Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2005-312

Taking knowledge engineering to the sky

E. Kesseler and W.J. Vankan

This report has been based on a paper presented at European Conference for Aerospace Sciences (EUCASS), Moscow, 4-7 July 2005.

Customer: National Aerospace Laboratory NLR
Working Plan number: AV.1.G
Owner: National Aerospace Laboratory NLR
Division: Aerospace Vehicles
Distribution: Limited
Classification title: Unclassified
June 2005

Approved by:

Author	Reviewer	Managing department
1/6/2005	16/6 '05	24-06 2005.

Abstract

Design of complex systems, like aircraft, requires contributions from various engineering disciplines. Expanding functional requirements in the coming decades, as reflected in European aeronautical vision 2020, increase the demands on the aircraft design process. While single discipline improvements are being depleted, multidisciplinary design and optimisation are becoming imperative. Moreover, different organisations (business units, suppliers, etc.) at different locations provide the discipline specialists involved in the aircraft design process. In addition, according to an aircraft industry characteristic, the early aircraft design phases determine most of the total life-cycle cost.

This paper presents a case study on multidisciplinary aircraft design based on the European initiative Value Improvement through a Virtual Aeronautical Collaborative enterprise (VIVACE). The value of such collaborative engineering and knowledge management is illustrated by using an example from the important early aircraft design phases. In VIVACE, dedicated metrics assess the achievable benefits against the original targets. An evolutionary approach for the collaborative engineering case study allows guiding subsequent iterations to maximise success in achieving the high level objectives. In this way VIVACE takes collaborative engineering to the sky.

Contents

(17 pages in total)

1 Introduction

Aircraft design involves complex processes that require multiple disciplines to achieve competitive products. As in depth knowledge of the various disciplines is required, the design has to be performed by a team of specialists. Usually each discipline, and the participating specialists, have their own models from which dedicated methods are derived and which are supported by a variety of custom-made or Commercial Off-The-Shelf (COTS) tools. This plethora of models, methods and tools is often not harmonised and complicates the organisation of the product design process. Consequently the collaboration between the various specialists involved becomes a key factor to competitively achieve the final product quality.

At the same time, the collaborative aircraft design process forms a challenge by itself, requiring technologically advanced methods and tools to be effective. The traditional approach for this design process has been to perform an exploration of the design space at top level during the early design phases, using heuristics or simplified tools like spreadsheet interpolation. The resulting initial top-level design produces a preliminary allocation of targets per discipline. Subsequently each discipline performs an initial design iteration guided by the results of the top-level design. These initial results are fed back to the global design. Typical target times for this phase are weeks to a month [1]. Once the top-level design is chosen, the conceptual design phase is entered (as indicated in Fig. 1), where the same top level and discipline level activities are carried out, but with more accurate and hence more time consuming methods and supporting tools. Already the refined models and their data are diverging from the top level models. Once the concept is defined, the definition phase is entered, where each discipline uses its full precision tools and methods. The current practice of aircraft design, with its many disciplines like aerodynamics, structures, engine, thermodynamics, avionics, economics, remains viable. However the resulting time-to-market is increasingly at odds with customer expectations [2].

Fig. 1 illustrates the aircraft industry’s characteristic that the choices made during early design phases already determine the majority of the total life-cycle costs of the aircraft. Consequently there is an incentive to improve the available knowledge about the complete product to be developed and apply it as early as possible in the product’s development process. The majority (65%) of the total life cycle costs are already determined during the feasibility phase, increasing to 85% in the concept phase. Therefore this paper focuses on these early design phases. Independent commercial pressures mandate a reduction of product development time to improve the time-to-market. In addition economic pressures demand a reduction of the total life-cycle cost. The latter two concerns are being addressed by the European initiative VIVACE [3].

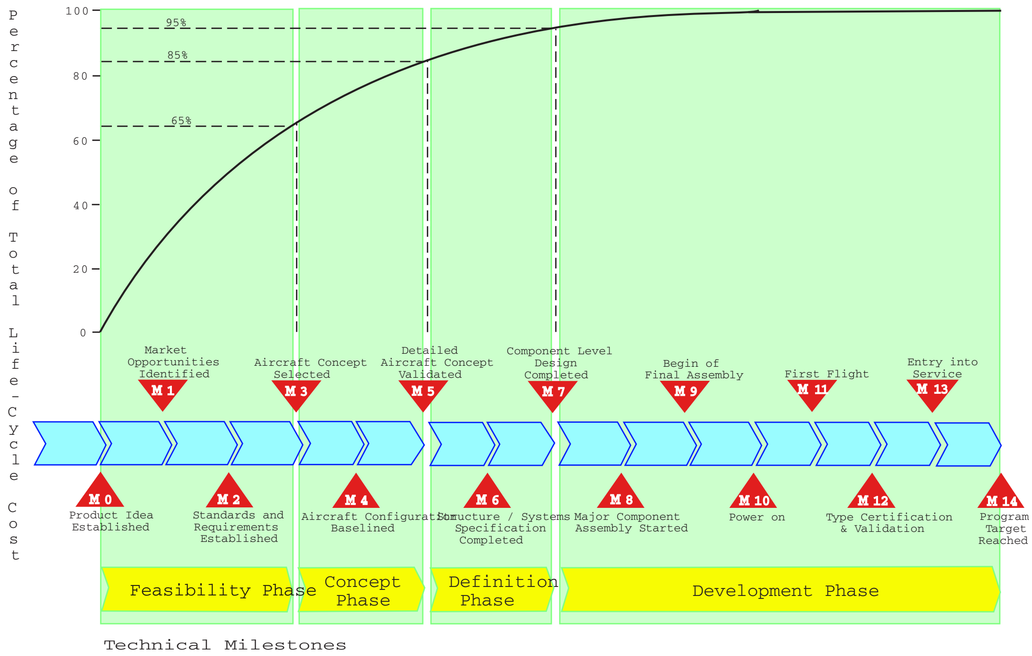

Fig. 1 Relative amount of Total Life-Cycle Cost Fixed during the Aircraft Lifecycle Phases (Cost data taken from [4], technical milestones from [5]).

Aircraft design and manufacturing involve significant financial investment of up to 10 billion Euros for new large commercial aircraft like Airbus A380 or the smaller Boeing 787 [6]. These investments and associated commercial risks have to be shared by a number of partners. Consequently these partners are involved from the start of the design. The resulting concept of a system integrator with first tier suppliers is already described by [7]. For the manufacturing phases this is also referred to as the extended enterprise. This paper discusses the expansion of such collaboration within the extended enterprise into the early design phase. Exploitation of high-tech solutions and continuous innovation are the only way to remain competitive, as stated in the European vision 2020 [2]. For design this implies that the specialists from the various disciplines are provided by different organisations. Each risk-sharing organisation uses its own proprietary methods and tools resulting in a heterogeneous set. Like their organisations, these specialists are geographically dispersed. The effects of these industry characteristics on collaborative solutions are considered more closely below.

In the following first the notions of concurrent engineering and coordination are explained. Next the context is focused upon the elaborated part of the VIVACE case study to improve collaborative engineering during the early design phases. The subsequent sections provide information about the objectives for feasibility/concept design phase. The advantages of the proposed approach are then discussed before arriving at the conclusions.

2 Concurrent engineering

In order to better understand the elaborated case study, first some general definitions are given.

Concurrent Engineering is defined in [8] as “a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from concept through disposal, including quality, cost, schedule, and user requirements”.

Similar needs as in aircraft development also apply to spacecraft development. The European Space Agency [9] defines concurrent engineering as “a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle”. Their concurrent engineering approach is based on five key elements:

- a process;
- a multidisciplinary team;
- an integrated design model;
- a dedicated concurrent engineering facility;
- a software infrastructure.

The case study elaborated below, presents improvements on the last three elements for the feasibility phase and concept phases of aircraft design (up to M5 as shown in Fig. 1).

3 Coordination

To realise the time-to-market reduction as one of VIVACE’s objectives, the coordination between the various design tasks needs to be improved. In order to better understand coordination, the often-referenced definition from [10] is included. Coordination is defined as managing dependencies between activities. Table 1 classifies activity dependencies and presents some approaches from different disciplines to solve these dependencies.

Table 1: Classification of Dependencies, Examples compiled from [10]

Dependency	**Examples of coordination processes**	**Methods from computer science**	**Methods from organization theory**
Shared resources	First come/first serve, budgets, managerial decision, market-like bidding	Techniques for processor scheduling and memory allocation	Different organizational structures, budgeting, organizational power, resource dependence
Producer/ consumer relationships	Notification, sequencing, tracking (e.g., "Just In Time") Concurrent engineering	Data flow and Petri net analyses	Participatory design; market research
Simultaneity constraints	Scheduling, synchronization	Mutual exclusion	Meeting scheduling; process modelling
Task/subtask	Goal Selection, task decomposition	Modularization techniques; artificial intelligence planning	Management by objectives; grouping people into units

From the observation that information technology (IT) tools can improve coordination, [10] predicts three effects. The first order effect will be that IT supported coordination will replace human coordination. The second order effect will be that coordination will increase as it becomes more affordable. The third order effect will be that the increased communication opportunities will change the organisation. In some highly competitive industries, like consumer electronics or personal computers, such changes have already occurred. Table 2 provides an overview of different types of resource allocation. To increase design process efficiency, providing more affordable coordination allows choosing from a larger set of resource allocation mechanisms to select the most suitable one.

Table 2: Different Mechanisms for Resource Allocation, from [11]

Step	**Market**	**Hierarchy**	**Network**
Identify needs	Based on specializations in market	Based on specializations in firm	Based on specializations in network
Identify resources	Broadcast a RFP and wait for replies, check advertising	Use known set of resources in firm	Use known set of resources belonging to network
Choose resource	Evaluate bids	Specialization, workload	Specialization
Assign resource	Contract	Employment relation	Network membership

Classification of coordination and possible resource allocation mechanisms serves as inspiration for change. The approach taken by the case study discussed in the next section of this paper, is to make coordination between tools available and affordable facilitating knowledge management. Subsequently new design strategies can materialise, like automated Multidisciplinary Design and Optimisation (MDO) or object oriented modelling of aircraft disciplines, aiming at the third order effect on aircraft design. VIVACE will apply knowledge management (see Fig. 2) to retain such experiences for re-use.

The next section describes the case study, the Value Improvement through a Virtual Aeronautical Collaborative Enterprise (VIVACE) initiative to realise this approach.

4 Case study: approach

4.1 Top-level work streams

VIVACE applies a three-tier management process to innovate aircraft design. The top tier result will be the long-term impact the initiative will have on European competitiveness and the aeronautics industry's ability to deliver air transport solutions that will meet society's needs in accordance with the European vision 2020. The second tier, and main project result, will be the consolidation of all activities and deliverables into the VIVACE system. This system will be a set of reference methods, processes and tools for the future of a competitive European aeronautics industry, as mentioned in the European vision 2020. The third tier will comprise all research results emerging from the project. These deliverable results are the VIVACE system components, see Fig. 2.

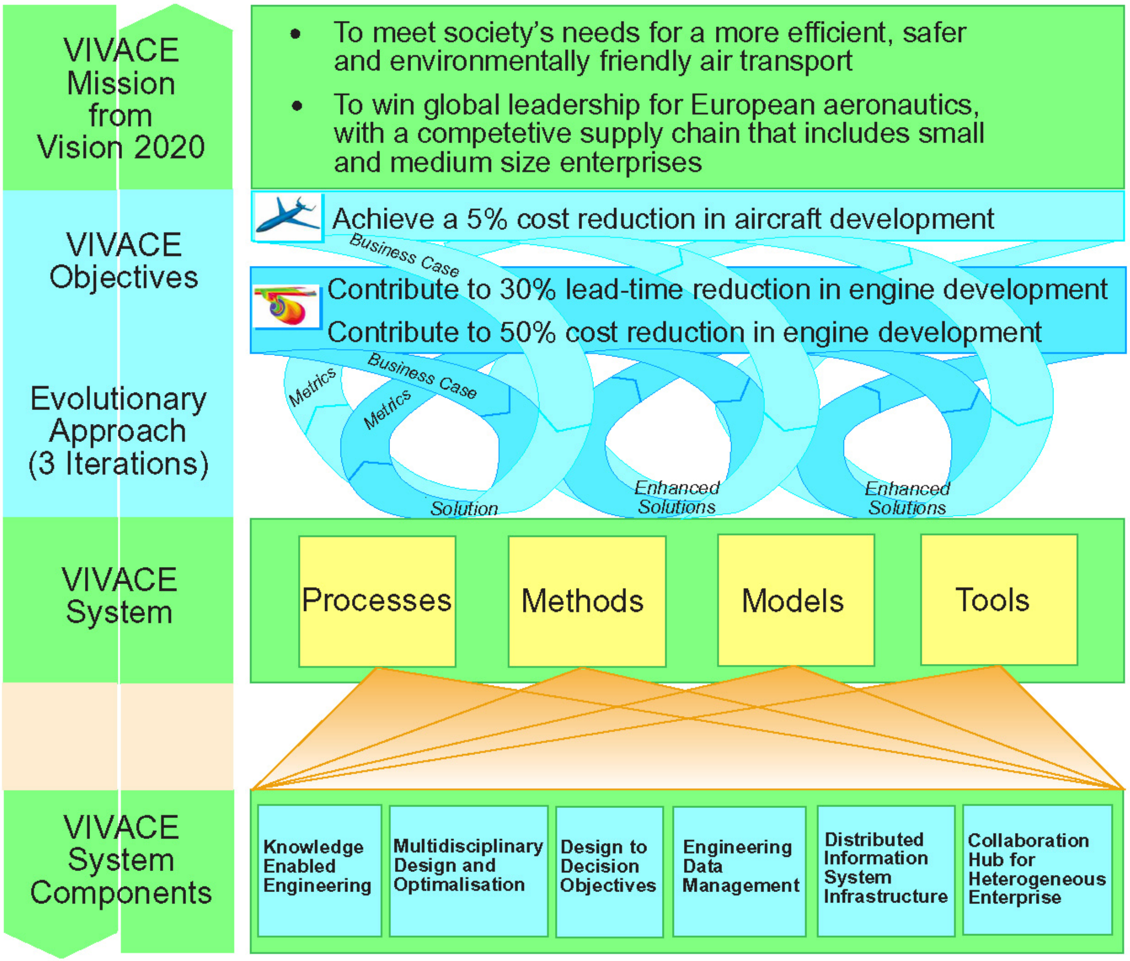

Fig. 2: The Relation between VIVACE Mission, Objectives and Realisation.

Evolutionary management [12] focuses on continuous intermediate deliveries that provide user value. The resulting user feedback is used to guide further system development. Taking this evolutionary approach into account, VIVACE uses three main iterations, while allowing for intermediate minor iterations at VIVACE system component level (see Fig. 2).

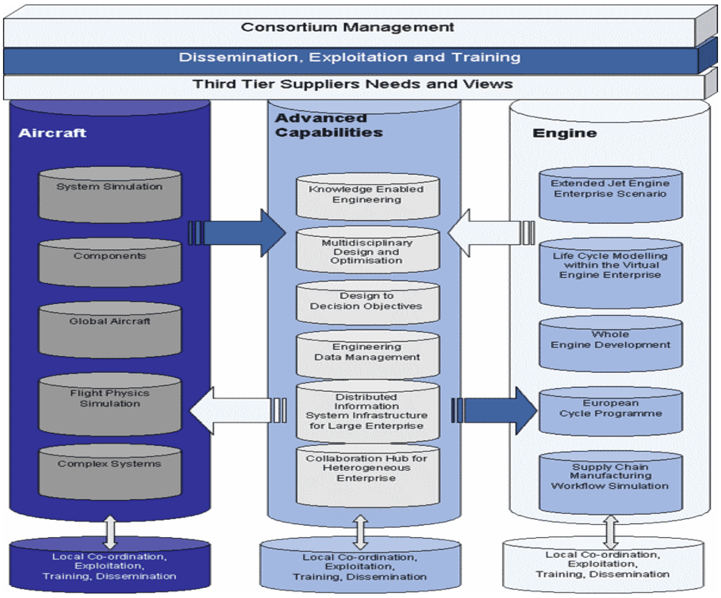

Fig. 3: The Relation between the Three Main Work Streams [3].

VIVACE research is organised in three technical work streams [3], depicted in Fig. 3. Based on the realities of the marketplace stated in the European Vision 2020, the first two work streams are dedicated to aircraft and engine respectively. The third work stream focuses on advanced capabilities, providing innovative technological solutions to enable collaborative engineering within and between the first two technical work streams. As such the advanced capabilities facilitate the integrated design model and provide a facility and a software infrastructure, three of the five key concurrent engineering elements.

4.2 Advanced Capabilities work stream

The Advanced Capabilities work stream provides the technology to ensure that the VIVACE objectives can be achieved. The work stream is organised by technical areas, each representing a technology with a high innovation potential for aircraft design and engine design. These technology areas concern knowledge enabled engineering, multidisciplinary design and optimisation, design-to-decision objectives, engineering data management, distributed information infrastructures for large enterprises and collaboration hub for heterogeneous enterprise.

The aircraft and engine work streams express their business needs. The advanced capabilities assist to transfer these needs into information technology requirements. Through the understanding of the state-of-the-art in the respective technological areas, the Advanced Capabilities work packages can address the feasibility of these technical requirements. After addressing these requirements, the innovative solutions are provided to the business driven aircraft and engine work streams for validation through detailed scenarios executed in the integrated VIVACE collaborative engineering environment.

4.3 VIVACE metrics

In true evolutionary fashion the success of VIVACE is being measured by comparing the expressed business needs of the aircraft and engine works streams with the stated VIVACE objectives, i.e. the user value obtained. The top level achievements are focused on achieving a 5% cost reduction in the development of a new aircraft design, contributing to a 30% lead time reduction in engine development and contributing to a 50% cost reduction in engine development as depicted in Fig. 2.

Both a top-down and a bottom-up metrics definition process are used. The top-down approach is based on an aircraft-development-processes model highlighting metrics like critical paths, critical loops, monitoring of critical design costs and coordination blocking the supply chain, complemented by qualitative criteria.

Given the scarcity of new aircraft and engine designs entering into service and the commercial sensitivity of the cost and time-to-market data involved, auxiliary metrics have to be derived to asses the realisation of the VIVACE top-level objectives. This bottom-up approach associates metrics and targets to each technical area and amalgamates these metrics into higher-level metrics at advanced capability level. An as-is state-of-the-art development process model is assessed using these metrics. Ranking the results obtained allows assessment of the user value obtained and guides the advanced capabilities effort to achieve the stated VIVACE objectives, complying with the basic objectives of the evolutionary approach [12].

Based on the above-mentioned need to apply improvements as early in the product life-cycle as possible, this paper concentrates on the aircraft feasibility/concept design phases (up to M5 in Fig. 1). The business driven requirements dealing with the effective sharing of information in these design phases are considered, as this is one of the critical aspects in the collaborative extended enterprise. The technology solutions developed are part of the advanced capabilities work stream topics namely multidisciplinary design optimisation and distributed information systems infrastructure for large enterprise. The following sections of this paper elaborate the chosen approach, which is innovative for the domain, and they present some results.

5 Case study: results

5.1 Feasibility/concept phases of aircraft design

The feasibility/concept phases of aircraft design include design disciplines like aerodynamics, structures, engine sizing, flight mechanics and weight and balance. For engine design in these phases the disciplines concerned are thermodynamic design, aerodynamic design and structural design.

As aircraft design has matured, single discipline conventional design cannot provide the required major improvements anymore as identified in the European vision 2020. Consequently a multidisciplinary approach is required. Additionally, new and unconventional configurations (e.g. blended wing body aircraft) have to be assessed with a level of detail and confidence similar to conventional designs.

5.2 Object-oriented paradigm

A physical object-oriented approach is proposed for new aircraft feasibility design. This approach reorganises existing methods and tools as well as it adds new ones. The new approach relies on an object-oriented model of aircraft design, allowing merging of numeric and geometric design information. Also the disciplines are divided into components based on information coupling. Fully or partly automated analytical methods assess the resulting aircraft design. Powerful mathematical resources assess technical design risk. A collaborative environment supports the exchange of models and data between the various disciplines involved to perform an overall aircraft design optimisation process. Providing automatic exchange of data between disciplines allows for IT support of the overall design optimisation process. Mathematical techniques can be employed to (semi) automatically explore more regions of the design space to find interesting optima realising true multidisciplinary design optimisation. Information technology allows the creation of workflows between the various models, methods and tools, i.e. the knowledge available at the various proprietary networks of the risk-sharing partners involved. Workflows obviate the need to consult discipline experts for every design variant considered, as the tools remain at the heterogeneous networks of the partners. Such solutions respect the rights of the knowledge owners while supporting collaboration in an integrated design network. This heterogeneity reflects the reality that an integrator cannot mandate a uniform set of tools or IT infrastructure for all partners in its supply chain.

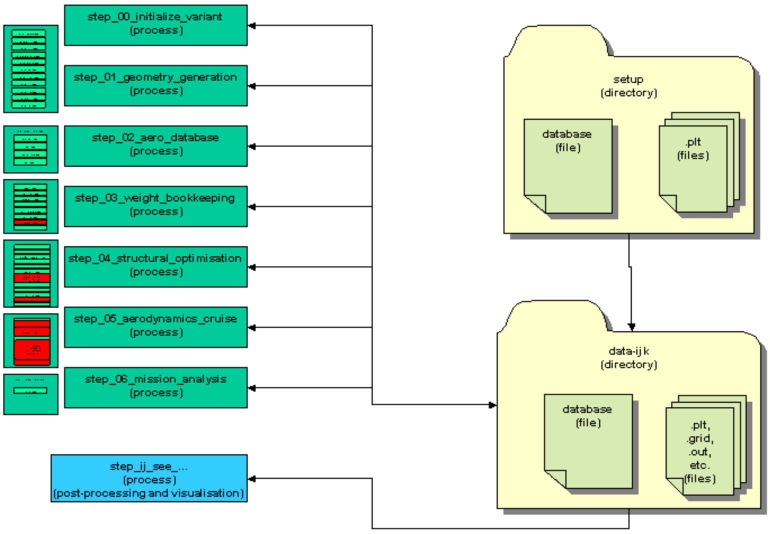

Fig. 4: Partial elaboration of aircraft design sub-processes.

Fig. 4 illustrates part of the aircraft design analysis processes. Each process consists of (sub)processes. The object-oriented approach allows to easily exchange or add (sub)processes e.g. add landing gear load to wing structural optimization process to explore and to optimise for taxiing conditions.

Target applications addressed by this approach are new derivatives of existing aircraft and all new aircraft, including novel unconventional concepts. Comparing conventional and unconventional aircraft configurations in a homogeneous way improves inter-disciplinary communication and human communication to considerably reduce the probability for showstoppers or unbalanced design in the early aircraft development phases (milestones M1 - M5 in Fig. 1). The resulting extended enterprise optimises aircraft families and aircraft fleets in an economic context.

A simple example of a top-down metric to assess this new aircraft design process is the calendar time needed for a feasibility study (a VIVACE objective depicted in Fig. 2). An example of a bottom-up metric is the effort needed to integrate a new optimisation algorithm in the design workflow or to integrate a new algorithm to calculate an unconventional wing into the total aircraft design.

5.3 Benefits

Using the object-oriented paradigm reduces design costs. It allows assessing unconventional configurations or deploying innovative methods while arriving at the same quality of the early aircraft design.

The physical object oriented approach reflects the extended enterprise of geographically dispersed single discipline specialists and their organisations.

The physical object oriented approach supports exchanging single discipline tools when partners change, which is not uncommon for risk sharing partners in new aircraft design. Additional data attributes ensure backward compatibility with the unique data structure required by the methods and tools already in use. Modern information technology allows improvement of the methods and tools used, into a continuously evolving collaborative engineering facility.

Data access and data security in a geographically dispersed extended enterprise requires deploying adequate security technologies. The various risk-sharing partners may have different data access rights implying the need for multiple authorisation levels and security attributes. Additionally non-risk sharing partners, like airports and certifying authorities, need access to some data as well. Key improvements for this complex environment are realised in a harmonised “data environment” where all partners have the appropriate access to design data, covering aspects like:

- direct link to partners’ heterogeneous internal data systems;
- harmonisation of data structures;
- support of different types of workflow and life-cycle data;
- secure and well managed data exchange among partners;
- connection of specific conceptual design tools and methods.

Geometry data stand out, as these are large in size, need to be exchanged at least daily between the integrator and the risk-sharing partners and use intricate formats. As these data sharing and security concerns are not domain specific, affordable COTS solutions from the general domain can be deployed so resources can be concentrated on the real value adding, improving the aircraft design process. This contributes to the software infrastructure element of collaborative engineering.

5.4 Future outlook

Collaboration opportunities, similar to those of the discussed case study, also exist for later phases of the aircraft design between first tier supplier and its second tier suppliers. As an example, MDO of Dutch industrial suppliers in the definition phase (see Fig. 1) is described in [13]. Consequently methods and tools like multidisciplinary optimization, risk assessment and heterogeneous networks can also have relevance for the second tier suppliers during later design phases i.e. can be beneficial to more parts of the supply chain.

As the design process moves towards the development phase (ref Fig. 1), 3rd tier suppliers become part of the design network and hence the collaborative environment. Knowledge management in such collaboration comprises the technical processes, its application on the product and at personnel level. It operates at all levels within the network from prime contractors through to the lowest level tier supplier to support the entire product life-cycle, including the production phase where the global supply chain has to operate based on the design to manufacture its parts. As such this work contributes to the vision of achieving a competitive supply chain by improving coordination to facilitate collaborative engineering.

6 Conclusion

The major part of aircraft total life cycle costs is determined in the early design phases, so design improvements concentrate on these phases. Due to the maturity of today’s aircraft design, achieving significant improvement requires multidisciplinary design optimisation. The aircraft design teams involve multiple organisations and are geographically dispersed. Collaborative engineering can improve such design by providing an integrated design model, a facility and a software infrastructure to the multidisciplinary team as illustrated in the case study. Such collaborative engineering allows creation of a continuously evolving facility incorporating new methods and tools e.g. for automatic optimisation or assessing unconventional designs. Using metrics the case study can assess how well it achieves its objectives. Using the evolutionary approach the effort of the next iteration can be focused on those areas, which will provide most benefits to the early phases of aircraft design, as such taking knowledge engineering to the sky.

Abbreviations

COTS	Commercial-Off-The-Shelf
IT	Information technology
MDO	Multidisciplinary Design and Optimisation
RFP	Request For Proposal
VIVACE	Value Improvement through a Virtual Aeronautical Collaborative Enterprise

Acknowledgment

The VIVACE integrated project is partly sponsored by the Sixth Framework Programme of the European Community (2002-2006) under priority 4 “Aeronautics and Space” as integrated project AIP3 CT-2003-502917.

References

1. Chachere, J., J. Kunz, and R. Levitt, Can You Accelerate Your Project Using Extreme Collaboration? A Model Based Analysis 2004 International Symposium on Collaborative Technologies and Systems, Stanford University, August 2004
2. P. Argüelles, et.al, Report of the group of personalities, European aeronautics: a vision for 2020, 2001
3. Anonymous, VIVACE, Annex 1, Description of Work, October 2003
4. J. Roskam, Airplane Design, Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing and Operating, RAEC, Ottawa, Kansas, 1991
5. T. Pardessus, Concurrent engineering development and practices for aircraft design at Airbus, ICAS2004, 2004
6. D. Pritchard, A. MacPherson, The trade and employment implications of a new aircraft launch, the case of the Boeing 7e7, December 2003
7. D.C. Mowey, International collaborative ventures in US manufacturing, Cambridge MA, Berlinger publishing company, 1988
8. J. G Lake, Concurrent Engineering – Systems Engineering Revisited? MORS Symposium at West Point, New York, USA, 1991

9. Anonymous, ESA, What is concurrent engineering, http://www.esa.int/export/SPECIALS/CDF/SEMQOF1P4HD_0.html, accessed November 2004

10. T. W. Malone and K. Crowston, The Interdisciplinary Theory of Coordination, ACM Computing Surveys, 26(1), p87-119, 1994

11. T. W., Malone, K. Crowston, and G. Herman, (Eds.), Tools for Organizing Business Knowledge: The MIT Process Handbook, Cambridge, MA: MIT Press, 2003

12. T. Gilb, Competitive engineering, Chapter 10, page 1-26, http://www.gilb.com/, June 2003 accessed December 2004

13. J.H. van Tongeren, Design method for cigar shaped bead stiffening in shear loaded glass-pps webs, BRP49221N, NIVR or NLR-CR-2004-507