MEASURING THE EFFICIENCY OF COMMONALITY IMPLEMENTATION: APPLICATION TO COMMERCIAL AIRCRAFT COCKPITS

Damien P.M.D. Bador[1], Warren J. Seering[2] and Eric S. Rebentisch[3]

[1]Lean Aerospace Initiative (LAI), Cambridge, MA;
MIT Dept. of Aeronautics and Astronautics, Cambridge, MA;
MIT Engineering Systems Division (ESD), Cambridge, MA;
École Nationale Supérieure des Arts & Métiers (ENSAM), Paris.
[2]Lean Aerospace Initiative (LAI), Cambridge, MA;
MIT Dept. of Mechanical Engineering, Cambridge, MA;
MIT Engineering Systems Division (ESD), Cambridge, MA.
[3]Lean Aerospace Initiative (LAI), Cambridge, MA;
MIT Center for Technology, Policy and Industrial Development (CTPID), Cambridge, MA.

ABSTRACT

Increasing commonality across their models allows commercial aircraft manufacturers to reduce the product development cycle time and tailor their models to their customers' needs. The cockpit is an area where commonality is thought to be particularly desirable, since it also simplifies the pilots training process for the airline companies. However, no set of metrics is currently able to measure the efficiency of commonality application at this level from a total lifecycle standpoint.

In this paper, we propose a set of metrics adapted to large commercial aircraft and taking into account the main parts of the product lifecycle. The concept of lead time is central in our measurement of commonality, as it strongly influences the value of the aircraft for all primary stakeholders. We examine the extent to which these metrics are independent from aircraft particularities (such as physical dimensions). We indicate their limitations and what additional research should be performed to obtain a set of metrics able to measure the efficiency of commonality implementation for the whole aircraft.

We use the example of two competing medium-haul aircraft families to test our set of metrics. We evaluate the efficiency of commonality according to our metrics and we compare with field results obtained from the manufacturers' studies and from the results of interviews of airlines pilots. We show how our set of metrics can help determining how to optimize the level of commonality for all stakeholders.

Keywords: Product Development, Product Family, Commonality, Flexibility, Metrics, Lean, Aeronautics, Commercial Aircraft, Cockpit

1 INTRODUCTION

Eliminating waste with the goal of creating value for all stakeholders in an enterprise is the root concept of Lean [1]. But improving separately each part of the lifecycle of a product, or each product in isolation from the others is less likely to produce any lasting result. Even if it allows to creating some islands of success within the enterprise, it will only result in a general suboptimization of the enterprise value flow [2]. Improvement must focus at the enterprise level. Multi-project management and concurrent technology transfers have long proved to increase the efficiency of product development in industry working on complex engineered products [3] [4]. One of the most adapted solutions is to increase the level of commonality between models or even between different product families. Creating aircraft product families with a high level of commonality has yielded positive results for the manufacturers [5]. It has allowed important reduction of the development lead time of new aircraft and similar reductions of development costs, while rationalizing the manufacturing departments [6].

The cockpit is a section of the aircraft 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 [7]. Digital fly-by-wire now allows for using the same hardware instruments for all types of aircraft [8]. The only major architectural differences that are needed in the cockpit come from differences in the propulsion system. Commonality in the cockpit is a selling argument as well, since it contributes to maximizing some types of exterior benefits for the airline companies [9]. Less functional differences between the cockpits of different models of aircraft 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. It will also permit the company to keep fewer standby pilots in its major hubs, since each of them will be able to fly on more types of aircraft.

However, no precise measures of the effects of commonality on the efficiency of aircraft cockpit development currently exist. Therefore, determining what is the optimal level of commonality or what are the potential drawbacks of an excess of commonality in the cockpit is almost impossible. The goal of this article is to create a set of metrics that could be used by commercial aircraft companies as a decision tool to determine the efficiency of commonality implementation at the level of the cockpit. We will discuss each separate metric and its related variables. We will show that the resulting set covers all aspects of commonality and is the smallest set able to achieve this. We will also look at its limitations. We will sketch which additional metrics should be considered to extend the current to cover all aspects of commonality for the entire aircraft. We will briefly show how the current set of metrics could be adapted to be used on other types of aerospace vehicles. A parallel could be drawn with the application of commonality in the automotive industry.

A last section will be dedicated to a case study where we will analyse the case of two medium-haul families of aircraft to test the validity of the set of metrics developed here. First, we will detail how commonality was implemented in the cockpit of these families, and what have been the resulting consequences of these architectural choices, both from the point of view of the aircraft manufacturer and from the point of view of the customer airline companies. In this section, we will rely on published data by the manufacturers, on independent analyses of the performances of these families of aircraft and on pilot interviews. We will then detail to what extent these families of aircraft are in alignment with our set of metrics. Finally, we will show how our set of metrics could be used in this case to optimize the level of commonality for all primary stakeholders. The conclusion of this article will sum up the results obtained so far and detail what will be our future research in this domain.

2 SET OF METRICS

2.1 Definitions

There are two types of commonality that need 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 would refer to the common aspects of a given cockpit subsystem across a family of aircraft or across all families of aircraft of a manufacturer. The other type can be called *temporal commonality*. It deals with the common aspects of a subsystem that evolves over a period of time. In our case, this type is particularly important, since a model of aircraft

has a very long lifecycle compared to most electronic subsystems found in the cockpit. Each model of aircraft is periodically upgraded to stay up-to-date with the evolution of cockpit subsystems.

From two types of commonality, we can derive three constructs: *standardization*, *reusability*, and *modularity*. The first one is related to transverse commonality, the second one to temporal commonality and the last one 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 customer (here being assumed no intermediary between the aircraft manufacturer and the airline company). The denomination of customer can be further decomposed in primary customer and secondary customer, the first one being the user of the product in the usual sense of the term (i.e. the pilots, in this case), the second one dealing with its maintenance. But in our case, as the airline companies are most often in charge of the maintenance of their airplanes, we will not need to make this distinction. Our set of metrics will need to measure accurately each of the six aspects of commonality exposed here to determine the quality of commonality implementation in a cockpit. We will now determine which variables should be measured to determine at the same time the level and the quality of the commonality implementation.

2.2 Variables

Standardization

From the point of view of the manufacturer, standardization impacts both the design and the manufacturing departments [10]. The optimal standardization level will minimize the development and production costs of the entire range of aircraft that will occupy the target market segment [11]. The degree of standardization (*Sd*) will be given by:

$$Sd = 1 - \frac{\sum_{i=1}^{k} Dd_i}{k \times Db} \tag{1}$$

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 a derivative.

The total development and production costs of the range of aircraft considered (*TDPC*), which is used to determine the efficiency of commonality implementation, can be expressed as:

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

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 gth product family, $Dd_{g,i}$ the development costs of a derivative, n_g the number of aircraft of the gth model produced, Pb_g the production costs of the baseline aircraft of the gth product family, and $Pd_{g,i}$ the development costs of a derivative.

For the customer, standardization will be considered from the functional point of view. Technical standardization depends on the same parameters as modularity and will be discussed in the modularity 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 number of crew errors. The evaluated cost of the latter variable being considered as proprietary information by most airline companies, each company will then have to determine the optimal functional standardization with the two metrics.

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. The effective length of this additional training will depend of the airline company policies, but the minimum length is determined by the major aviation administrations: the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA). The Figure 1 below shows the length of the required Cross Crew Qualifications (CCQ) for the major Airbus aircraft currently produced:
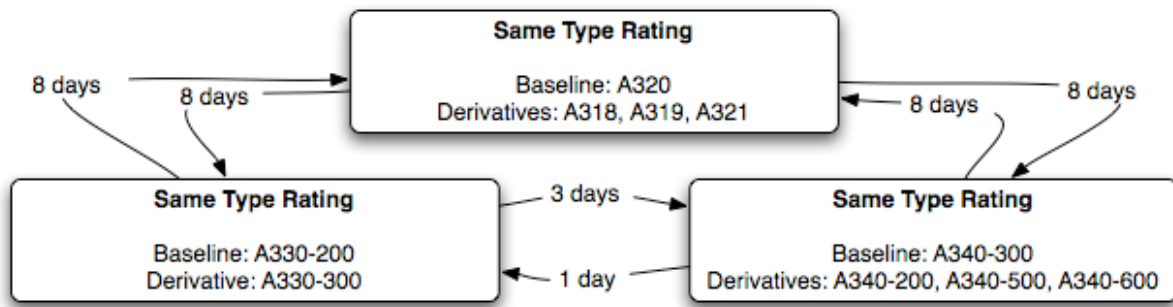
Airbus Cross Crew Qualifications (CCQ)

Figure 1. Length of Cross Crew Qualifications for three Airbus aircraft families, as determined by the FAA Advisory Circular 120-53 [12]

Kõvári [13] and Green [14] find that the majority of aircraft accidents can be related to wrong decisions taken by the crew. The wrong reading of the cockpit instruments, which leads to inappropriate action from the pilots, is one of the major causes of crew errors [15]. The number of crew errors is directly linked with the complexity of the instruments layout. The effect of standardization on crew errors is thus complex to analyse: standardizing the instrument layout will shorten the transition from one model to another but will increase the complexity of the original training, since slight variations between the models will need to be memorized from the beginning [16]. The extent of this increase will also depend on the specific procedures adopted by the airline company [17]. Pilots mention as well that a too great standardization between the cockpits of two models of aircraft having different flying performances can lead to the inappropriate handling of a situation by the crew. Thus, there is 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.

Table 1. Metrics - Standardization

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

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 the question is not to measure how many such subsystems are reused but how much development time they represent for the enterprise. Therefore, Equation 3 gives the degree of reusability of the subsystems of the cockpit for the manufacturer (Rd_m):

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

With Dn the amount of time spent in developing the new subsystems in the cockpit and Dt the total development time spent in developing the cockpit. We can notice that this metric assumes that no gain of efficiency is realised in the development process between the time where the original subsystems are developed and the time where a new cockpit is designed. Else, it would lead to overestimating the reusability rate. Yet, if the productivity gains are correctly estimated, it is possible to normalize the two factors and obtain an unbiased 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 we will focus solely on it. Ko *et al.* [18] have shown that extrinsic reusability is a probabilistic assessment. They have expressed it 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*:

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

$$R(t,F,K(t)) : (t,F,K(t)) \mapsto \Re / \begin{cases} K(t) = \{k \mid \Pr(t,k) > 0\} \\ R(t,F,K(t)) \in [0,1] \end{cases} \qquad (4)$$

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 [19]. Developing metrics to measure the efficiency of product development methods is beyond the scope of this article, but can certainly be viewed as a future extension of this set of metrics.

The reusability construct is also a capital factor for the customer. It will determine the homogeneity of the airline fleet, which is one of the dominant factors for the global maintenance costs [20]. In this case, the degree of reusability of a given subsystem from the airline point of view (Rd_a) can be measured by the following expression:

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

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.

Table 2. Metrics - Reusability

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

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 [21] Sosa *et al.* have [22] defined a method allowing to

determining whether a product is integral or modular, based on component interactions matched against each other in the Design Structure Matrix (DSM) [23]. A refinement of this method was developed by Pimmler and Eppinger [24], who detailed the nature of the interaction and used coefficients in the DSM to represent its desirability. Stone *et al.* [25] developed the function structure heuristic method, which is based on the function structures created by Pahl and Beitz [26]. 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. Zamirovsky and Otto [27] developed additional heuristics to define common modules in a product family. A third type of method to determine the degree of modularity is the Modular Function Deployment (MFD) [28]. It is also based on functional decomposition, but modularity depends on more constructs than mere functionality. Twelve modularity drivers are identified in MFD. 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 insufficient to very large, highly integral products like an airplane. Once a subsystem is proved to be more efficient in being modular by one of these methods, the effective degree of modularity for the manufacturer (Me_m) will be obtained by the following ratio:

$$Me_m = \frac{Std_{Int}}{Tt_{Int}} \tag{6}$$

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. The following ratio in Equation 7 determines the degree of modularity for the airline company (Md_a):

$$Md_a = \frac{Com_{Air}}{Tt_{Air}} \tag{7}$$

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 [29] for a B_2 shortage costs structure (see also Federgruen and Zheng for more details on the relevant algorithms [30]):

$$ETRC(s,Q) = \frac{AD}{Q} + \frac{1}{Q} \sum_{y=s+1}^{s+Q} \left[rv \sum_{i=0}^{y} (y-i) p_{po}(i \mid \hat{x}_L) + B_2 Dv \sum_{i=y}^{\infty} p_{po}(i \mid \hat{x}_L) \right] \tag{8}$$

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)
$p_{po}(x_0 | \hat{x}_L)$ = 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)

Table 3. Metrics - Modularity

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

2.3 Summary table

Table 4. Metrics Summary

Commonality Types	Constructs	Manufacturer Metrics	Customer Metrics
Transverse Commonality	Standardization	Degree of Standardization: Sd	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
Temporal Commonality		Modularity Efficiency: Me_m	Estimated Total Relevant Costs: ETRC(s,Q)
	Reusability	Reusability Efficiency: Rd_m, R(t,F,K(t))	Degree of Reusability: Rd_a

3 DISCUSSION

3.1 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 [31] [32]. Technical (flight) performances become major concerns and need to be balanced with the advantages provided by commonality [33] 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 [34].

Such a balance is however difficult to achieve, since commonality considerations impact the entire range of products manufactured and technical considerations are specific to each product. The case is 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 becomes necessary to introduce the estimated rate of technical change as a new parameter. Further research is 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.

3.2 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 problematic 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 research 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 [35]. Technical performance, field maintenance and robustness become prominent parameters. 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.

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 [36]. 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. This will be a significant aspect of our future research.

4 CASE STUDY

4.1 Description

The primary focus of this case study is to test the validity of our set of metrics and determine its usefulness as a decision tool. It will also help us determine the current limits of this set of metrics. We will consider the two following product families: the Airbus A320 family and the Boeing 737 family. Both are well-known families of medium-haul aircraft with comparable seating (*cf.* Table 5 and Table 6). However, the design choices that were made for each family are very different. The A320 family is considered to be a family that has an important commonality with the longer-range families of the manufacturer (A330 and A340). By opposition, the 737 family has a low commonality with other Boeing aircraft models [37] [38]. The main characteristics of the two families are as follow:

Table 5. Characteristics of the Airbus A320 family [39]

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 6. Characteristics of the Boeing 737 family [39]

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

4.2 Alignment with the metrics

The differences between the concepts that directed the design of these two aircraft families translate accurately in the metrics that we have been able to measure accurately in the two cases. However, this work is not completed yet, and we still need to perform additional analyses for three out of the ten dimensions proposed. This will be the object of further research from us.

The degree of modularity for the customer is the first metric where differences between the two families are noticeable. To measure it, we have evaluated the modularity of the main subsystems of the cockpit for two airline companies: Air France and Continental Airlines. The first one uses almost exclusively the A320 family for medium-haul flights (and has planned to phase out its remaining 737), and the second one uses mainly 737 for this category (and a few remaining MD-80/90). The composition of the fleet of the two companies is taken from the Airfleet website [40]:

- Air France: $Md_a = 94.2\%$
- Continental Airlines: $Md_a = 72.3\%$

In the second case, the lower modularity mainly comes from Continental's 737-300 and 737-500, which do not feature fly-by-wire commands.

The degree of reusability is very characteristic of the difference between the two families. For practical purposes, we will consider the 737-300 as the original model of the 737 family, since the previous models were developed at a time where the design lead time for aircraft was far shorter. This gives us:

Table 7. Reusability of the cockpit A320 and the 737 families, manufacturer point of view

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%

Interestingly enough, from the point of view of the customer, the reusability measure gives opposite results. To measure it, we have again compared the fleets of Air France and Continental Airlines:

- Air France: $Rd_a = 91.5\%$
- Continental Airlines: $Rd_a = 99.4\%$

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 creating more heterogeneity for the customers who bought the same model for a long period of time. It would be interesting to measure this metric for other airline companies to determine whether the comparison results obtained her accurately reflects the composition of Airbus and Boeing fleets in the world or a strategic choice from either of the two companies studied.

Comparing the cost structure of the A320 and the 737 families is difficult, since neither of the two aircraft manufacturers publishes its development costs. Still, some amount of non-dimensional data is publicly available, which allows to constructing an estimation of the costs of the two product families [41]. Additionally, comparing former Airbus subsidies and the acknowledged share that these subsidies represented in the Airbus programs enable us to refine our estimations. This gives us:

- A320 family: $Sd = 83\%$
- 737 family: $Sd \cong 75\%$

Comparing the total costs of the two families is even less evident, since the 737 program was initiated during a period where Boeing dominated the commercial aircraft market. However, being able to reuse the airframe of the 737-100/200 was a significant advantage for Boeing. Our estimations show that the difference between the A320 family and the 737 family TDPC(l) is on the order of 10 to 15%.

The length of the CCQ is not a significant criterion of difference here. Both families have a same type rating for all derivatives, and each family fully occupies the category considered (medium-haul aircraft with a typical seating between 100 and 200). However, this would not longer be the case if we were expanding the comparison to other aircraft families of the two manufacturers, since the commonality between families is higher in the Airbus case.

The number of crew errors is estimated through an analysis of all reported incidents or accidents that occurred in the world between year 2000 and 2005. A comparison is made with the total number of incidents during that period (incidents solely caused by an exterior factor: weather, controllers, other aircraft, etc are not taken into account). Both categories are expressed as a percentage of the number of operated aircraft in their family. 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), which tend to confirm a better standardization efficiency for the A320 family.
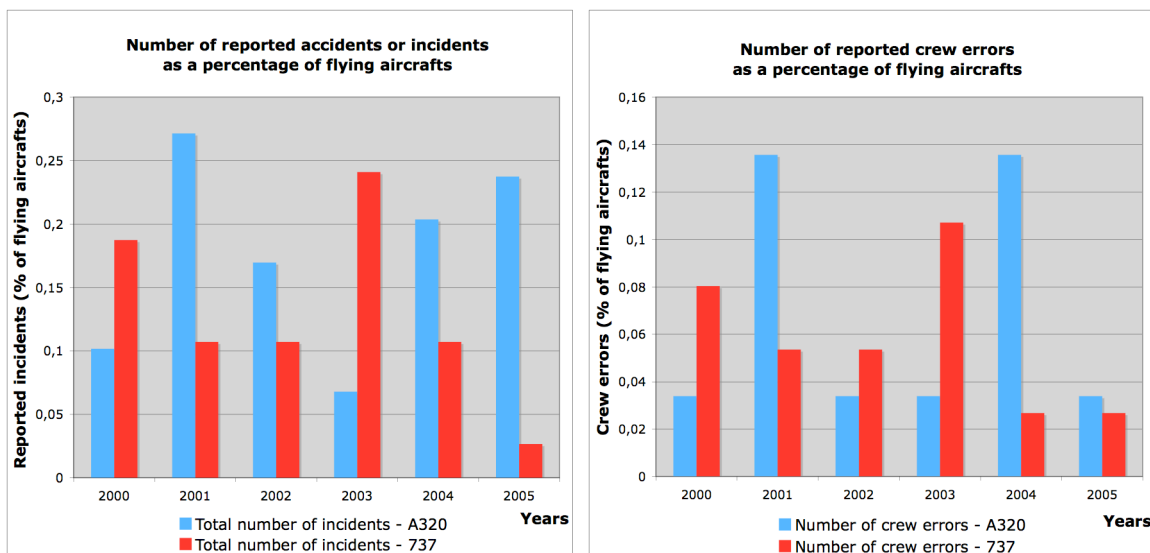
Figure 2. Total number of reported incidents for the A320 and the 737 families [42]
Figure 3. Total number of reported crew errors for the A320 and the 737 families [42]

4.3 Analysis

It is interesting to notice that the comparison between the two aircraft families is more contrasted than what could have been expected. From the point of view of the manufacturer, the A320 family seems to have a more efficient implementation of commonality, but the A320 does not provide significant advantages for the airline companies when we consider solely the medium-haul aircraft market. Besides, if the older members of the 737 family (737-300 to -500) were excluded from this study, the differences between the Airbus and the Boeing families would be far smaller. Apart from flight-by-wire innovation, this commonality analysis does not fully explain the rise of the A320 family in the commercial aircraft market. However, integrating the long-haul families of both manufacturers in the study would radically change the picture. Boeing maintained a very efficient level of commonality within the 737 family, but failed to integrate it with its other families. In practice, keeping the same airframe hindered a better integration of the 737 with the more modern Boeing aircraft models [43].

This analysis shows that the set of metrics is so far a good predictor of the quality of commonality implementation in commercial aircraft cockpits. However, it also reveals the conceptual limits of commonality when its analysis is restricted to a unique family of aircraft. More interesting results will be obtained once this analysis includes the entire range of aircraft from both manufacturers. This stresses the need for continuing research in this domain to determine what additional parameters should be taken into account to obtain a full picture of commonality for the entire aircraft. Another potential weakness of this method is that optimizing the different metrics presented here depends upon the priorities of the user of this set of metrics. While this choice has been made to allow the maximum flexibility for industrials that would use this set of metrics as a decision tool, it does not provide an integrated synthesis of commonality at the level of the cockpit. Since the metrics we have defined are not dependent on specific features of cockpits, tailoring this set of metrics for other engineered products seems an attainable objective. Further research is needed in that domain.

5 CONCLUSION

This paper has presented a set of metrics to measure the quality of commonality implementation in the cockpit of commercial aircraft. Commonality is considered here in abstraction from the technical properties of the products studied. It is divided into three constructs: standardization, reusability and modularity. Each of these constructs is measured from the manufacturer and from the customer points of view. A total of eleven metrics is necessary to fully comprehend the cockpit commonality efficiency. Further analysis discusses the application of this set of metrics to the entire aircraft as well as to other types of aerospace vehicles. A parallel is drawn with the automotive industry, and further research in that domain could lead to a better understanding of the applicability of commonality metrics to other types of engineered products. A case study tests this set of metrics by comparing two competing medium-haul aircraft families: the derivatives of the A320 and those of the 737-300.

While it had not yet been possible to analyse all dimensions of the set of metrics, we can already conclude that it accurately measures some of the major aspects of commonality in the cockpit of commercial aircraft. Further development of these metrics will show that this set completely defines commonality in this area. Yet, the results obtained also show that commonality within a product family is less strategic than commonality between the different product families. Since measuring this requires to determining the trade-offs between commonality and technical performances of the various aircraft models, further research in this area will be necessary, before being able to extend this model. Therefore, after completing the analysis of these two aircraft families, our next steps will concern the integration of the remaining dimensions needed to measure the implementation of commonality to the entire aircraft. This will enable us to compare the entire range of aircraft of Airbus and Boeing. A long term objective is to expand this set of metrics to other types of aerospace vehicles.

REFERENCES

[1] Womack J.P. and Jones D.T. *Lean Thinking*, 2003 (Free Press, New York, NY).
[2] Murman E.M. *et al. Lean Enterprise Value*, 2002 (Palgrave, New York, NY).
[3] Cusumano M.A. and Nobeoka K. *Thinking Beyond Lean*, 1998 (Free Press, New York, NY).
[4] Willcox K. and Wakayama S. Simultaneous Optimization of a Multiple-Aircraft Family. *Journal of Aircraft*, Vol.40, No.4, July-August 2003, pp.616-622.
[5] Nuffort M.R. *Managing Subsystem Commonality*, 2001 (MIT, Cambridge, MA).
[6] Wang F. *et al.* Toward Modelling the Evolution of Product Families. In *DETC'03 ASME 2003 Design Engineering Technical Conferences and Computer and Information in Engineering Conference*, Chicago, IL, September 2003.
[7] Robertson D. and Ulrich K. Planning for Product Development. *Sloan Management Review*, Vol.39, No.4, 1998, pp.19-31.
[8] Todd J.R., Hay J.A. and Noble D.S. Flexible architectures: a key to low cost fly-by-light. In *Digital Avionics Systems Conference*, 13th *DASC, AIAA/IEEE*, Phoenix, AZ, October-November 1994, pp.599-604.
[9] Ruston N. Commonality. *FAST*, No.14, February 1993, pp.7-11.
[10] Simpson T.W. Product platform design and customization: Status and promise. *Cambridge University Press*, Vol.18, No.1, January 2004, pp.3-20.
[11] Martin M.V. and Ishii K. Design for Variety: A Methodology for Understanding the Costs of Product Proliferation. In *ASME Design Engineering Technical Conferences and Computers in Engineering Conference*, Irvine, CA, August 1996.
[12] Vadrot R., van Dijk G. and Aubry C. Airbus Flight Operational Commonality in Action. *FAST*, No.32, July 2003, pp.9-16.
[13] Kõvári B. Air Crew Training, Human Factors and Reorganizing in Case of Irregularities. *Periodica Polytechnica Transportation Engineering*, Vol.33, No.1-2, 2005, pp.77-88.
[14] Green R. Human error on the flight deck. *Philosophical Transactions of the Royal Society of London*, Series B, Biological Sciences, 1990, pp.503-511.
[15] Cranfield University, Department of Air Transport *International General Aviation and Corporate Aviation Risk Assessment (IGA-CARA) Project*, Final Report, Issue 1.1, June 2005.
[16] Bureau d'Information Technique de la Division Airbus 320 *Différences A318/319/320/321 et particularités*, February 2006 (Air France, Paris)
[17] Wiener E.L., Chute R.D. and Moses J.H. Transition to Glass: Pilot Training for High-technology Transport Aircraft, *Flight Safety Digest*, Special Issue, June-August 1999, pp.1-136.
[18] Ko J., Hu S.J. and Huang T. Reusability Assessment for Manufacturing Systems. In 55th *General Assembly of CIRP*, Antalya, August 2005.
[19] Holsapple C.W. and Joshi K.D. Description and Analysis of Existing Knowledge Management Frameworks. In 32nd *Hawaii International Conference on Systems Science*, Maui, HI, January 1999.
[20] Smith B.C. and Johnson E.L. Robust Airline Fleet Assignment: Imposing Station Purity Using Station Decomposition. *Transportation Science*, Vol.40, No.4, November 2006, pp.497-516.
[21] Holtta K.M.M. and Salonen M.P. Comparing Three Different Modularity Methods. In *DETC'03 ASME 2003 Design Engineering Technical Conferences and Computer and Information in Engineering Conference*, Chicago, IL, September 2003.
[22] Sosa M.E., Eppinger S.D. and Rowles C.M. Identifying Modular and Integrative Systems and

their Impact on Design Team Interactions. *Journal of Mechanical Design*, Vol.125, 2003, pp.240-251.

[23] Ulrich K.T. and Eppinger S.D. *Product Design and Development*, 2000 (McGraw-Hill, New York, NY).

[24] Pimmler T.U. and Eppinger S.D. Integration Analysis of Product Decomposition. In *AMSE Design Theory and Methodology Conference*, Minneapolis, MN, 1994.

[25] Stone R.B., Wood K.L. and Crawford R.H. A Heuristic Method for Identifying Modules for Product Architectures. *Design Studies*, Vol.21, No.1, 2000, pp.5-31.

[26] Pahl G. and Beitz. W. *Engineering Design*, 1999 (Springer-Verlag, London).

[27] Zamirovsky E.J. and Otto K.N. Identifying Product Family Architecture Modularity Using Function and Variety Heuristics. In *11th International Conference on Design Theory and Methodology, ASME*, Las Vegas, NV, 1999.

[28] Otto K. and Wood K. *Product Design: techniques in reverse engineering and new product development*, 2001 (Prentice Hall, Upper Saddle River, NJ).

[29] Silver E.A., Pyke D.F. and Peterson R. *Inventory Management and Production Planning and Scheduling*, 1998 (John Wiley & Sons, Hoboken, NJ).

[30] Federgruen A. and Zheng Y.-S. An Efficient Algorithm for Computing Optimal (s, S) Policies. *Operation Research*, Vol.32, No.6, 1984, pp.1268-1285.

[31] Hölltä K., Sue E.S. and de Weck O. Tradeoff Between Modularity and Performance for Engineered Systems and Products. In *International Conference on Engineering Design, ICED'05*, Melbourne, August 2005.

[32] Ulrich K.T. The role of product architecture in the manufacturing firm. *Research Policy*, No.24, 1995, pp.419-441.

[33] Pasaribu H.M. and Wijanarko B. Analysis of Flight Performance and Stability of Family of Transport Airplane Designs With Fuselage Commonalities. In *23rd ICAS Congress*, Toronto, 2002.

[34] Simpson T.W., Seepersad C.C. and Mistree F. Balancing Commonality and Performance within the Concurrent Design of Multiple Products in a Product Family. *Concurrent Engineering: Research and Applications*, Vol.9, No.3, September 2001, pp.175-190.

[35] Hauser J.R. Research, Development and Engineering Metrics. *Management Science*, Vol.44, No.12, December 1998, pp.1670-1689.

[36] Clark K.B. and Fujimoto T. *Product Development Performance*, 1991 (HBS Press, Cambridge, MA).

[37] Vakil S.S. *Analysis of Complexity Evolution Management and Human Performance Issues In Commercial Aircraft Automation*, May 2000 (MIT, Cambridge, MA).

[38] Rogers J. and Nazzaro P. *The American Boeing and the European Airbus: Competition for aviation technology and markets. A comprehensive analysis*, 2006 (RIT: College of Liberal Arts, Rochester, NY).

[39] See: http://www.airliners.net/info

[40] See: http://www.airfleets.net/recherche

[41] Markish J *Valuation Techniques for Commercial Aircraft Program Design*, June 2002 (MIT, Cambridge, MA)

[42] See: http://www.fss.aero/accident-reports

[43] Sandholtz W and Love W Dogfight over Asia: Airbus vs. Boeing. *Business and Politics*, Vol.3, No.2, 2001, pp.135-156.

Contact: D.P.M.D. Bador
Massachusetts Institute of Technology
Dept. of Aeronautics and Astronautics – Engineering Systems Division
Lean Aerospace Initiative
77 Massachusetts Avenue
Room 41-205, Cambridge, MA
United States
1 (617) 253-7633
1 (617) 258-7845
elendil@mit.edu
http://lean.mit.edu.