System Engineering Approach to Research on Aircraft Integration

Professor S RAGHUNATHAN, Dr. M PRICE, Dr. R CURRAN, Dr. J EARLY, Dr. E BENARD, Dr. A MURPHY & Dr. J WANG

Centre of Excellence for Integrated Aircraft Technologies (CEIAT)
School of Mechanical and Aerospace Engineering
Queens University Belfast, United Kingdom

Ph: +44(0) 2890975607 Fax: +44(0) 2890975576 Email: s.raghunathan@qub.ac.uk

Abstract

The ACARE Vision 2020 looks towards the realization of reduced aircraft emissions and noise combined with increased safety, and in response new approaches to design and development are required. Systems Engineering has emerged as an integrated, multidisciplinary, lifecycle approach to product design, involving both traditional physical and behaviour/process-oriented sciences. Currently, the knowledge base in this area is limited, and engineers who have awareness/training in this area are not available for employment within academia or industry.

It is in this context that the CEIAT was founded at Queens University Belfast, with the strategic aims to (a) research into new technologies, (b) develop integrated models and tools for design and (c) develop models for knowledge/technology transfer. Since its inception, the Centre has made significant progress in establishing national/international industrial linkages, and developing some of the major building blocks for integration. The paper presents completed/ongoing programmes of research within the Centre.

1. Introduction

The major challenges in Aerospace Engineering in the next two decades (as set out by the European ACARE Vision 2020)[1] are to reduce nitric oxide emission by 80%, carbon monoxide/carbon dioxide by 50%, noise by 50%, while at the same time reducing cost and improving safety. While challenging, the issues are further complicated by trends which indicate that within the same twenty year period, the industry can anticipate an increase in capacity and customer demand. Such challenges are presented in an environment where the understanding of the physics of flight has changed very little over the years, and industrial growth is driven primarily by cost rather than new technology. In order to respond to these needs, innovative technologies combined with an integrated, efficient process for lifecycle design are required, and Systems Engineering is one such method by which this may be accomplished.

Systems Engineering is a holistic, interdisciplinary management process, aimed at evolving a lifecycle balanced set of system solutions which satisfy customer needs[2]. By integrating the traditional aeronautics disciplines (for example, aerodynamics, structures and flight mechanics) with emerging disciplines (such as system management, manufacturing and technology transfer) within an integrated design framework, issues such as risk analysis, trade study, optimization and lifecycle costing may be approached from a ‘whole system’ viewpoint, reducing the likely instance of system failure/redesign (Figure 1).

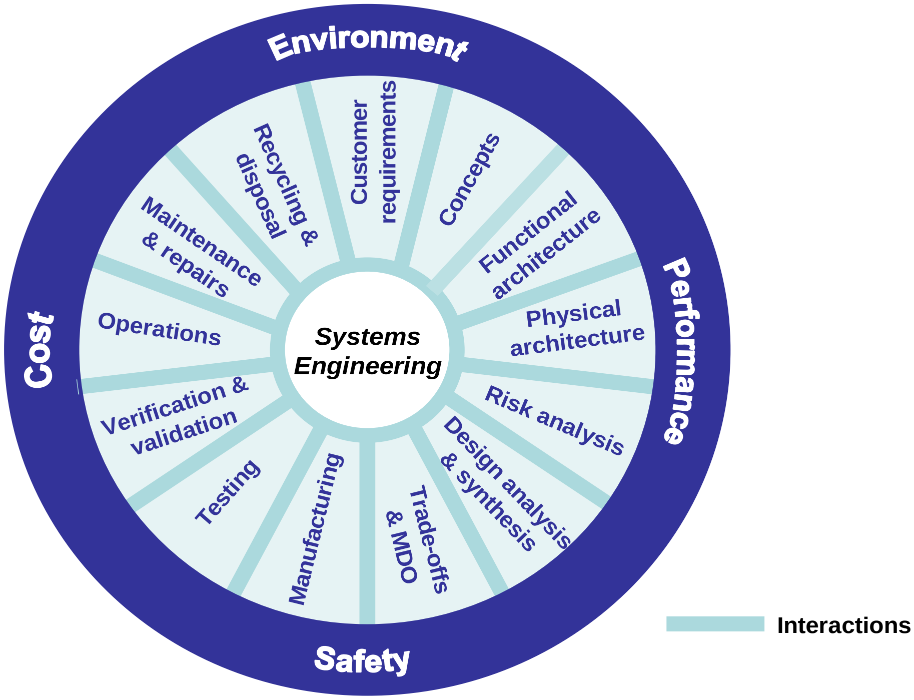

Figure 1 Lifecycle analysis from a Systems Engineering perspective

Within this context, the Centre of Excellence for Integrated Aircraft Technologies (CEIAT) was established at Queens University Belfast in 2003, with the support of Bombardier Aerospace. The initial strategic aims of the Centre were aligned with the targets of the ACARE 2020 Vision - to conduct research into new technologies and develop models/tools for use in aircraft design processes in order to link critical disciplines using a Systems Engineering approach, while simultaneously developing models for knowledge/technology transfer between academia and industry[3,4] and training a new generation of aerospace engineers in integrated design/Systems Engineering techniques.

The Centre was initially funded by InvestNI for a three year period (2003-2006) with a £5M budget under the auspices of Peace II, and supported by Bombardier Aerospace. The initiation period of the CEIAT concentrated mainly on the development of methods and technologies in the fields of Integrated, Nacelle Aerodynamic and Process Technologies (Figure 2), and through the combined research programs, has made significant progress in the establishment of infrastructure, national/international industrial linkages, and the development of key technologies and processes to facilitate integration within aerospace products. This has led to significant technology advancement and has been supported by several industrial trade studies. CEIAT is now looking forward to continued sustained research within these areas in order to support the key objectives of the European Vision for Aeronautics[1].

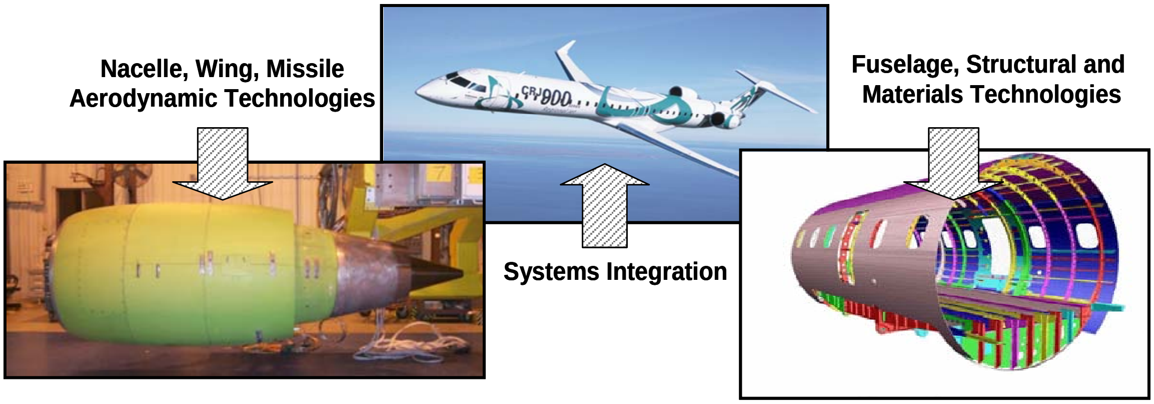

Figure 2 Initial CEIAT Strategic Research Areas

2. Integrated Aircraft Technologies

Within the Centre of Excellence for Integrated Aircraft Technologies, the main focus of research was based around the development of tools in order to support a number of aspects of the Systems Engineering process, including the understanding and development of tools for integration of design, analysis and synthesis; system architecture development; trade study processes and cost modelling. Some of the key areas are presented in greater detail within the following sections.

Integration of Design Analysis and Synthesis Methods in a Systems Engineering Framework:

Integration of analysis disciplines is now seen as a key element in the development of engineering technologies. Obtaining improved designs at better cost[5] is difficult to achieve when the various elements of the design are considered in isolation. However it is recognised that the complexity of fully detailed simulations in different disciplines such as manufacturing process simulations and aerodynamic or flight performance simulations are difficult to fully utilise in themselves, before any consideration is given to integration. In fields such as aerospace, preliminary design is carried out on simple conceptual models and this early design data is built up from a multi-disciplinary viewpoint. However, once the initial design outline is fixed the detailed design and analysis work largely proceeds within individual disciplines independently. As details are added to the design each discipline gradually diverges from the others in the detail and complexity of the models, largely due to the simple fact that a critical feature for one discipline is an irrelevant detail for another. Typically analyses are driven by the design.

An implementation of a framework for the integration of analysis models with design has been performed[6-8]. The framework provides for using existing CAD functionality to rapidly generate CAD and analysis models and provides a mechanism whereby detail design changes can be accounted for in an updated coarse model to enable rapid evaluation of design alternatives in an integrated environment and permits analysis driven design. In CEIAT to date tools have been developed which can link a hierarchy of multi-disciplinary models from structural details up to the full aircraft level. Although not all of the linkages are present or fully automated capability includes automatic generation of solid models, structural and aerodynamic models, cost models and weights models. This framework is continually being developed to include more disciplines and greater depth[9-11].

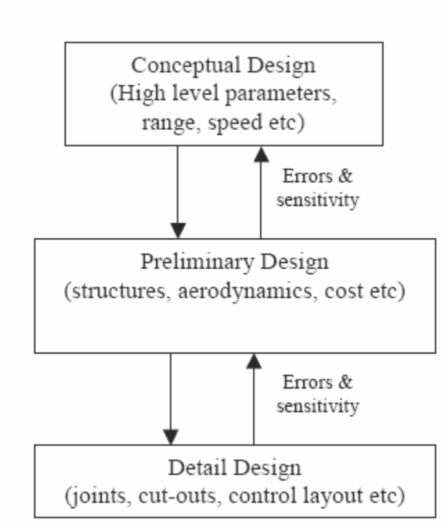

Figure 3 MDO Framework for Aircraft Design[6]

Trade–off studies- Aerodynamic Tolerances, Manufacturing and assembly for Life Cycle Cost:

Aircraft design has traditionally been driven by aerodynamicists, who promote the use of smooth surfaces with tight tolerances in order to reduce drag (and as a result, fuel burn), but this requires a high level of investment in manufacture.

Consideration of the Direct Operating Cost (DOC) for the Airbus class of aircraft has indicated that the cost of manufacture may be as high as three to four times that of the fuel cost[12] (Figure 4). With this in mind, while the relaxation of aerodynamic tolerances may lead to an increase in drag (and therefore fuel consumption cost), the manufacturing cost of the aircraft should decrease, hence leading to an overall saving in the DOC.

The work to date (jointly funded by EPSRC and Bombardier Aerospace) has shown that by optimizing the aerodynamic tolerances, a saving up to 2% in DOC may be achieved (Figure 5). The potential for saving in smaller aircraft classes could be even higher.

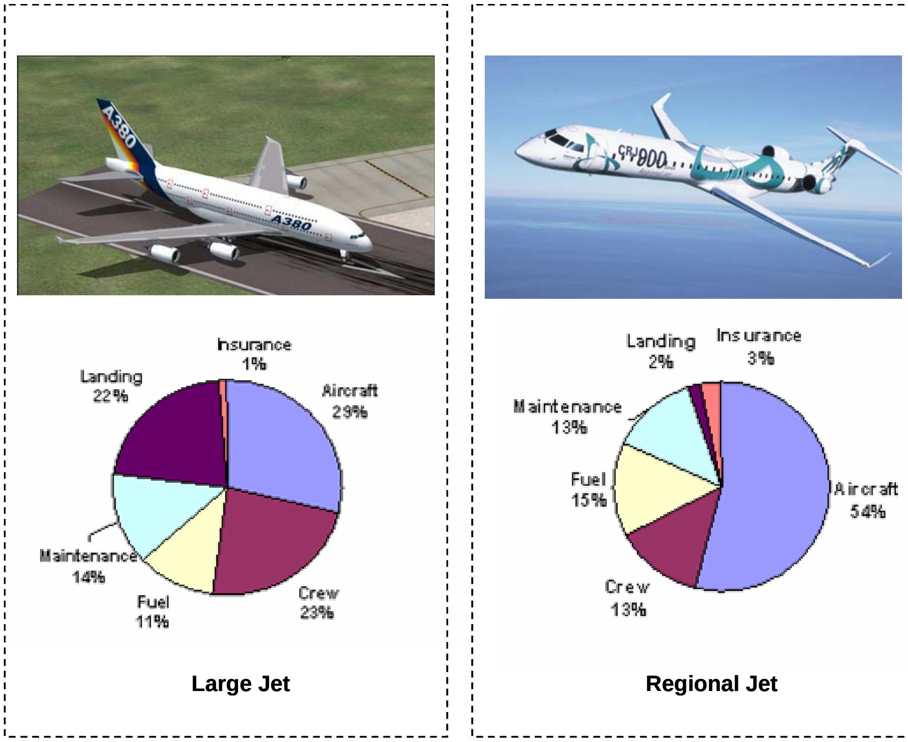

Figure 4 Comparison of Direct Operating Cost between large and regional jets[12]

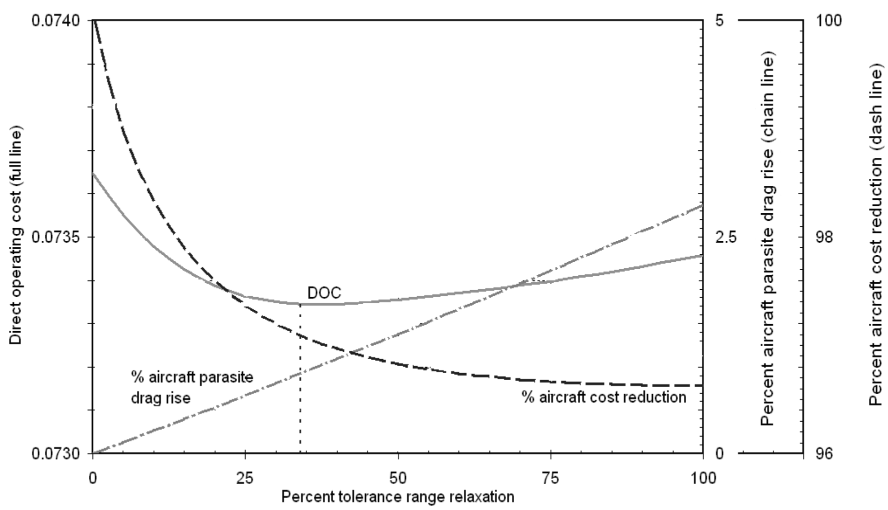

Figure 5 Trade–off studies- Aerodynamic Tolerances, Manufacturing[12]

Nacelle Aerodynamic Technologies

The main function of aircraft nacelle (Figure 6) is to provide smooth airflow to the engine within all flight conditions, as well as housing several safety and environmental protection systems. The work with Queens University Belfast, carried out in conjunction with Bombardier Aerospace, has concentrated on some of the major challenges facing the industry in this area, and some of the key areas of research within the Centre have included extensive examination of thrust reverser mechanisms and anti-icing solutions.

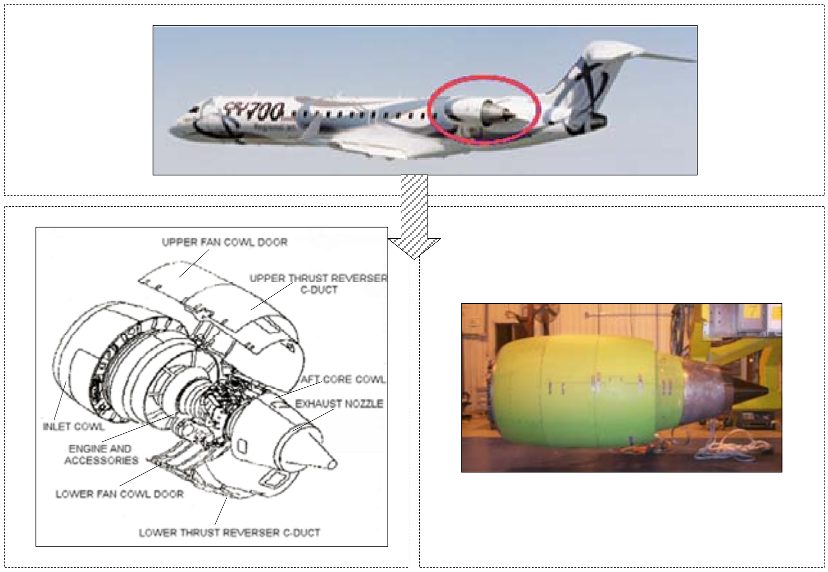

Figure 6 Key Nacelle Aerodynamic Technologies has formed the focus of much of the ongoing research within the Centre[13]

The Anti-Icing System:

Aircraft flying at high altitude are subject to ice formation on the wings, which leads to undesirable performance degradation, and at the engine inlet, which may result in ice ingestion into the propulsion system impairing its performance. In both of these situations, there is the potential for disastrous consequences. Ice protection in aircraft is provided by the anti icing system, which consists of hot air (in the form of jets) bled from the compressor and impinging on inside surfaces of wing leading edges and nacelle lips (Figure 7)[13]. By doing this, the system effectively evaporates impinging water/melts ice accretion on the external engine surfaces, fulfilling the stringent safety regulations for flight into ice conditions. Accuracy of prediction of heat transfer in such systems is still a state of art, and as the system has to be reliable, the designs are usually conservative.

By improving the heat transfer predictions, it opens up the possibility for less conventional designs to be adopted, and hence lead to potential weight and cost savings. Through a joint programme of research with Bombardier Aerospace, a unique correlation for heat transfer in a piccolo anti-icing system has been developed[14] in which the correlation is independent of the diameter, number of the holes, and the distance between the holes and the impinging surface. It has also been demonstrated that the effect of aircraft normal vibration on heat transfer is negligible, and that normal vibration of an engine is not a key parameter in design of anti-icing system[15]. Further studies have also proven that a pulse-jet piccolo anti-icing system could produce an enhancement in heat transfer of 10-20% compared to a similar steady jet system, or indeed reduce the bleed air requirements by 10-20%[16].

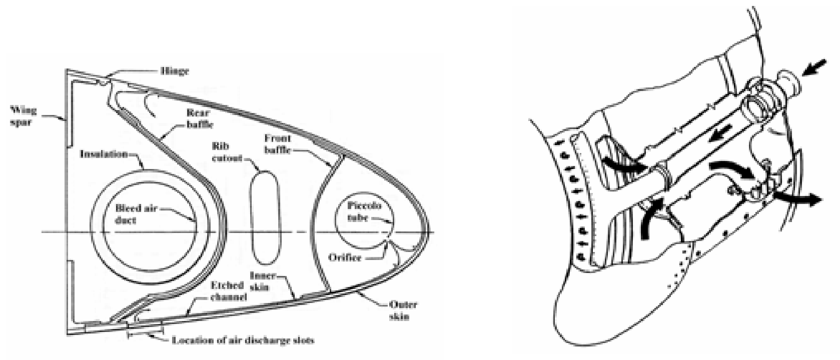

Fig 7a: Piccolo and jets

Fig 7b: Bleed system

Figure 7 Piccolo Anti-Icing System[13]

The Thrust Reverser:

In modern aircraft, the thrust reverser is built into the aircraft engine, and through the reversal of the forward thrust airflow direction, produces a deceleration force (Figure 8). The thrust reverser design is complicated by the multiple, often conflicting objectives that it needs to satisfy - maximizing reverser efficiency while minimizing the cruise drag penalty, noise; minimization of the adverse effects on engine performance, aircraft stability and control; and the weight of the reverser components – but it does offer a number of operational advantages. By incorporating the thrust reverser into the nacelle, landing runs may be shortened, there is less 'wear and tear' on aircraft brakes, landing in adverse weather conditions is safer, and there is additional safety and control margins present during aborted take-offs.

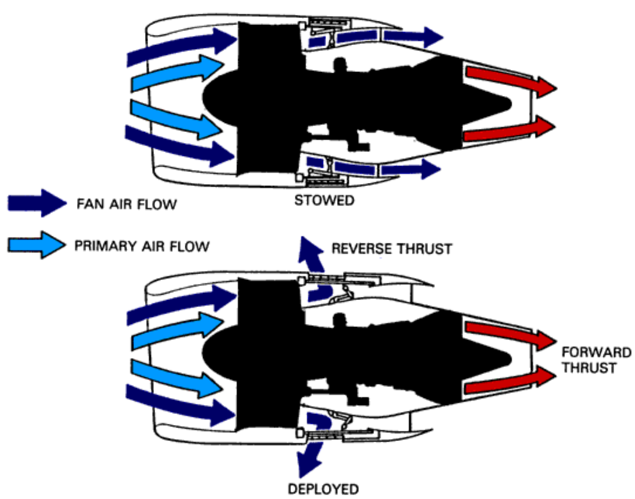

Figure 8 Thrust Reverser Operation[17]

One specific type of thrust reverser that operates on the fan flow is the natural blockage concept, first implemented on an aircraft by Bombardier Aerospace. This manner of achieving thrust reversal has several notable advantages, the main ones being the reduction in moving parts and an increase in thrust reversal efficiency. Several studies within QUB have considered this concept[18], the most recent a cascade-less design based upon the natural blockage concept. This cascade-less design represents the next generation in cascade/translating cowl style designs, and delivers a number of benefits to the customer, such as increased reverse thrust effectiveness; further reduction in part count; cleaner fan duct; increased acoustic attenuation and improved reliability.

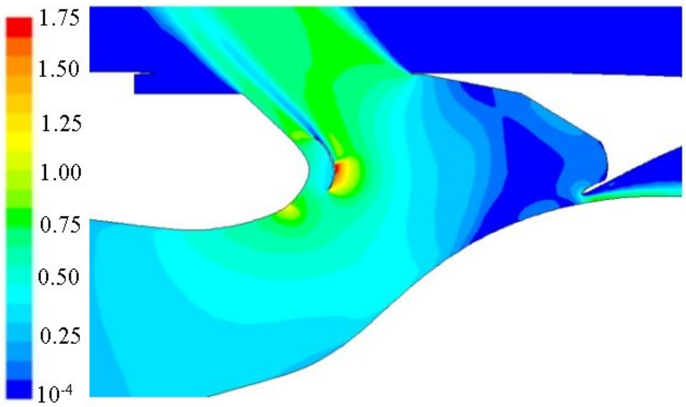

Figure 10 CFD analyses of the cascade-less configurations have been carried out, presented with typical Mach number contours[13]

3. New Programmes of Research

Throughout the initial three year period, the Centre of Excellence for Integrated Aircraft Technologies has established an international reputation for research in integrated technologies, and through industrial/academic partnerships forged in this time, is now participating in a number of new and innovative research areas. Through a number of academic and industrial collaborative working agreements, the CEIAT now contributes to several UK and European wide initiatives, all of which are targeted at meeting the needs of the Aerospace Community. The following section will highlight the major ongoing projects, and how these link into the higher level objectives of the Centre and contribute to the overall objectives of the ACARE Vision 2020.

Advanced Technology Vehicle Programme:

In meeting the ACARE 2020 Vision, the Aerospace Innovation and Growth Team (AeIGT) identified key UK strengths to build upon in order to ensure continuing UK world-leading capability for the next twenty years and beyond. From this, QUB/CEIAT has become involved in two programmes under the heading of Advanced Technology Vehicle Programmes, which are aimed at meeting these objectives – the Integrated Wing and Technology Validation Programme, and the Environmentally Friendly Engine. Both projects are being undertaken as part of a UK-wide industrial/academic consortium.

The Integrated Wing and Technology Validation Programme is aimed at the full development and deployment of an integrated wing concept that enables cost and weight reduction to be realized along side performance and safety enhancement, based upon the current research and design within this field within the UK. By considering advanced flow control methodologies; novel noise reduction, materials, design and manufacture concepts; superior fuel and landing gear systems; and the development of a ‘virtual’ integration and validation environment, the project aims at building on the combined strengths of the UK partners in order to develop optimum configurations to meet the challenging requirements of the modern aerospace community.

Complimentary to this programme, the Environmentally Friendly Engine programme is targeted at addressing the emission and noise goals as set out by ACARE through the development of UK Aerospace capabilities within several fundamental technologies – high temperature materials, high efficiency turbine components, low emissions combustion, advanced manufacturing technologies, engine controls, actuation technologies and nacelle aerodynamic technologies.

Network Enabled Capabilities through Innovative Systems Engineering (NECTISE):

Within the worldwide context, the manner in which large scale operations are approached is rapidly changing, as increasing customer demand for cost effectiveness becomes one of the largest drivers. This is evident in many large businesses and within the military sphere, and has seen the emergence of Network Enabled Capability (NEC). The NECTISE programme, supported by both BAE Systems and EPSRC, is aimed at addressing the requirements for NEC, and the manner in which Systems-of-Systems may be successfully realized in order to ensure operational effectiveness while maintaining value for money. The development of life-cycle costing methods are the focus of the CEIAT work in this programme.

Single European Sky Implementation Support through Validation:

The European Air Transport industry forms a key factor in the European economy, not only through a contribution of more than € 130 Billion to the European GDP, but also through the employment of about 2 million people and as a strong pillar facilitating mobility and business across borders. On average around 500 million passengers are transported every year by European airlines alone on more than 5,000 aircraft. A large majority of exports out of the European Union members are transported by air (30% of today's export leave Europe by plane) and this is set to rise. However, growth of air transport in Europe is heavily constrained by traffic congestion and delays. Considering the 5% annual traffic growth forecast by ICAO (greater in the NMS), and taking into account the specificity of the European region, a two-fold growth of air traffic in Europe is anticipated in the 2002-2020 timeframe. Therefore, the Single European Sky Implementation Support through Validation programme aims at addressing the need for new technology within the European Air Traffic Control and the manner in which this can be implemented in time for realization by 2020 through a worldwide network of both academic and industrial partners. The role of QUB is to develop system-wide models of impact assessments.

Precision Concept Modelling of Manufacture for Competitive Advantage (PreMade):

The 'PreMade' project was part of the DTI's Technology Programme second call entitled "Design, Simulation and Modelling". The aim is to develop a methodology and toolkit to assist in the deployment of lean manufacturing principles, working within a network of UK academic and industrial partners. Specifically, cost modelling will be looked at very closely to complement the functionality of Dassault Systemes' Product Lifecycle Management (PLM) software, and allow costs to be generated both with greater accuracy and earlier in the design process[19,20]. Design assumptions and manufacturing solutions will be challenged in an attempt to better balance the digital analysis of design relative to manufacturing implications. The first focus is on the DS DELMIA software products, then moving on to consider how the developed principles will affect generic PLM implementation. Ultimately, a methodology will be developed for a semi automated Lean decision-making process that will give real time metrics about each decision made.

Detailed Multi-Physics Modelling of Friction Stir Welding (DEEPWELD):

Friction Stir Welding is a new technique that could revolutionize the way aircrafts are built, replacing riveting by welding. The benefits of FSW include the ability to join materials which are difficult to fusion weld. It is a simple, robust process that involves no consumables. When handled properly, FSW results in a defect free weld with superior properties. The objective of DEEPWELD is to draw on the experience of wide number of European academic and industrial partners in order to develop a multi-physics multi-scale numerical tool for simulating the Friction Stir Welding (FSW) process that will be able to obtain accurate predictions of residual stresses, weld properties and tool loads.

Unsteady Effects in Shock Wave induced Separation (UFAST):

With an estimated average growth of 5% per year, air traffic will triple by 2020. Thus the major goals of Vision-2020 are dedicated to the reduction of both, noise and pollutants, a crucial item for innovative new aircraft concepts. In that respect, the UFAST project indirectly contributes to this by providing means for an improved understanding of the flow phenomena in the area of unsteady shock wave/boundary layer interaction. The general aim of the UFAST project is to foster experimental and theoretical work in the highly non-linear area of unsteady shock wave boundary layer interaction, distributed across a number of European partners (both academic and industrial). The main study cases, shock waves on wings/profiles, nozzle flows and inlet flows, will serve as a sound basis for open questions posed by the aeronautics industry and can easily be exploited to enable more complex applications to be tackled.

4. Training

Training of engineers for employment in key sectors of aerospace is one of the major aims of the Centre. Two major initiatives for training namely, Engineering Doctorate scheme and visiting professor in Integrated Systems Design are described in this section

The EPSRC-Engineering Doctorate Scheme:

The Engineering Doctorate (EngD) is a four-year postgraduate award intended for the UK's leading research engineers who want a managerial career in industry. It is a radical alternative to the traditional PhD, being better suited to the needs of industry, and providing a more vocationally-oriented doctorate in engineering. Initial evidence suggests that students (known as Research Engineers) do have better job offers and starting salaries than those carrying out more traditional PhD or MSc training (source: EPSRC). The scheme started in 1992 and the first graduates entered the employment market in 1997.

The Systems Engineering EngD is a four-year programme combining research and taught elements in Systems Engineering. The Research Engineers (REs) will spend around three-quarters of their time working directly with their sponsoring company, on research projects designed and supervised jointly by academics and the sponsoring company. The other quarter of the four-year period will be spent undertaking masters-level training in systems engineering skills, in the development of management capabilities, and specialist technical subjects directly relevant to each REs research. The scheme provides industry with an unparalleled opportunity to engage the services of a high quality engineer in the most cost effective manner.

The participants are Universities of Bath, Leicester, Loughborough, Strathclyde and Queens Belfast and several supporting industries, including BAE Systems and Bombardier. During the period 2006-2011, it is anticipated that there will be 40 doctorate awards made from the partner institutions. The benefits for the engineers include an Engineering Doctorate in Systems Engineering, training in systems engineering core competencies, an appreciation of industrial research and development culture, research capability derived from challenging industry-sponsored projects and high quality research.

EPSRC Systems Engineering Visiting Professor Scheme:

The strategic aim of the proposed project is to develop high quality undergraduate and postgraduate degree programmes in Systems Engineering in the Faculty of Engineering at Queens University Belfast. The appointed visiting Professor (VP) will develop a taught undergraduate module in Systems Engineering as a first step in achieving this aim. The VP will also assist in enhancing the quality of a number initiatives at Queen's University which are related to Systems Engineering, including (i) International Design Exercise, (ii) EPSRC Engineering Doctorate scheme on Systems Engineering, (iii) CDIO (Conceive, Design, Implement, and Operate) module in a new degree course in Product Design, (iv) Centre of Excellence for Integrated Aircraft Technologies (CEIAT), and (v) education and training of students and staff on Network Centric Operation (NCO).

5. International and Industrial links

The type of research conducted in the Centre, to be effective in the context of Technology Readiness Level (TRL) of the team, required strategic links with Aerospace and allied industries. In this context, Mechanical and Aerospace Engineering has developed strategic links with Bombardier Aerospace. Bombardier Aerospace Belfast founded the first Chair in Aeronautical Engineering at Queen's University in 1955, and in 1999, the UK Royal Academy of Engineering and Bombardier Aerospace Chair in Integrated Aerospace Engineering was established. Bombardier Aerospace, in partnership with the government, (including the Engineering and Physical Sciences Research Council), have contributed significantly towards the research activities in the research cluster in cash, kind and advisory support. The school has additional research linkages with Thales Defence Ltd, FG Wilson (Caterpillar), BAE Systems, Airbus, Qinetiq, and Rolls-Royce.

Within the UK and Europe, the Centre has developed and maintained research links with several universities, many of these linkages being developed through the Framework 6 program. The centre has developed links to Canada, Japan and Korea through research projects and academic collaborations, and has a strong linkage with the American Institute of Aeronautics and Astronautics (AIAA), with several members of the group active within the AIAA Technical Committees. AIAA have also established a student branch in Belfast, the first of its kind in the UK.

CEIAT organized the 1st International Conference on Innovation and Integration in Aerospace Sciences in Belfast on 4th-5th August 2005 The conference was co-sponsored by American Institute of Aeronautics and Astronautics (AIAA) and the Royal Aeronautical Society (RAeS). Following on from this success, the AIAA Aviation Technology Integration and Operations Forum will be jointly held with the 2nd CEIAT International Conference on Integration and Innovation in Aerospace Sciences and the 17th Lighter-Than-Air Systems Technology Conference in Belfast from the 18th-20th September 2007.

6. Conclusions

Complimentary to the ACARE Vision 2020, the Centre of Excellence for Integrated Aircraft Technologies (CEIAT) was established at Queens University Belfast in 2003. The programme of activities which have been completed in the period 2003-2006 have been presented, and an outline of the future direction of the CEIAT for the next five years highlights the achievements of the centre since its inception.

The initial strategic aims of the Centre to develop research into new technologies, integrated models/tools for aircraft design through the adoption of Systems Engineering methodologies and techniques to foster industrial/academic links through knowledge and technology transfer have proven to be within the scope of the centre, and these objectives have been successfully realized within the initial period, providing a solid foundation for the continuation of research within all of these critical areas. This has led to the new generation of research projects – Integrated Wing and Technology Validation Programme, the Environmentally Friendly Engine Programme, NECTISE, Single European Sky Implementation Support through Validation, PreMade, DEEPWELD and UFAST. Continuing internationalization of the centre has generated multiple scientific publications, involvement in international aerospace bodies, and attracting the highly regarded AIAA Aviation Technology, Integration and Operations forum to Belfast in 2007.

Following on from the initial strategic aims of the CEIAT, the future direction of the Centre is now focused on the fostering of highly collaborative linkages with industrial partners in order to develop more complete models for integration while exploiting international research linkages in order to facilitate this.

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