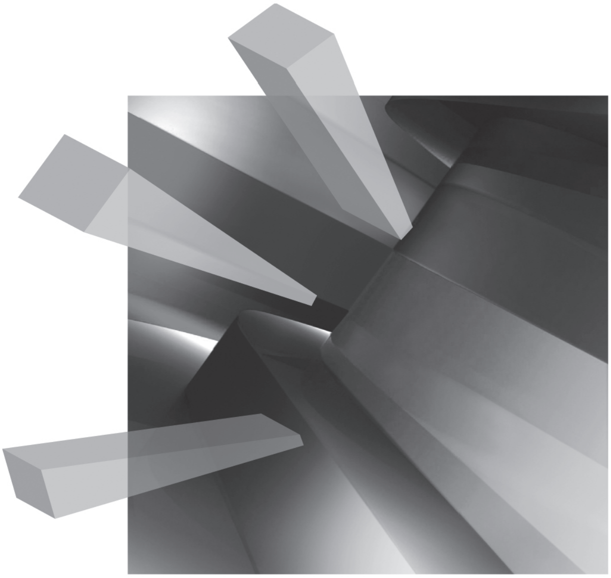
NAUKI O ZARZĄDZANIU

MANAGEMENT SCIENCES

4 (25) • 2015



Wydawnictwo Uniwersytetu Ekonomicznego we Wrocławiu
Wrocław 2015

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ISSN 2080-6000
e-ISSN 2449-9803

Wersja pierwotna: publikacja drukowana

Zamówienia na opublikowane prace należy składać na adres:
Wydawnictwo Uniwersytetu Ekonomicznego we Wrocławiu
ul. Komandorska 118/120
53-345 Wrocław
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www.ksiegarnia.ue.wroc.pl

Druk i oprawa: TOTEM

Spis treści

NAUKI O ZARZĄDZANIU MANAGEMENT SCIENCES 4(25) • 2015

ISSN 2080-6000
e-ISSN 2449-9803

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A NEW APPROACH TO AVOIDING COST OVERRUNS AND IMPLEMENTATION DELAYS IN FUTURE LARGE PROJECTS IN AEROSPACE BUSINESS

UNIKANIE OPÓŹNIEŃ I PRZEKRACZANIA KOSZTÓW W REALIZACJI WIELKICH PROJEKTÓW W PRZEMYŚLE AERONAUTYCZNYM – NOWE PODEJŚCIE

DOI: 10.15611/noz.2015.4.08

Summary: Large Projects in Aerospace Business (LPAB) notoriously face significant delays and cost overruns. The starting point is: reduction of risk for both deviations between planned and actual cost and time would increase profitability of a project. That means, if project duration and volume could be predicted more precisely, the risk for delays and cost overruns would be reduced while profitability would be improved through allocating resources when and where they are actually needed. This questions the efficiency of presently applied planning methods to yield proper estimates for project volume and duration. The initial approach to this problem started off with learning curves and developed into parametric estimate models mainly for cost. Over decades it was a main attempt to make the models robust for technical progress and to increase flexibility with regard to different kind of aircraft but there were still significant deficiencies. This article introduces a new approach to overcome above deficiencies and the corresponding parametric estimate models to determine project volume and duration for future aircraft projects. The model uses the degree of new technologies applied (technical complexity) and the number of countries, suppliers and final assemblies (organizational complexity) as independent variables. The parameters of the regression analysis were determined by analysing 5 large aircraft projects (Boeing 787, Airbus A380, A350, A400M, Lockheed Martin F-35B and Eurofighter). As a result, the model meets the requirements of application in practice while its accuracy is still within the range of legacy models.

Keywords: project implementation, cost overruns, risk, parametric estimate, planning very large scale projects, aircraft.

Streszczenie: Wielkie projekty w przemyśle aeronautycznym (LPAB) notorycznie stoją w obliczu poważnych opóźnień i przekroczenia kosztów. Punktem wyjścia jest stwierdzenie: przez zmniejszenie ryzyka odchyleń pomiędzy planowanymi a rzeczywistymi kosztami oraz planowanym i rzeczywistym czasem realizacji wzrośnie rentowność projektu. Oznacza to, że jeśli czas trwania projektu i wielkość można przewidzieć dokładniej, ryzyko opóźnień i przekroczenia kosztów zostanie zmniejszone, podczas gdy rentowność mogłyby zostać poprawiona poprzez alokację zasobów wtedy i tam, gdzie są rzeczywiście potrzebne. To stawia pod znakiem zapytania skuteczność obecnie stosowanych metod planowania i uzyskania na ich podstawie bardziej wiarygodnych szacunków rozmiarów i czasu trwania projektu. Wcześniej stosowano w analizie krzywe uczenia się, później modele parametryczne szacujące głównie koszt. Przez dziesięciolecia starano się ulepszać modele oraz zwiększać ich elastyczność, by mogły być stosowane do analizy różnego rodzaju statków powietrznych, ale wyniki ciągle nie były zadowalające. To opracowanie przedstawia nowe podejście do przezwyciężenia powyższych braków w modelach parametrycznych szacujących wielkość i czas trwania projektu dla przyszłych projektów aeronautycznych. Zmiennymi niezależnymi modelu są złożoność techniczna (w jakim stopniu projekt stosuje nowe technologie) oraz złożoność organizacyjna (liczba krajów, dostawców i miejsc końcowego montażu). Parametry modelu wyznaczono, analizując informacje z realizacji pięciu wielkich projektów (Boeing 787, Airbus A380, A350, A400M, Lockheed Martin F-35B i Eurofighter). W efekcie model spełnia wymagania praktycznych zastosowań, a jego dokładność jest nie gorsza starszych modeli.

Słowa kluczowe: realizacja projektu, przekroczenia kosztów, ryzyko, wycena parametryczna, planowanie bardzo dużych projektów, samoloty.

1. Introduction

Over the past 10-15 years some Large Projects in Aerospace Business which shall be abbreviated LPAB have been continuously in the press for their significant delays and cost overruns. Comprehensive application of new technologies causing significant problems in development (e.g. Boeing F-35, 787), lengthy harmonisations in multi partner international programmes (Eurofighter, Airbus A400M) and severe challenges in modern, highly complex supply chain structures (Boeing 787) are the mainly mentioned reasons when it comes to these consequences. It seems as if it is a natural law that large projects face the described problems and although the consequences can be and sometimes are quite severe it does not protect the companies from happening it again. There is a wide range of impacts e.g. delayed delivery to customers forcing them to define interim solutions at additional costs but if cost overruns reach dimensions threatening a company´s economic basis (like with EADS/Airbus and A380/A400M) then it could be vital to a company to have a reliable estimation of risk with regard to potential delays and cost overruns of an envisaged future project. In general the consequences of cost overruns and/or delays come along with wrong and inefficient allocation of resources like time and money leading to waste of taxpayers or investor's money. Given the number of employees in German aerospace business of approximately 100,000 [Beschäftigte der Deutschen…] in 2011 generating a revenue of 25.7bn € [Umsatz der Deutschen…] and the revenue of European aerospace business in 2012 which is 186.8bn € [Umsatz der europäischen…], it is obvious that there is some potential for savings if it could be possible to reduce delays and cost overruns and thus waste of money with LPABs.

This leads to some basic reflections. A private enterprise has to be profitable in order to succeed and to survive in business. As nowadays aerospace companies are mainly privately owned companies this is applicable to them, too. As a consequence, the products and services of those aerospace companies have to be profitable. Since the making of aircraft is usually organized in projects or programmes which are large projects, the projects or programmes have to be profitable in order to pay back the relevant investments plus a profit. At the same time, profitability is inseparably linked to risk. The higher the risk, the higher is the potential gain and thus profitability. Now risk is resulting from uncertainty. Uncertainty is increasing with project duration and the extent to which new technologies are applied. With LPABs being very long lasting projects and involving a lot of new technologies, uncertainty and thus risk is high. Given a certain LPAB, there is an opportunity to make profit associated with a certain risk. If it is possible to reduce the risk while retaining the opportunity to make a certain profit, profitability of the project improves. With the main overall risk to LPABs consisting of delays and cost overruns, profitability can be improved if the risk for delays and cost overruns can be reduced. That means, if project duration and volume can be predicted more precisely, the risk for delays and cost overruns will be reduced while profitability will be improved through allocating resources when and where they are actually needed. This questions the efficiency of presently applied planning methods to yield proper estimates for project volume and duration. The initial approach to this problem started off with learning curves and developed into parametric estimate models mainly for cost. Over decades it was a main attempt to make the models robust for technical progress and to increase flexibility with regard to different kind of aircraft but there were still significant deficiencies. This article introduces a new approach to overcome above deficiencies and the corresponding parametric estimate models to determine project volume and duration for future aircraft projects.

The context of risk reduction with appropriate contingency and using parametric estimation for the risk and contingency elements is also described by Hollmann [2009]. This draws the attention to historical activities of cost and time estimating techniques for aircraft development and production in science and practical application.

Until the mid 1930ies, apart from some rudimentary work from time to time, there was no widespread use of any cost estimating technique beyond a laborious build-up of labour-hours and materials. A type of statistical cost estimating had been suggested in 1936 by T. P. Wright in the Journal of Aeronautical Science [Wright 1936] which came to be called the learning curve. The learning curves were used to predict the unit cost of airplanes in the early years of World War II. In the late 1940's, the U.S.A. began a study of multiple scenarios concerning how the country should proceed into the age of jet aircraft, missiles and rockets. It started off with the Source Book of WWII Basic Data: Airframe Industry [U.S. Air Material Command 1947] the U.S. Air Force published in 1947 and which presented a number of learning curves relating direct hours per pound of airframe weight to the cumulative number of aircraft produced. Most of the early statistical analysis focused on direct factory labour and learning curves like the RAND report of Asher and Harold [1956]. The learning curves of 50s fighters, bombers and transports turned out to be close for subsonic but not for supersonic aircraft. This led to adding speed as another independent variable in the early 60ies, and it proved to be statistically significant. It was a problem of those days that the data available were frequently too sparse to support statistical analysis. Still, for example, direct labour hours, total engineering cost and total tooling cost were expressed in equations depending on aircraft maximum speed and airframe weight. The introduction of computers solved the problem of calculating, but not the data problem. The result was the study "Cost-Estimating Relationships for Aircraft Airframes" of Levenson and Barro in 1966 [Levenson, Barro 1966] that presented a complete parametric cost model for the development and production of airframes. It followed the general pattern of the earlier study, but despite a search for additional independent variables that would explain more of the variance, the conclusion was that weight and speed were still the only two that could be justified statistically [Large 1981, pp. 4, 8, 16]. The model produced estimates that were found useful although it was still thought that the accuracy could be increased by including additional variables. Therefore other companies developed models using additional variables like the Planning Research Corporation [Sanchez, DeiRossi 1967] that used among others airframe weight growths, year of Initial Delivery (ID) for the delivery rate [Large et al. 1976, p. 1]. In 1972, the RAND Corporation published an updated version of the 1966 Levenson and Barro model [Levenson et al. 1972] that considered additional aircraft in the database, further a method for distinguishing prototype and full development programmes. They also improved the methods and forms of regression but only added quantity of aircraft as an independent variable along with weight and speed which still were considered the main explanatory variables. Levenson et al. [1972] emphasized that there was great uncertainty when the equations were applied to aircraft whose technological or performance characteristics are outside the range of the sample. For example, the introduction of new materials like titan or stainless steel instead of aluminium spoiled the historical references of aircraft built of 100% aluminium. Such a problem arose again some years later with the introduction of composites and other new materials. In general, the technological progress was regarded as a problem as it makes it difficult to extrapolate results generated with a past data base to future aircraft. However, an underlying assumption of parametric estimating was that the historical framework on which the parametric model is based is applicable to the new project (i.e., the technology has not radically changed) [Dysert 2008, p. 1].

Referring to Large [1981], in 1972 the U.S. Navy contracted Noah et al. [1973] to conduct a study that resulted in an airframe model which included a novel index of technological advance as well as a user judgement of complexity. But although Large recognized the index of technology advance, he regarded judgemental factors as unreliable to include in a parametric cost model [Large 1981, p. 18]. The problem of considering technological advance has also been addressed by the study of Alexander and Nelson [1972] who developed a technology index for aircraft turbine engines using a number of engine characteristics. This index was then used in an engine development and production cost model [Nelson, Timson 1974] for calculating the Time of Arrival (TOA) at its 150-hr Model Qualification Test that feeds into the cost model. The models have not only been calculated for military but also for civil jet engines. This technique has been extended to the complete aircraft in the study of Stanley and Miller [1979]. In addition to Nelson and Timson [1974], they aimed to provide a quantitative framework to characterize not only the change in but also the level of the technology of the aircraft. This should help to make different aircraft comparable. The model attempted to predict first flight date based on a combination of performance variables. Unfortunately, technological advance as measured by the variables appeared to be totally unrelated to aircraft cost. In 1975, Large et al. [1976] conducted a further study aiming to update the earlier studies of Levenson and Barro [1966] respectively Levenson et al. [1972]. The study developed Cost Estimate Relationships (CERs) for estimating development and production costs of aircraft airframes on the basis of weight and speed. The study checked 15 new variables (e.g. climb rate, range factor, static thrust etc.) apart from weight and speed for inclusion in the model but none of them turned out to be suitable. With already three RAND models (Development and Procurement Cost of Aircraft, DAPCA) from 1966 to 1976 and some more of other organizations, the question arose which of them is the most useful. This was evaluated in a study of Large and Gillespie [1977]. Apart from the three already mentioned RAND models, they included one developed by Planning Research Corporation (PRC) in 1965 and revised in 1967; two form J. Watson Noah (JWN) Associates (1973 and 1977); and a transport aircraft model from Science Applications, Inc. (1977). It turned out that all the models had deficiencies and should be used with caution although it could be observed that the newer models appeared to be better than the older ones. In general the accuracy of the models compared is moderate. Only about one third of the cost estimates showed a deviation of less than 10 percent compared to the actual costs. In 1987 an update of the study by Large et al. [1976] was conducted by Hess and Romanoff [1987]. The update mainly included new aircraft platforms. CERs were developed for many cost elements but still utilizing empty weight and speed as the basic size/performance variable combination. None of the equations met the standard-error-of-estimate goal of –16/+20% in accuracy. Finally, also an attempt to add a technology index to help account for the ever increasing complexity of aircraft was explored but only within the fighter category. As a technology index Hess and Romanoff [1987] used the predicted first flight date in months since 01.01.1940, assuming a constant and linear increase in technical complexity. It turned out that it was only the engineering CER in which the technology index was significant along with the variables airframe unit weight and specific power. This CER was compared with alternate equations that did not include a technology index. Based on standard error comparisons, it was determined that the inclusion of a technology index had little benefit for the fighter airframe CERs.

Like in the early 70s, the introduction of new materials to aircraft manufacturing led to a study of how to consider the new materials in existing airframe cost estimates. This was conducted by Resetar et al. in 1991. They expanded the variables previously considered in estimating airframe costs to examine the effects of advanced materials as composite materials and new metal alloys. It turned out that for both the recurring and non-recurring airframe elements, the cost of aircraft with these new materials would increase. An adjustment factor was then developed to account for the effect of advanced materials on airframe cost within each cost element.

In 2001, Younossi et al. [2001] expanded upon the 1987 Hess and Romanoff [1987] and the 1991 Resetar et al. [1991] studies investigating the effects of material mix, manufacturing technique, and part geometric complexity on cost but the results were only applicable to fighter/attack-class aircraft. One year later, Younossi published another research where he and his team elaborated on Military Jet Engine Acquisition [Younossi et al. 2002]. The study focused on estimation of parameters for various turbofan engines, and the addition of new observations to update a series of parametric cost-estimating relationships published in earlier RAND studies. In addition to the conventional performance and physical parameters, they added a series of technical risk and maturity measures like "Technology Readiness Levels" and a "Technical Change Scale for Aircraft Engines" in order to improve the estimates. These measures quantified the relative difficulty of developing and producing a particular engine. However, it turned out that for new engine developments, basic performance measures define the CER. There was no significant technical maturity/risk measure that correlated with development cost and development schedule. Till date, these fundamental weaknesses have not been solved to a satisfying extent [Killingsworth 2013, p. 16].

In summary, although, over the years, a lot of effort has been put into finding suitable independent variables to explain airframe cost, only partial improvements could be observed. Research has not yielded a one-model-fits-all solution. Furthermore, only very few models used time as a dependent variable that allows the prediction of project duration. In addition, due to technical progress and, for example, the use of new materials in aircraft design, the historical data and thus the models which rely on it became of little benefit when a new aircraft project deviated significantly from its predecessors. Finally, it has to be borne in mind that the models have been only applied to military aircraft and they do not consider any non-technical changes in aircraft development and production like complex supply chain structures and multi-national aircraft programmes including the resulting problems. This forms the underlying problem of this research that there is no model available that meets these requirements.

As a consequence, this research served to define a method of estimating project duration and volume of LPABs that considers technical progress without its outdating impact on the database used for the model. It has to be applicable to military as well as civil aircraft and it has to consider the complexity of modern supply chain structures as well as multi-national projects. The method should predict project duration and volume and thus reduce risk for delays and cost overruns.

2. Methods

2.1. Approach to Variables

The effort to develop new products in aerospace business has been increasing constantly over the past decades as they became more and more sophisticated and thus complex. To stem these projects and to use resources more efficiently a concentration of aerospace companies on national and later international level took place. Since necessary expenses (and capacities) even brought national budgets at their limits, multi-national co-operations were introduced. Another concept aimed at sharing resources and risk was brought to a new level by Boeing (Dreamliner) when it started to outsource a great portion of development and production work packages to suppliers all over the globe with the 787 program. Actually, it turned out that this concept meant a significant increase in risk to the Aircraft Manufacturers (AMs) that could – if it materializes to a great extent – even threaten the economic basis of the AMs. This brief recall of the general situation of AMs leads to the key characteristics all large aerospace projects feature nowadays. Dealing with and developing tailor made state-of-the art technique has always been a key feature of aerospace business due to high performance demands with regard to, especially, military use. But also civil aerospace business with outstanding requirements towards reliability, safety and cost effectiveness aligns with these characteristics. The extent to which new high tech is applied correlates with the risk it is generating for the project. Since it is uncertain how long the development of new high tech will take and, sometimes, even if it ever works, there is a risk linked to the need for additional time and budget depending on what is technically feasible and what are the preferences of the AM since to a certain extent there is a trade-off possible between both. Therefore this technical key characteristic could be named Technical Complexity (TC). Another key characteristic could be named Organizational Complexity (OC) and it describes the organizational structure of a project which includes participating AMs and the structure of the partnership as well as the supply chain. One could assume that with more partner companies involved and more suppliers and supplier levels engaged, the risk of problems leading to cost overruns and/or delays will increase. Last but not least a political key characteristic (Political Complexity) could summarize all constraints given which are beyond direct influence of the AM and thus, although not necessarily supporting a project, are an inevitable pre-requisite of it. This could comprise governmental interests/decisions, strikes, fundamental changes in global political situations etc. Of course it would be conceivable to make a more detailed approach by distinguishing more detailed characteristics of a dedicated project and thus identify more complexities but as there is only a limited number of existing projects to test any hypothesis. Consequently, the number of variables should be kept small. It is assumed that these key characteristics put a certain risk on aerospace projects to be reflected in requirements for time and budget. If this is true and there is a common pattern behind, than it would be of interest if similarly structured projects with regard to time, budget (volume) and the above mentioned characteristics, lead to similar figures of time and budget requirements. This would allow to do a dedicated prediction of total project duration and volume and thus to identify potential delays and cost overruns against the planned project duration and volume. Considering these three complexities, the Political Complexity is the least tangible of the characteristics introduced above and therefore further investigations will focus only on the TC and OC. With the above mentioned reflections the following variables can be defined.

2.2. Definition of Independent Variables

Technical Complexity, TC (X_{tc}): TC is described by the degree of development and research effort required and the degree of introduction of new techniques in production. In order to make the TC tangible and measurable, the following was considered. A new scheme should be introduced that focuses on the extent to which new technologies are applied in a given product. The adopted approach uses technology ratings. The new approach consists of 5 levels which are rated from 1 to 5 and each level is assigned to a certain level of new technologies introduced with 1 being the level of lowest introduction of new technology. The individual level is defined as follows:

Level 1: Application of available, proven technology.

Level 2: Application of mainly available, proven technology, moderate adaption.

Level 3: Combination of available, proven technology and enhanced technology.

Level 4: Combination of some available, proven technology but mainly enhanced technology and some new technology but no technology leap.

Level 5: Mainly enhanced and new technology inclusive technology leaps.

The above could be applied to aircraft projects in the way that some technical areas of an aircraft are identified and rated according to the above mentioned scheme. It takes into account that usually not all technical areas of an aircraft (structure, engines, equipment etc.) experience the same level of new technologies to be introduced. This, in turn, depends mainly on the purpose of the aircraft. Therefore 5 areas were defined:

- Airframe and Manufacturing,
- Flight and Flight Control Systems,
- Avionics,

- Propulsion,
- Interior/Armament/Payload.

Above areas have been identified as main areas of technical changes when it comes to development of a new aircraft. In order to make different aircraft projects comparable with regard to TC, a total score is calculated just by multiplying the level numbers of the different technical areas. The approach assumes that the potential impact of problems resulting from technical risks in individual areas is similar. This approximation was done in order to avoid too much complexity of the approach but leaves some potential for future refinements.

Organizational Complexity, OC (X_{oc}):
OC reflects the number of AMs, countries and suppliers involved and the degree of de-centralized production. In order to make this OC tangible and measurable, some simplifications had to be introduced. Since nowadays, due to fusions of aerospace companies on national level, in general only one national key player is remaining the number of AMs and countries involved was assumed the same. The de-centralized production and complexity of supply chain should be represented by the number of final assemblies in parallel of an aircraft and the number of suppliers. The number of final assembly contributes significantly to the OC as the number of specialists is usually limited. For further investigations the product of the number of countries, final assembly sites and suppliers was used as indicator of OC.

Planned Project volume (V_{pl}): The planned budget of a certain project is needed to calculate cost overruns.

Time (t) and the **Planned Project Duration (t_{pl}):** t describes the time elapsed since start of the project and t_{pl} is the reference for delays.

2.3. Definition of Dependent Variables

Cost Overruns ($C_{overrun}$): It can be further distinguished between cost overruns caused by TC ($\mathbf{C}_{overrun\ tc}$) and by OC ($\mathbf{C}_{overrun\ oc}$). In a simplification it was assumed that cost overruns only relate to delays. That means that additional cost is generated proportionally to the delays a project faces. This leaves aside that delays can be avoided or even recovered to a certain extent by increasing capacity like investing in machinery or man power [Pinedo 2009, pp. 63-71]. However, the measures are limited by lead times of machinery deliveries and the limited availability of dedicated workforce and thus justify the assumption.

Delays (Δt): It can be further distinguished between delays caused by TC ($\Delta\mathbf{t}_{tc}$) and by OC ($\Delta\mathbf{t}_{oc}$).

Total Project Duration (t_{to}): This is the total project duration under influence of TC, $\mathbf{t}_{tc}$ and under influence of OC, $\mathbf{t}_{oc.}$ The review of the data base showed that sometimes comprehensive preparation work has been performed until a project has been officially launched or contracted. In addition, some projects make extensive use of capability demonstrators or other development studies which pave the way for certain technologies then further matured for practical application. However, as each of the aerospace projects under investigation has its very individual history it is difficult to define certain criteria for project start which will be fulfilled by a considerable number of projects. At the same time, hardly any project related event is made public like the official launch date with civil aircraft projects or contract signature date with military aircraft projects. Therefore the latter was chosen to constitute the date of project start. When it comes to the definition of the end of the considered timeframe, there was the problem that in civil aircraft manufacturing it was unclear how many aircraft of one model would be built as it depended on customer orders over production time. With military aircraft projects, the number of aircraft to be procured is defined in the procurement contract but projects like Eurofighter or A400M showed that this number might be adjusted over production time. Bearing in mind that delays and cost overruns mainly occur during the development and production preparation phase, the initial delivery to the customer was chosen to constitute the end of the timeframe in consideration and thus the reference date for delays.

Total Project Volume (V_{to}): It can be further distinguished between the project volume related to TC (**V_{tc}**) and OC (V_{oc}). The Planned Project Volume had to be specified as well. With civil aircraft projects, because of the initially unknown total number of aircraft to be built, the planned project volume comprises only the non-recurring cost that comprises the development and production set-up expenses. Therefore this volume should be the reference for cost overruns. With military aircraft projects the contractual Planned Project Volume comprises both the non-recurring and the recurring cost. That means the expenses for development, production set-up as well as the production of the aircraft to be procured. Therefore the available data base of the military projects was checked for a possible split of the initial contract volume in a non-recurring and a recurring volume and, if possible, it was referred to the first as the Planned Project Volume for further analysis.

2.4. Estimation Model

Development of the estimation model started with the overall equations for project duration and volume.

$$t_{to} = t_{tc} + t_{oc} = t_{pl} + \Delta t_{tc} + \Delta t_{oc} \qquad (1)$$

$$V_{to} = V_{tc} + V_{oc} = V_{pl} + C_{\text{overrun tc}} + C_{\text{overrun oc}} \qquad (2)$$

The equations (1) and (2) assume that the total project duration and the total project volume consist of shares related to TC (t_{tc}, V_{tc}) as well as OC (t_{oc}, V_{oc}). The sum of these shares equal the planned duration (t_{pl}) and planned volume (V_{pl}) of a project plus the corrections in the form of delays (Δt_{tc}, Δt_{oc}) and cost overruns ($C_{\text{overrun tc}}$, $C_{\text{overrun oc}}$). Theoretically it is possible that the corrections could also be negative. It depends on the planned values. If planning is made very generous, the corrections would be only small or even negative. Since the data processing of delays and cost overruns allowed separating the technical from the organizational components, the equations were split into two parts. As the available data base did not provide any hint with regard to the share of both complexities, the assumption was made that there is an equal share in the values which leads to the following CERs and time estimate relationships:

$$t_{tc} = 0.5\ t_{pl} + \Delta t_{tc}(X_{tc}) \tag{3}$$

$$t_{oc} = 0.5\ t_{pl} + \Delta t_{oc}(X_{oc}) \text{ and} \tag{4}$$

$$V_{tc} = 0.5\ V_{pl} + C_{\text{overrun tc}}(X_{tc}) \tag{5}$$

$$V_{oc} = 0.5\ V_{pl} + C_{\text{overrun oc}}(X_{oc}). \tag{6}$$

The values for the variables were extracted out of the data base of the chosen sample of projects and the characterizing TCs and OCs will be estimated according to their definition. The intention is to determine the mathematical form that best explains the relationship. However, simple description of the relationship does not explain the mechanisms of the relationship. “Association is not causation.” Therefore the mechanisms which describe how the dependent variable is affected by the independent variable have to be analysed and evaluated [Kurowski, Sussmann 2011, p. 363]. This is done by conducting regression analysis. In a next step, for each of the four equations a regression analysis has been done in order to receive values for the parameters and an indication of the goodness of fit of the approximation. The resulting four linear equations for t_{tc}, t_{oc}, V_{tc} and V_{oc} were then implemented in equation (1) and (2) leading to an estimate value for t_{to} and V_{to}. The results allow further analysis of a project given by comparing the expected project values with the planned project values and thus defining different scenarios of mitigation measures. The latter could be either changing elements which influence the complexities or simply adjust the planned project values.

2.5. Operational Definitions/Research Method

The sample projects chosen were the Boeing 787 Dreamliner, Airbus A380 and A350 civil aircraft projects, the A400 European military transport aircraft programme, the Lockheed Martin F-35B Lightning II Joint Strike Fighter and the Eurofighter military aircraft because these are the only projects of recent years which qualify for this research. All mentioned projects are very large in volume, some multi-national, expected project duration of several years, state of the art techniques and had been in the press for many problems resulting in delays and cost overruns and thus very suitable for the intended analysis. Main source for data gathering was press releases from 2007 until 2014 and internet articles since the selected projects had been closely monitored by the mass media. The database was searched for reasons for key characteristics of the projects, cost overruns, delays, cause-and-effect combinations as well as quantitative estimations. A profile of each project object was created featuring the total score of new technologies applied in dedicated technical areas of the aircraft and the number of countries/final assembly sites/suppliers involved in the project. In addition, the planned project volume and duration, as well as the delay and cost overruns related to the two complexities were extracted. In order to make the data comparable, all cost figures were converted into 2010 constant Euros only by using the relevant rate of inflation to escalate and de-escalate the relevant values. However, this was an approximation as it assumes that the costs related to the structure of the project (labour, material, services) change to the same extent as the basket of goods and services which define the inflation rate.

3. Results

3.1. Summary of Empirical Results

The empirical results are shown in the following tables. In addition, the values for t_{tc}, t_{oc}, V_{tc} and V_{oc} were calculated according to the equations (3), (4), (5) and (6) and shown in column 7 and 8 of Table 1 and Table 2.

Table 1. Summary of Empirical Results for Delays

1	2	3	4	5	6	7	8
Project	Originally planned Project duration t_{pl} in months	TC $\mathbf{X}_{tc}$	OC $\mathbf{X}_{oc}$	Delay due to TC $\mathbf{\Delta t}_{tc}$ in months	Delay due to OC $\mathbf{\Delta t}_{oc}$ in months	Project Duration due to TC $\mathbf{t}_{tc}$ in months	Project Duration due to OC $\mathbf{t}_{oc}$ in months
B787	049	540	0784	19.75	20.25	44.25	44.75
A380	067	432	0526	10.50	10.50	44.00	44.00
A400M	077	720	1785	19.25	26.75	57.75	65.25
A350	078	360	0254	12.00	06.00	51.00	45.00
EF	121	900	1920	16.00	40.00	76.50	100.5
F-35B	086	960	1080	23.13	13.87	66.13	56.87

Source: Processed data extract of dedicated press releases from 2007 until 2014 and internet articles.

Table 2. Summary of Empirical Results for Cost Overruns

1	2	3	4	5	6	7	8
Project	Originally planned Project Volume V_{pl} in constant 2010 bn €	TC $\mathbf{X}_{tc}$	OC $\mathbf{X}_{oc}$	Cost overrun due to TC $\mathbf{C}_{overrun\ tc}$ in constant 2010 bn €	Cost overrun due to OC $\mathbf{C}_{overrun\ oc}$ in constant 2010 bn €	Project Cost due to TC $\mathbf{V}_{tc}$ in constant 2010 bn €	Project Cost due to OC $\mathbf{V}_{oc}$ in constant 2010 bn €
B787	05.20	540	0784	4.10	2.30	6.70	4.90
A380	12.29	432	0526	2.32	2.32	8.47	8.47

A400M	23.05	720	1785	2.51	4.25	14.04	15.78
A350	10.80	360	0254	0.88	0.36	6.28	5.76
EF	22.74	900	1920	1.50	3.00	12.87	14.37
F-35B	190.10	960	1080	54.30	44.70	149.35	139.75

Source: Processed data extract of dedicated press releases from 2007 until 2014 and internet articles.

3.2. Analysis of Empirical Results – Methodology

The model was tested by conducting at first a correlation analysis of the identified project durations and volumes versus the complexities of the different projects followed by a check if a given correlation is significant. In order to check the initial assumption that the project duration and volume follow a linear function, these two steps were also conducted assuming a non-linear (exponential) function. In the next step, the linear and the nonlinear Pearson´s correlation coefficients were compared, and if both were significant (F-Test), the model with the higher correlation coefficient was further analysed by conducting a full regression analysis for the relevant data set. Excel Data Analysis Regression function was used with $Y_i = t_{tci}$, t_{oci}, V_{tci} or V_{oci} and $X_i = X_{tci}$ or X_{oci} or the logarithmised values. The result yielded slope (β_1) and intercept (β_0) of the model equation, standard errors of parameter estimation ($s(\beta_0)$, $s(\beta_1)$) and of regression model(s) as well as the coefficient of determination (R^2). This gave an indication of the goodness of fit of the model. Furthermore the goodness of the individual parameters of the regression function were checked by conducting a t-test with the test criteria t-statistics followed by a check of the standard deviation. Finally, the usual prerequisites of a regression analysis were checked for the results.

3.3. Summary of Analysis Results

Analysis of Project Duration under influence of Technical Complexity

The calculation of Pearson´s correlation coefficient R yielded $R_{ttc\ Xtc} = 0.8600$ and $R_{lnttc\ lnXtc} = 0.81839$ with the logarithmised values. As the F-Test indicated a correlation of both, a linear relationship was regarded as more likely. The regression analysis yielded a coefficient of determination (R^2) value of 0.73960 that means that approximately 74% of the variation is explained by X_{tc}. That means that the duration of the project that has been assigned to TC can be explained to an extent of approximately 74% by the model used to express the TC. The standard error of regression model (s) with almost 7 month is moderate and in line with the t_{tc} values in Table 1. The check of the goodness of the individual parameters of the regression function was done by conducting a t-test with the test criteria t-statistics. Instead of defining a required level of significance, the level of confidence that corresponds to the t--statistics value (two-sided confidence interval) was calculated by using the degrees of freedom of this model (df = 5), t-statistics values and a t-statistics programme

[Andreß 2001]. This yielded a level of confidence of 0.9698 for β_0 and 0.9801 for β_1. That means with a confidence level around 97% and 98% TC does influence project duration. For evaluating the goodness of the parameters it is referred to the standard error. $s(\beta_0)$ (9.15732) reaches about one third of the relevant parameter value (27.44532) while $s(\beta_1)$ (0.01327) is of about a quarter of the parameter value (0.04472). That means the probability that these parameter values represent the true values is high. In a last step, the regression model was checked against the prerequisites of a regression analysis and all requirements were fulfilled.

That leads to the equation describing t_{tc} dependent on TC $X_{tc:}$

$$t_{tc} = \beta_0 + \beta_1 X_{tc} = 27.44532 + 0.04472 X_{tc} \text{ in months.} \tag{7}$$

Analysis of Project Cost under influence of Technical Complexity

The initial correlation analysis revealed that there was no correlation as long as the F-35B project volume was considered. It turned out that the project volume of the F-35B was of a much different (greater) dimension than the other projects so that it prohibited further analysis of the sample. Therefore, the F-35B was excluded from the volume analysis which limited the validity of the analysis to a project volume ranging from 6 to 15bn €. Calculation of Pearson´s correlation coefficient R yielded $R_{Vtc\ Xtc} = 0.87216$ and $R_{lnVtc\ lnXtc} = 0.88126$ with the logarithmised values. As the F-Test indicated a correlation of both, a non-linear relationship was regarded as more likely. It could be concluded that the project volume is probably increasing even more progressively over X_{tc} than the project duration t_{tc}. The regression analysis yielded a R^2 value of 0.77661 that means that approximately 78% of the variation is explained by X_{tc}. Thus the volume of the project that has been assigned to TC can be explained to an extent of approximately 78% by the model used to express the TC. The standard error of regression model (s) with approximately 0.21 is moderate and only of around 10% of the $\ln V_{tc}$ values. The check of the goodness of the individual parameters of the regression function now with only four degrees of freedom yielded a level of confidence of 0.8812 for β_0 and 0.968 for β_1. That means that with a confidence level around 88% and 97% TC does influence project cost. For evaluating the goodness of the parameters it is referred to the standard error. $s(\beta_0)$ (1.76268) is about half of the relevant parameter value (-3.49059) while $s(\beta_1)$ (0.27826) is about one third of the parameter value (0.89864). That means the probability that these parameter values represent the true values is basically high. In a last step, the regression model was checked against the prerequisites of a regression analysis and all requirements were fulfilled.

That leads to the equation describing V_{tc} dependent on TC $X_{tc:}$

$$\ln V_{tc} = \beta_0 + \beta_1 \ln X_{tc} = -3.49059 + 0.89864 \ln X_{tc} \tag{8}$$

In order to get V_{tc}, equation (8) is exponentiated.

$$V_{tc} = 0.03048\, X_{tc}^{0.89864} \tag{9}$$

in constant 2010 € valid for a minimum range of project volume from 6 to 15bn €.

Analysis of Project Duration under influence of Organizational Complexity

The calculation of Pearson´s correlation coefficient R yielded $R_{toc\ Xoc} = 0.85983$ and $R_{lntoc\ lnXoc} = 0.79725$ with the logarithmised values. As the F-Test indicated a correlation of both, a linear relationship was regarded as more likely because of the significant higher R. The regression analysis yielded a R^2 value of 0.73930 that means that approximately 74% of the variation is explained by X_{oc}. Thus the duration of the project that has been assigned to OC can be explained to an extent of approximately 74% by the model used to express the OC. The standard error of regression model (s) with approx. 12 months is moderate compared to the t_{oc} values in Table 1. The t-test with the test criteria t-statistics with 5 degrees of freedom yielded a level of confidence of 0.9683 for β_0 and 0.9801 for β_1. That means with a confidence level around 97% and 98% OC does influence project duration. For evaluating the goodness of the parameters it is referred to the standard error. $s(\beta_0)$ (10.12571) reaches about one third of the relevant parameter value (29.92160) while $s(\beta_1)$ (0.00827) is about a quarter of the parameter value (0.02785). That means the probability that these parameter values represent the true values is high. In a last step, the regression model was checked against the prerequisites of a regression analysis and all requirements were fulfilled.

This leads to the equation describing t_{oc} dependent on OC $X_{oc:}$

$$t_{oc} = \beta_0 + \beta_1 X_{oc} = 29.92160 + 0.02785 X_{oc} \text{ in months.} \tag{10}$$

Analysis of Project Cost under influence of Organizational Complexity

As with project cost under influence of TC, the F-35B values had to be omitted in order to find any correlation. The calculation of Pearson´s correlation coefficient R yielded $R_{Voc\ Xoc} = 0.88557$ and $R_{lnVoc\ lnXoc} = 0.76747$ with the logarithmised values. As the F-Test indicated a correlation of both, a linear relationship was regarded as more likely because of the significant higher R. The regression analysis yielded a R^2 value of 0.78423 that means that approximately 78% of the variation is explained by X_{oc}. Thus the volume of the project assigned to OC can be explained to an extent of approximately 78% by the model used to express the OC. The standard error of regression model (s) with approximately €2.6bn is moderate compared to the V_{oc} values in Table 2. The t-test with the test criteria t-statistics with 4 degrees of freedom yielded a level of confidence of 0.8668 for β_0 and 0.9786 for β_1. Thus with a confidence level around 87% and 98% OC does influence project volume. For evaluating the goodness of the parameters it is referred to the standard error. $s(\beta_0)$ (2.19083) is about half of the relevant parameter value (3.92542) while $s(\beta_1)$ (0.00175) is about a third of the parameter value (0.00578). That means the probability that these parameter values represent the true values is basically high. In a last step, the regression model was checked against the prerequisites of a regression analysis and all requirements were fulfilled.

That leads to the equation describing V_{oc} dependent on OC $X_{oc:}$

$$V_{oc} = \beta_0 + \beta_1 X_{oc} = 3.92542 + 0.00578 X_{oc} \tag{11}$$

in 2010 € valid for a minimum range of project volume from 5 to 16bn €.

Referring to the equations (1) and (2) t_{to} and V_{to} can be calculated with the equations (7)-(11):

$$\mathbf{t_{to} = t_{tc} + t_{oc} = 27.44532 + 0.04472\ X_{tc} + 29.92160 + 0.02785\ X_{oc} = = 57.36692 + 0.04472\ X_{tc} + 0.02785\ X_{oc}\ \text{in months}} \tag{12}$$

$$\mathbf{V_{to} = V_{tc} + V_{oc} = 0.03048\ X_{tc}^{0.89864} + 3.92542 + 0.00578\ X_{oc}\ \text{in constant 2010 €.}} \tag{13}$$

Equation (13) is valid for a minimum range of project volume from 6 to 15bn in constant 2010 €. This is the minimum intersecting set of values of the equations for V_{tc} and V_{oc}.

4. Discussion

In order to range the quality of the model, the standard error of each CER will be put in relation to the mean value of the underlying project value. The result is shown in Table 3.

Table 3. Mean Deviation of t_{tc}, V_{tc}, t_{oc} and V_{oc} in %

1 - s for	**2**- Mean for	**3**- s/Mean in %
t_{tc}= 7.35 months	Project Duration due to TC $\mathbf{t_{tc}}$ in months: 56.61	12.98
V_{tc}= 1.23bn €	Project Cost due to TC $\mathbf{V_{tc}}$ in 2010 bn €: 9.67	12.72
t_{oc}= 12.48 months	Project Duration due to OC $\mathbf{t_{oc}}$ in months: 59.40	21.01
V_{oc}= 2.64bn €	Project Cost due to OC $\mathbf{V_{oc}}$ in 2010 bn €: 9.86	26.77

Source: Processed results of regression analysis based on data of Table 1 & 2.

Table 4. Mean Deviation of different Cost Estimating Models

Sample Size	DAPCA I	DAPCA II	DAPCA III	PRC	JWN I	JWN II
	Mean Deviation in %					
30	32.25	24.38	19.13	30.25	20.00	10.88
100	34.13	21.38	17.50	26.50	11.66	10.14

Source: Large and Gillespie, 1977, p. 45, Table 10, aircraft A-7 not considered because of assumed gross error.

Column 1 shows the standard errors of each estimate relationship. For V_{tc}, s had to be exponentiated in order to get the money value. Column 2 depicts the values of project cost and duration according to Tables 1 and 2 and in column 3 the calculated relation between s and the mean project values is listed in percent. Referring to the only comparison of the quality of different cost estimate models [Boren 1967; 1976] which is the analysis of Large and Gillespie [1977, p. 45, Table 10], their table can be summarized as follows.

Comparing the mean deviation of V_{tc} (12.72%) and V_{oc} (26.77%) shown in Table 3 with the same of different historic cost estimating models shown in Table 4, it is obvious that the estimate for V_{tc} reaches a level of accuracy similar to JWN II while still using a smaller sample size. V_{oc} does not fully reach the level of accuracy of JWN I or DAPCA III and is more in the range of DAPCA II but definitely better than the PRC model taking into account the small sample size. With regard to the time estimates t_{tc} (12.98%) and t_{oc} (20.01%) the result is similar. While the level of accuracy of t_{tc} is comparable with the one of JWN II, t_{oc} does not fully reach the level of JWN I or DAPCA III. The latter can be seen in the range of DAPCA II but is significantly better than the PRC (Planning Research Corporation) model. Given the small number of heterogeneous projects – civil and military aircraft, transport aircraft and fighter aircraft – which is more challenging than the database used of Large and Gillespie [1977], the result has to be regarded as more than satisfying. It is obvious that the estimates related to TC are more accurate than the ones related to OC. An explanation for this might be that the delays and cost overruns related to TC are often explicitly mentioned in press release while the same for OC is very rare.

As the initial results were promising, the growth potential of the model developed should be discussed. At first, the assumptions made could be further reviewed and refined like the use of the inflation rate to adjust for different economic conditions, further it is mentioned the assumption that half of the project budget and duration is assigned to TC and OC. As with CERs in general, it would be conceivable that the introduction of further independent variables might improve accuracy, however, the current ones already explain the variations of the CERs by approximately 80%. Therefore it has to be deliberated whether the benefit of a probably small increase in accuracy outweighs the increase in complexity of the model. A significant growth potential is seen in the possibility to adapt the model to other areas as the explanatory variable X_{tc} is not limited to aerospace business and X_{oc} not either.

Finally, the developed tool is of significant benefit to potential customers, as it is easy to handle and does not require information which is not available to a customer. The information to calculate OC is easy to access and the input data to define TC depends on the specification of a new aircraft which is either defined by the customer or at least defined in close collaboration with the customer. The application of the tool does allow for an easy evaluation of the reliability of quotations especially the volume and the delivery plan. Since customers have to do comprehensive investments and preparation work before new aircraft can be commissioned, the main benefit results of a better alignment of investments and resources with the actual need and avoiding penalties. Military customers, for example, have to prepare infrastructure, train pilots and to assure that the latter complete their required flight hours while civil customers have to invest in pilot and crew training as well as maintenance capacity and capability. As better alignment usually means postponement, it leads to delayed and reduced cash out which increases profitability. In this case, the project consists of the in-service phase of an aircraft or fleet of aircraft. At the same time, the need for expensive ad hoc interim solutions like aircraft leasing will be reduced, thus saving cost and increasing profitability.

5. Conclusion

The underlying phenomenon of this research was the significant delays and cost overruns of many LPABs in recent years. It was concluded that reducing the risk for both deviations would increase profitability of a project. That means, if project duration and volume could be predicted more precisely, the risk for delays and cost overruns would be reduced while profitability would be increased through allocating resources when they are actually needed. In the past, comprehensive research was done on parametric cost estimating with the aim to predict development and production cost of future aircraft but the models mainly lacked the ability to be applied to a broad variety of aircraft and especially to cope with technical progress without its outdating impact on the database used for the models. Furthermore, the complexity of modern supply chain structures as well as multi-national projects has not been considered in any legacy model. In order to overcome these deficiencies a model has been developed that is based on Technical as well Organizational Complexities which characterize the individual projects and yield a more realistic prediction for project volume and project duration. Verifying the model with up to five contemporary aircraft projects confirmed the principle applied with an accuracy within the range of legacy models. With focussing on Technical Complexity there is no further need for distinguishing between civil and military aircraft, fighter and transport aircraft and technical progress is only resulting in increased TC. Supply chain characteristics are well captured by OC and both complexities show growth potential for further refinement depending on the effort applied. The outcome of the model allows a more realistic allocation of investments and resources (personnel) with significant reduction of idling time as well as avoiding of penalties and thus a significant improvement of project profitability.

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