Chapter 20
Concurrent Engineering and Integrated Aircraft Design

Richard Curran, Xiaojia Zhao and Wim J.C. Verhagen

Abstract With the increasing size and complexity of development projects at large companies and organizations in the aviation industry, concurrent engineering (CE) and integrated aircraft design has become of crucial importance in the design process of new products. In order to remain a competitive position and achieve a customer driven approach, aspects of the product's life cycle should be adopted at an early stage in the design process. These aspects include, among others: the overall cost performance and the ability of new system integration. This chapter discusses the implementation of CE in the life cycle of aircraft and systems in general. Challenges related to process parallelization and multidisciplinary design, involving the exchange of knowledge and information throughout the design process, are covered. Supporting techniques along with practical case studies are presented to illustrate the implementation of CE and IAD in real life. Expected future developments with respect to CE as applied to aviation conclude this chapter.

Keywords Aviation · Aircraft life cycle · Concurrent engineering · Design process integration

20.1 Introduction

The civil aviation industry plays a crucial role in fostering trade and making the world quickly accessible and connected. As of 2014, world civil aviation generates a total direct output of $606 billion and is responsible for 8.7 million direct jobs [1]. It has been reported [2] that in 2009 the civil aviation industry in the U.S. provided 10.2 million jobs, contributed $1.3 trillion in total economic activity and accounted for 5.2 % of total U.S. gross domestic product (GDP); these estimates clearly

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J. Stjepandić et al. (eds.), *Concurrent Engineering in the 21st Century*,
DOI 10.1007/978-3-319-13776-6_20

incorporate indirect economic output. Air carriers transported 3.1 billion passengers in 2013 as well as a mere 0.5 % of world cargo volume—which however accounts for over 35 % of world cargo value. In 2012, commercial aircraft production was shown to be in a prolonged up-cycle, shown in Fig. 20.1 [3, 4] and largely driven by the growth of passenger travel demand in Asia and the Middle East. Moreover, the innovation in aerospace technology, such as the new engine development for the Airbus 320NEO and Boeing 737MAX, also generate significant product demand. It is forecasted that between 29,226 and 35,280 commercial aircraft are expected to be produced over next 20 years [5, 6], with estimates recently revised upward [7].

Commercial aircraft can be subdivided into a range of products. Typically, seating capacity, configuration and range are taken as the primary characteristics to segment the aircraft market. Starting from the small, the business jet aircraft segment serves the need for personalized transport; business jets are typically employed to transport small groups of people from point-to-point. The main manufacturers in this segment are Bombardier Aerospace, Gulfstream Aerospace, Dassault, Cessna and Embraer. The regional airliner segment of the market serves capacities between 20 and 100 passengers on short- to medium-range flights, typically for continental routes that act as feeder routes (or 'short-hops') in the conventional hub-and-spoke system of airline transport. The regional airliner segment can be further characterized by considering the two main types of aircraft: turbofan-powered and turboprop-powered. Turboprop aircraft have the longest history in the regional market and typically have greater fuel economy [and thus lower direct operating cost (DOC)] and lower noise when compared to turbofan aircraft. However, the latter can operate at higher cruising speeds, which can lead to higher utilization and consequently higher operating revenue. In practice, both types are utilized in the regional airliner market. Major manufacturers operating in this segment are Embraer, Bombardier, and ATR.

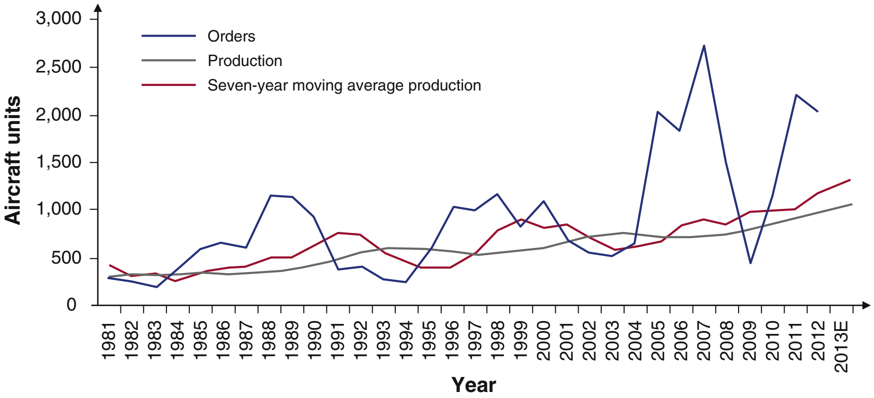


Fig. 20.1 History and forecast for large commercial aircraft orders and production (1981–2013) [3, 4]

Perhaps the most recognizable aircraft market segments are formed by narrow-body (single-aisle) and wide-body (multi-aisle) transport aircraft, having a trans-continental range. In this market, Boeing and Airbus are the primary manufacturers, each offering a range of aircraft to serve a wide variety of routes and capacities. Though much is made of the distinction between hub-and-spoke and point-to-point airline strategies and associated developments in manufacturer portfolios, both major OEMs offer a range of products that can fit within both strategies. In recent years, Embraer, Bombardier and COMAC have been emerging as entrants in the narrow-body market, as they respectively offer the E195, CSeries and C919 narrow-body aircraft. These aircraft are positioned to compete with the workhorses of the Airbus and Boeing aircraft families (the Airbus A320 and Boeing 737).

With the reduced armed conflict in Afghanistan and Iraq, and a reduction in budget for traditional military active governments, global defence spending has declined. The impact of this downward trend is partly attenuated by an increase in defence spending in other countries such as the Middle East, India, China, Russia, South Korea and Brazil. Nevertheless a downward trend can be observed of global revenues for defense companies, which declined 1.3 % in 2012 and 1.9 % in 2011 (Fig. 20.2) [4].

In order to cope with this changing environment, the global defence industry has to find a way to grow profitably in a declining market and maintain an acceptable financial performance by reducing their costs.

In contrast, as highlighted, significant growth is forecasted for all segments of the civil aviation market. This puts significant requirements on its main stakeholders, including original equipment manufacturers (OEMs), aircraft operators and civil aviation authorities. It demands not only highly efficient production process with a large production capacity, but also user-friendly and environmentally friendly design, manufacturing and operation. This can be evaluated by certain

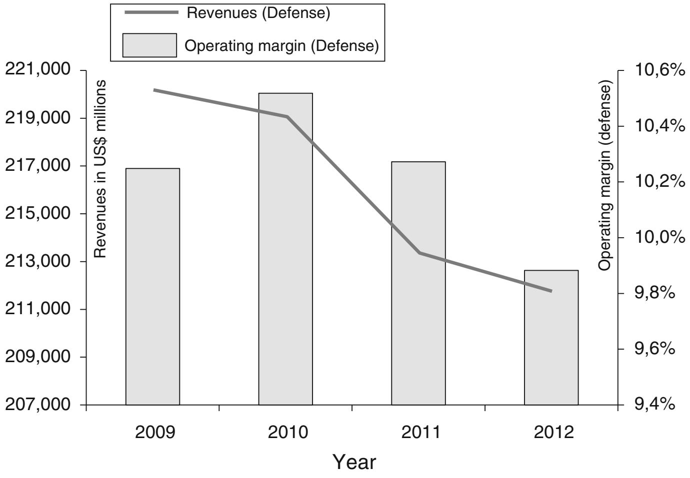


Fig. 20.2 2014 global aerospace and defense industry outlook [4]

performance indicators during the aircraft life time right through from concept design to the ultimate disposal, such as safety, economics (low cost), comfort (good infrastructure), noise (less noise), cleanliness (less emissions) and energy efficiency (less fuel burn). They are generally regarded as life cycle performance indicators and along with market expansion, are seen to represent the critical performance criteria of the aviation industry [8].

One of the main issues of the aviation industry that could limit market growth is the environmental impact caused by air transportation. With the expected three-fold air travel over the next 30 years, environmental awareness has become even more important [9]. With a current yearly production of 628,000,000 tons of CO_2, which represents 2 % of the human induced CO_2 emissions, the aviation industry has to react on this further evolving threat [10]. In Fig. 20.3, a prediction of the annual growth of international aviation emissions, made by ICAO [11], is given.

From this graph it can be seen that the global air transportation induced emissions will increase by a factor of five in 45 years time, if not reacted upon adequately. Multiple initiatives, such as Europe's Advisory Council for Aviation Research and Innovation in Europe (ACARE) [12], have been started to reduce environmental impact, which besides CO_2 also consists of NO_x emissions, perceived noise, and the environmental impact caused by aircraft manufacturing, maintenance and disposal [10]. In order to anticipate on this, companies involved in the aviation industry should strive for improvement of the efficiency of aircraft and engines, and improve the aircraft lifecycle and current Air Traffic Management system.

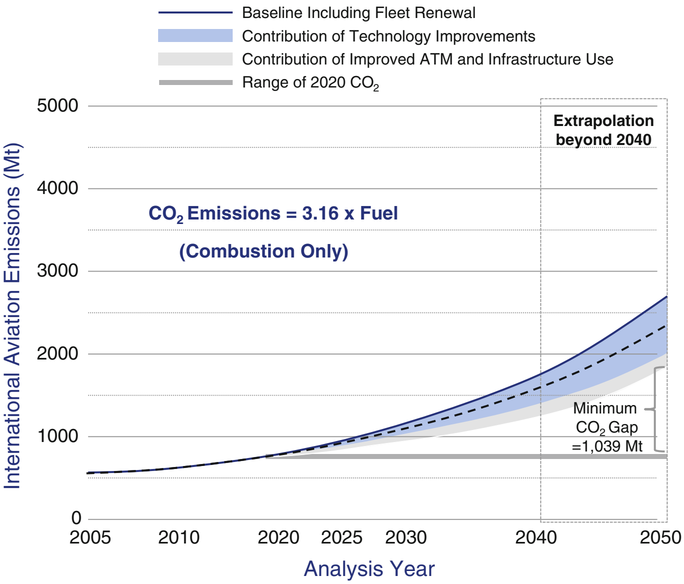


Fig. 20.3 ICAO/CAEP fuel burn trends from international aviation, 2005–2050 [11]

These developments highlight the need for an integrated and advanced design process that is able to ensure the concurrent synthesis of many life cycle performance drivers within a complex and collaborative aviation enterprise. It is the aim of this chapter to present recent developments in aviation research that contribute to this overall need.

The structure of this chapter reflects this focus. In Sect. 20.2, the aircraft life cycle including its phases and components are discussed. Subsequently, the aircraft design process is described in Sect. 20.3, which is then put into the context of concurrent engineering (CE) and its application to aviation in Sect. 20.4. In Sect. 20.5, applications of various elements of CE as presented in this book are discussed; this includes the areas of Multidisciplinary Design and Optimization (MDO), digital mock-up (DMU), value engineering (VE) and life cycle costing (LCC) within the context of aviation. Finally, a concluding section gives insight into future research and development of aviation from a CE perspective.

20.2 The Aircraft Life Cycle

The civil aviation activities relevant to the aircraft life cycle are categorized in Fig. 20.4. For each phase within the aircraft life cycle, a process or activity series are identified, along with the associated participants and relevant entities.

At the early phase of the life cycle, the research and development phase starts with identifying the current market needs. Standards and design requirements are then established so that based on a list of requirements (LOR), designers can generate promising aircraft concepts, accompanied by a series of feasibility and

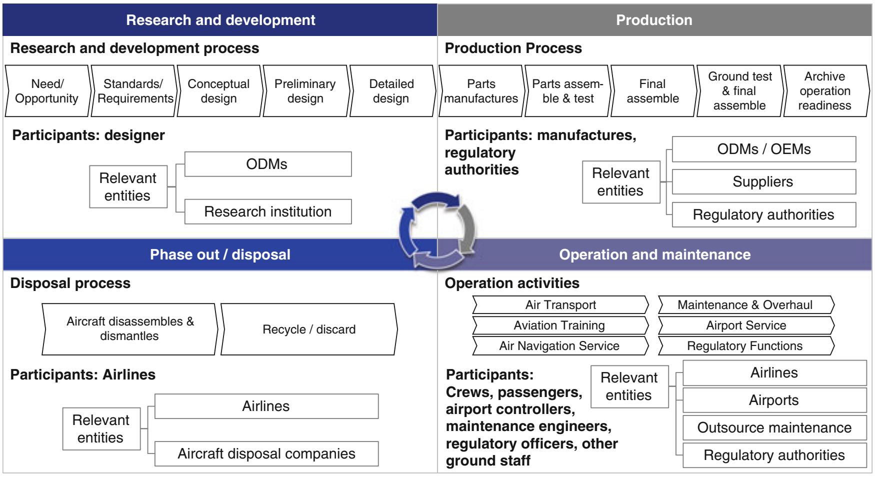


Fig. 20.4 Aviation industry relevant to aircraft life cycle [13–15]

verification studies. In practice, the design of aircraft is organized into design programs: a dedicated organization-within-an-organization aiming to design a (family of) aircraft and the supporting activities throughout the lifecycle (i.e. not only the product is designed, also production, operation and support are developed). For instance, as a global aircraft manufacturer, Airbus has design and engineering teams at multiple sites around the world that are involved in the same aircraft program [16]. In order to ensure that the required knowledge is available throughout the design process for each department, Airbus's headquarters in Toulouse, France gathers the top-level competencies. These include the architecture integration, general design, structural design and computation, integration tests and systems, and propulsion.

The actual design exercise starts from the conceptual design phase according to the performance and life cycle goals identified, and the designers are required to generate possible competing concepts, after which iterations on performance evaluation and optimization (on an aircraft level) are performed, leading to the selection of a baseline configuration. The output of the conceptual design is a 3-D geometric representation of the baseline aircraft design with associated performance indices. Subsequently, the concept is further developed through the use of parametric sizing studies in the preliminary design phase. The size of the baseline concept is refined while the aircraft level configuration is frozen, while modest changes on the sub-assembly and component level are still possible. The main deliverable of the preliminary design phase is a 3-D drawing and representation of the aircraft concept with sized components. Finally, the detailed design phase involves the precise design iterations from the global level for the whole aircraft to the system design level and ultimately the local level associated with detailed parts design. The final outputs are the detailed production drawings, finalized aircraft specifications and performance properties. Furthermore, design of the production process is carried out concurrently during the preliminary and detailed design phases. The entities involved in the research and development phase are the design group from the original design manufactures (ODMs) or the OEMs (such as the Airbus and Boeing companies) and research institutions such as aerospace research laboratories (e.g. ENAC, DLR and NLR) and of course universities.

Manufacturers and designers are working closely during the production process. Parts manufacturing is initiated firstly, followed by sub-assemblies for manufactured parts and components, and then the final assembly process is carried out. The testing of components and systems are conducted during the whole phase and once the ground tests are completed multiple prototypes are prepared for the first flight and a series of subsequent flight tests. When the aircraft is validated to have achieved all the standard specifications an airworthiness certificate can be issued by the regulatory authorities. Then mass production is initiated based on the orders received, with Airbus for instance building more than 1 A320 aircraft per day as per 2009. In addition, the aircraft needs to achieve operational readiness. The OEMs and ODMs invest significantly in intensive and automated manufacturing capabilities for the whole production and assembly process. Other supply chain entities and outsourcing manufacturing companies play a major role in the extended enterprise and the OEM becomes more of a designer and integrator, and there is additional input to be integrated from regulatory authorities such as FAA, CAA, EASA.

Operation and maintenance activities define the life cycle once the aircraft enters into service. Associated activities include air transportation operations, aviation training, air navigation service provision, maintenance and overhaul services, airport services and regulatory functions. The activities of the operation and maintenance process are performed simultaneously and recursively. As aircraft age, 'heavier' maintenance checks and overhaul activities are scheduled to keep the aircraft in an airworthy state. Other stakeholders during this lifecycle phase of course include the passengers, airline crews and tickets staff, air traffic controllers responsible for flight and ground control, and again regulatory authorities for example responsible for the continued airworthiness of each aircraft.

Aging aircraft are retired, sold-on, or disposed of according to the airlines' fleet management strategy. Based on the aircrafts' service condition, the disposal process is defined, and normally involves being 'parked' in a dry desert graveyard or being disassembled so that the dismantled parts can be recycled or sold-on by outsourcing companies involved in end-of-life-solutions.

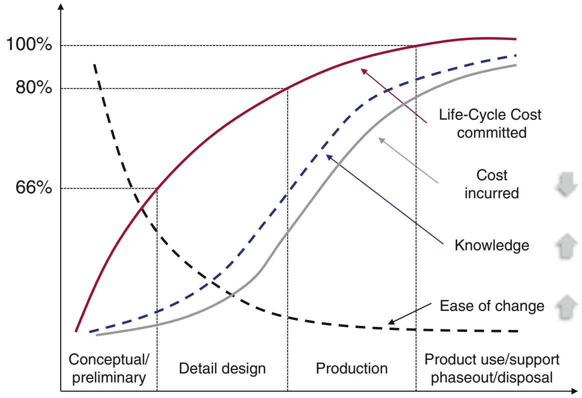
Cost performance is concerned with every aspect of the life cycle. It is the fundamental driving element within the aviation industry and air transport market, along with safety. All associated and relevant industry activities are assessed and even enabled by effective cost performance. From a depth perspective, all of the relevant disciplines and parameters for an aircraft or within air transport are highly interrelated and mutually influential, including for examples aerodynamics, materials, structures, systems (such as avionics, hydraulics and power), cost, market demand, environment impact and energy utilisation.

20.3 Integrated Aircraft Design Process

Considering the aircraft life cycle, the vital factor which controls the final decision of a bid is always cost. The cost performance needs to be evaluated within every aspect of the life cycle, including the life cycle activities and all participants. The cost associated with each phase of the design is shown in Fig. 20.5. The reduction of cost is always the goal of the whole aviation industry, along with extremely safe operational performance. Consequently, the evaluation of cost in an accurate and effective manner is always the goal of the analyst. While for cost engineers, it is important to link the design and cost properties together, and to reduce the cost while keeping the aircraft at a required performance and technical operational level. This demands an integrated design and development process, in which life cycle performance and requirements are considered at the early design stage.

After a century of design practice, the integration of disciplines and design process has evolved continuously and design activities have changed from a specialization focused approach to a more systems focused approach already in the

Fig. 20.5 Aircraft life cycle and cost, knowledge relation [13]



1950s. However, the analytical specialist remained more influential in some ways than the design engineer. In the 1970s, computer-aided design (CAD) exploded on the scene along with the promotion of a life cycle cost (LCC) approach within the design process, with the balance between performance, LCC, reliability, maintainability and safety being facilitated through the emergence of advanced information and computing technologies in the 1980s [17]. The trend is always on improving the design capability for reducing development time, and achieving more complete design synthesis at an earlier time.

Various advanced methodologies and technologies have been embraced over the years by aviation in order to advance the integrated design and development process, including: CE, product life management (PLM), multidisciplinary design optimization (MDO), DMU, collaborative engineering (CE), Digital Manufacturing, knowledge based engineering (KBE), etc. Each has definite strengths and is also inter-connected with the CE philosophy that has been developed initially in the 80s. This emphasizes the need for concurrent design and analysis that incorporates all aspects of the aircraft life cycle, integrating their influence into the design decision process and also helping to make the process more efficient. Gradually, based on the CE principle of process parallelization, the combined and integrated analyses and optimizations on multiple disciplines was promoted and facilitated. Ultimately, MDO in its broadest sense addresses the integration of aerospace analytical disciplines such as aerodynamics, propulsion, structures, and control—as well as manufacturing, operations and maintenance issues in the life cycle context. By employing mathematical optimization methods, a minimum weight or cost design can be achieved [18]. It can be used to strengthen the conceptual design process by providing more analytical design space for multi and inter-disciplinary integration and ultimate optimization. MDO has been applied successfully in multiple design programs, for instance the design of the Airbus A380, where numerical structural optimization incorporating lifecycle constraints [19] has resulted in significant weight savings. Multiple other success stories are available for the aviation domain—see e.g. Chap. 15 and Sect. 20.5. In addition, KBE techniques can now be employed to link the development of the central design geometry with the necessary extensive supporting knowledge so as to improve the efficiency of performing often repetitive and time consuming tasks, which frees the designer and engineers up for focusing on innovation and creative solutions [20]. Examples for the aviation industry are discussed in Chap. 10. A recent development is embodied in the value driven design (VDD) approach which embraces the concept of MDO but promotes it in a more performance driven way. Such VE techniques can be adopted in order to produce a balanced measure of product function, cost and ultimate utility. More theoretical background and practical examples of VDD are given in Sect. 20.5.

20.4 Concurrent Engineering Within Aerospace

CE was a term first coined by Winner et al. [21] of the DOD Institute of Defense Analysis and is defined in full in Chap. 2. The definition stresses the parallel, concurrent, execution of product and process design activities by integrating multiple design disciplines and upstream and downstream functions involved in the lifecycle of a product. CE is known under various names such as Simultaneous Engineering, Concurrent Product Development, and Integrated Product Development [22–24]. It has been noted that there are three fundamental characteristics: the early involvement of key participants, the team approach, and the simultaneous effort on different phases of the product development [25]. CE teams typically consist of the functions marketing, product engineering, process engineering, manufacturing planning, and sourcing activities. The principle focus initially was on the integration and alignment of design and manufacturing functions, while taking into account consumer demands and supplier capabilities.

Cross-functional CE teams incorporate experts focused on different aspects such as marketing on usability, engineering on functionality, production on manufacturability, and purchasing on affordability [26]. In such situations, communication needs to be predominantly personal and involve face-to-face contact [27]. The early involvement of relevant stakeholders in the design and development process enables exchange of preliminary information, thereby potentially reducing the number of engineering change orders, which are often the reason for delay in product development projects. Strategies for the exchange of preliminary information exchange may differ with the level of downstream uncertainty and costs of process idleness [28].

In order to support collaboration in teams and facilitate information exchange and use, significant effort has been made to develop engineering knowledge and collaboration tools [29], although these are still limited [30]. Lu et al. [30] with reference to the VIVACE European project [31] has reported that 26 % of project meetings in Airbus involve international partners and more than 400 one-day trips were taken by Airbus engineers to collaborate with other project members on a daily basis. They also spend an average of 49 % of their daily activities in meetings

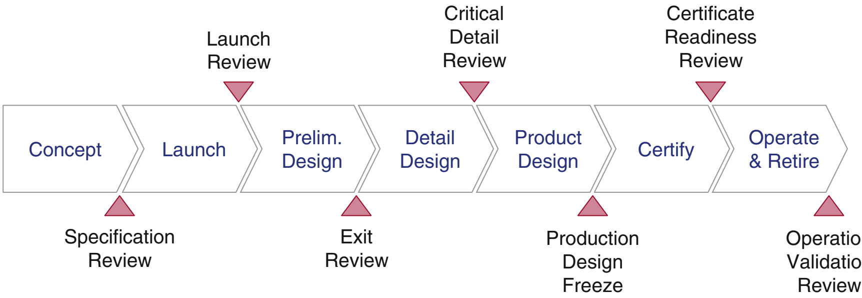


Fig. 20.6 The aircraft life cycle process

and discussions with stakeholders. In addition, paper documents and electronic files, like e-mail records, are still the standard for supporting these meetings, while 50–80 % of the documents are in paper form and 70 % are for multi-cultural working sessions only.

The life cycle process within aerospace is conceptualised in Fig. 20.6 [32], showing the major phases in the life cycle. This illustrates the challenge of a more serial view on the management of information throughout the life cycle, where ideally, any information and analysis relevant to the concept stage from the subsequent stages is available during the conceptual design stage; like certain regulations regarding retirement, which may already be considered within the conceptual stage.

Based on the fundamental principle of data/knowledge sharing within CE, it can be seen from PLM systems that the integration and the optimal running of tasks may be achieved by establishing a knowledge hub that includes Product, Process and Resource information and forms, or attributes. In addition, another implied key element from PLM is information/knowledge storage, control and utilisation! This all part of the PLM paradigm that is the vision of associated software and framework suppliers such as Dassault Systems, Parametric Technology, and Siemens PLM Software.

The collaborative effort and organisational challenges of the whole CE endeavour is extremely challenging and early attempts at solving this are exemplified by the concurrent design facility at the European Space Agency (ESA), as illustrated in Fig. 20.7. It is interesting to note that the disciplinary experts arranged around the outer space, with access to their tools through the desk-top workstations, and that their input is then facilitated through the concept of a multimedia wall that primarily helps to provide diverse and fragmented information in an effective manner to the whole team [33]. In relation to this, a methodology to visualise aircraft design tasks is further explored in Dineva et al. [34].

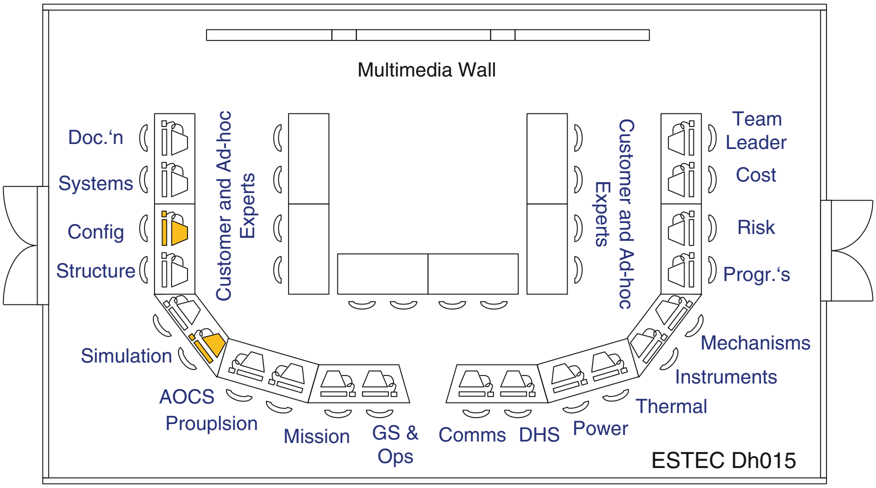


Fig. 20.7 The integrated multidisciplinary design facility at the Europe Space Agency

20.5 CE in Aviation: Supporting Techniques and Use Cases

As part of recent developments in the application of CE to the aviation industry, a number of supporting techniques, associated brief theoretical background and examples of application to the aviation domain are highlighted in this Section, with a particular emphasis on application. The following techniques and methods are discussed: CE, DMU, MDO, VE, LCC, and Systems Engineering (SE).

20.5.1 Collaborative Engineering

The desire for incorporating multiple lifecycle considerations requires tight integration of multi-disciplinary knowledge and collaboration between engineers across various cultural, disciplinary, geographic and temporal boundaries [35], whereas environmental concerns have also added to product design and development complexity [36]. As discussed at more length in Chap. 2, putting the emphasis on collaboration has led to the term Collaborative Engineering (CE*) with the following definition [37]:

> Collaborative Engineering is a systematic approach to control lifecycle cost, product quality, and time to market during product development by concurrently developing products and their related processes with response to customer expectations, where decision making ensures input and evaluation by all lifecycle functions and disciplines, including suppliers, and information technology is applied to support information exchange where necessary.

In aviation, all these elements are highly relevant; the global supply networks that are currently in use to finance and execute development, production and delivery of wide-body aircraft such as the Airbus A380 and A350XWB and Boeing 747-8 and 787 drive the need for application of CE*. For instance, in a well-known example, the Boeing 787 has been developed and is currently manufactured in a network including dozens of major partners, covering some major continents [e.g. Boeing (USA), Alenia Aerospatiale (Italy), Kawasaki Heavy Industries (Japan)]. Each of these major partners in turn manages their own supply network (with input from Boeing), creating a tiered supply chain network.

Both aviation research and practice have a long-standing interest in lifecycle considerations including cost (see also Sect. 20.5.5), early supplier involvement (ESI) and information (technology) support [38]. In this Section three use cases illustrate the crucial importance of engineering collaboration in the aviation industry. In the first, supply chain harmonization is covered (entailing aspects of ESI and information technology support) by considering the development of the Boost Aerospace digital hub. In the second case, supplier integration and technology support (through PDM and PLM systems) is described for the case of a manufacturer of fixture equipment. Finally, supply chain communication and collaboration for the case of buyer-furnished equipment (BFE) is discussed.

20.5.1.1 Use Case: Boost Aerospace

The long lifecycle of an aircraft requires sophisticated configuration management tools. The aviation industry has major potential in harmonization of its supply chains. To strengthen European aerospace programmes (i.e., product development projects), competitiveness has to be improved at the extended enterprise level. In order to enable and accelerate the deployment of digital processes and tools across the extended enterprise from the OEM to the tiered suppliers and to customers, harmonized solutions and open standards are a key factor for success [39]. The verticalisation of the supply chain requires comprehensive digital PLM collaborative platforms. This requirement was accepted by five leading European aerospace and defense companies (EADS/Airbus, Dassault Aviation, Safran and Thales) which have created a European digital hub called BoostAeroSpace (see Fig. 6.7) for the management of collaborative programmes and their supply chains [40]. It provides highly value-added standardised and secured collaborative services for stakeholders in the entire supply chain. Therefore, these services dramatically reduce the specific environments dedicated to each customer, providing interoperability with their information systems.

BoostAeroSpace provides the following service levels:

- AirCollab (collaborative workspace, e-meetings)
- AirDesign (Product Lifecycle Management (PLM) collaboration, DMU sharing)
- AirSupply (Supply Chain Management (SCM) collaboration, logistics exchanges, vendor managed inventory)

These services have become productive in 2011 and as of 2014 serve more than 300 companies. The platform is used by its founders and their international partners and suppliers. Two main benefits are targeted: first, the use of these standardized services by the main European OEMs is anticipated to dramatically improve the generic collaboration with suppliers and interoperability with their information systems. Second, the platform is to reduce process cycles and overall costs. The mentioned services are provided as "Software as a Service" (SaaS) for all OEMs, suppliers and small companies along the whole supply chain, enabling them to potentially make the same gains in competitiveness as the five founders.

AirCollab provides generic collaboration services based on its customized standard collaborative solution Microsoft Sharepoint. It enables "turnkey" collaboration with external partners and internal teams by using collaboration utilities like e-meeting and pre-defined templates for collaborative project management and information sharing. For the aftermarket it maintains a reference document library.

AirDesign is focused on aircraft program design and manufacturing processes and deploys the Enovia/CATIA V6 collaboration suite of Dassault Systemes. It serves the following five use cases which are typical for almost each collaborative project:

1. Technical data package exchange: Secured data exchange management between partners/suppliers.
2. PLM collaboration using data exchange: Shared product structure based on STEP AP2013 (see Chap. 6) integrating partners/suppliers's product design data deliveries through secured data exchanges mechanisms.
3. Co-review: Allows design co-review on shared product structure between partners connected to PLM hub (enable context deliveries and assembly/sub-assembly review based on shared DMU according to the project scope, see Chap. 13).
4. Share catalog and new part request process: Publication of harmonized standard parts catalogue to be used by partners/suppliers (see Sect. 14.5).
5. PLM collaboration @Hub: Provide collaboration workspaces with generic V6 PLM functionalities (see Chap. 16).

AirSupply is a central aerospace SCM platform that facilitates secured and traceable communication across companies and provides valuable assistance at both operational and management level. As a result, processes with external partners are more transparent and dependable while various alert mechanisms allow exception-based management of the supply chain. It is based on technology from SupplyOn, a specialist in cross-company supply chain collaboration which is already established in the automotive industry. In close cooperation with BoostAeroSpace, SupplyOn's platform has been adapted to meet all requirements specific to the aerospace industry.

AirSupply comprises the following six functions:

1. Demand forecast: Send demand forecast to supplier based on flexible horizon, projected horizon

2. Purchase order: Send purchase order to supplier based on firm horizon
3. Consigned Vendor Managed Inventory: With or without consignment stock, associated to Self-billing
4. Dispatch advice and Receipt advice: Supplier sending dispatch advice and customer sending receipt advice
5. Self billing receipt advice: Customer sending billing to supplier
6. Cockpit and exception: Indicators, alert and exception management.

20.5.1.2 Use Case: Collaboration on Fixture Equipment [41]

This use case reflects the design and manufacturing processes of fixture equipment for the aeronautic industry. The equipment supplier is a basic manufacturer of the assembly tools with sequential design and manufacturing processes. As shown in Fig. 20.8, three departments are engaged in the global process of assembly tools purchasing: production service specifies the assembly needs, the tooling R&D designs the tooling structure, and the purchase service negotiates and sends the order to supplier which are distributed globally [42]. After the completion of the tool, it is sent directly to the production shop for use. In case of changes in design, these modifications imply changes on the specification of the assembly process and, thus, of the assembly tool. The whole cycle of the assembly tool ordering is then repeated to cope with the new specifications. Thus, a new PLM-based approach is developed for the seamlessly integration of all the information specified throughout all phases of the equipment's life cycle between OEM and a new global supplier

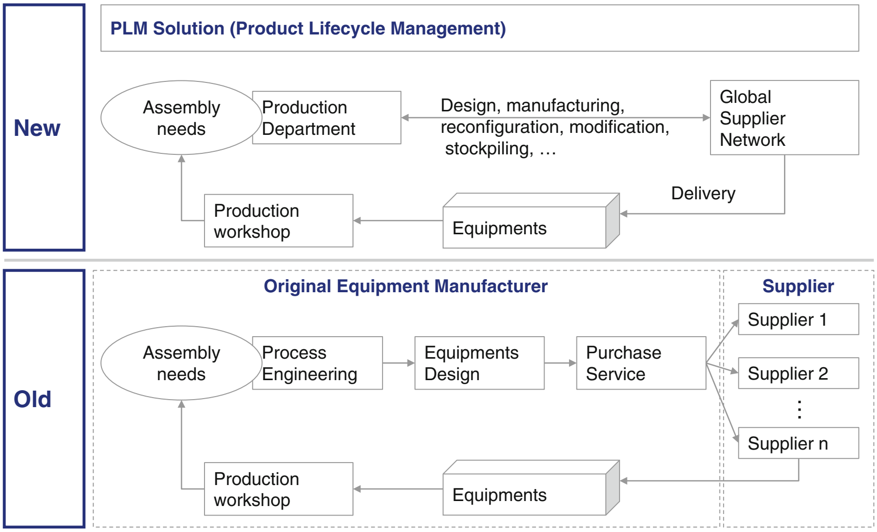


Fig. 20.8 Solution concept for collaboration OEM—supplier

network (GSN). Figure 20.8 also shows the new configuration where tasks of design, configuration and fabrication of the assembly tool are performed collaboratively with the new GSN. Suppliers are simultaneously informed about new modifications of the assembly operations and design the new tool by themselves. The implementation is based on the concept of working situation to describe different relations between supplier network (and assembly tool) and OEM (and aircraft part).

This approach aims not only for better integration of the supplier in the design and manufacturing processes, but induces a new collaboration strategy between OEM and supplier. Suppliers are going to be involved early in each new project. Important evolutions in the current configuration of the development process occur by the shift from a linear and sequential process to a much more “collaborative” one. This reconfiguration leads to significant improvement in saved cost and time in association with a greater innovative potential. The supplier gets a new role, not only as an efficient manufacturer, but more as a partner, collaborating in different product development project stages.

Horizontal collaboration will be improved by means of a “back office” interface that gives suppliers the possibility to share their knowledge and to get a common representation about the project evolutions (see Sect. 7.3.1). Subsequently, the specification and manufacturing of the assembly equipment are performed progressively and jointly by different units of GSN. When the engineering starts the design process of the fixture equipment, production planning might simultaneously schedule the manufacturing operations in order to optimize the production process. Furthermore, during the whole development process, engineering can inform progressively the production and other furniture suppliers about the bill of material structuring the equipment, in order to shorten the purchasing time.

Based on the conceptual specifications, various functions are available by modern, well-customized PDM systems (see Chap. 16) for collaborative work [43]:

Product data interfacing: The OEM defines on his own system the assembly activities and the references of concerned product components. However, to fulfill the equipment development operations, the GSN members should get some information about the OEM product (structure, geometry, materials, etc.). Based on the meta-model structuring the relations between processes and products, the PDM system extracts from the OEM system only the relevant and authorized aircraft data (see Sect. 16.6). In the opposite way, data can be sent for DMU (see Chap. 13).

High level of transparency: The OEM gets more visibility about the supplier’s workload and might take into account their constraints when it defines the manufacturing planning. The suppliers get insight in the OEM’s planning and project activities very early (see Chap. 7). For instance: when the OEM decides the re-scheduling of its activities, the suppliers are automatically notified by these modifications to ensure their possible reaction. The triggering of the equipment delivery process depends at least on supplying activities that are managed in the OEM organization. It helps to reduce the number of iterations for the cost estimates and negotiation since it is based on common procedures and will be fulfilled through a collaborative process.

Track the project progress: The project coordinator gets more visibility about the GSN workload and the OEM assembly planning. These constraints can be taken into account when managing and scheduling the remainder of the project. For this function, the PDM system extracts planning information from different partner's inputs and aid coordinator to schedule the equipment project.

Collaborative project management: The PDM system plays the role of a mediator between different partners. GSN users download the equipment order with their associated requirements, and upload the different documents defining the corresponding equipment. The PDM system notifies the partners simultaneously by subscription mechanism about the evolutions of both aircraft and equipment projects (see Sect. 16.6.2). At the end of the project, OEM validates the reception of the equipment.

Apart of all benefits, this approach works properly only if a certain level of interoperability is preserved between the PDM backbone at OEM and supplier's IT systems. It includes a high level of subordination at the supplier's side as well as a well-adjusted collaboration model. Like other industries which deal with complex products (automotive, transportation, shipbuilding), this is still subject of basic research and development [44] (see Chap. 6).

20.5.1.3 Use Case: Communication with Buyer-Furnished Equipment (BFE) Suppliers

Like other complex products, airline customers customize a wide variety of airplane features provided by aircraft manufacturers and needed to properly differentiate individual brands and to satisfy operational requirements. Airlines have the choice to modify or add among a wide variety of pre-qualified selections available from a large pool of industry-leading suppliers (see Chap. 14). Options are provided by either Seller-Furnished Equipment (SFE) or BFE. BFE is a term used in the aerospace industry to denote components supplied at no charge to the manufacturer by the purchaser for use in the assembly procured by the purchaser from the manufacturer. Typically, such equipment comprises specific cabin equipment (seats, galleys and galley equipment, entertainment equipment, kitchen, bathroom).

Whilst the SFE supplier is required to be fully integrated in the product creation process of the aircraft manufacturer, there is no strong contractual precondition for similar treatment of a BFE supplier, although it participates in the product creation process of an aircraft. Therefore, several issues in the process chains arise, in particular in data exchange. DMU could become a serious issue (see Sect. 13.3.2).

Basically, there are two possible solutions: use of a neutral process format like JT (see Sect. 11.6) or deployment of a data exchange service portal which supports a plethora of CAD systems and formats (Fig. 20.9) [45]. In both cases sufficient data quality is the decisive impact factor [46] and can be achieved by appropriate methodical measures which include manual rework [45]. As JT is not yet widely

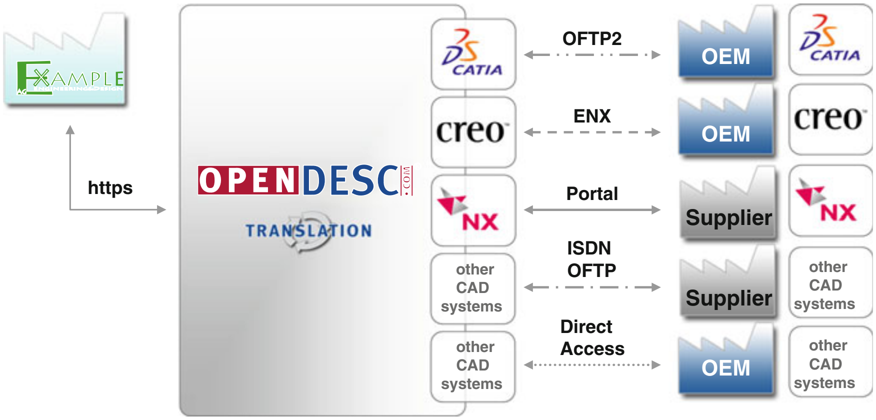


Fig. 20.9 Supplier portal for data translation and exchange [45]

adopted in the aerospace industry, many current programs are conducted using supplier portals which support a multitude of physical connections and transfer protocols too.

20.5.2 Digital Mock-Up

DMU is a core method in CE in the aerospace industry for assembly examination, layout examination, interference checking, and maintainability (see Chap. 13). Based on complete CAD data and a powerful PDM system, DMU can be created synchronously with each design activity. Based on advantages of DMU, the use of the Physical Mock-up has been reduced dramatically over the past years. Beside of standard monitors, many different graphics devices are used for graphical output in aerospace industry (mobile devices, virtual, augmented and mixed reality).

After the complete aircraft has been built in its full-size virtual environment including the adjacent manufacturing or operation equipment, the engineering examination, assessment and decision making can be conducted in a virtual space. The advantages of such DMU are that one can easily establish the specific advantages and disadvantages of any design solution by applying a variety of scenarios to a subject. In addition, during an assembly or decommissioning, any interference or collision with a subject can be elucidated, and possible errors can be prevented in the design. What is more, the location of an operation and the methods can be conveyed to workers by means of a industrialization DMU (IDMU) before an operation, and thus the understanding of an operation could be improved and the time required for an operation could be considerably reduced.

However, the industrial use of DMU in aerospace is struggling with many limitations due to the large scale and complexity of an aircraft. Neither the standard software packages from leading PLM vendors nor the standards viewers nor the communication facilities are able to handle the huge amount of data which is still needed to describe a full DMU of an aircraft. Thus, appropriate examination procedures are needed to perform the DMU tasks in singular zones of an aircraft and, subsequently, to aggregate the results. The DMU for the aircraft systems which are distributed along of entire aircraft, remains as an especially challenging task.

20.5.2.1 Use Case: Final Assembly Line Design [47]

The design of a final assembly line (FAL) at Airbus is carried out as concurrent development process during the product industrialization activity and can be decomposed into three assembly line design phases: concept, definition and development. During the conceptual phase, designers require defining FAL alternatives with different values for the input requirements.

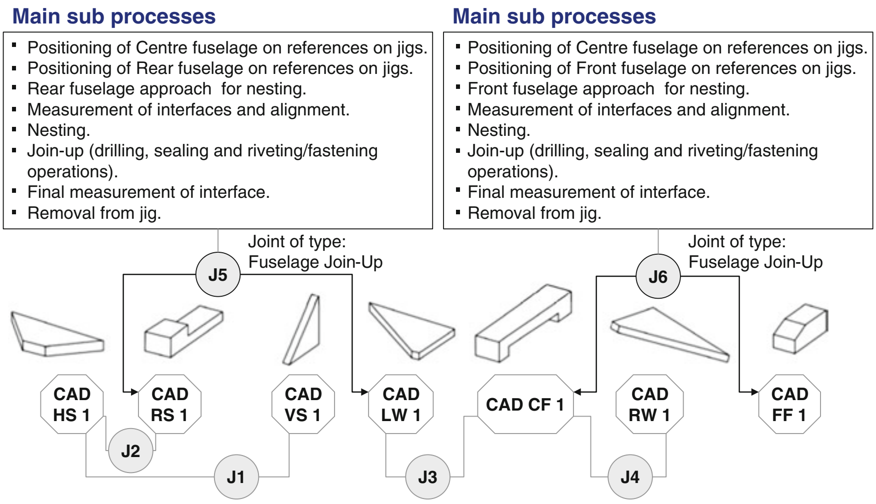
Based on the product configuration and the scenario, Manufacturing Engineering is responsible for executing the case and for defining the DMU of the industrialization solutions or FAL alternatives. Both the scenario and the FAL design are part of the IDMU which comprises product, processes and resources information, both geometrical and technological. At the conceptual phase, the process of generating industrialization solutions depends heavily on personnel experience and is time-consuming. Thus, manufacturing engineers can only check a simplified set of cases to generate early manufacturing processes and resource requirements. In order to enhance this process, it was decided to develop a software application to assist designers in the definition of scenarios and to generate FAL alternatives at the conceptual stage.

A ‘to be’ IDEF0 process model was defined, focused on the Industrialize activity, to conduct the information flow and helps to identify the concepts and knowledge involved in the aircraft FAL conceptual design process. The next step was to develop a knowledge model using UML. The knowledge modeling of aircraft assembly lines requires reviewing works dealing with modeling of assembly information, processes and lines. From this review it was concluded that the semantic concepts involved in the conceptual design phase of an aircraft assembly line were not fully taken into account in the identified models. Models presented in the literature provide three main views: product, process and line balancing. The modeling of the conceptual phase demanded to integrate and to extend concepts from the three views, particularly from the process view. The used conceptual model was divided into three interrelated sections or knowledge units: Product, Processes and Resources, together constituting the IDMU. The product section comprises the concepts to define the joints to be assembled and both the functional (as designed) and the industrial (as planned and as prepared) views. The process section comprises the concepts, in terms of technology, sequencing and resources, to define a procedure to assemble each joint defined in the product section. Technology, sequencing and resources are collected in the work station concept, and work stations are grouped into the assembly line concept. The resources section comprises the concepts to define three main types of resources: jigs and tools, industrial means and human resources.

To implement the developed IDMU model, classes were mapped into elements of the commercial software (CATIA/Delmia V5). CATIA/Delmia V5 provides the Process-Product-Resource (PPR) structure to support the IDMU concept. The model is implemented by means of CATIA V5 macros within the application programming interface (API). The main result is an assistant tool, integrated within CATIA V5, which helps designers to generate FAL alternatives by defining scenarios and using knowledge rules, which are derived from technical staff's expertise. The application generates technological information integrated within an IDMU supported by the commercial PLM system. A very simple aircraft model was created and used to test the application. The results obtained in the executed case studies relate to requirements for: space, transport, resources, industrial means and cost; and allow validating the conceptual approach.

Defining an assembly process alternative, as proposed in the assistant application, requires use of the scenario information. It involves fixing an assembly sequence, establishing sub-assemblies associated to the sub-stages of the process, locating them into real industrial plants belonging to the set of available company's facilities, adding sub processes depending on the type of joint to be executed (e.g.: fuselage join-up) and assigning the resources to be used. Once the sequence is defined, sub-stages must be defined. Each one must contain a number of executions of joints and is related with a sub-assembly or set of components depending on the position of the involved joints within the sequence.

The next step is to assign sub processes to the work stations. A library, with a set of basic types of joints, was defined, where each basic type comprises the main sub processes to be carried out. Figure 20.10 shows the example of the Fuselage



Main sub processes

- Positioning of Centre fuselage on references on jigs.
- Positioning of Rear fuselage on references on jigs.
- Rear fuselage approach for nesting.
- Measurement of interfaces and alignment.
- Nesting.
- Join-up (drilling, sealing and riveting/fastening operations).
- Final measurement of interface.
- Removal from jig.

Main sub processes

- Positioning of Centre fuselage on references on jigs.
- Positioning of Front fuselage on references on jigs.
- Front fuselage approach for nesting.
- Measurement of interfaces and alignment.
- Nesting.
- Join-up (drilling, sealing and riveting/fastening operations).
- Final measurement of interface.
- Removal from jig.

Fig. 20.10 Main sub processes for joint of type fuselage join-up [47]

Join-Up joint type. For each work station, depending on the type of joint to be executed in it, the design assistant, making use of the joint sub process library, automatically generates the main level of sub processes to be carried out and the corresponding nodes are created in the Process List structure provided by CATIA/ Delmia V5.

The assignment of resources is the last step in the configuration of the process structure alternative. The designer has to select the resource type, input the value for each attribute and select the process node where the resource will be used. At this stage, a conceptual structure of a possible FAL solution is defined, and the designer is requested to select if more alternatives need to be evaluated.

Although the evaluation of alternatives is conducted at the industrialization conceptual phase, when products are still preliminarily defined, the evaluation of different scenarios allows creating estimates for different criteria that help in the decision making process. In addition to full implementation of the resource knowledge model, future work aims at implementing multi-criteria decision analysis and an automatic process planning capability in the form of an algorithm to create the 'as prepared' alternatives from the information defined in the 'as planned' structure, the joints to execute and the process information.

20.5.3 Multidisciplinary Design and Optimization

During the 90s, there was a trend to integrate structures and control disciplines into the early aircraft design process [14]. The complex aircraft system requires the coupling of the interacted disciplines, which then influences the performance of the whole system, where the optimal design can be facilitated by mathematical optimization. MDO has been widely implemented and adopted in aviation industry and frameworks with advanced optimization algorithms and KBE techniques have been built [15]. The MDO process is pushed to higher fidelity by coupling efficient analysis tools [14, 48, 49]. Technological fundament is explained in Chap. 4.

In recent years there has been an increased emphasis on integrating the structures and control disciplines into the design at an earlier stage [50, 51]. In structures, the increased use of advanced materials with their flexibility and reliability based design philosophies has been one driving force in MDO. One example is the deep coupling of powerful computational structural mechanics (CSM) and computational fluid dynamics (CFD) solvers. Another example is the use of composite materials for aeroelastic tailoring, as it couples structural detail (using skin fiber orientation angle) with the flexible wing aerodynamics and, ultimately, the aircraft performance.

20.5.3.1 Use Case: Fluid-Structure Interaction Simulation [52, 53]

For high-fidelity fluid-structure interaction simulations different tools are necessary to allow the highest possible accuracy. In this context the data transfer between the aerodynamic surface and the structural model, and the CFD mesh deformation are the key parameters for high performance due the high accuracy of modern CFD solvers. Therefore, the fidelity of these codes, which usually solve the Reynolds averaged Navier-Stokes (RANS) equations, is limited by the correct definition of the geometric boundaries. High fidelity models are not available in the early design phase of aircraft. Basic structural models, in which the wing is only represented by a beam, are often the starting point for fluid structure coupled simulations. In a later development stage more complex structural models are used which include a detailed representation of the lifting surfaces including control surfaces, but also of other aircraft components like the fuselage.

Here a coupling methodology is presented, which enables the combination of different structural representations in one coupling matrix. Different coupling methods facilitate the representation of aircraft components modeled with differing detail level. Detailed structural models, as well as beam structures and single-point representations can be treated in one method. Detailed finite element (FE) models are typically available for the wing, which allow to use radial basis function (RBF) interpolation, while the engines and flap track fairings are only modeled by single mass-points. Thus, only basic rigid-body splines can be used for the coupling of these parts. If the structural model is used in a high detail level, the size of the coupling matrix will get an issue in terms of performance and memory consumption. On account of this a comparison of an exported spline matrix and FSAdvanced-Splining, a fluid-structure-interaction (FSI) tool in the FlowSimulator software environment, is derived.

Afterwards an update to the mesh deformation module is presented, which enables to represent the exact deflections for every CFD surface grid node, which are delivered by the coupling matrix. Performance limitations do not allow to use all points as input for the basic radial-basis-function based mesh deformation method. Then the FSI-loop to compute the static elastic equilibrium is described and the application to an industrial model is presented. Finally, a strategy how to couple and deflect control surfaces is shown. Therefore, a possible gapless representation by means of different coupling domains and a chimera-mesh representation is shown. This section describes the bricks, which are combined to a fluid-structure interaction loop. Most of the tools are part of the FlowSimulator software environment (Fig. 20.11).

The coupling method allows to combine different interpolation methods for different model components. For the case of complex structural models with differently resolved components, this is a very important feature for fluid-structure coupling. Therefore, the structural and aerodynamic domain is spitted into several domains. These domains can be components, or further divided components to increase the numerical performance of certain interpolation methods. The technical integration of Nastran into the process is done via file exchange. Either binary or ASCII files are written and read to exchange forces and displacements. The data exchange of all FlowSimulator modules is done in memory.

The solving methods are combined to compute iteratively the static equilibrium state for certain aerodynamic target coefficients. The process loop is outlined in Fig. 20.11. The starting point for the solution sequence is the CFD-solver.

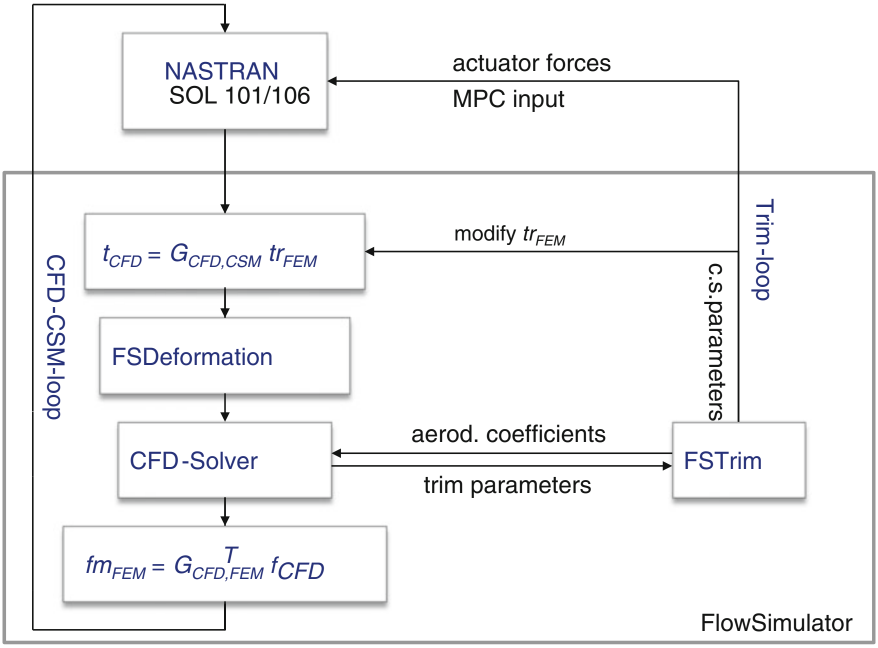


Fig. 20.11 Static fluid-structure interaction loop with additional trim loop

The diagram includes two loops, one for CFD-CSM-interaction and one for trimming. The trim loop begins after the CFD-CSM loop has reached a certain convergence level. Then the CFD-CSM-loop continues after the trim loop has fulfilled its convergence criterion. When both criteria are fulfilled, the elastically trimmed CFD-CSM solution is achieved.

Furthermore, it is shown that the trim module FSTrim computes parameter for the CFD solver like the different angles of attack, but also the control surface deflection angles (c.s. parameter). Depending on trim parameter, the trim loop continues with the CFD-solver, the displacement interpolation or the structural solver. This is necessary since the control surface deflection is handled on the structural node set. Either the structural deflection vector tr_{FEM} is modified by a rigid control surface deflection, or input is given to the structural model itself. For example actuator forces or multi-point-constraints (MPCs) can be used to change the position of the control surfaces. Actuator forces represent a force pair of equal magnitude but opposite direction, which is used to extend or shorten the length of actuator elements. An alternative way to model control surface deflections is provided by MPCs. Both allow to cover control surface deflections in the structural and aerodynamic domain. Additionally geometric consistency is assured. Another attribute of control surface deflections in the structural model is the advantage that the interpolation matrix can be used to take care of possible CFD-grid discontinuities.

As reference to the CFD-CSM-result a standard design tool result is used. The agreement of the two results is very good, only in twist a small deviation can be observed. The two introduced fluid-structure coupling methods did not show differing results. The coupling methodology allows the combination of different interpolation methods, each fitting to the boundary conditions of the used models. Since the spline matrix computes displacements for all surfaces nodes of the CFD-surface mesh, a correction algorithm for mesh deformation with RBFs is shown. As application example a complex aircraft example with a very detailed structural and aerodynamic model is presented. For the same test case the benefit of a "spline-on-the-fly" method is shown. It reduces dramatically the necessary amount of stored data for fluid-structure coupling. Finally, the flexibility of the coupling approach is underlined by giving some examples about the integration of a trimmed horizontal tail plane (HTP) and control surfaces into the coupling process.

20.5.4 Value Engineering

VE as a concept was developed at General Electric in the 40s on by Lawrence Miles as a method for considering the customer's willingness to pay for each element of added functionality in a product, where:

$$\text{Value} = \text{Function/Price} \tag{20.1}$$

VDD [54] is the process of optimising a product or service through a value function that best quantifies the value added of that product by following the steps of Definition, Analysis, Evaluation, and Improvement. Value operations methodology (VOM) [55] is an extension of the VDD approach with a focus on operational value that in turn requires optimal operations to be understood and utilised in the engineering evaluation process. VOM drives the design process with a more realistic operations based performance assessment that can pull better operational solutions into the market place. VDD and VOM rely on the use of a hedonic function, the typical form of the hedonic function of which relates the variation in cost to the variation in design characteristics, as presented in Eq. (20.2).

$$\ln(P_1) = \alpha_1 + \sum_{j=1}^{m} \beta_j x_{ij} + \varepsilon_i \tag{20.2}$$

where most importantly $j = 1 \ldots m$ is a set of value levers of the system analyzed, P is the price, and is a weighting factor associated to a defined value lever (or design characteristic) x. The value model is an evolution of Keeney's [56] representation of theorems for quantifying values using utility functions, as proposed by Fishburn, where Keeney defines Fishburn's function as the additive utility function as shown in Eq. (20.3):

$$u(x_1, \ldots, x_n) = \sum_{j=1}^{N} k_j u_i(x_i) \tag{20.3}$$

where u_i is an integral attribute utility function for attributes x_i, and k_i are the scaling constants that define a user's value system. Assuming that the additive utility function does not need to account for interdependencies relating to each consequence x, then there exists a corresponding magnitude of utility u that indicates the value [54]; as shown by Fishburn in 1965 [57]. The hedonic model establishes: (a) the Delta Price Principle: that it is reasonable to relate the price of one design instantiation to another and (b) the Additive Utility Principle: that the utility relating to a design instance can be simply accumulated according to the utility added by each feature or attribute. The VOM approach builds on both these principles.

Relative to (a) the Differential Principle, it is reasonable to assess the value of one design instantiation with another in terms of the value gradient relating to the value levers, resulting in a given delta value from the original state, whether positive or negative. This principle is further expressed in Eq. (20.4) relative to the value gradients:

$$\vec{\nabla} v = \vec{\nabla} f(x, y, z) = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right) \tag{20.4}$$

where the value gradients are associated with a scalar function of the individual value functions or value levers (x, y, z). The Differential Principle suggests the use of both deltas and more fundamentally the gradients which give rise to the deltas. Equation 20.4 proposes that any value gradient or gradient vector field, $\vec{\nabla} v$ of the scalar function, $f\ (x,\ y,\ z)$ is indeed a function of the value gradients or partial derivatives; which are associated with the value model (as a scalar function) being a function of the individual value functions or value levers. Therefore, it can then be deduced that this can be expressed in terms of the standard vectors (I, J,K) associated with the individual value functions (x, y, z) and their partial derivatives, as shown in Eq. (20.5):

$$\left(\frac{\partial f}{\partial x} \hat{\mathbf{I}}, \frac{\partial f}{\partial x} \hat{\mathbf{J}}, \frac{\partial f}{\partial x} \hat{\mathbf{K}} \right) \tag{20.5}$$

Relative to the Additive Principle, it is reasonable to assess the value delta presented in Eq. (20.5) as an aggregation of all the individual levers' delta values. Consequently, this principle is further expressed in Eq. (20.6):

$$\Delta V(x_i, \ldots, x_n) = \sum_{i=1}^{N} \alpha_i \sum_{j=1}^{M} \omega_j \frac{(v(x_{ij}))_{\text{end}}}{(v(x_{ij}))_{\text{start}}} + \varepsilon_{ij} \tag{20.6}$$

where a change in value V is caused by a change in a set of associated value levers x_i, when moving from some initial state to some new state. Each value lever of the set $i = 1 \ldots N$ has an associated scaling factor a_i and error e_i and is in turn defined by a subset of lower level value parameters, x_{ji} *for* $j = 1 \ldots M$ and associated scaling factor ω_j, that describe the causal nature of each of each driver. The establishment of the lower level value parameter functions are carried out using the genetic-causal approach (GCA) presented by Curran et al. [18]. In short, this approach advocates modelling of value and cost by setting up families of products and establishing causal links between high-level cost drivers and its constituent elements.

20.5.4.1 Use Case: Applying VOM in Aircraft Design [55]

In the application of VOM to aircraft design, a model is proposed that captures the value of the aircraft design choices in terms of the operational impact and realisation through explicit value-adding criteria. The following value levers were utilised in a differential additive valuation manner as shown in Eq. (20.7). These value levers are subjective in nature and are to be selected by the user (as well as the weightings) but the authors included: Cost efficiency C (revenue/cost), Utilization U, Maintainability M, Environmental Quality E, and Passenger Satisfaction P. The methodology also proposes to use Safety S as a value lever as well as considering an error term. The differential principle is incorporated in the left-hand side of the equation while the additive principle is incorporated in the right-hand side of the equation.

$$\Delta V = \alpha_C\left(\frac{C_1}{C_0}\right) + \alpha_U\left(\frac{U_1}{U_0}\right) + \alpha_M\left(\frac{M_1}{M_0}\right) + \alpha_E\left(\frac{E_1}{E_0}\right) + \alpha_P\left(\frac{P_1}{P_0}\right) + \alpha_S\left(\frac{S_1}{S_0}\right) + \varepsilon \tag{20.7}$$

The influence of the value levers on each other is modeled with reference to Asavathiratham's influence modeling approach [58]. The value levers consist of the sum of specific system characteristics deltas multiplied by their associated weighing factors. The system-characteristic deltas are based on a reference aircraft's characteristics, correlating to those of the aircraft under consideration. For example, the *Cost* value lever is expanded as shown in Eq. (20.8).

$$\begin{aligned} C = {} & \omega_1 \cdot d[\text{DepreciationIOC}]\left(\frac{c_1}{c_0}\right) + \omega_2 \cdot d[\text{Tickets \& sales}] \\ & + \omega_3 \cdot d[\text{Admin \& other}] + \omega_4 \cdot d[\text{Staff}] + \omega_5 \cdot d[\text{Maintenance}] \\ & + \omega_6 \cdot d[\text{Fuel}] + \omega_7 \cdot d[\text{Crew}] + \omega_8 \cdot d[\text{Interest}] + \omega_9 \cdot d[\text{Insurance}] \\ & + \omega_{10} \cdot d[\text{DepreciationDOC}] + \omega_{11} \cdot d[\text{Airport}] \\ & + \omega_{12} \cdot d[\text{Navigation}] + \omega_{13} \cdot d[\text{PaxServices}] \end{aligned} \tag{20.8}$$

where *C* is the *Cost* value lever that represents the value score corresponding to the cost of the aircraft under consideration, *w* are the weight factors corresponding to the individual deltas, *d*[Depreciation IOC] is the delta of the cost depreciation for Indirect Operating Cost (IOC), *d*[Ticket/sales] represents the ticket/sales cost delta, *d*[Admin/other] defines the administration and other costs delta, *d*[Staff] is the staff cost delta, *d*[Maintenance] is the maintenance cost delta, *d*[Fuel] the fuel cost delta, *d*[Crew] Flight crew cost delta, *d*[Interest] is the interest cost delta, *d*[Insurance] defines the insurance cost delta, *d*[Depreciation DOC] defines the depreciation of the DOC delta, d[Airport] is the delta of the airport costs, *d*[Navigation] is the delta of the navigation costs and *d*[Pax Services] defines the passenger services cost delta. As mentioned, in implementation, the value model is based on a reference aircraft as a benchmark (subscript 0) relative to the performance data of the aircraft being designed (subscript 1), where the aim of the value model is to return the value of the aircraft under consideration relative to the benchmark aircraft. In essence, this is similar to the gradient based approach within optimization, where an improvement is sought rather than a specific level of value. However, the profound characteristic is that all value drivers are being taken into consideration and a balanced objective function is being used to find a more holistic global optimal.

Curran et al. [55] describe an application of the VOM model described above to a set of four aircraft types, being the Boeing 737–200, Boeing 737–800, Airbus A320 and Embraer ERJ-145. The top-level value levers were assigned weights as given in Table 20.1. For the individual lever weights, input values used for the specific value levers and value estimates, the reader is referred to Curran et al. [55].

The resulting estimates are highly dependent on the weights used, the accuracy of the used input values and assumptions such as linearity in performance characteristics, similarity in mission profiles, etc. Furthermore, this concerns a post hoc value analysis of aircraft performance. VOM may have further and more meaningful impact when used as a decision support tool in conceptual and preliminary aircraft design, when parametric estimates of aircraft operational performance may be used to investigate the value and consequently trade-off various competing design concepts. As such, VOM extends VDD by incorporating lifecycle considerations and is representative of the CE philosophy.

Table 20.1 VOM—airliner application—value model top level weights

Value in airliner design	Percentage
Cost	30 %
Sustainability	30 %
Market	10 %
Utilization	15 %
Maintainability	15 %

20.5.5 Life Cycle Costing [59]

Airlines globally are financially under cost pressure by rising fuel prices and introduction of CO_2 taxation schemes. In the past decade alone, the price of jet-fuel has quadrupled and the fuel component of DOC has increased from 14 to 30 % in 2013 [59]. With an increasing demand for jet-fuel and a reduction in global supply, the cost of fuel is expected to increase further.

Fuel consumption per passenger-km has already reduced significantly due to technological advances. The aviation is currently concentrating its initiatives on “drop-in” fuel solutions to achieve the necessary eco-economic transformation from petroleum derived Jet-A-fuel. The two major proposed solutions are biofuel and synthetic kerosene (Syn-Jet) made from natural gas/coal through the Fischer-Tropsch (FT) process. “Drop-in” fuels are currently being used experimentally in a blend with kerosene, but are still a long way from being commercially viable. Use of liquid natural gas (LNG), comprising upwards of 90 % methane, is already being used successfully in both automotive and maritime applications. It has also been explored as an aviation fuel, although LNG fuel applications have not extended to commercial fleets. Previous LNG feasibility studies raised questions over airport compatibility, safety and technology readiness levels (TRL).

To determine the impact of potential use of LNG, the LCC technique is used. This is the holistic analysis of the total cost of ownership (TCO) of an asset from its initial acquisition to its end of life disposal. It is typically used to determine the most economically rational option between competing alternatives that cannot be split based on technical appropriateness.

20.5.5.1 Use Case [59]: Life Cycle Costing of Alternative Jet Fuels

Transition to LCH_4 fuel will reduce airline DOC. Currently, fuel is 33 % of DOC and LCH_4 is less than 30 % of the cost of jet-fuel. This gap will widen as the cost of jet-fuel increases due to limited availability. Multi-national carbon emissions policies increase airline DOC. Environmentally, LCH_4 use will reduce CO_2 emissions by 20 % compared to jet-fuel, reducing carbon tax commitments. Consequently, the reduction in DOC will allow a reduction in fare prices, supports customer growth and increases income streams.

LCH_4 can be created from LNG or biogas generated from biological waste. This ensures a more sustainable supply of LCH_4 in the future and induces price stability. To assess airline DOC reduction from LCH_4 fuel use, an evaluation was conducted into the relative prices of competing fuels, the influencing factors governing these prices and the key impacts that may have on other aspects of airline DOC through stakeholder consultation and traditional research methods. Moreover, LNG is currently less than 30 % of the per energy cost of jet-fuel and promises to be available from untapped reserves of shale gas, harvested by the fracking technology.

To estimate LCC a modified approach on the TCO is used: every cost element of each technical alternative is assessed and summated for overall cost comparison; this approach assesses the particular cost elements that are deemed to have the greatest comparative impact on the overall LCC of an LCH_4 aircraft relative to a current baseline comparator aircraft. Additionally, contrary to traditional application, this report assesses the TCO from the perspective of the global commercial aviation industry in the event of a worldwide fleet introduction, as opposed to an individual aircraft acquisition by a particular transportation company. The three key cost elements that were seen to have a significant bearing on the relative TCO of an LCH_4 aircraft compared to a Jet-A kerosene baseline aircraft were identified as the cost of fuel for operation, the acquisition cost of the aircraft and the airport airline charges (which have been assumed as a worst case scenario where airlines shoulder the entire cost of infrastructure for a new fuel).

In order to provide an estimate of the comparative fuel costs for future years, the fuel prices for each year were estimated based on the percentage increase of the average yearly fuel price for the past 10 years (since 2003) for LNG (1.75 %) and kerosene (7.33 %). Whilst the extrapolation of the LNG price seems to align reasonably well with recent developments and the future outlook with the incorporation of shale gas reserves, it was highlighted that the continued rapid increase in the Jet-A Kerosene price projected may be more severe than the actual development. Therefore, to offset this, a more conservative projection, based on a projection of the future oil price provided by Airbus has also been included in all calculations.

Accounting for all cost components discussed (fuel, acquisition and new infrastructure), the total yearly cost savings by the introduction of LCH_4 aircraft compared to an equivalent number of baseline Jet-A kerosene aircraft for conservative fuel cost prognoses is depicted in Fig. 20.12. For the new airport infrastructure cost

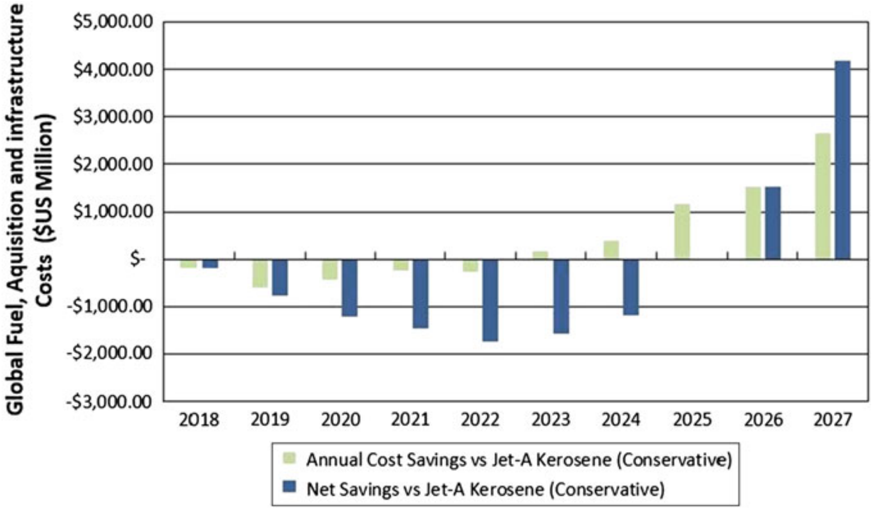


Fig. 20.12 Global fleet yearly fuel and acquisition costs [59]

component, there is no comparable cost incurred for Jet-A kerosene case as it is assumed that all required infrastructure is already in place for the new aircraft produced.

For the case that the Jet-A kerosene costs continue to rise at the same rate as the past 10 years, the aviation industry will run a relatively slight deficit before breaking even after 3 years and experience increasing savings. Alternatively, for the conservative prognosis of the Jet-A kerosene price, the breakeven point occurs 7 years after the initiation of the proposed global transition. With regards to the relative fuel, aircraft acquisition, and infrastructure costs, the aviation industry could make a net saving of US$4 billion to US$47 billion within 10 years if LCH_4 aircraft are introduced into the global fleet compared to the continued use of the Jet-A kerosene aircraft. This net saving represents 0.6–7.5 % of the total aviation industry's 2012 DOC from only a very small fraction of the global aircraft fleet. If the same rationale for LCH_4 variant was applied to other aircraft models on a larger scale, the savings would greatly multiply.

The design of LCH_4 aircraft alone is not a significant challenge as such aircrafts have been designed and operated in the past. The most significant upfront investment is in the infrastructure required for supply and storage of LCH_4 at airports. However, if the price of kerosene continues to rise as expected, conservative estimates show a breakeven in about 7 years after transition to LCH_4 is possible with a net saving of US$4 billion to US$47 billion within 10 years, if LCH_4 aircraft are introduced into the global fleet compared to the continued use of the Jet-A kerosene aircraft.

20.5.6 Systems Engineering

The main outlook of the SE approach has been defined at length in Chap. 9, as well as in sources such as the US Department of Defense (DoD) [18, 60] . Based on tasks integration and control as well as interfaces management, a requirements loop, which defines the iterative process between the requirements analysis and the functional analysis, forms the basis of the structure. The requirements loop identifies the relation between all the performance and other limiting requirements of the product. These requirements are used in the next iterative process which Curran et al. [18] term the 'design loop'. The goal of this loop is to move from a functional architecture towards a physical architecture. This is done by, trading off concepts, which are defined by configuration items, system elements and physical interfaces. SE is also adopted as a comprehensive, holistic approach to master the product complexity of complex products like aircrafts and foster the development of sustainable vehicles (see Chap. 27). It presupposes system thinking, in particular in design teams [61].

An important aspect of SE is the adoption of cost performance evaluation throughout the design process. Different costing methodologies are used throughout the design process such as the development of a cost breakdown structure (CBS).

The systems analysis and control has the task to monitor and manage all the aspects throughout the design process, that are needed for the technical analysis and the quantitative evaluation of alternatives (decisions made, requirements, risks, and others).

NextGen Air Transportation Systems (ATS) The Federal Aviation Administration (FAA) aims to transform the U.S. air transportation infrastructure from a ground-based navigation system to a net-centric satellite-based navigation system [62]. Due to the large number of involved stakeholders and high complexity of the project, the FAA has decided to introduce a SE approach. The project was initiated to anticipate on the increasing capacity of the navigation system and its side effects, which include an increasing number of delays and worsening of the aviation induced environmental impact.

In order to meet these goals, new technology needs to be integrated into existing systems at airports, aircraft and navigation system facilities. Besides the technological changes, processes and organizational structures need to be altered as well, to fulfill the requirements of the new system. Due to the transition from an isolated system towards a net-centric system, the verification and validation of NextGen requires a close collaboration of the involved systems.

The challenges above made the FAA chose a system of systems (SoS) approach. During the design process, multiple different development programs rely on each other to achieve the desired capabilities of NextGen. With 1820 FAA acquisition professionals working on 250 unique highly related programs, the FAA SE experience could be a pilot of high value for similar projects [61].

Network centric operations (NCO) occurs when systems are linked or networked by a common infrastructure, share information across geographic borders, and dynamically reallocate resources based on operational needs [63]. NCO recognizes that interdependence (sharing information among many) is vital to an organization's future. Information must be quickly distributed, its value understood and the desired effect created. NCO is an environment where seamless collaboration between networks, systems or elements within systems is possible. Understanding system-of-systems engineering (SOSE) is critical to a robust architecture development of NCO systems. There are five system-of-systems (SoS) characteristics but the dominating one is emergent behavior.

20.6 Conclusion and Outlook

This chapter has explored some the obvious coupling of CE within the integrated design approach within aerospace industry. Extended CE concepts such as CE have been discussed as well as some enabling concepts such as MDO and VE. Aircraft design, production and operation is a complex extended enterprise that demands life cycle integration and the compression of time without losing the fidelity of knowledge. MDO enables state-of-the-art integration of the CE process through tool development and integration into the business process. VE offers a radical view to the CE process in that the parallelization of tasks and life cycle requirements must be driven primarily with a view to what the ultimate value function or value goal is. The ultimate vision of design integration is to achieve concurrency in the integration of all relevant knowledge and to apply that to achieve the maximum with regards to the value that the product provides to the user. The VOM provides this component in particular in respect to what value the product or service adds. CE offers an encompassing approach to further developing these ideas and is long established in seeing them implemented by industry for value enhancement [64].

Future developments in the aircraft industry involve the introduction of new materials and/or material applications, new engine technologies, new control systems and evolution of the integration of the aircraft in the overall transport system. For the immediate future, the major OEMs (Boeing, Airbus) have chosen to design new iterations of their work-horse narrowbody aircraft families (e.g. the B737-MAX, A320neo), in essence representing an evolution of the conventional aircraft type.

The rise of new competitors (Embraer, Bombardier, COMAC) for the current market leaders Boeing and Airbus will enforce continuous consolidation in the entire supply chain like we have already experienced in the automotive industry during the past two decades [65]. Furthermore, common aircraft programs of two or more today's competitors can be expected in the near future which will induce additional complexity in the product creation process. Therefore, we will face additional challenges in the PLM of the extended aerospace enterprise (see Fig. 18.2). In comparison with the automotive industry (see Sect. 21.2), the product lifecycle of an aircraft is significantly longer than the lifecycle of any used software (PDM, CAD, etc.) and will, subsequently, set new requirements to the IT infrastructure in term of longevity, stability and scalability [66]. The process harmonization and standardization will get a significant impact. Long-term archiving and retrieval of product data, which is currently supported by the LOTAR International consortium, will, therefore, gain an increasing importance [67].

In the medium to long term, many adverse pressures on the aviation market will likely promote risk-adverse behavior in design, meaning that innovation on the overall aircraft configuration is likely to remain limited. However, on subsystem level, innovation will continue to be pushed as airliners are in a highly competitive environment where any saving is welcomed; on top of that, regulations (e.g. on emissions) are likely to strengthen the push for further innovation, in particular, if the current trend of continuously rising air traffic and even more aircraft in operations will be continued [3–6]. On the longer term, more esoteric designs such as blended wing bodies (BWB) may finally arrive in the civil aviation market.

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