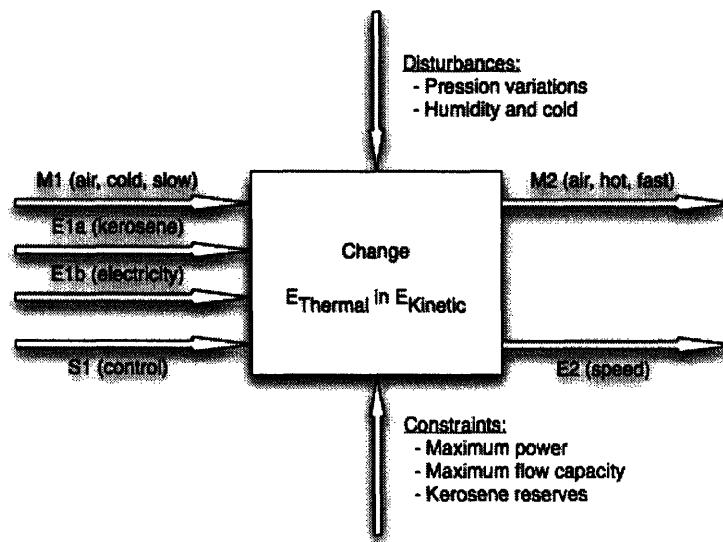


Figure IV-7: Function structure of a turbofan, level 0.

A third type of method to determine the degree of modularity is the MFD (Otto & Wood, 2001; Hölttä-Otto, 2005). It is also based on functional decomposition, but modularity depends on more constructs than mere functionality. Twelve modularity drivers are identified in MFD. Not all of them need to be taken into account when carrying the modularization:

- Carry over
- Technology evolution
- Planned changes
- Different specification

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- Styling
- Common unit
- Process and/or organization
- Separate testing
- Supplier availability
- Service and maintenance
- Upgrading
- Recycling

This last method has the advantage of being more adaptable to the strategic needs of the enterprise, since most modularity drivers are business-oriented. However, this method has not been designed to identify modularity across a product family.

While efficient for products with a limited complexity, these metrics are somewhat too intricate to allow effective comparisons between large, highly integral products like airplanes. Once a subsystem is proved to be more efficient in being modular by one of these methods, the efficiency of modularity of a subsystem (Me_m) will be obtained by the ratio given in Equation IV-7:

$$Me_m = \frac{Std_{Int}}{Tt_{Int}} \quad (IV-7)$$

With Std_{Int} the number of standardized interfaces with the rest of the aircraft, and Tt_{Int} the total number of interfaces with the rest of the aircraft.

From the point of view of the customer, modularity mainly impacts the maintenance of the product, since modularity is not apparent to the pilots. Here, the need is no more to consider the trade-offs between modularity and integrality for a given product but the practical impact of modularity across all types of aircraft belonging to the airline company. Although the cost of a spare part might be considered at first as one of the drivers determining the efficiency of modularity, experience shows that the immediate availability of the spares is the dominant factor in this case. Then, the problem becomes a simple case of inventory management. First, the modularity degree will be defined by

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analogy with the standardization degree defined above, as a function of the number of aircraft using interchangeable subsystems for a given function and of the total number of aircraft in the fleet. Thus, Equation IV-8 determines the degree of modularity from the point of view of the airline company (Md_a):

$$Md_a = \frac{Com_{Air}}{Tt_{Air}} \quad (IV-8)$$

With Com_{Air} the number of aircraft of the airline company using interchangeable subsystems for accomplishing the same function, and Tt_{Air} the total number of aircraft of the airline company using the function in question.

The optimal ratio is the one that minimizes the total relevant costs per year ($ETRC$) for slow-moving, critical items as defined by Silver, Pyke and Peterson (1998) for a B_2 shortage costs structure. A B_2 shortage costing method implies that the costs of shortage are measured by number of units short. This allows to distinguish the case where several airplanes would be grounded for want of the same piece from the case where only one would require that piece, as the two events would not yield the same cost for the airline company. The $ETRC$ takes into account three different types of costs: the order costs, the storage and inventory costs (which include the carrying charge, or rate at which an item stored deteriorates), and the shortage costs, as shown in Equation IV-9:

$$ETRC(s, Q) = \frac{AD}{Q} + \frac{1}{Q} \sum_{y=s+1}^{s+Q} \left[rv \sum_{i=0}^y (y-i) p_{po}(i | \hat{x}_L) + B_2 Dv \sum_{i=y}^{\infty} p_{po}(i | \hat{x}_L) \right] \quad (IV-9)$$

Where:

s = Order point

Q = Quantity of items ordered

A = Cost per order (\$/order)

D = Average demand per year (units/year)

r = Carrying charge (\$/\$/year)

v = Cost per item (\$/item)

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$p_{po}(x_0 | \hat{x}_L)$ = Probability that a Poisson variable with mean \hat{x}_L takes on the value x_0

B_2 = Cost per missing item when a stockout occurs (% of item cost)

In Table IV-4 are summarized the modularity metrics:

Metrics User	Metrics Type	Expression
<i>Manufacturer</i>	Modularity degree	Design Structure Matrix Function structure heuristics Modular Function Deployment
	Modularity efficiency	$Me_m = \frac{Std_{Int}}{Tt_{Int}}$
<i>Customer</i>	Modularity degree	$Md_a = \frac{Com_{Air}}{Tt_{Air}}$
	Modularity efficiency	$ETRC(s,Q) = \frac{AD}{Q} + \frac{1}{Q} \sum_{y=s+1}^{s+Q} \left[rv \sum_{i=0}^y (y-i) p_{po}(i \hat{x}_L) + B_2 Dv \sum_{i=y}^{\infty} p_{po}(i \hat{x}_L) \right]$

Table IV-4: Metrics – Modularity.

IV.3 Summary Table

Commonality Types	Constructs	Manufacturer Metrics	Customer Metrics
<i>Transverse Commonality</i>	Standardization	Degree of Standardization: Sd_m	Degree of Standardization: Length of CCQ
		Total Development and Production Costs: $TPCD(t)$	Standardization Efficiency: Number of crew errors
<i>Temporal Commonality</i>	Modularity	Degree of Modularity: DSM, MFD, function structure heuristics	Degree of Modularity: Md_a
		Modularity Efficiency: Me_m	Estimated Total Relevant Costs: $ETRC(s,Q)$
	Reusability	Degree of Reusability: Rd_m	Degree of Reusability: Rd_a
		Reusability Efficiency: $R(t,F,K(t))$	Reusability Efficiency: Re_a

Table IV-5: Metrics Summary.

IV.4 Discussion

IV.4.1 Establishing Trade-offs Between the Metrics

It may be noticed that no trade-off has been proposed to determine the comparative importance of each dimension studied here. As detailed economic studies on the cost of aeronautics product development and of airplane maintenance were not available, it would have been difficult to compare directly one metric with another. In addition, metrics may differ in importance depending on the manufacturer or customer, as each company may have a different strategy in this respect. As a consequence, I deemed appropriate to avoid making hypotheses in this respect, in order to maximize flexibility in this respect.

IV.4.2 Application of the Set of Metrics to the Entire Aircraft

The limitations concerning the application of the set of metrics to the entire aircraft can be defined as *horizontal limitations*. In this case, while the criteria used to measure commonality remain the same, the ideal degree of commonality will depend on additional factors. Integral aircraft architecture optimizes local performance characteristics while minimizing the size and weight of the product. Technical (flight) performances become major concerns and need to be balanced with the advantages provided by commonality to optimize the present value of the entire fleet considered. Seven fundamental constraints can be identified: fuel weight, empty weight, direct operating costs, purchase costs, ratio lift/drag, maximum cruise speed, and maximum attainable range. While I have used metrics that are not system specific, this set of metrics has only been tested with respect to the development and production of the cockpit of commercial aircraft. Validating this set of metrics for the entire aircraft would be necessary before removing these horizontal limitations.

Attaining a balance between technical performance and process efficiency is difficult to achieve, since commonality considerations impact the entire range of products manufactured and technical considerations are specific to each product. The case might be

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particularly problematic in the aerospace domain, where the lifecycle of a product is particularly long and the rate of introduction of new products significantly lower than in other industries. Yet, failing to keep a focus on commonality at the enterprise level would lead to introducing new standards whenever a new product is launched. To overcome this limitation, which is intrinsic to the set of metrics defined here, it might become necessary to introduce the estimated rate of technical change as a new parameter. Further research in this domain is needed to construct an efficient set of metrics for measuring the efficiency of commonality implementation at the level of the entire aircraft.

IV.4.3 Application of the Set of Metrics to Other Types of Vehicles

The limitations concerning the application of the set of metrics to other types of vehicles will be defined as *transverse limitations*. While the commonality trade-offs do not differ very much from those that have been described above for other commercial or private motorized aeronautic vehicles, many other factors will need to be taken into account when the domain of use changes. Even if a private piston aircraft has almost nothing in common with a large airliner, the commonality problematics will be the same in both cases, except that in the former case, it may not be relevant to consider the cockpit in isolation from the body of the aircraft. Further validation should therefore be conducted to confirm the applicability of this set of metrics for private jets or piston aircraft and for civil helicopters.

The case is however very different for military aircraft or for space vehicles. Product development in those domains is much closer to basic research than in the case of commercial aircraft. Therefore, it is likely that the corresponding metrics will be different. Technical performance, field maintenance and robustness become prominent parameters in these cases. The product development process radically changes, since these concern developed-to-order vehicles rather than mass customized ones. Commonality becomes a secondary parameter in front of the customer specifications. Consequently, there cannot be any direct application of this set of metrics to military or space vehicles.

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It is interesting to notice that the assumptions used to construct this set of metrics are quite similar to those that would apply in the automotive domain. Comparing this set of metrics with the methods used to construct product families in the automotive industry would help determine how much this set of metrics should be tailored to be applicable to other industries focusing on complex engineered products.

V. Validating the Commonality Metrics

V.1 Basis for Comparison

After establishing the set of metrics in the preceding chapter, my first concern is to test its validity and to determine the usefulness of this set of metrics as a decision tool for the aircraft manufacturers and the airline companies. Thus, it is necessary to verify its accuracy and consistency. It is also important to ensure that each metric measures a separate, unique aspect of commonality and that no metric overlaps with another. I will first verify that all aspect of commonality implementation in the cockpits of commercial aircraft are taken into account, and I will further discuss the metrics that could be used to complete the current set and enable it to measure the quality of commonality implementation for an entire aircraft. Finally, I will examine whether other metrics might have been more efficient for the task of measuring commonality in this case.

As I already mentioned, two comparable aircraft product families will be studied in this chapter: the Airbus A320 and the Boeing 737 families. An interesting fact is that both are advertised as the most successful aircraft families of their respective manufacturers. As Figure V-1 shows, the A320 family originated the emergence of Airbus as one of the major commercial aircraft manufacturers. Even if the 737 never represented such a share in Boeing sales of commercial aircraft (cf. Figure V-2), this family has also been a huge success. In fact, the 737 family is the largest selling family of the history of commercial aviation: more than 6825 aircraft ordered between 1965 and 2006. Yet, it is traditionally assumed that the design philosophies of the two families are very different, Airbus putting an important emphasis on commonality and Boeing being more interested in customizing their aircraft to best fit the customer. Comparing the two families should therefore yield interesting results regarding the quality of commonality implementation.

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These two families are even more comparable, as the A320 family was developed during the same period as most of the 737 versions derived from the 737-300. Figure V-3 presents a development timeline for the aircraft of those two families.

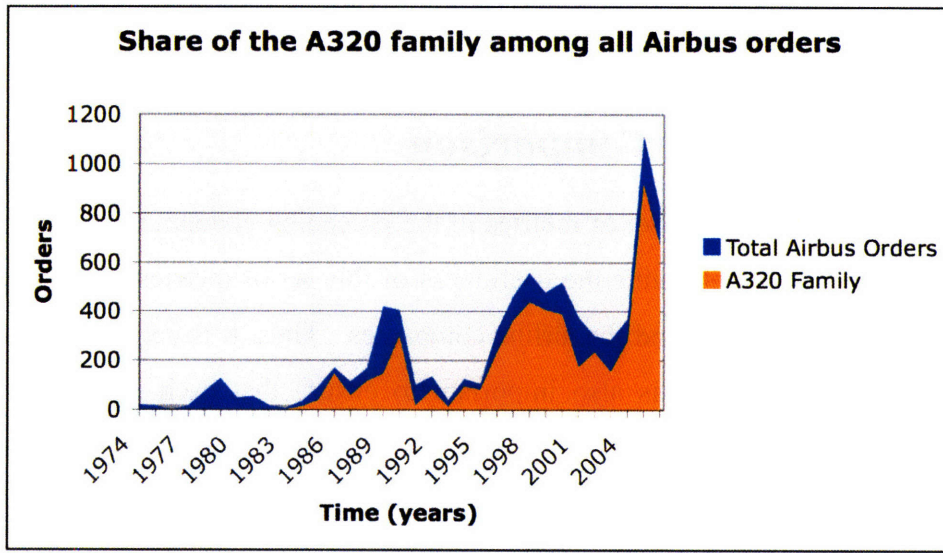


Figure V-1: Orders for the Airbus A320 family (Airbus, 2007).

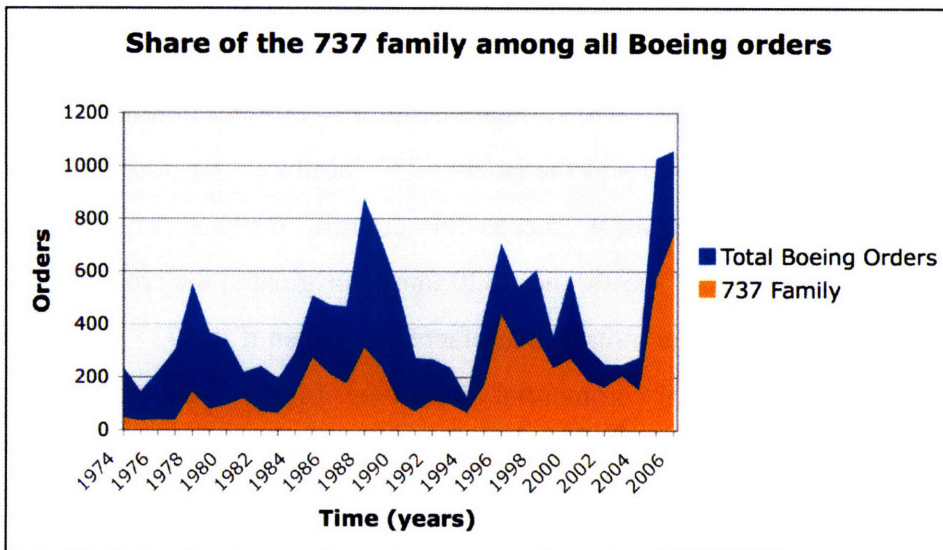


Figure V-2: Orders for the Boeing 737 family (Boeing, 2007).

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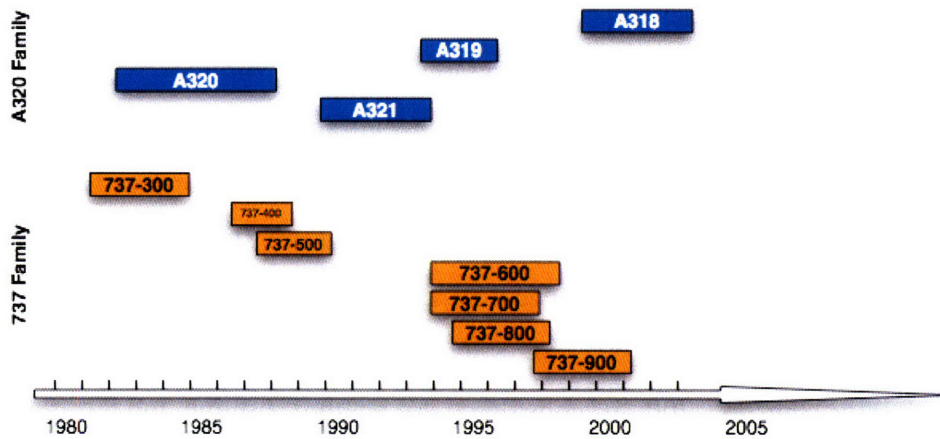


Figure V-3: Development timeline for the A320 and 737 derivatives.

V.2 Alignment with the Metrics

V.2.1 The Manufacturers' Point of View

V.2.1.1 Standardization

We will first examine the results obtained by the metrics from the point of view of the manufacturers. In Figure V-4, the degree of standardization Sd_m will be measured for the entire aircraft, not for the cockpit only, as neither aircraft manufacturer communicates its detailed engineering development costs. Equation V-1 recalls the formula linked with the degree of standardization:

$$Sd_m = 1 - \frac{\sum_{i=1}^k Dd_i}{k \times Db} \quad (V-1)$$

With k the number of derivatives in the aircraft product family, Db the engineering development costs of the baseline aircraft, and Dd_i the engineering incremental development costs of the derivative i .

It was thus easier to evaluate the engineering development costs for the entire aircraft, at the program level. In addition, an important amount of information is available concerning the Airbus development subsidies. Knowing the share that these subsidies

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represented for each Airbus development program enabled me to refine the estimations obtained (the 1992 US-EU Large Civil Aircraft Agreement limited EU launch aids to Airbus to one third of the development costs of a new aircraft, and EU publishes the details of the launch aid agreements). Due to the limited figures available for the Boeing 737 derivatives, I will only take into account the models that are still in production for this metric. The aircraft that are still produced by Boeing are regrouped in the sub-family 737NG, which contains the 737-600, -700, -800 and -900. Thus, the first model of the 737NG sub-family, the 737-700, is considered to be the baseline model. As neither manufacturer has confirmed the numbers provided in Table V-1, I use here a typical $\pm 5\%$ uncertainty interval around the Sd_m value obtained.

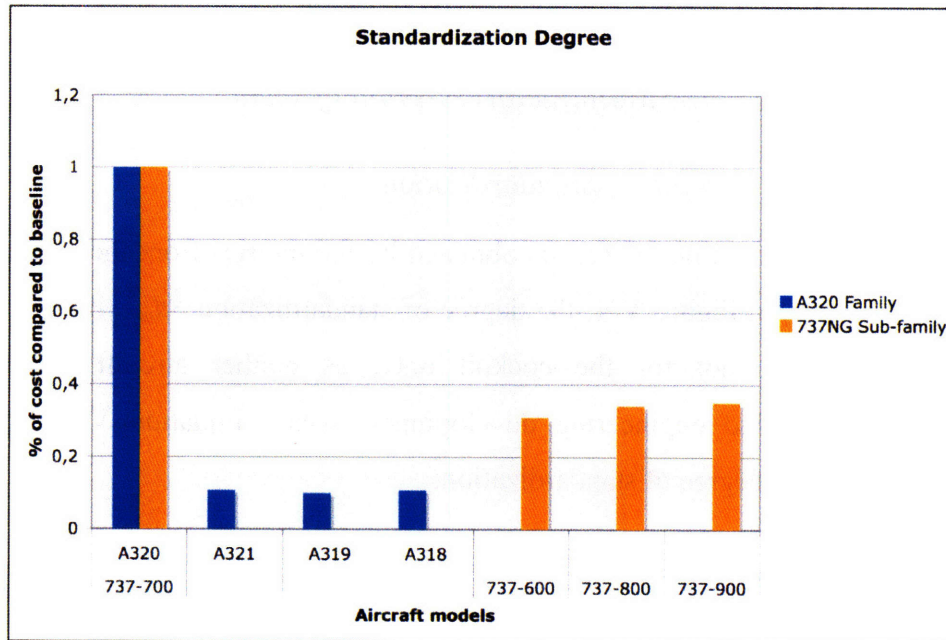


Figure V-4: Engineering development costs of the A320 and 737NG derivatives (de Melo, 2000; Lawrence, 2001; Sandholtz & Love, 2001; USA, 2006).

Aircraft family	Standardization degree (Sd_m)
A320 family	$0.85 \leq Sd_m \leq 0.94$
737NG sub-family	$0.63 \leq Sd_m \leq 0.70$

Table V-1: Standardization degree of the A320 family and the 737NG sub-family.

VALIDATING THE COMMONALITY METRICS

The results tend to confirm the higher standardization of the A320 family compared to its Boeing counterpart. This appears logical, as Airbus was by far the smaller company of the two when the A320 program was launched. Its goal was to constitute a complete range of aircraft in the shortest amount of time possible. It must be recognized that a number of parameters can also influence the engineering development costs to some extent. In particular, the engineering development costs seem to be exponentially correlated with the size of the aircraft. This is an additional reason why normalizing the derivatives development costs and comparing them with the development costs of the baseline appeared to be the best solution. Separating the effects of standardization from the other unobserved effects would require studying a wider sample of aircraft families. Accomplishing this would certainly be useful for precisely determining the dollar value of standardization.

Now, let us consider the efficiency of standardization (*TPCD*), whose formula is repeated in Equation V-2:

$$TDPC(l) = \sum_{g=1}^l \left(Db_g + \sum_{i=1}^k Dd_{g,i} \right) + \sum_{g=1}^l \left(n_g \times Pb_g + \sum_{i=1}^k n_{g,i} \times Pd_{g,i} \right) \quad (V-2)$$

With l the number of product families, k the number of derivatives in the aircraft product family, Db_g the development costs of the baseline aircraft of the g^{th} product family, $Dd_{g,i}$ the development costs of a derivative, n_g the number of aircraft of the g^{th} model produced, Pb_g the production costs of the baseline aircraft of the g^{th} product family, and $Pd_{g,i}$ the development costs of a derivative.

To keep these metrics coherent, the efficiency of standardization will also be measured for the entire aircraft and I will only focus on aircraft that are still produced by the two manufacturers. Again, this metric relies on publicly available data, which makes it less precise than if the exact manufacturing costs were available. Here, the manufacturing costs are derived from the public price of each aircraft model, and from the estimations of the number of aircraft that have to be sold by the manufacturer for each model to pay back for its investment. The public prices of commercial aircraft are available in several

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specialized aviation publications, such as the Avmark newsletter. The number of aircraft that have to be sold to pay back for a given aircraft model are either taken from the manufacturers' communications or from estimations by commercial aerospace experts.

I will make two further assumptions: the minimum number of aircraft that have to be sold in order to pay back is based on the public price of the corresponding aircraft; and this public price increases at a rate which corresponds to the sum of the inflation and of the discount rate used in the industry. This assumption seems pretty robust over the years where the evolution of the public price of several aircraft models is available. It must be noticed that the public price of commercial aircraft does not correspond to the real price paid by the airline companies, as they almost always obtain a sizeable rebate during the bargaining negotiation. Thus, we assume that the public price of aircraft does not depend on any negotiation with the airline companies but only on the real costs of the corresponding aircraft model. As the uncertainty over the values of this metric is high, I prefer using a non-dimensional approximation for the direct costs of aircraft. This approximation will take into account the development costs and the direct production costs related to an aircraft model. Figure V-5 shows how many times an aircraft model has been sold by the end of 2006, compared with how many sales would be required for each model to break even. In this graph, a value of 1 denotes a model that is exactly breaking even:

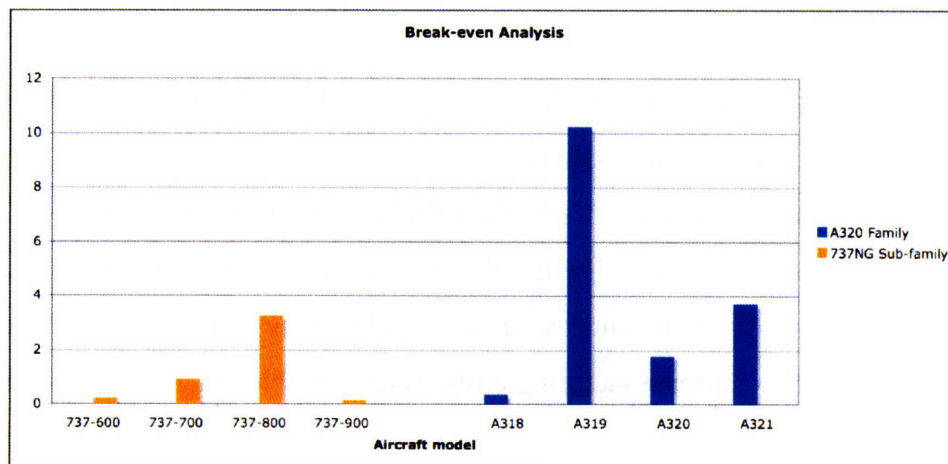


Figure V-5: Break-even analysis of the A320 and 737NG derivatives.

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Before interpreting these results, it is necessary to notice that the A320 family has been on the market for approximately twice as much time as the 737NG. This can contribute to explaining the disparity between the two. The fact that the 737-700 was a derivative from an older aircraft -instead of being a clean sheet project like the A320- might also have played a role here. However, a very clear fact appearing here is that in both cases, the baseline aircraft is not the most profitable model of the family. This stresses the importance of standardization across aircraft models. However, it is interesting to notice that there are huge disparities between the derivatives. Thus, a high commonality is not necessarily a determinant factor. From my discussions with aircraft manufacturing professionals, three major factors need to be taken into account at this level: market positioning, fuel efficiency and affordability. The A318 is a good example of a case where these factors weight more than commonality. By its size, it is competing with regional jets from Bombardier and Embraer, which have both a far better fuel efficiency and a lower price. According to David Almo, JetBlue fleet planner (2005), compared to the Embraer 190, “the A318 just doesn’t bring the economics.”

V.2.1.2 Reusability

From the point of view of the manufacturer, the degree of reusability Rd_m of the cockpit is obtained by identifying the main subsystems of the cockpit instruments and grouping them in functional units (for instance, the gear command and the three gear lights form one logical unit). In Equation V-3 is repeated the formula used to obtain Rd_m :

$$Rd_m = 1 - \frac{Dn}{Dt} \quad (V-3)$$

With Dn the amount of time spent in developing the new subsystems in the cockpit (*alt.* the new subsystems in the aircraft) and Dt the total development time spent in developing the cockpit (*alt.* the aircraft).

Appendix 3 summarizes the instrument units identified. I then determined when variants of the original units had been used in later versions or models of the aircraft. Once the number of versions is known, the last step is to evaluate the length of the

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development lead-time for each variant, compared to the development lead-time of the original unit. Making the average over all such functional units of the cockpit permits to evaluate the degree of reusability in the cockpit (*cf.* Table V-2). For the sake of simplicity, I assumed that the productivity of manufacturing techniques did not change significantly over the period considered. While this may not be exact, this approximation does not alter the comparison between the two aircraft families, since they were developed over the same period. However, it might have led to a slight overestimation of the absolute degree of reusability.

A320 family	A318		A319		A321	
Rd _m	31%		52%		31%	
737 family	737-400	737-500	737-600	737-700	737-800	737-900
Rd _m	39%	25%	< 0%	< 0%	6.8%	< 0%

Table V-2: Reusability degree of the cockpit subsystems of the A320 and 737 derivatives.

The most striking element of this table are the negative values (<0%) for the 737-600, -700 and -900. This denotes that the development lead-times of several derivatives of the Boeing 737 have been longer than the development lead-time of the model chosen as the baseline. A closer analysis shows that the denomination 737 for both the “Classic” (737-300/400/500) and the “Next-Generation” (737-600/700/800/900) sub-families might be misleading. The two sub-families differ by many aspects, and the 737-300 itself was a redesign based on the “Original” (737-100/200) sub-family. Had the 737-700 been chosen as the baseline for the 737NG variants, both the 737-800 and -900 would have presented a degree of reusability higher than zero, albeit not as high as for the A320 variants. Interestingly, the variants with the highest standardization also have a high *Rd_m*, but this metric is not totally correlated with the previous one, as equivalent values for the degree of reusability do not necessarily yield the same standardization efficiency.

Lack of data unfortunately prevented me from performing a comparative analysis of the efficiency of reusability from the manufacturer point of view. Boeing chose not to disclose any detail pertaining to its manufacturing organization.

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V.2.1.3 Modularity

I will use the DSM to measure the degree of modularity from the point of view of the aircraft manufacturer. After identifying the main instrument subsystems of the forward part of the cockpit by a visual analysis (cf. Appendix 3), I investigated their physical connections with each other, with the help of cockpit technical documents. For this metric, I use the A320 and the 737-700 respectively as the baseline aircraft. The DSMs obtained are given below in Figure V-6 and Figure V-7.

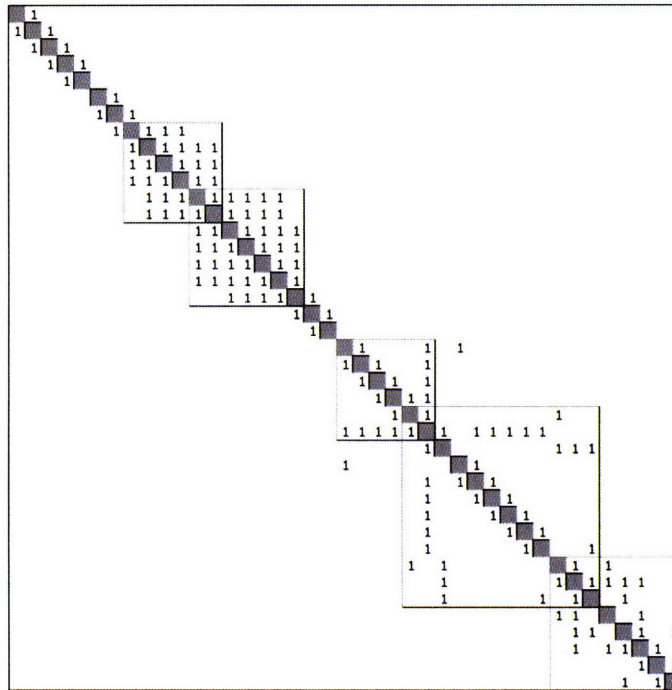


Figure V-6: Design Structure Matrix of the cockpit instruments of the Airbus A320¹.

¹ Main source of data:

http://www.content.airbusworld.com/SITES/Customer_services/index1.html.

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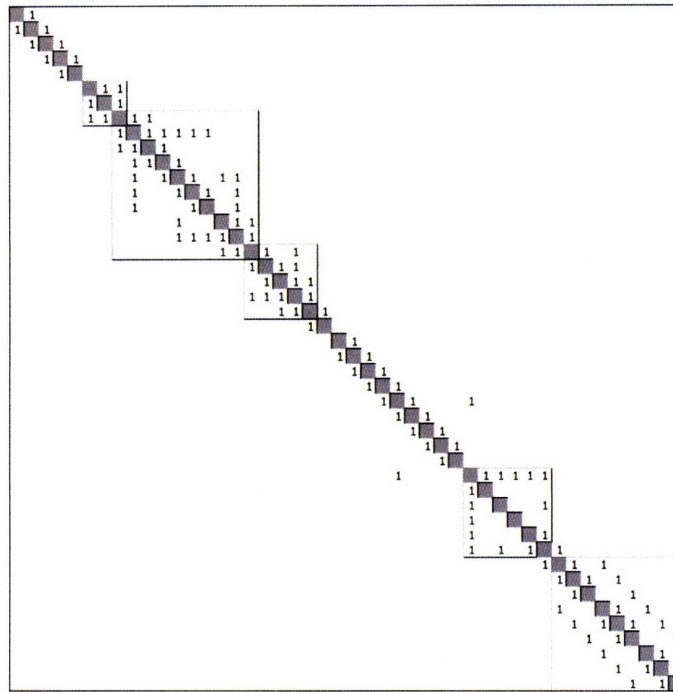


Figure V-7: Design Structure Matrix of the cockpit instruments of the Boeing 737-700².

Interestingly, a graphical identification of the modules clusters indicates that the instrument panels of the 737 display a higher modularity than the ones of the A320. This is confirmed by the ratio of the number of liaisons between the modules over the total number of modules considered, which is approximately 29% lower for the 737 than for the A320. Interviews of aircraft manufacturing professionals tend to confirm that the A320 cockpit instruments are less easily accessible than the 737 ones for the maintenance operations.

Using the same cockpit instruments as for the preceding question, I performed an analysis of the efficiency of modularity Me_m for the two aircraft families (*cf.* Equation V-4 for the formula of Me_m). The type of interface between the different modules was determined through the same documents as for the precedent metric:

$$Me_m = \frac{Std_{int}}{Tt_{int}} \quad (V-4)$$

² Main source of data: <http://www.b737.org.uk/>.

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With Std_{Int} the number of standardized interfaces with the rest of the aircraft, and Tt_{Int} the total number of interfaces with the rest of the aircraft.

Having determined the interfaces between the instruments, I only had to identify which ones are standardized throughout the aircraft family and which are not. The results obtained are presented in Table V-3:

Aircraft family	Efficiency of modularity (Me_m)
A320 family	95%
737NG sub-family	75%

Table V-3: Modularity efficiency of the Airbus A320 and Boeing 737 families.

For this metric, the A320 family displays a significantly higher modularity than the 737 family. This may be explained by the fact that Boeing acknowledges a very high degree of tailoring of its aircraft for each of its customers, whereas Airbus aims to reduce the logistic costs of the airline companies that buy its aircraft and thus pursues the opposite strategy (Interviews with Airbus and Boeing product development engineers). It is interesting to notice that the two modularity metrics related to the manufacturer do not measure the same aspect at all. One focuses on the number of potential interdependencies between the modules, and the other determines the actual number of interdependencies. The Airbus solution creates more constraints during the aircraft design phase, but simplifies its logistics during the manufacturing and assembly phases.

V.2.2 The Customers' Point of View

V.2.2.1 Standardization

For the customer, the degree of standardization is defined by the length of the CCQ (*cf.* sub-section IV.2.1). In this test, I have been comparing this training time between all types of aircraft currently produced by the two manufacturers and the A320 family or the 737 respectively. I have only excepted the A380 and the 747, which do not have any direct counterpart among their competitor's range. Table V-4 gives the length of the CCQ for the Airbus aircraft, and Table V-5 deals with the Boeing ones.

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Common type rating	A320 Family	A330 Family	A340 Family
A320 Family		8	8
A330 Family	8		
A340 Family	8		

Table V-4: Length of the CCQ between the Airbus A320 and other Airbus families (Airbus, 2007).

Common type rating	737-300 to -500	737-600 to -900	757/767 Family	777 Family
737-300 to -500		2	≥ 8	≥ 8
737-600 to -900	2		8	8
757/767 Family	≥ 8	8		
777 Family	≥ 8	8		

Table V-5: Length of the CCQ between the Boeing 737 and other Boeing families (Boeing, 2007).

The differences are remarkably minor, leaning in favor of Airbus if the 737 Classic sub-family is taken into account in the comparison. Both the A320 family and the 737NG sub-family have a common type rating for all aircraft belonging to the family or the sub-family, respectively. The 737NG sub-family appears to share the same degree of standardization with the other aircraft family currently produced by Boeing as the A320 family does with the corresponding aircraft family from Airbus. I have been unable to find the exact value of the CCQ between the 737-300/400/500 and the other Boeing aircraft family considered here. The value presented here corresponds to the CCQ between the 737NG models and the other models considered, to which has been added the training needed to make the transition between the analog-based and “glass” (i.e. digital) types of cockpit. Thus, a reasonable estimate for this value is between eight and ten days. We can notice once more the relative heterogeneity of the 737 family, and particularly the differences between the “Classic” and the “Next-Generation” sub-families. As a comparison, transitioning from the A340 family to the A330 family takes also two days.

The number of crew errors corresponds to the efficiency of standardization for the customer. This number is estimated through an analysis of all reported incidents or

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accidents that occurred in the world between year 2000 and 2005³. A comparison is made with the total number of incidents caused by commercial aircraft during that period. Incidents caused by weather, the intervention of controllers, other aircraft or any other exterior cause are not taken into account. Both categories are expressed as a percentage of the number of operated aircraft in their family. Figure V-8 presents the number of incidents that occurred during these years; Figure V-9 presents the number of incidents attributed to crew errors; Figure V-10 presents the ratio between the two).

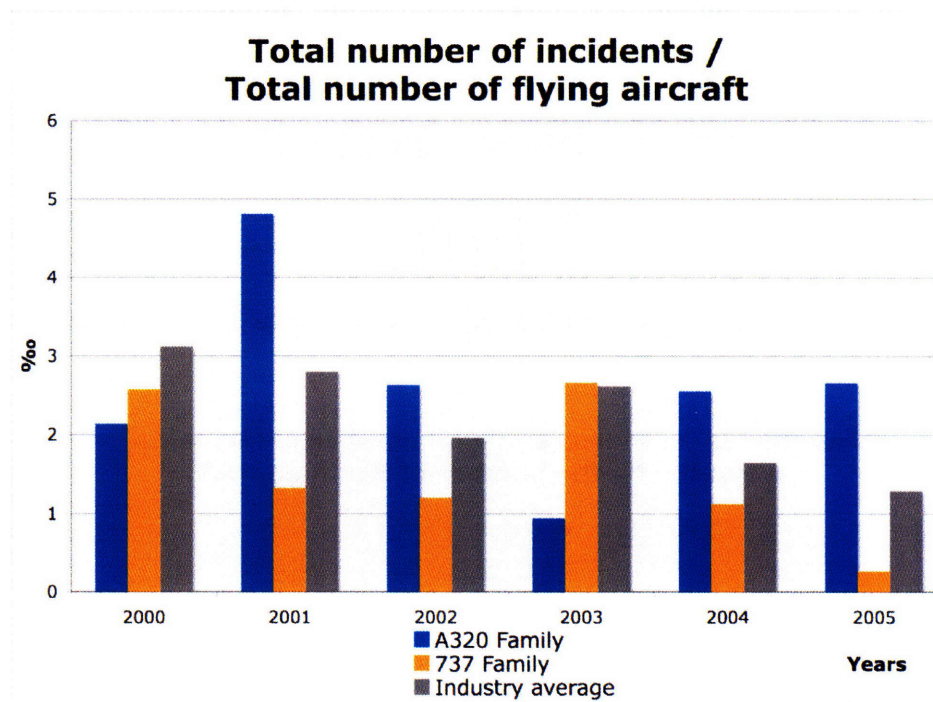


Figure V-8: Number of incidents for the Airbus A320 and Boeing 737 families⁴.

³ These dates have been chosen because they correspond to years where all incidents records in the World are publicly available.

⁴ Main source of data: <http://www.fss.aero/accident-reports/>.

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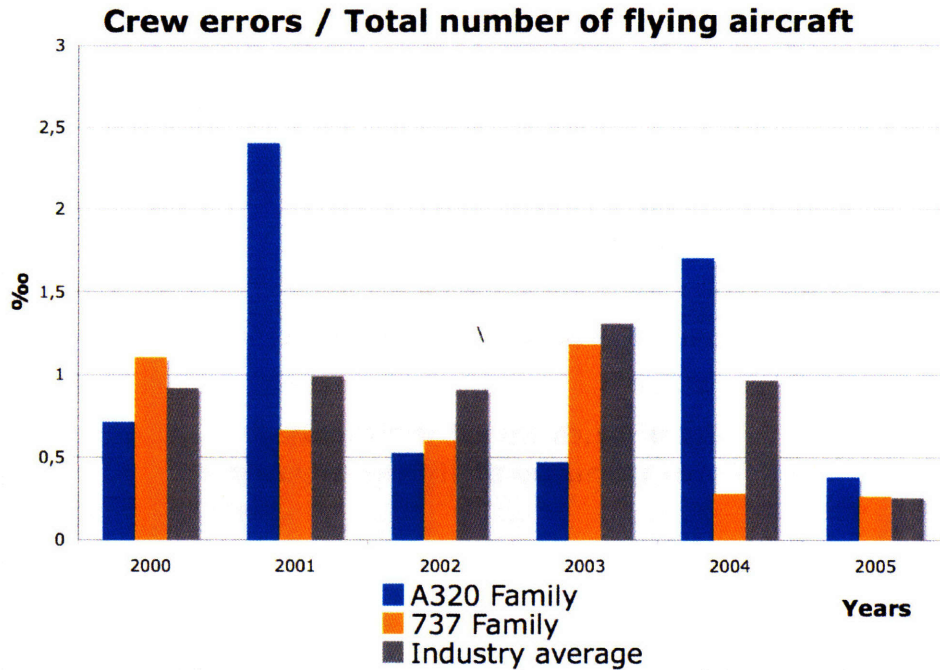


Figure V-9: Number of crew errors for the Airbus A320 and the Boeing 737 families.

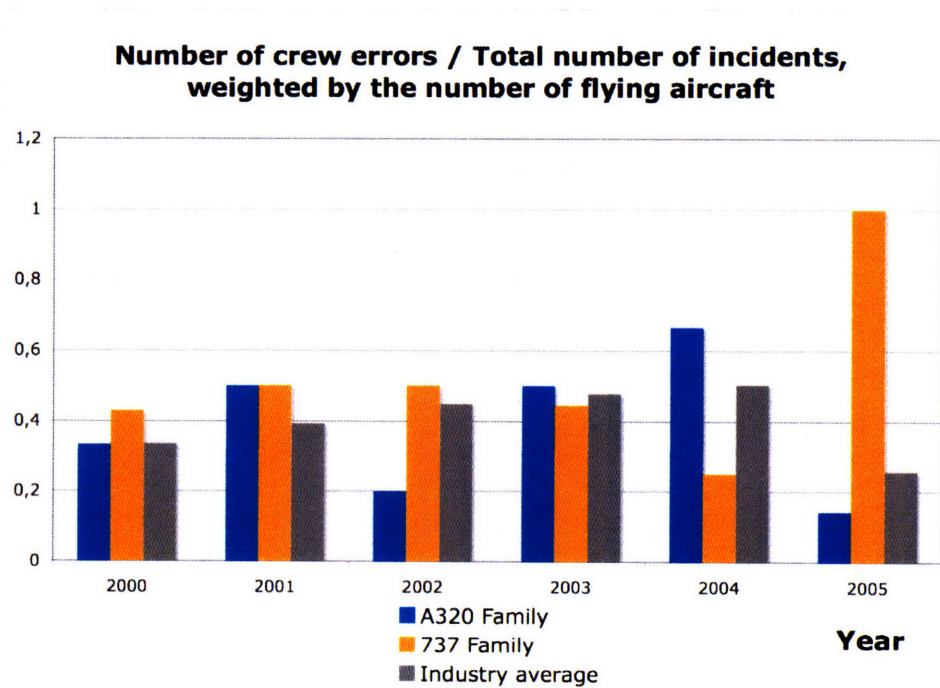


Figure IV-10: Ratio of crew errors over incidents for the two aircraft families.

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The total number of incidents is significantly higher in the Airbus case, but the proportion of crew errors over the total number of incidents is comparatively smaller (39% for Airbus, 52% for Boeing). This tends to confirm that the layout of the cockpit of the A320 aircraft derivatives is less complex than for the 737 family. Of course, several factors can also influence the number of incidents per year. For instance, creating a European-wide ground-based control rather than relying on the independent ground-based controls of each European country contributed to reducing the number of accidents per year in this region. Also, we may notice that the annual number of incidents per year almost seems to follow a Poisson law. Yet, when computing the ratio of crew errors over the total number of incidents over the last decade, we can see that the A320 family is clearly performing better than its direct competitors.

This, in turn, can be linked with the fact that Airbus has always striven to follow the same architecture for the cockpits of all aircraft it produces. Hence, it suggests a better standardization efficiency for the A320 family. The two limits to the validity of this study is the limited availability of data concerning aircraft incidents, and (perhaps more significant) the bias occurring from the fact that we deal here only with reported incidents. Thus, many near-miss or non-detected errors not occasioning injuries may not appear here, if the crew omits to report them. Unfortunately, I have no way to determine how many incidents are not reported. I can only make the assumption that the rate of unreported incidents should be the same for all types of aircraft, on average.

V.2.2.2 Reusability

For the reusability construct, I have only evaluated the metric measuring the degree of reusability Rd_a , as the one measuring the efficiency of reusability cannot be measured by focusing on cockpit and is thus beyond the scope of this study. Equation V-5 provides the formula of Rd_a :

$$Rd_a = 1 - \frac{\sum_{i=1}^l \left(\frac{St_i - 1}{n_i} \right)}{l} \quad (V-5)$$

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With l the number of aircraft models in the airline fleet, n_i the number of aircraft of model i and St_i the number of variants of the subsystem considered that are installed on the aircraft of model i .

For repeated customers, the homogeneity of the fleet will depend how much an aircraft model evolves over its lifecycle. Each upgrade of a given model decreases its overall reusability, as these upgrades always feature significant changes in key subsystems of the aircraft. In order to evaluate the homogeneity of the fleet based on the Boeing 737 and on the Airbus A320 models, I have selected two major airline companies: Air France and Continental Airlines. Each of them uses primarily (but not exclusively) one type of aircraft family for its short- and medium-haul flights. Air France almost exclusively relies on the A320 family, and is currently phasing out its remaining 737. Continental mainly uses 737 models, but also possesses a few remaining MD-80/90. The metric is measured for the entire aircraft: for each derivative, the number of versions used by the airline company is recorded, and weighted according to the number of aircraft that the airline company possesses for this type of derivative. Table V-6 gives the results obtained:

Aircraft family	Airline company	Reusability degree (Rd_a)
A320 family	Air France	91.5%
737NG sub-family	Continental Airlines	99.4%

Table V-6: Reusability degree of the Airbus A320 and Boeing 737 families.

Interestingly enough, the reusability metric measure yields different results for the customer than for the aircraft manufacturer. This is due to the fact that the only model of 737 that is present in several versions in the Continental fleet is the 737-800, whereas Airbus has periodically upgraded each of its models over the years. Thus, Airbus created more heterogeneity for the customers who bought the same model for a long period of time (among which is Air France). Continental bought most of its Boeing 737 in a short amount of time. As a consequence, there might be a bias due to the particular purchasing strategies of the two companies in this case. It would be interesting (and in fact necessary to verify the validity of this metric) to measure this degree of reusability for other airline companies.

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This way, we would have better chances to determine whether the comparison results obtained here accurately reflect the composition of Airbus and Boeing fleets in the world.

V.2.2.3 Modularity

In order to measure the degree of modularity for the customer (Md_a), I have again focused on the two airline companies mentioned above. Equation V-6 recalls the formula of the degree of modularity Md_a :

$$Md_a = \frac{Com_{Air}}{Tt_{Air}} \quad (V-6)$$

With Com_{Air} the number of aircraft of the airline company using interchangeable subsystems for accomplishing the same function, and Tt_{Air} the total number of aircraft of the airline company using the function in question.

I have determined which version of each cockpit instrument is used in each version of the aircraft of the two families. Then, using the current composition of the fleet of the two aircraft companies (as given by the Airfleets website⁵), I have evaluated the modularity of the main subsystems of the cockpit for two airline companies. The results are given in Table V-7:

Aircraft family	Airline company	Modularity degree (Md_a)
A320 family	Air France	94.2%
737NG sub-family	Continental Airlines	72.3%

Table V-7: Modularity degree of the Airbus A320 and Boeing 737 families.

As in the previous metric measurement, it is necessary to use some care before jumping to any conclusion, as these results might have been influenced by the airline companies' strategy. However, the trend seems firmly established in favor of Airbus. A closer analysis of the situation shows that the lower modularity in Continental's case mainly comes from the remaining 737-300 and 737-500 models still used by the airline. These aircraft do not feature fly-by-wire commands and differ significantly from the

⁵ <http://www.airfleets.net>.

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737NG models. Using only the 737NG models, the difference between the two airline companies would probably not be significant.

As the airline companies do not communicate on their logistic costs, it has unfortunately not been possible to measure the efficiency of modularity from the point of view of the customer. Still, maintenance professionals have repeatedly mentioned the factor of obsolescence as being one of the major problems of the airline companies in this respect. This is a factor where we would thus expect Airbus to perform better, since it still produces all the models of the A320 family, while Boeing has stopped producing the 737 Classic sub-family. Further information on this subject would greatly contribute to the validation of this set of metrics.

V.3 Comments

This analysis tends to confirm the opinions of the people interviewed concerning the advantages of each aircraft family on the market: the A320 family performs better concerning the metrics linked with pilot training (i.e. the standardization metrics) and with the logistic issue measured here (the modularity metric). As it has not been possible to measure the efficiency of modularity, it is not possible to compare the maintenance costs of the two aircraft. Interestingly, the reusability metric is in favor of the 737, a situation opposite to the evaluations of most airline professionals. Further research is needed in this area to determine whether this observation is airline dependent. Focusing on the instruments of the cockpit would also allow for more detailed results, which could help determine where the discrepancy comes from.

From the point of view of the manufacturer, the costs metrics (i.e. the standardization metrics and the reusability metric available) give a clear advantage to the A320 family, which may help understand its market share gains during the 1980s and the 1990s. The lack of data does not allow us to pursue this comparison on the manufacturing ground, where most aircraft professionals believe that Boeing has made more progresses than its competitor. Finally, the opposite results obtained through two modularity metrics stress the fact that both manufacturers have opted for different design approaches for their

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medium-haul aircraft families. It may also be noticed that these two metrics can be used to make an evaluation of the costs of maintenance for the customers, if we assume that the airline companies will buy a fleet composed of all derivatives of the family considered, in equal proportion. This assumption, of course, is wrong in almost all cases, and can only be accepted as a first order approximation. Yet, we may remark that most maintenance professionals interviewed agree to say that servicing the cockpit of the A320 derivatives is more complicated than doing the same task for the 737, as the A320 instruments are more clustered. This is remarkably aligned with the results obtained by the DSM analysis.

As a consequence, it is possible to conclude that the set of metrics analyzed here is so far a good predictor of the quality of commonality implementation in commercial aircraft cockpits. No metric has been found to contradict the consensus of the professionals interviewed, and these metrics seem relatively sensitive to the differences existing between the A320 family and the 737NG sub-family, which are relatively similar in many respects. Measuring this sensitivity more accurately would increase the confidence in the set of metrics. This could be achieved by comparing other similar aircraft families of the two manufacturers, such as the 787 for Boeing and the A350 for Airbus. Currently, the lack of precision of certain results unfortunately prevents us from characterizing the efficiency of the set of metrics with more accuracy. I expect that more interesting results will be obtained once this analysis includes the currently missing metrics and I advocate further research in this domain. Evaluating the additional metric linked with the aircraft technical performances is also needed in order to validate this set of metrics for the entire aircraft.

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VI. Detailed Analysis of Commonality Implementation

VI.1 On the Manufacturing Side

VI.1.1 Product-Development Phase

It is probably at the product-development level that the two aircraft manufacturers display the largest number of differences. As we will see, this can be explained by historical as well as strategic reasons. In a consistent manner, Airbus engineers refer to commonality as the overarching goal they strive to achieve. When developing a new aircraft, the first element Airbus stresses is the similarity of its cockpit with the cockpits of all other existing Airbus aircraft. Historically, two factors can be mentioned to explain this attitude. Airbus Industrie was formally created in 1970 as a consortium regrouping the French Sud Aviation and the German Deutsche Airbus (itself a German aerospace consortium formed of seven smaller companies). Its largest subcontractor was the British Hawker Siddeley (later merged into British Aerospace). At that time, a common design already existed in the commercial jet-engines aircraft industry. The Boeing 707 and the Sud Aviation Caravelle established the standards that are still followed nowadays. Hence, competing on production methods was deemed more efficient than focusing solely on aircraft design. Appendix 4 contains photographs of the cockpits of each model of aircraft whose product-development phase was investigated during my research.

In addition, the various companies that teamed to produce the first Airbus did not have the financial resources of the American manufacturers. They had the further disadvantage of having a decentralized design organization, each country participating (France, Germany and United Kingdom) being in charge of developing some specific part

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of the aircraft. None of the companies that formed the Airbus consortium had previously collaborated with the others for a project of this size. To complete the design of the first Airbus, the companies agreed to provide ready-to-fly sections. This naturally increased the modularity of the design. The success of the first Airbus (the A300B2) made them decide to pursue their collaboration. The consortium resolved to produce an entire range of aircraft. Due to the heavy investments they had to make for the first model, their goal was to minimize product-development costs in the future. Increasing commonality was seen as a way to quickly develop a range of aircraft that could compete with the American aircraft manufacturers in all segments of the market. The tremendous success of the A320 model and of its derivatives transformed this policy in a corporate objective.

By opposition, Boeing built its reputation during the Second World War as a military aircraft manufacturer, and always aimed to produce the highest-performing jets in the market. This culture of technical excellence has lasted during the entire history of the company. Initially, implementing commonality was not seen as a valuable goal for Boeing, since it could impede technical innovation in future models. The manufacturer switched side in the early 1980s, with the 757 and the 767, which were developed simultaneously and featured almost identical cockpits. In the 1990s, Boeing progressively standardized the models belonging to the same product family (cf. Figure VI-6). Starting with the 777 program, Boeing stated that one of its objectives was to attain a higher degree of commonality between its various aircraft families. However, increasing reusability was more difficult. As a Boeing engineer recognized, the cockpit of each new commercial aircraft family is developed as the new standard that will be the basis for all future models. Yet, by the time the next model is launched, technical innovations have rendered the previous layout obsolete, and the same process occurs again.

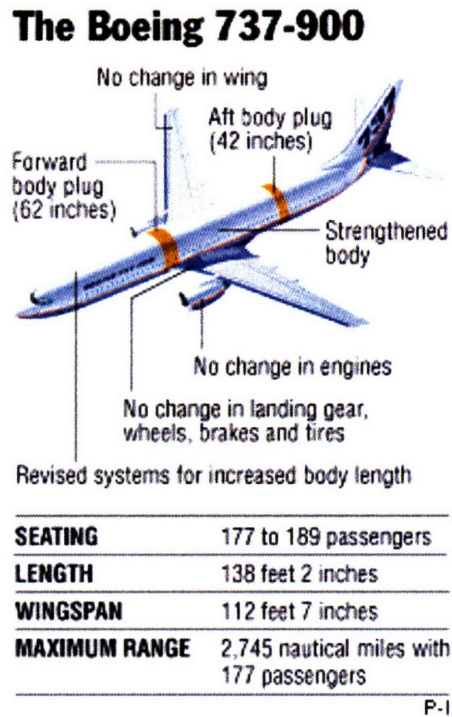


Figure VI-1: 737-900 changes, compared to the 737NG baseline¹.

Measuring precisely the current efficiency of the product-development phases of both manufacturers is difficult, as neither of them discloses much information in this respect. This is also the reason why it is not possible to determine the evolution of commonality implementation during the product-development phases since the A320 family and the 737NG sub-family. For further analysis on the product-development strategies of Airbus and Boeing, I refer the reader to the upcoming PhD Thesis of Theodore Piepenbrock (Engineering Systems Division, MIT). Fortunately, obtaining information concerning the manufacturing and assembly phases at Airbus and Boeing was easier. More precise comparisons are possible in the next sub-section of this analysis.

VI.1.2 Manufacturing and Assembly Phases

The manufacturing organization of Airbus and Boeing is also different. Yet, we can observe that the convergence is more important on this level. The former Airbus CEO,

¹ <http://www.boeing.com/commercial/>.

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Christian Streiff, stated that one of the objectives of Power8, the Airbus reorganization plan, was to move toward a role more oriented toward systems integration. He compared this strategic change with the comparable move that Boeing had undertaken for about fifteen years. Beyond the strategic orientations, what distinguishes most the Airbus production organization from the Boeing one is the history of the two companies. Being the inheritor of the aerospace companies of four different countries (including Spain, as CASA joined the Airbus consortium in 1971), the Airbus sites are spread throughout Europe. No overarching plan originated this dispersion. One of the best example is the company largest assembly line, situated in Toulouse. It was chosen as the assembly site of all Airbus long-haul and high-capacity aircraft, despite the fact that it cannot be reached through maritime transportation. This history also explains the important dispersion of the Airbus network, as plants are spread over four different countries.

Figure VI-2 presents a simplified representation of the production organization for the derivatives of the A320 model. The production organization of the A320 is slightly different, as the final assembly line for this aircraft is situated in Toulouse instead of Hamburg. The simplification lies in the fact that no attempt has been made to represent the hundreds of first-tier supplier that deliver parts for the aircraft derivatives. Only the Airbus plants involved in the production of the A320 derivatives are present on the graph. Most Centers of Excellence (CoE), which define the major competency areas, are split along the states' boundaries. France deals with the cockpit and the forward fuselage; Germany works on the fuselage and the cabin interiors; Spain specializes on horizontal tail manufacturing; and the United Kingdom has the responsibility of wing design and integration. Yet, other CoE are set up across boundaries, like the CoE Electricity, split between France, Germany and the United Kingdom.

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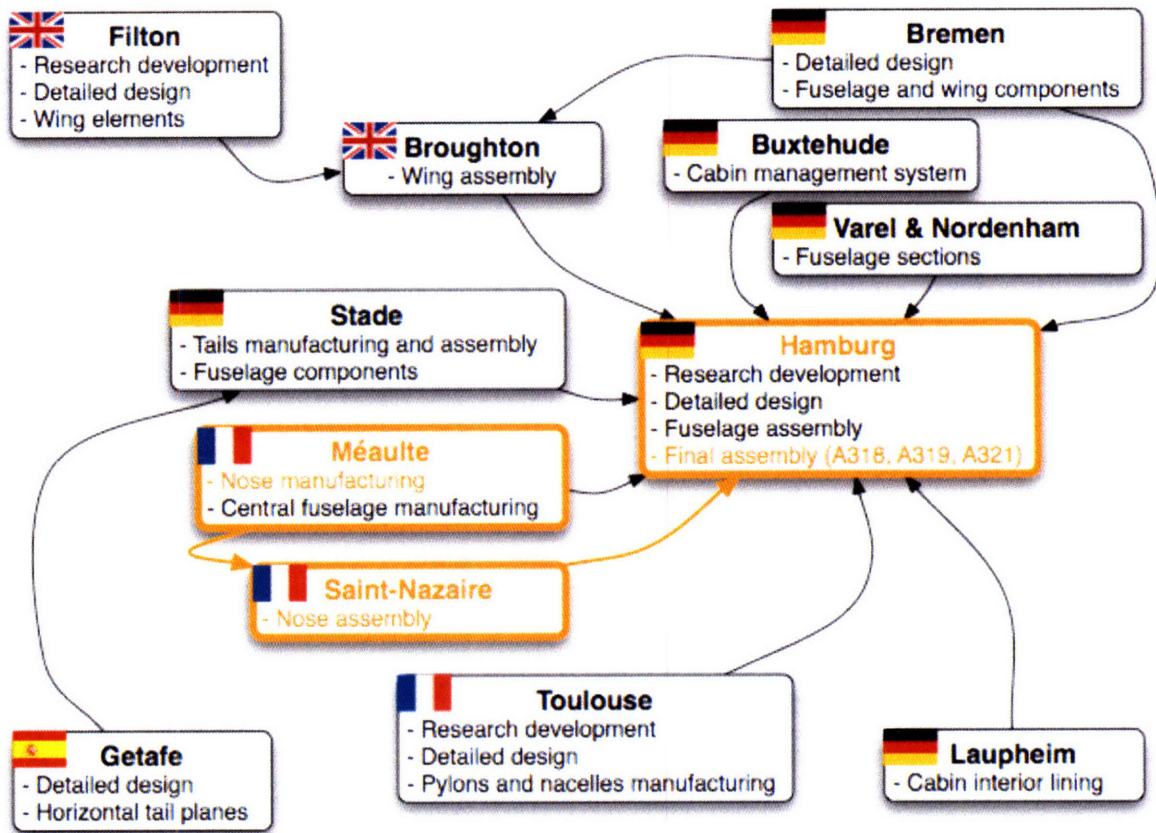


Figure VI-2: Manufacturing organization of the Airbus A318, A319 & A321.

Boeing had to integrate a heterogeneous set of plants and of products after it merged with McDonnell-Douglas. Yet it does not have the same issues as Airbus. During its early 1990s crisis, Boeing completely reorganized its production. It avoided dispersing the production of its aircraft, and only maintained production of the Douglas-originated aircraft in the former Douglas plants. Boeing only pursued research on its original in-house programs in order to rationalize its offer. As we can see in Figure VI-3, the Boeing production organization for the 737NG sub-family is consequently much simpler than the Airbus corresponding one. Far fewer plants are involved and there is only one final assembly line location. Similarly to the Airbus production organization chart, most subcontractors were not represented for this aircraft family, despite the fact that they are far less numerous than in the Airbus case. An exception was made for the Tulsa and

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Wichita plants. These plants were part of Boeing until 2004, when they were sold to Spirit Aerosystems. It is the most noticeable move of Boeing from aircraft manufacturing toward systems integration. It occurred at the same time as Boeing reorganized its suppliers and dramatically reduced the number of its first-tier suppliers.

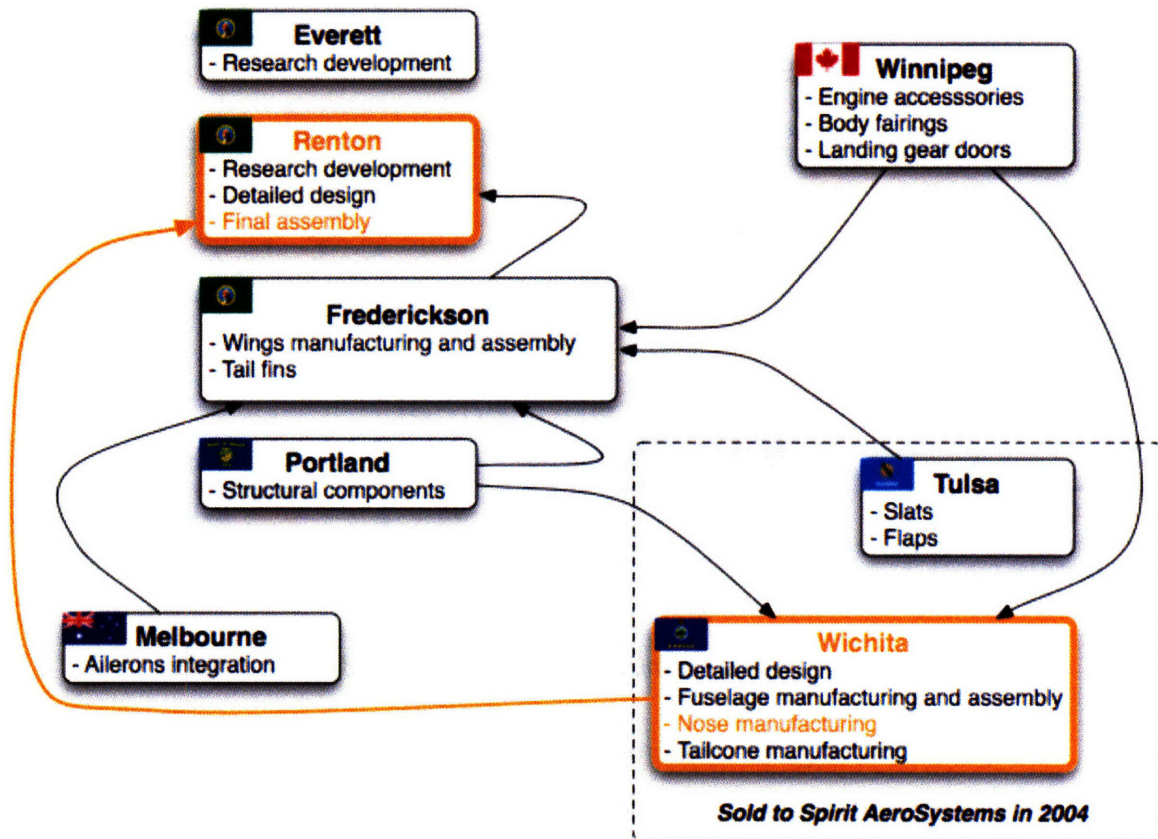


Figure VI-3: Manufacturing organization of the Boeing 737NG sub-family.

Even if comparing development and production costs across all Airbus and Boeing aircraft families is not possible, other aspects might provide elements of answer. Considering the entire aircraft, a measurement of the efficiency of the manufacturing network can be the number of first tier suppliers. The larger this number is, the more expensive are suppliers' management and transaction costs. Table VI-1 gives the approximate number of first-tier suppliers for the two aircraft manufacturers.

DETAILED ANALYSIS OF COMMONALITY IMPLEMENTATION

Company	Airbus	Boeing
Number of first-tier suppliers	3000	6450

Table VI-1: Number of first-tier suppliers for Airbus (Dougherty, 2006) and Boeing (Arkell, 2005).

Interestingly, these findings contradict the opinions of most professionals interviewed. Airbus is often found to have a large and flat base of suppliers. Indeed, the number of local small suppliers is very important at Airbus, and few suppliers are subcontracted complex assembly elements. For the cockpit manufacturing at Méaulte, only one supplier is considered as a subsystem integrator, against approximately 1000 suppliers of separate instruments, simple elements and raw materials. This perception explains why Airbus has planned to slash the number of its suppliers by a factor of six in its Power8 reorganization plan. On the other hand, Boeing is estimated as having already rationalized its supplier base during the 1990s. As the two manufacturers have delivered a comparable number of aircraft each year for almost a decade, there is no obvious reason for this discrepancy between the data presented here and the professionals' perception. It is possible that the two aircraft manufacturers do not determine their number of suppliers according to the same metrics. However, I have not been able to find data either supporting or rejecting this hypothesis.

A second element of the answer is the cost of transportation for the aircraft elements. As both manufacturers transport most of their aircraft sections by air, this cost can be approximated by the distance that aircraft elements have to cover between manufacturing and final assembly. Here, I will focus on the aircraft nose section, which includes the cockpit. Table VI-2 presents the distances covered by the nose sections of the different types of aircraft produced by the manufacturers. As in the preceding chapter, I except the Airbus A380 and the Boeing 747 from this analysis, since those two aircraft have no counterpart in the range of aircraft proposed by their competitor.

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Company	Airbus		Boeing	
Models	A318, A319 & A321	A320, A330/A340 families	737 family	767 & 777 families
Final assembly location	Hamburg	Toulouse	Renton	Everett
Distance covered (km)	1585	970	2320	2330

Table VI-2: Distance covered by nose sections between manufacturing and assembly.

A better approximation of the total transportation costs might have been obtained by weighting each nose model by the average number of aircraft of this type produced each month. These was not performed here, as the mix of aircraft type produced by each manufacturer is susceptible to change considerably from year to year. The results presented here seem to contradict again the common evaluation that Boeing's network is more aligned than Airbus's one. Yet, a closer analysis will show that they are not surprising. While the Airbus network is clearly more dispersed than Boeing's one, the network of plants producing the major sections of the Airbus airplanes is certainly more concentrated.

Boeing chose to concentrate on the aircraft integration as its core business (Bragg *et al.*, 1998). Hence, it subcontracted more and more sections of the aircraft to international risk-sharing partners. It divested itself of the manufacturing plants that were no longer critical for its strategy. As these were often the plants farthest away from the Washington State, it allowed Boeing to simplify its internal logistics at the same time. The drawback was an increased dependence on large external suppliers, whose locations were far from optimal from the Boeing's perspective. On the other hand, Airbus had always the objective to serve the European interests in aeronautics (de Melo, 2000; USA, 2006). It was originated to stop the dependence on foreign technology in what was perceived as a critical sector. Airbus avoided relying on suppliers for any parts of its airframe. It accepted a suboptimization of its network in order to maintain more strategic flexibility. Its current international strategy illustrates this difference with its competitor. While Boeing sought foreign partners to boost the sales of its aircraft in the corresponding

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countries, Airbus created new facilities in the countries it targeted. In Russia, it opened an engineering research center. In China, it is building a new assembly line for the A320 derivatives that will be sold for the Chinese market.

Going down to the level of the plant, it is possible to further investigate and compare the management of commonality by the two aircraft manufacturers. I will first analyze the production organization of the Airbus Méaulte factory (France). Méaulte is a legacy factory: it was first founded in 1922 by Henry Potez, one of the aeronautics pioneers in Europe. Méaulte currently produces the two first sections of all Airbus aircraft: Section 11 (the aircraft nose) and Section 12 (the passengers' access). It also manufactures other aircraft sections for some Airbus models, such as the forward barque, but I will not study their production in detail. Figure IV-4 below describes the physical layout of the Méaulte plant. The industrial facilities are regrouped in four main buildings, which correspond to the successive steps of the nose manufacturing process. The first building contains the machining, control and coating steps. Ingots are transformed into individual pieces during the machining step, which then go through control and coating. After a batch is ready, the pieces enter the second building, where they are riveted into sub-sections. Once riveted, the sub-sections are transported to the Erebus assembly hall (the most modern building of the plant). In this hall, the individual sections are assembled. Each section then goes to the painting shop, in a separate building. It is immediately shipped after the end of the painting step.

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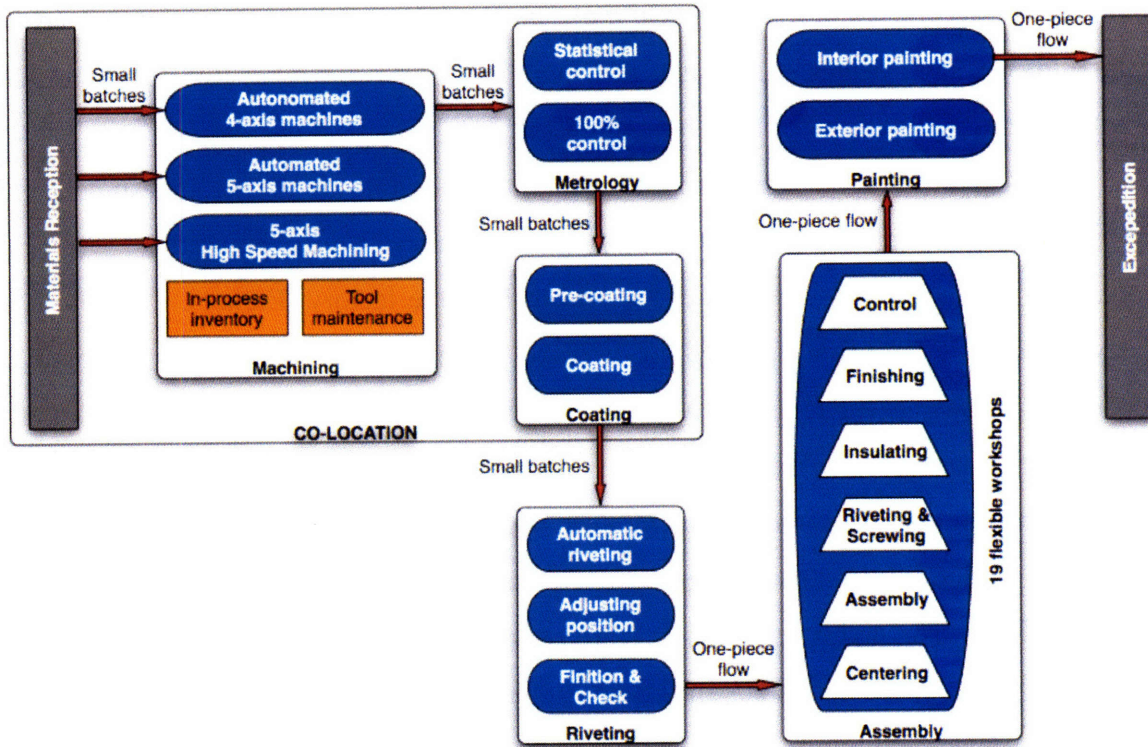


Figure VI-4: Physical layout of the Méaulte plant.

The first element we can notice is a relative lack of alignment of the production. During the three first steps, pieces and materials are moved by small batches (10-20 pieces), which represent between half a day and a day of production. Pre-process inventories are important: they are worth between a few days of production for the elements that are manufactured in the region around Méaulte to a couple of weeks of production when they are shipped from a country outside the European Union –like China. On the other hand, the second half of the Méaulte plant is much more aligned in this respect: after the riveting step, elements are moved on a one-piece flow. Almost no in-process or post-process inventory exists. It is also clear that production alignment is increasing. The Erebus assembly hall was precisely built to co-locate the entire assembly process in one building, and improving production flow is one of the key objectives of the plant management.

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But how does Airbus take advantage of the high level of commonality between its aircraft models? Analyzing Figure VI-5 provides some answers. In several cases, there seem to exist a gap between aircraft design strategy and production forecasting. In particular, the metrology and coating tools have been planned to accommodate all Airbus aircraft indiscriminately. New tools are explicitly selected to provide a higher flexibility than what is currently forecasted to be necessary. This strategy directly ties in the question of intrinsic and extrinsic reusability. The failure of being able to estimate what extrinsic reusability is needed forces tooling engineers to increase intrinsic reusability beyond what is strictly necessary. The riveting step follows the same pattern: most riveting machines are specialized on one type of aircraft size (A320 family, A330/340 families and A380 family). Setup times are particularly long (two hours), since each aircraft model has to be positioned with an absolute precision for automatic riveting. In order to increase flexibility, the latest investments consist in two automatic handling bridges (costing a few million Euros apiece) that can accommodate all types of aircraft.

The machining department exploits commonality to a higher degree. Machine tools are specialized by piece size, complexity and type of material used. The older 4-axes machines produce the all aluminum-based composite pieces smaller than 0.8 m x 0.8 m 0.8 m. 5-axes machines create the larger and more complex structural pieces, such as the cockpit glass frames. High-speed machining tools produce the large, flat elements that compose the skin of the aircraft. Machining programming takes advantage of the similarities between the various Airbus models designs. Yet, taking advantage of commonality is not necessarily a synonym of lean operations. Setups, maintenance, revisions and loading processes require a numerous and competent workforce (a 5-axes machine is operated by a team of five). This workforce specializes on one type of machine only. The defect rate is approximately one per day and per machine. I was not able to assess whether a plan for improving this rate existed.

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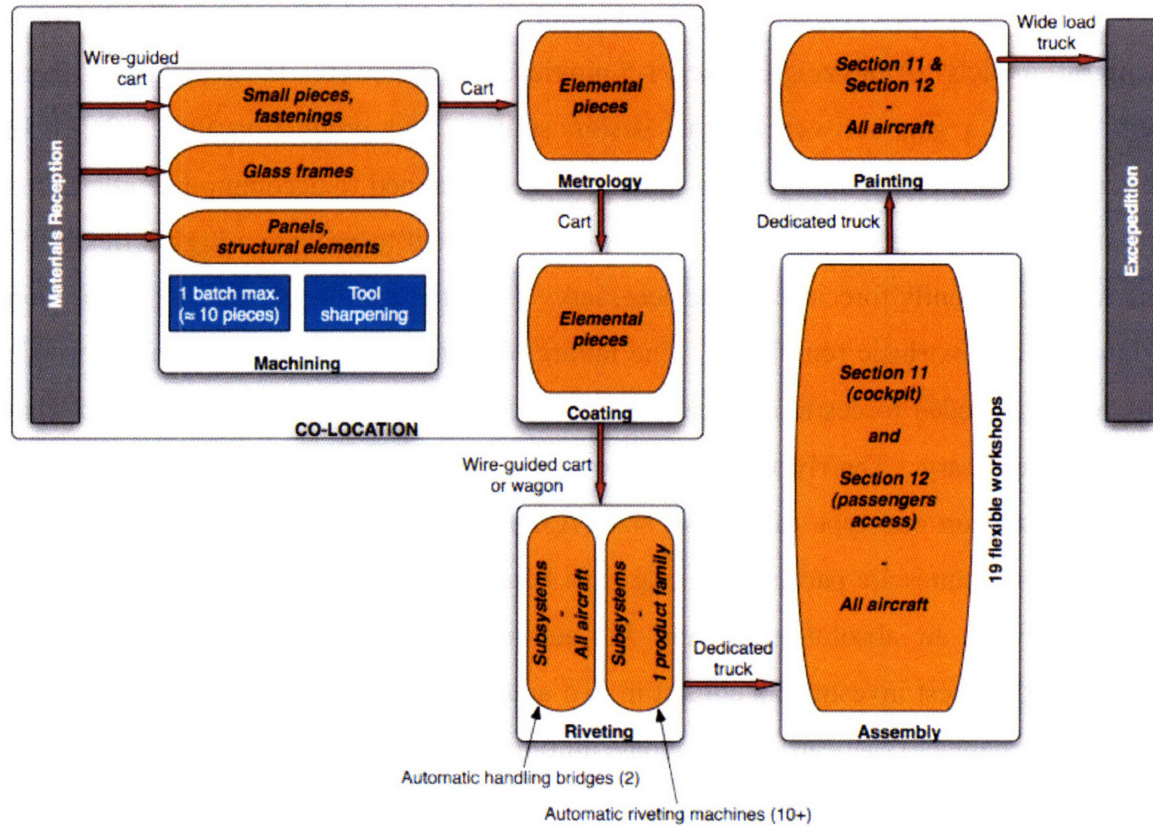


Figure VI-5: Work repartition inside the Méaulte plant.

One step deserves a particular attention: the section assembly. This step exploits commonality to a much higher degree than any other process at Méaulte. For section assembly, it is particularly critical that the different subsections be assembled with the low level possible of residual stresses. A low level of residual stresses will considerably increase the useful life of the structural parts of the cockpit. Hence, the most obvious solutions would be to specialize each machine on one aircraft model or to readjust the jigs for each new cockpit. Neither solution would be economically viable. The first one would require a huge investment or would constrain the mix of aircraft that can be produced, the second solution would require setup times of six hours or more. Instead, a two-levels system is used: each cockpit model is mounted on a specific jig, which has standard connections with the fixtures that maintain the cockpit vertical. Each jig is recognizable by its color, which is specific to the type of aircraft it accommodates. Figure VI-6 displays

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the cockpit of an A340 on its jig in the assembly hall. With this system, the production flexibility is total and the setup times have been reduced to a mere hour for most models. Even the models that are in a preproduction phase can be put in position within four hours.



Figure VI-6: Nose assembly of an Airbus A340 within the Erebus hall².

After the two forward sections of the aircraft are produced, they are shipped by air to Saint Nazaire. This facility produces the central parts of the fuselage and assembles them with the two forward sections. The fuselage assembly facilities follow a traditional design. A number of electric elements are first mounted in the cockpit. All fuselage sections are then brought to an assembly shop, where a gigantic jig sustains the central part of the fuselage. The process appears to be quite similar to what exists in the riveting department in Méaulte. Once these parts of the fuselage are assembled, the partially completed aircraft is shipped (by air again) to Hamburg or Toulouse. Both assembly lines follow the same principles and remain traditional in their design. The aircraft is placed in a

² Airbus (2007): <http://www.airbus.com/en/>.

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jig, and receives its tail, wings and landing gear. Figure VI-7 displays an A320 assembly shop in Toulouse. Once the assembly finished, it is moved to the painting shop.



Figure VI-7: Assembly line of the Airbus A320 at Toulouse³.

Despite the fact that I was not able to visit the Boeing Renton factory, a comparison is possible with the methods employed at Airbus. The most famous feature of the Renton factory is certainly its moving assembly line, which slowly translates the 737 across the colossal assembly hall. Each assembly step is precisely defined and has to be completed before the aircraft reaches the next area, delimited by floor paintings. The steps are performed in the same order as for the Airbus assembly line, but instead of bring the various assembly tools to the aircraft, the aircraft moves from one to the other. Instead of using automated bridges, dedicated vehicles are used, the “crawlers”. These vehicles allow heavier charges and can adapt to the different sizes of aircraft built. The painting shop is directly at the end of the line, and not in a separate building. Figure VI-8 shows the Renton moving assembly line. As for Airbus, each size of aircraft has its own dedicated final assembly line, with almost no in-process inventory. However, contrary to the European manufacturer, Boeing policy is to increase production not by opening new assembly lines (such as the one built in Hamburg for the A320) but by reducing the cycle

³ Airbus (2007): <http://www.airbus.com/en/>.

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time. In the reusability domain, moving assembly lines require huge investments, compared to the more traditional workshop. However, it is too early to determine if this new philosophy will be reused for the jets that will succeed to the 737 and to the 777.



Figure VI-8: Moving assembly line of the Boeing 737NG sub-family at Renton⁴.

VI.1.3 *Managing Commonality Toward the Customers*

While the two manufacturers have very different research-development and production philosophies, there has been an increasing alignment between them concerning commonality management toward the customer. Airbus was first to point out benefits for the airline companies in terms of training, maintenance and logistics costs. Boeing followed the same path after the creation of the 777 and explicitly listed commonality as a selling argument for the 787. However, Boeing put a stress even more important on technology improvements, on weight savings and on environment friendliness. It consistently compared its new aircraft with the current Airbus ones on this ground. After the initial lack of success of the A350, Airbus put more stress on the technical

⁴ Boeing (2007): <http://www.boeing.com/commercial/>.

performances of its aircraft and on the level of comfort it would provide to the passengers. Thus, commonality ceased to be a competitive advantage to become one of the commoditized features of commercial aircraft. The surest proof of this evolution is that the two outsiders, Bombardier and Embraer, also embraced this selling argument. Embraer in particular stated how it grew its range of aircraft by producing larger and larger derivatives for its E-Jet family.

VI.2 On the Customers' Side

VI.2.1 Purchase Decisions

Airline companies base their purchase decision on two factors: the destinations they serve and the cost of ownership of the aircraft they buy. Of those two, the first one can be considered as given, dependent on the global strategy pursued by the companies. The second factor can be further divided into two aspects: the technical performance of the aircraft and the operational costs. Establishing the trade-offs between these two factors is what distinguishes most aircraft companies. Investigating further on the operational factors, I have been able to identify a set of common factors that are considered as determinant in the purchase decision by all companies I have investigated:

- Aircraft fuel consumption
- Length of pilots' training
- Number of on-hold pilots needed
- Flexibility of fleet reassignment
- Repair pieces availability
- Logistics costs

It is noteworthy that among these six factors, five are directly linked with commonality, although fuel consumption remains the single most important factor. When considering the length of pilots training at Air France, we can notice that the aircraft specific training represents almost 12% of the initial training length (*cf.* Figure VI-9). A pilot instructor evaluated the total costs of pilot training at about 100,000€. A cross

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qualification from one manufacturer to the other takes approximately five times as much as a cross qualification from a medium-haul to a long-haul aircraft from the same manufacturer. Hence, Air France decided to simplify its fleet by retiring its 737s and keeping only A320 airplanes for its medium-haul flights. The company decided to keep a mixed fleet for the long-haul aircraft, as both the 777 and the A330/340 families had their own advantages. The A330/340s share a high commonality with the A320 family; the 777s hold a similar advantage with regard to the 747s.

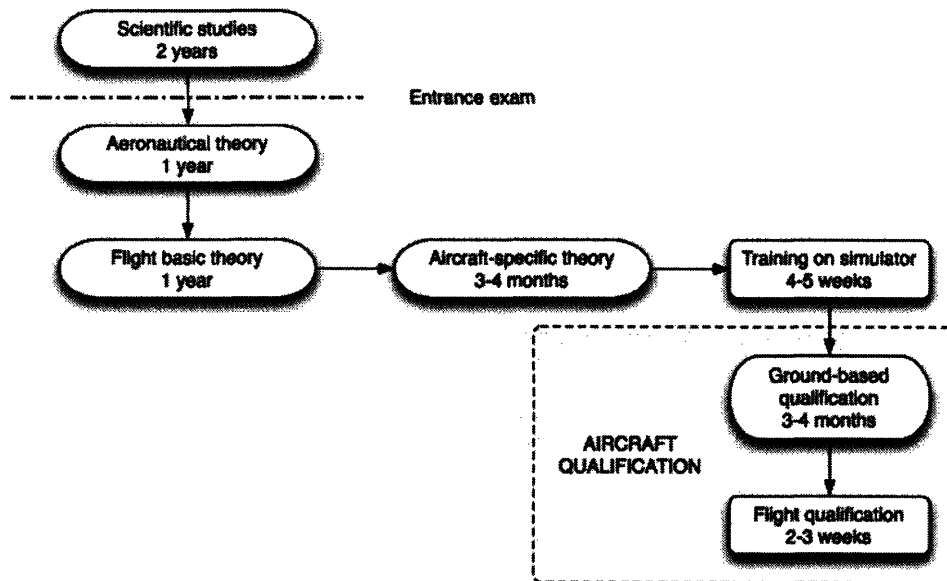


Figure VI-9: Organization of the pilots' initial training at Air France.

The number of on-hold pilots is also a critical factor for the airline companies. On-hold pilots are charged to replace the crew that are scheduled but cannot pilot a flight due to a delay or a sudden illness. Typically, these pilots are on hold only in the major hubs of the airline company. For each type of aircraft, several on-hold crews are needed. As these pilots are rarely needed, increasing the number of aircraft that one of these pilots can fly is valuable. Air France can again be taken as an example: Table VI-3 shows the numbers of on-hold pilots at the airport Roissy – Charles de Gaulle compared to the number of aircraft operated from this hub. This table lacks data for the A330/340 families, for which I was not able to obtain the number of on-hold pilots required.

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Type of aircraft	A320 family	777 family
Number of aircraft	142	42
Number of on-hold pilots	4	2

Table VI-3: Number of on-hold pilots and number of aircraft operated at Air France.

This data shows that the more one type of aircraft is operated from a hub, the less on-hold pilots are required per aircraft. In fact Air France recently decided that instead of keeping on-hold pilots for the 777 and the A330/A340 families, the company would simply keep one A340 on hold and dispatch it whenever an aircraft from these family would not be able to depart because a pilot was missing.

The flexibility of fleet assignment is a third factor influencing aircraft purchase decisions. A company is not able to have on-hold pilots waiting in all the destinations it serves. If an aircraft is blocked in one of these destinations, it is particularly important for the airline company to ensure that the passengers are able to get to their destination (the hub) as soon as possible. Whenever a second flight to the same destination is supposed to occur the same day, the easiest solution is to replace it by a larger aircraft. This aircraft will then be able to fly back not only the passengers it was supposed to take but also the passengers of the previous flight scheduled. Figure VI-10 displays the destinations served by Air France-KLM in North America. Among the twenty destinations the two companies serve, fifteen are served by two flights a day or more. Out of a total of 64.5 daily flights, 44.5 are in a position to benefit from such a replacement, assuming that the last flight of the day can never benefit from this system. But this replacement can only occur if the pilots that were supposed to fly the next flight are qualified on a larger aircraft and if this aircraft is available. This explains why airline companies tend to homogenize their fleet according to the destinations served (station purity).

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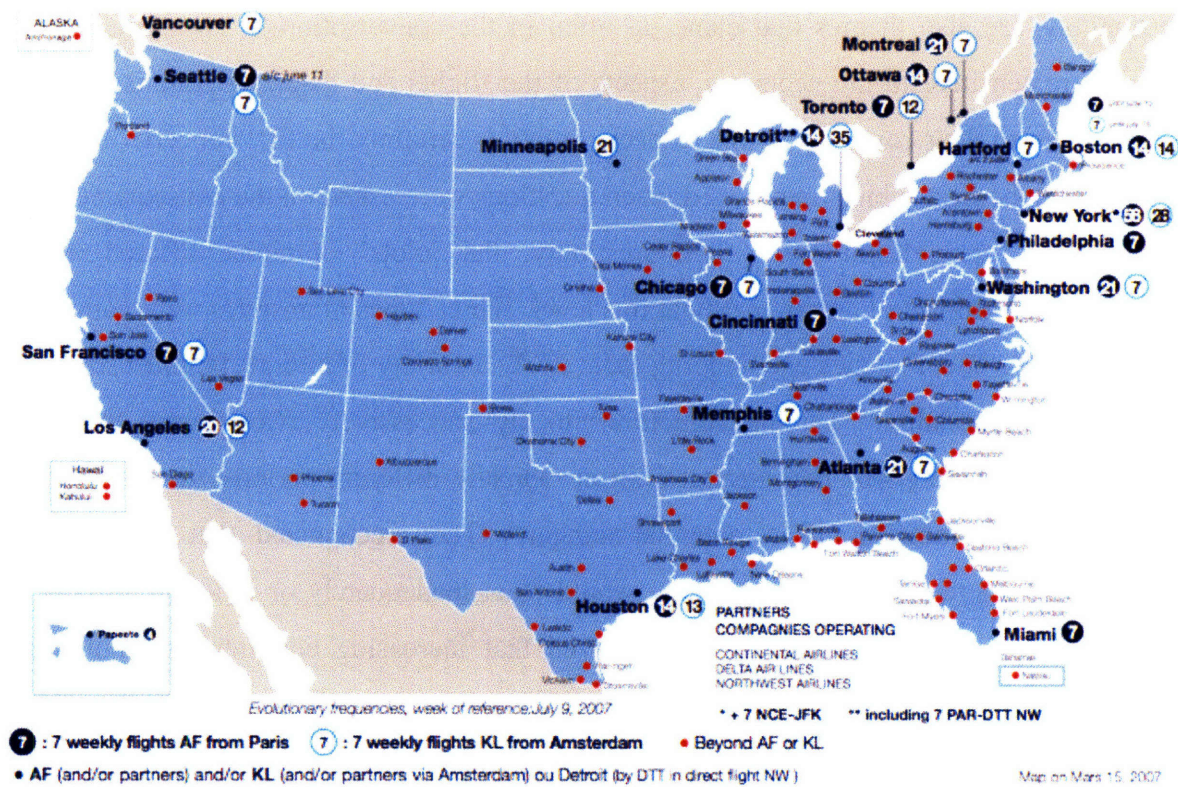


Figure VI-10: North-American destinations of Air France-KLM⁵.

The availability of repair pieces and the logistics costs are the two last factors that the airline companies recognize as determining their purchase decision. Yet, these do not seem to play as great a role as the preceding ones. From the interviews I conducted (cf. Appendix 1), I retained the impression that mainstream airline companies such as Air France did not find many differences between the two manufacturers at this level. In order to improve this metric, they mainly relied on their airline networks and practiced risk pooling.

VI.2.2 Perception of Commonality

Among airline pilots, the perception of commonality can vary a lot. Still, some concerns seem to be shared by the majority of the profession. Safety and pilot fatigue are two key issues mentioned by all pilots I interviewed. The comfort and the choice of

⁵ Air France (2007): <http://www.airfrance.com/>.

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destinations are also themes that came up often in the conversations. The captains are often more sensitive to the economic aspects of the flights and display opinions that are often similar to their company in this respect. Safety is certainly the first concern of pilots. It was often the first subject mentioned when questions were asked on the consequences of commonality upon flight safety. Interestingly, the pilots' opinions differed a lot concerning the impact of commonality at this level. Three types of answers were gathered. Pilots working in companies encouraging them to fly a variety of aircraft families strongly approved commonality. Having sometimes to fly successively two aircraft built by different manufacturers or two aircraft built at radically different periods, they perceived the lack of commonality as a potential danger. They recognized that the lack of commonality increased the risk that they would react inadequately or failed to register a signal during a time of stress. They believed that increasing commonality, not only between models built by the same manufacturer but also between the models developed by several manufacturers, would yield positive results for them. These pilots often worked for low-costs companies, which have on average a heavier workload for pilots than the mainstream airline companies.

A second category of pilots, belonging to mainstream airline companies, tends to reject commonality. They believe that increasing commonality, by creating common certifications, will force them to work on more types of aircraft. They argue that a too high commonality in the cockpit can create confusion for the pilot, who might react as if he were in a different type of aircraft. One of the pilots I interviewed mentioned the example of the A330 and of the A340 families: while the cockpit is almost identical between the two families, their performance limitations are very different. Being a four-engines aircraft, the A340 is limited by its maximum lift. On the contrary, the A330, which has almost the same size as the A340, is limited by the maximum drag of its two engines. Finally, a third category of pilots agrees with this analysis, but keeps a positive judgment on commonality. According to them, these risks force the pilots to be more attentive during the flight and to remain more flexible throughout their career. Hence, they believe

that pilots having to fly on several types of airplanes would react faster and with more precision in time of danger.

The implications of commonality upon comfort are another domain where pilots do not agree. The second category of pilots mentioned earlier argues that an increased commonality increases the stress of the pilots, and adds to the workload they have during the flight. The third category, by opposition, reports that flying on more aircraft types increases the challenges of flying and reduces the monotony of what would otherwise be boring flights. It is particularly noticeable that pilots belonging to the second category tend to have less experience on average than pilots of the third category. Similarly, pilots of the second category fly mostly on medium-haul aircraft, where the number of maneuvers per unit of time is much higher than for long-haul flights. Unfortunately, the sample of pilots I interviewed is too small and is not completely representative of the pilots' population. A statistical analysis of these observed tendencies is not possible. Further work in this domain would clearly be useful for a better understanding of the pilots' needs. The benefits of commonality concerning destination flexibility were mainly reported by pilots flying on long-haul aircraft, but no pilot denied it. Long-haul pilots mentioned that the same type of aircraft often served the same destinations, and that they appreciated being able to fly different aircraft to fly to different places. In particular, they reported that long-haul flights were often particularly tiring and uninteresting for the pilots, which explained why they wanted to be able to fly shorter flights from time to time.

VI.3 Best practices?

It is interesting to notice that the differences between the two aircraft manufacturers might lie on a different ground than what is often thought to be the case. The philosophies that have led to the adoption of the commonality concept are completely divergent. This translates into very different product development strategies, even if some convergence has recently been observed. More significant is the fact that the manufacturing techniques are much more similar than what the professionals of the two companies believe. When we look at the details of commonality implementation, the

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A320 family seems to benefit from a more efficient implementation of commonality, at the manufacturer level. Yet, the benefits the two aircraft provided to airline companies were comparable. Commonality only cannot fully explain the rise of the A320 family nor the later success of the 737NG sub-family. As we will see in the next chapter, other parameters also have to be taken into account.

From the point of view of the customer, it seems that the rules determining fleet replacement and expansion do not really integrate the commonality concept. While many parameters are influenced by commonality, this criterion is not considered in all of its dimensions. It is unclear whether this leads to a suboptimization of the airline fleets or not, but a closer study of this concept could only benefit the airline companies. There seems also to exist a gap between the primary users of the aircraft (the pilots) and the airline purchase department. The only concern common to the two groups is flight safety. And even for this issue, the influence of commonality is not perfectly understood. Implementing visual marks in the cockpit is a solution that was mentioned by some pilots to prevent confusion resulting from a high level of commonality. Yet, there does not seem to exist any evaluation of this idea at the level of an airline.

Commonality has been progressively implemented because of the immediate financial benefits it provides to the aircraft companies. As it had also a positive influence on the airline training and logistics costs, it rapidly encountered a wide success. However, no company seems to fully understand this concept today. Without any benchmark, optimizing commonality seems difficult for most companies.

VII. Study Limitations

VII.1 Data Availability

VII.1.1 Testing the Metrics

Lack of data validated by the manufacturers decreased the precision of some metrics tests in Part V, compared to what could have been achieved otherwise. Among the six metrics, two are based on economics parameters (standardization metrics), two on product characteristics (modularity metrics) and two again on process methods and organization (reusability metrics). As the aircraft manufacturers do not communicate on either their production costs or their process organization, both the standardization and the reusability metrics have been measured using publicly available data. For the two reusability metrics, these estimates have been supplemented by information obtained from interviews and personal knowledge. Similarly, the absence of data concerning the logistic costs of maintenance for airline companies prevented me from determining the efficiency of modularity metric.

When the data presented here is based on estimates, it should be used with care. As often as possible, such data has been extracted from sources listing their estimates for the two product families used to test the metrics in Part V. Thus, any systematic error would not bias the comparison. This is one of the reasons why non-dimensional comparisons have been performed for some metrics. As many sources as possible have been used in order to crosscheck the results and remove random errors as much as possible. Some sources have been excluded when their estimates blatantly contradicted all other sources available. As many official and professional articles do not systematically mention their sources, it is of course possible that several sources I used were taken from

the same original estimates, thus giving this estimate more weight than it deserves. At this point, it does not seem possible to prevent this from occurring.

The heterogeneity of the metrics presented in this thesis is partly due to the fact that an economic evaluation of some phenomena was not available. Thus, it was not possible to directly compare some metrics and elaborate a higher-level measurement method subsuming the metrics used here. For instance, both the CCQ length and the number of crew errors describe the quality of standardization for airline companies. The two metrics have important consequences on airlines' operational costs. Thus, a composite metric might have been sufficient for measuring standardization. As I was not able to access the data that would have allowed me to weight the two phenomena, I had to keep them separate in my set of metrics. Yet, this heterogeneity has an advantage: it allows for more flexibility, and make this set of metrics directly applicable for any airline company or aircraft manufacturer, even if they have different costs structures than the ones of the companies I studied.

VII.1.2 Evaluating Commonality Implementation

Similar lapses exist in the data collected for evaluating the current practices linked with commonality implementation during the product development phase of commercial aircraft. The main limitation of this study is probably the limited first-hand data I was able to gather concerning the product-development phase of commercial aircraft. My interviews with engineers charged with studying new aircraft designs were too few to make a comprehensive analysis of this phase. In most cases, my interlocutors were not at liberty of communicating dimensional data, and this considerably increased the complexity of my comparative study. Similarly, my access to data related to the aircraft manufacturing and assembly phases was sometimes limited. I was only able to visit one Airbus plant, and I did not have the occasion of visiting an equivalent Boeing plant. This explains why I was able to gather more precise data in the Airbus case than in the Boeing one. Thus, most of the data concerning manufacturing at Boeing was obtained from

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interviews and from published papers. Observing Boeing's manufacturing activities from a distance may have created a bias I am not aware of.

Concerning the customers, schedule constraints forced me to concentrate my study on a small number of large companies in the United States, in France and in the Netherlands. Thus, some bias may exist concerning my discussion of the airline companies' concerns and operational methods. Expanding these results to regional companies should be performed with particular care, as the operational factors may be very different. Regional airline companies are centered on one or several hubs, and do not have the logistic problems of the larger companies. The airplanes they use often come from different manufacturers than those that are operated by the companies I concentrated on, and belong to a different size class.

VII.2 Conceptual Limits of Commonality

Despite its usefulness, the commonality concept possesses some limitations that have to be understood before trying to optimize its implementation in commercial aerospace. The main limitations are that commonality does not properly take into account market positioning and technical performances. The first one concerns both the interrelations between aircraft manufacturers and the design for variety question. Technical performance deals with the trade-offs between product and process efficiency.

VII.2.1 Market Positioning

One of the main concerns of aircraft manufacturers is to maximize the range of products offered while minimizing the number of variants needed accomplish this goal. Developing a new aircraft is a long and expensive process: for a new aircraft family such as the 787, four to five years are expected to occur between the official program launch and the first delivery (USA, 2006). This is why the aircraft manufacturers usually endeavor to develop one aircraft family at a time (with some overlap possible, as when Boeing worked simultaneously on the 737 Classic sub-family and on the 747-400, the latest derivative of the 747 family).

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As a consequence, the aircraft manufacturers have to assign priorities on their development programs. Their new programs have to take care of the existing offer they already propose in order to provide replacement for the oldest (or least selling) aircraft families and to avoid cannibalizing the market of a successful aircraft family. Thus, rather than perfectly mapping the global market, the aircraft manufacturers may desire to maintain some overlap between several aircraft families. For instance, when Airbus was still producing its A300/A310 family, these aircraft had similar range and seating capacity as the smaller derivatives of the A330 family. This was due to the fact that Airbus had decided to discontinue the A300/A310 family, because its commonality level with the other Airbus aircraft family was found to be lower than optimal. The manufacturer's metric measuring the efficiency of standardization does not take such a strategy into account. Therefore, when comparing the total development and production costs of two ranges of airplanes, one must be aware that other factors might require to be taken into account.

Another factor should also be considered in this respect. Commercial aviation being in essence an oligopolistic market, each manufacturer's action has necessarily a great impact on its direct competitors. The success of an aircraft model does not only depend on how it is situated with respect to the other models of its manufacturer, but also on how well competitors' models perform. For instance, the lack of success of the Lockheed L-1011 TriStar has mainly been attributed to the fact that its biggest competitor, the McDonnell Douglas DC-10 had been achieved almost one year before (Collopy, 2004). Superior technical performances and a higher safety track record were not sufficient to compensate for the advance of its rival. Thus, aircraft manufacturers may be conducted to reduce the development time of an aircraft, making it less efficient than it could have been, in order to bar the way to a competitor. Or they could choose not to optimize the distribution array of aircraft they produce in order to dispute a critical market to a competing aircraft manufacturer. Such behaviors cannot be measured by the commonality metrics I have defined. Yet, they need to be taken into account to reach a correct understanding of the aircraft manufacturers' strategy.

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VII.2.2 Technical Performances

One of the untested metrics, the efficiency of reusability, measures the aircraft fuel efficiency. Yet, this set of metrics does not aim to capture the technical performances of the aircraft considered. It does not compare the value of technical performances and of process efficiency. Several reasons explain this fact. Certain technical performance measures, such as seating capacity and range, define the category to which the aircraft belong. The value of some other technical performances will vary according to the category of the aircraft. For instance, this will be the case for the maximum payload and for the maximum cruise speed. Finally, aircraft manufacturers and airline companies have divergent opinions on this subject. As a consequence, providing an unbiased basis for comparing the two performance aspects would be difficult and in any case beyond the scope of this study.

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VIII. Conclusion

VIII.1 Research Summary

Since the emergence of Airbus, implementing the right commonality into commercial aircraft has been perceived as an important competitive advantage. Hence, evaluating the quality of commonality implementation is of the utmost importance for ensuring the success of an aircraft. In this thesis, I have consistently studied the various aspects of commonality in commercial aerospace. Both from the literature and from direct observation, I have been able to identify three constructs that entirely map the conceptual domain of commonality. These constructs are standardization, reusability and modularity. They can be defined as follows:

- Standardization characterizes the common aspects of a subsystem accomplishing identical or analogous functions across a range of products.
- Reusability characterizes the common aspects of a subsystem accomplishing identical or analogous functions across a series of products fulfilling the same needs and developed in a successive manner.
- Modularity characterizes the degree to which a subsystem can be maintained, replaced and modified without altering its surrounding environment.

These three constructs can be considered from a design point of view or from a functional point of view. The first will correspond to the characteristics that directly concern the manufacturer, and the second to the characteristics that are of importance for the final customer, in this case the airline companies.

This research has identified a set of metrics measuring the efficiency of commonality implementation. For each commonality construct and each point of view on commonality, two types of metrics have been defined. One metric measures the degree to

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which the corresponding aspect of commonality is implemented; the other measures the efficiency of this implementation. When it has not been possible to identify the best metric in an indisputable manner, several metrics are presented for the same type of metric. This set of metrics is summarized in Table VIII-1.

Constructs	Manufacturer Metrics	Customer Metrics
Standardization	Degree of Standardization: Sd_m	Degree of Standardization: Length of CCQ
	Total Development and Production Costs: $TPCD(l)$	Standardization Efficiency: Number of crew errors
Modularity	Degree of Modularity: DSM, MFD, function structure heuristics	Degree of Modularity: Md_a
	Modularity Efficiency: Me_m	Estimated Total Relevant Costs: $ETRC(s,Q)$
Reusability	Degree of Reusability: Rd_m	Degree of Reusability: Rd_a
	Reusability Efficiency: $R(t,F,K(t))$	Reusability Efficiency: Re_a

Table VIII-1: Metrics summary.

This set of metrics has been tested in a case study. I analyzed the quality of commonality implementation in the cockpit of two competing aircraft families: the Airbus A320 and the Boeing 737 families. When comparing flying aircraft, the Boeing 737 family was studied as whole. When comparing currently manufactured aircraft, the study focused on the 737NG sub-family. Due to lack of available data, I have not been able to accurately test two metrics, which are displayed in blue in Table VIII-1. Additionally, one metric only applies to the entire aircraft and could not be measured through the case study performed. This metric is displayed in orange in Table VIII-1. The results of the case study confirm the efficacy of the metrics that have been tested. In some cases, uncertainty might remain, especially when precise data was not made available by the manufacturers

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or by the airline companies. In such cases, expanding and reiterating the validation process could be useful to attain a higher precision.

I have performed a larger investigation to assess the current practices of the commercial aircraft industry with regard to commonality measurement and implementation consistency. This part of the research mainly focused on Airbus, Boeing and a selected number of their customers. This study showed that the two manufacturers have a very different approach of commonality, especially in terms of product development. Aircraft manufacturing and assembly techniques of the two manufacturers diverged more because of historical reasons than because of opposed conceptions in that respect. These techniques have displayed recent signs of convergence. Both companies seem to orient themselves toward a role closer to system integrator than to end-to-end manufacturer. This move was initiated by Boeing in the 1990s and the current Airbus reorganization plan follows the same principles. Airline companies have not yet integrated the commonality concept as a whole, even if many of the parameters they use to select their new aircraft are heavily influenced by commonality. The pilots' expectations in that domain do not seem to be efficiently communicated to the airlines' management. This can lead to a situation where safety problems are addressed only after the fact. Overall, there seems to be no company that could be used as a benchmark for commonality application.

VIII.2 Research Applicability

This research is closely related to the central preoccupation of the aerospace industry stakeholders, in the United States as well as in the world. Optimizing value creation at the company level implies a multi-program optimization for most large aerospace companies. This requires an efficient transfer of knowledge both horizontally and vertically across the enterprise. Commonality is the name of the new language required in product development, manufacturing and maintenance. But to use it efficiently, having unbiased, company-wide metrics is mandatory. This thesis proposes such a set of metrics, and distinguishes between the perception of commonality by the aircraft manufacturers and by the airline companies. By documenting that no benchmark

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company exists in this area, the present research stresses the need for adopting new paradigms in this area.

This thesis mainly focuses on the cockpit of commercial aircraft. As avionics and electronics become some of the most critical parts of an aircraft, the cockpit is the obvious place where such a study should begin. Yet, the concepts it explores have a much wider applicability than aircraft cockpits. This set of metrics is planned to be applicable to the entirety of the aircraft. This will require determining whether other metrics are needed to evaluate the quality of commonality implementation at the level of the entire aircraft. When this will be achieved, it will be possible to compare the entire commonality strategy of commercial aircraft manufacturers.

Several other domains can also benefit from these metrics, as long as they are first tested to confirm their applicability in new areas. Regional commercial aviation and general aviation are two of the most obvious candidates. As there is no conceptual difference between regional aviation and large commercial aviation, the transition should be easy. The question is slightly different for general aviation, where the customers play a very different role than for commercial aviation. In this last case, the customer's metrics would probably have to be adapted. Other markets where these metrics could be applied are the helicopters and the UAVs markets. There, the adaptation would have to be even more thorough concerning the customer's metrics. Finally, the corresponding military markets are one more possible domain of application for the concepts developed here. However, as the military priorities are extremely different from the commercial and civil ones, it is likely that this set of metrics would have to be redesigned and tested anew.

The costs of using this set of metrics are very limited. Fine-tune testing of the set of metrics is the only upfront cost. Most of it could be shared with other initiatives requiring to gathering data about research, development and production. Further use of the set of metrics would be regular data gathering across product families. On the other hand, planning for the right commonality is extremely beneficial: in effect, it allows to creating the ideal real options for a product family. It also contributes to reducing the total lead-

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time and costs related to derivatives design and manufacturing. It helps avoiding unnecessary increase in the upfront costs for the baseline design.

VIII.3 Future Steps

Having arrived at the end of this research, I realize that many aspects of commonality need to be studied before being able to define best practices in this regard in aeronautics. The first priority should be to fine-tune the metrics validation and complete them by analyzing commonality at the entire aircraft level. The next steps will be to expand the application of these metrics and adapt them to the specificities of other industries. This will allow determining the core, non-industry specific part of these metrics. It could lead to further understanding on how commonality application varies from one industry to another, and how this concept is tied to product complexity.

Should this become feasible, a large part of Lean product development could be understood, and integrated, at least. In most domains, product development is still largely an art, with few immovable rules. Understanding the relations between commonality and product complexity would contribute to the transition of this field toward true science. And this is a worthy goal for an Engineer.

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Appendix 1: Interviews Summary

Analyzing the consequences of commonality implementation in commercial aircraft on airline companies is a subject that has not been explored much previous to this study. Hence, little data was available on the subject. My tasks was further complicated by the fact that aircraft manufacturers communicate little on their costs and their manufacturing techniques. Thus, it was necessary for me to corroborate the data publicly available by first-hand information. Given the time available for this research, interviewing professionals from various origins and performing some on-site visits were the best means to collect first-hand evidence.

I interviewed people working for the aircraft manufacturers and for airline companies. I also interviewed independent experts, most of who were from academia. On the manufacturing side, I endeavored to interview representative samples of people working for the various departments collaborating in the product development and manufacturing of a commercial aircraft. These included product development engineers, industrial engineers and manufacturing operations managers. On the airline side, I mainly interviewed aircraft pilots, in order to determine the various aspects of commonality that had an influence on their daily tasks. I also interviewed a few managers involved in the aircraft acquisitions procedures. In academia, I interviewed specialists of various fields: modularity measurement, flexibility management, airline purchase strategies, Airbus-Boeing competition, etc...

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Company	Manufacturer	Customer
Airbus	1	
Air France		1

Table A-1: Number of on-site visits.

Due to lack of time and security restrictions for visiting aeronautics manufacturing plants in the United States, only two on-site visits were possible. Visiting the Renton plant at Boeing or the Wichita plant at Spirit Aerosystems would have considerably enriched this research.

Affiliation	Manufacturer	Customer
Airbus	8	
Boeing	4	
Other aircraft manufacturers	2	
Air France		9
Continental Airlines		2
Other airline companies		1
MIT	6	2
Other organizations	2	3

Table A-2: Number of interviews.

Time constraints also restricted the number of companies I could contact. While this was not a real issue on the manufacturing side, it would certainly have been beneficial to my research if I had been able to contact more airline companies. In particular, interviewing pilots from low-costs airline companies might have introduced novel insights regarding the importance of commonality.

Appendix 2: Interview Questions

As the interview questions were tailored to each category of interviewees, the list presented here reproduces the questions that were asked to pilots, airline maintenance specialists and airline managers:

Corporate Strategy

- To what extent do you participate in defining the platform strategy of your suppliers?
- Who is in charge about this in your enterprise?
- Which other stakeholders are involved?
- What is the influence of maintenance operations on these issues?
- What is the integration of platform strategy into corporate objectives?
- To what extent are you involved when the decision is taken to create a new aircraft project?
- What are the most influential parameters taken into account?
- Do you feel that commonality issues have an impact on customer satisfaction? How is it measured?
- What is the influence of technology upon platform strategy?

Relations With the Aircraft Manufacturers

- Do you compare suppliers according to their platform strategy?
- Do you discuss world class/best in class performance level for platform strategies? How is this validated?

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- Do you benchmark platform strategies in other enterprises in and out of the commercial aircraft market? How is this achieved?
- Do you have direct interactions with the suppliers? In which domain?
- Do you think that the platform strategy of your suppliers enable your company to make savings? What is the order of those savings, compared to what you would have to spend with aircraft having no parts in common?
- Where do these savings mainly come from?

Training

- What are the formation requirements for your task?
- How long is the specific training for your task?
- To what extent is it specialized to a given product family? To a single aircraft?
- How much additional training is needed to do the same task on a different aircraft of the same family? On a different aircraft family?
- How much additional training would you need if you had to work on aircraft having no commonality at the subsystems/components level?
- Is your training more complex because of the current level of commonality between different types of aircraft? To what extent?
- Are there requirements for periodic training in this domain? How often? How long does it take?
- How is proficiency measured?
- Is cross-functional experience encouraged? Required?
- Could you give me a rough estimation on the total costs linked with training?
 - Employment costs
 - Material and capital costs
 - Other human costs

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Personal Involvement

- Do people see the platform strategy of your suppliers as having an influence on their job? Positive or negative?
- Is feedback from the employees gathered about commonality issues? How is it gathered? How is it used?
- How is the influence of feedback communicated to the employees?

Aircraft Utilization

- Do you feel that commonality issues affect the execution of your task (safety, ease of use, weariness, etc)? Positively or negatively?
- Do you usually work with the same crew for long periods of time, or do you frequently change?
- Do you usually work on the same model of aircraft, or on aircraft belonging to the same family? How often do you change?
- Do you work on aircraft belonging to different manufacturers?
- What are the advantages to fly on various types of aircraft?
- How is organized the promotion system? Are there some relations with the type of aircraft you fly in?
- How often do you have to fly on a given type of aircraft to remain qualified?
- Does your aircraft qualification allow you to fly on all derivatives of the model your are qualified on?
- Does flying on a given aircraft count as if you had flown on any other derivative of the same aircraft family, in terms of qualification renewal?
- What is the level of teamwork/cooperation with the rest of the team members that is usually needed in your job?
- How are organized the replacement crews that will fly if a problem occurs to some members of the original crew?

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- How many replacement crews are present at the same time in your company and how are they dispatched?
- What is the influence of commonality across aircraft on the replacement crew quantities and organization?
- Does commonality allows you to make a better use of your capabilities and knowledge?
- Do you have other comments linked with platform issues on:
 - Safety items and system layout
 - Accessories and comfort items
 - Others

Maintenance and Repairs

- Does commonality across subsystems make any difference in terms of spare parts availability?
- Does commonality across subsystems make any difference in terms of availability of people able to handle the repair?
- What are the main productivity improvements you noticed?
 - Less rework or inappropriate processing
 - Faster repair time
 - Less idle time
 - Less fitting or overprocessing
 - Less unnecessary motions
 - Less inappropriate tools or methods
- To what extent commonality contributes to improve indirect maintenance costs?
 - In engineering?
 - In planning?
 - In technical documentation?
 - In ground support equipment?

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Wrap-up

- What is your level of experience in the job you currently have (in terms of years or relative to your colleagues)?
- What additional issues do you have with platform strategy?

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Appendix 3: List of Functional Units in the Cockpit

The list of functional units in the cockpit is different from one manufacturer to the other, even if it is possible to observe correspondences. The following list corresponds to an Airbus cockpit. A similar identification process has been performed for the Boeing cockpits:

- Primary Flight Display (PFD)
- Navigation Display (ND)
- Primary ECAM (E/WD)
- Primary Engine Display (PED)
- Secondary ECAM
- Secondary Engine Display (SED)
- Primary Multi-function Control and Display Unit (MCDU)
- Electronic Flight Instrument System (EFIS)
- Flight Control Unit (FCU)
- Light control
- Landing Gear
- Landing Gear Indicator
- Brake and Accumulator Pressure Indicator
- Stowaway tables
- Standby horizon
- Digital Distance and Radio Magnetic Indicator
- Standby Altitude Indicator
- Standby Airspeed Indicator
- GPS receptor
- Attention Getters

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- Loud Speaker Controls
- Switching Panel
- ECAM Switching
- ECAM System Pad Keys
- Radio Management Panel (RMP)
- Audio controls
- Left Flood Light Controls
- Right Flood Light Controls
- WX Radar Controls
- TCAS/ATC Controls
- Speed Brake Lever
- Parking Brakes
- Rudder Trim
- Flap Lever
- Engines Start and Ignition Control
- Thrust Control System
- Pitch Trim Wheels
- Secondary MCDU

Appendix 4: Cockpit Photographs

The photos presented here display the main instrument panels of the cockpits of the aircraft models I have studied. Only the models belonging to currently produced aircraft families will be found below. I used this type of photos to perform a first-level analysis of the arrangement of the cockpit subsystems I studied. As each aircraft ever built is to some extent unique, the photo captions identify with precision which aircraft is represented.

Airbus Cockpits

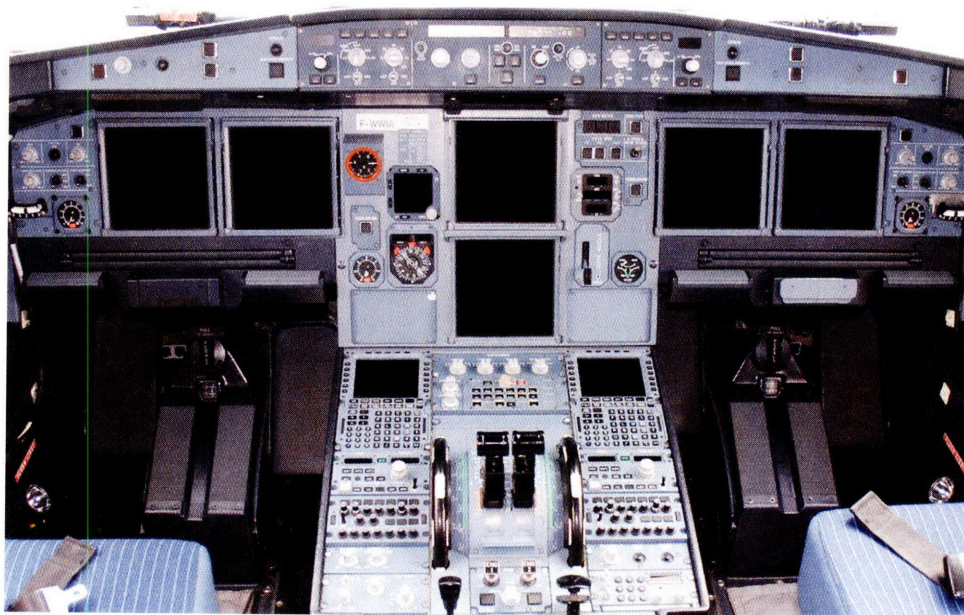


Figure A-1: Instruments of the Airbus A318-121. © Michal Kaczmarek, 2006.

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Figure A-2: Instruments of the Airbus A319-112. © Gabriel Savit, 2006.



Figure A-3: Instruments of the Airbus A320-232. © Farhad Piran, 2006.

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Figure A-4: Instruments of the Airbus A321-211. © Harri Koskinen, 2004.

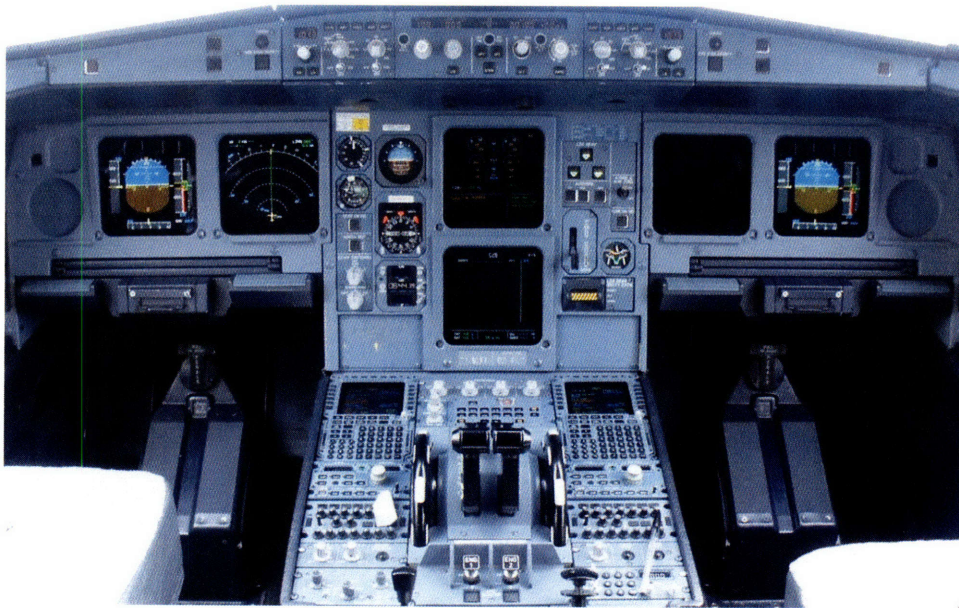


Figure A-5: Instruments of the Airbus A330-202. © Giovanni Paolo Colombo, 2002.

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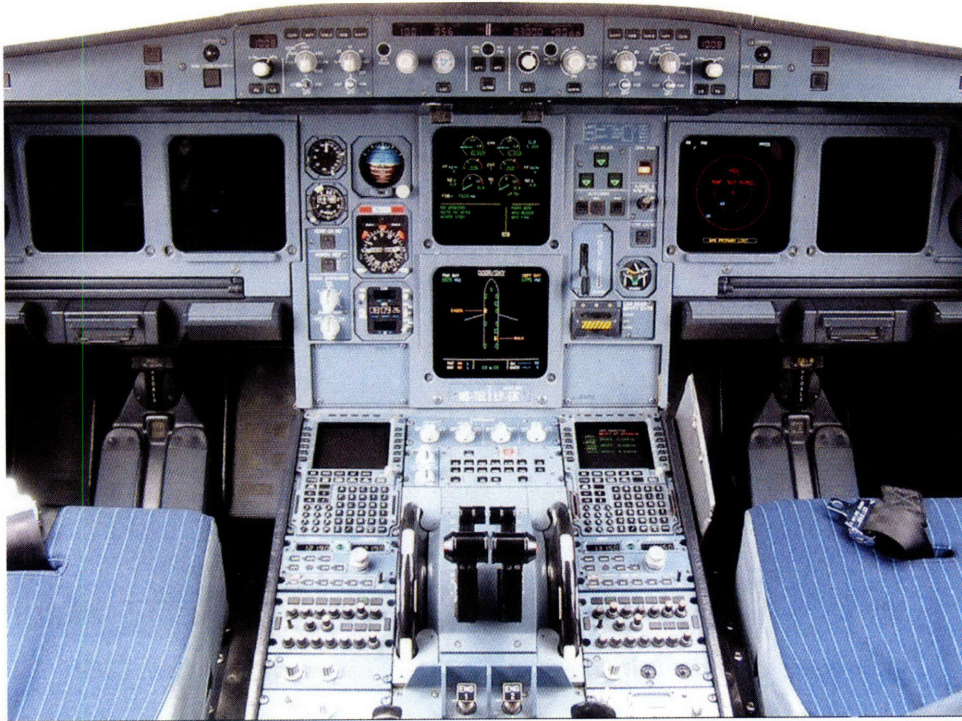


Figure A-6: Instruments of the Airbus A330-322. © Poowin Bunyavejchewin, 2003.

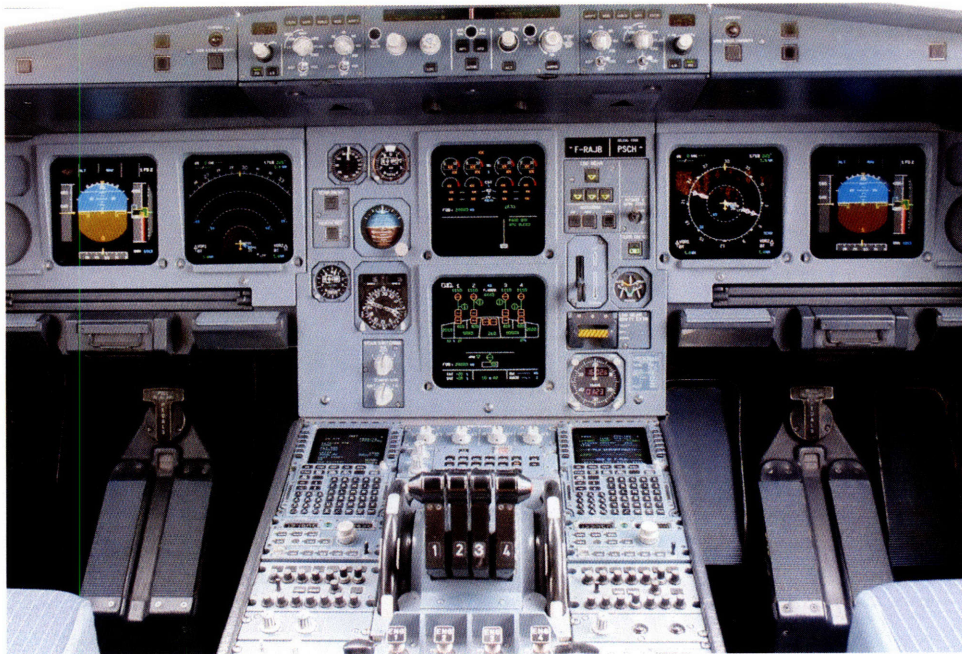


Figure A-7: Instruments of the Airbus A340-211. © Philippe Noret, 2006.

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Figure A-8: Instruments of the Airbus A340-313. © T. Pang, 2007.



Figure A-9: Instruments of the Airbus A340-541. © Vector Grafix, 2003.

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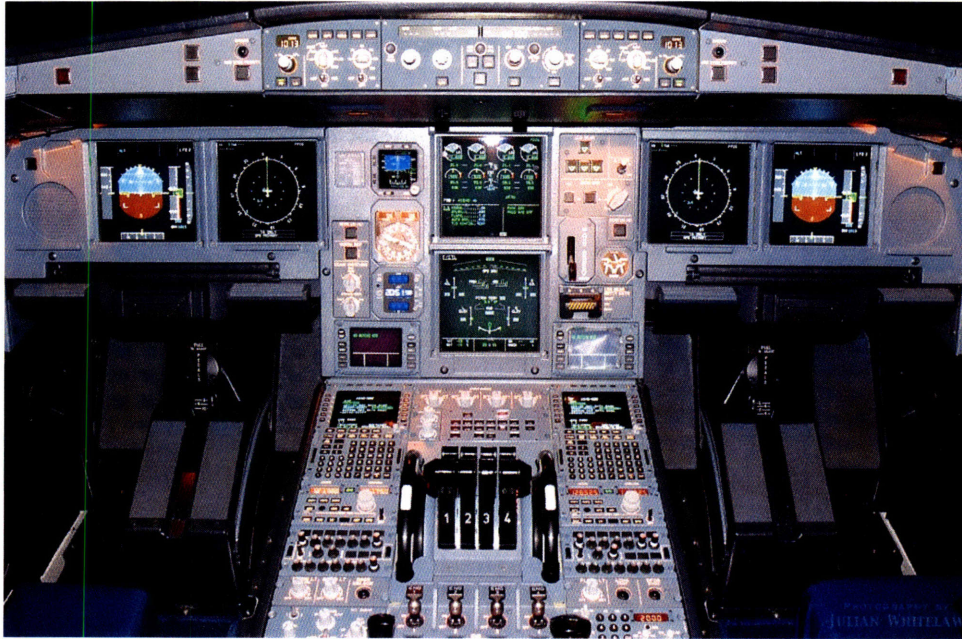


Figure A-10: Instruments of the Airbus A340-642. © Julian Whitelaw, 2003.

Boeing Cockpits

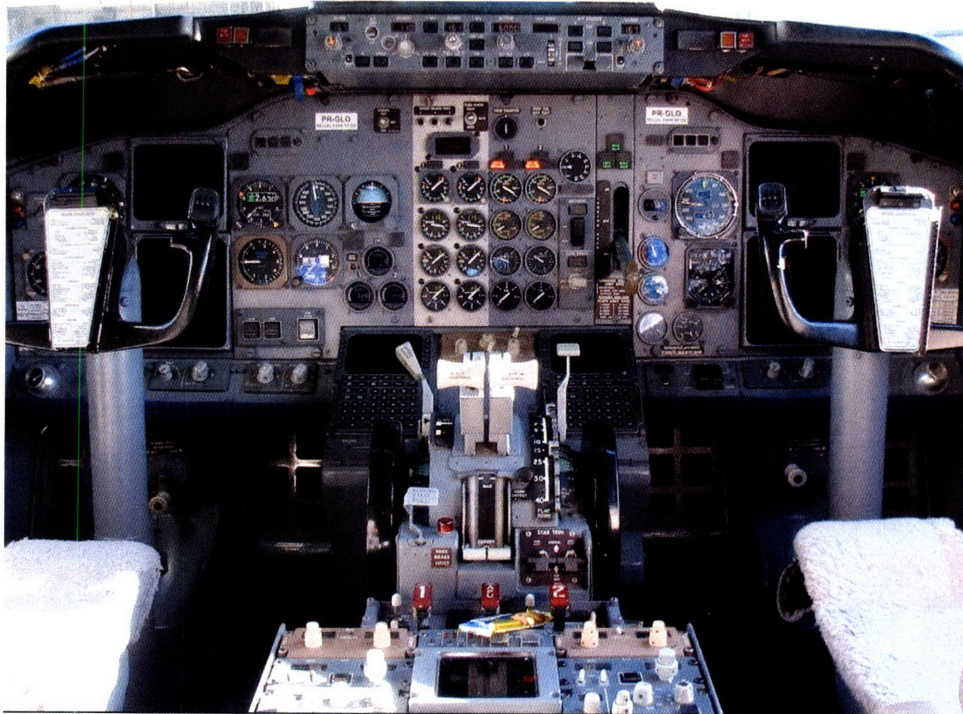


Figure A-11: Instruments of the Boeing 737-322. © Antônio Lima, 2007.

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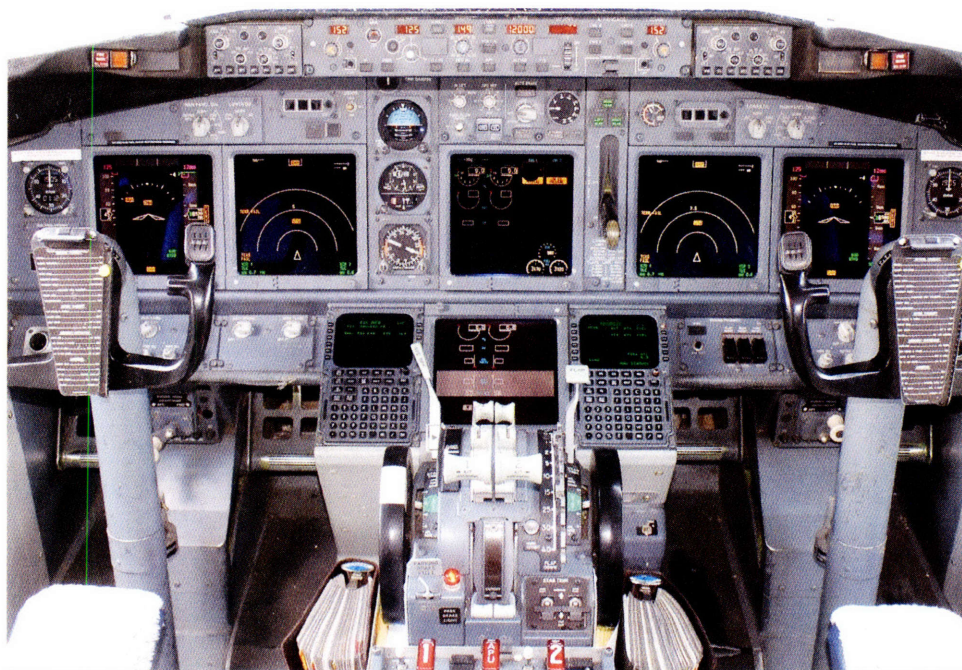


Figure A-12: Instruments of the Boeing 737-76N. © Luis Tena Orozco, 2005.

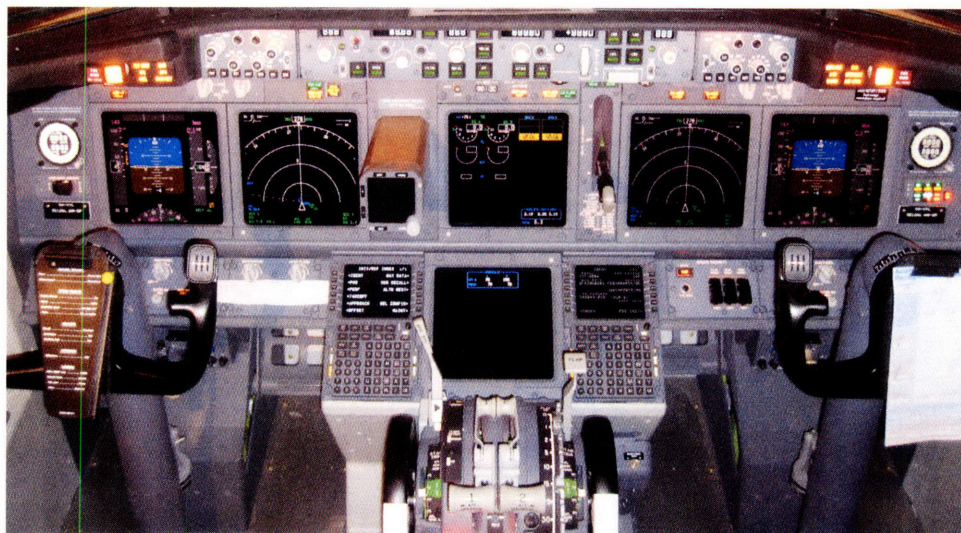


Figure A-13: Instruments of the Boeing 737-838. © Justin Madden, 2006.

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Figure A-14: Instruments of the Boeing 767-2EY/ER. © Miguel Snoep, 2005.



Figure A-15: Instruments of the Boeing 767-34P/ER. © "superaccipiter", 2004.

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Figure A-16: Instruments of the Boeing 767-432/ER. © Ryan Gaddis, 2000.



Figure A-17: Instruments of the Boeing 777-2H6/ER. © JKSC, 2006.

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Figure A-18: Instruments of the Boeing 777-346/ER. © Farhad Piran, 2006.

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