Reliable and Relevant? CAE analyses that are fit-for-purpose: the role of NAFEMS

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Abstract

The numerical simulation and digital solution of many engineering problems in solid mechanics, fluid dynamics and a wide range of other fields is now widespread. Design processes rely more and more on the results of CAE modelling, bringing an increased need to ensure that those results are reliable – not only in the verification of basic algorithms and their embodiment in computer code, but also at the level of the processes by which these codes are used and the good judgement of the people using them. The 'fitness for purpose' of any modelling and analysis process must be established: firstly its 'purpose' – in design, optimization, certification and so on – and then its 'fitness'. This paper addresses the requirements for benchmarking and quality assurance of CAE methods; their appropriate application and integration into engineering design and certification processes; and the education and training – and potential accreditation – of users.

The NAFEMS organization has existed for over 25 years – commencing in the UK and growing into a worldwide, independent association for the engineering analysis community – dedicated to addressing these needs in an independent and unbiased way.

Key words: CAE, finite elements, CFD, quality assurance, education, certification, verification

1. INTRODUCTION – RELIABLE DESIGN BY ANALYSIS ?

There is an increasing trend to put economic value on all human actions in the developed economy, and especially time itself is given a cost. This has brought tremendous pressures to bear in design and manufacture of products and engineered systems of many different types. In order to reduce the cost of manufacture, or make better use of scarce resources, or bring to the marketplace a product that is better-adapted to the customers' desires or functional requirements, the design must be optimised. Amongst other things, this usually means designing it to meet the required performance with less margin for error, less 'conservatism', and therefore with greater precision and reliability. In order to reduce the time from the first concept and plan to the delivery of a finished product, system or construction, the design process itself must be speeded-up and the opportunities for iteration on physical prototypes are greatly reduced. In some industry areas, such as large civil constructions, power plants, oil and gas structures and defence systems, physical prototyping (at least at full scale) is impractical and uneconomic. Therefore, the emphasis is placed on so-called 'virtual prototypes' – the use of simulation to model the physical world of the design and calculate its functional performance. The time and cost to calculate the benefits of modifications and iterations on the design, whether to meet changing performance requirements or to optimise the performance, are usually much less using a virtual prototype than with physical tests. The development of digital computing in recent decades means that 'virtual prototyping' can be adopted as the normal design process, at least in principle. As we shall see, implementing this in a reliable way may not be so simple.

The economic and time imperatives mean that many industries are adopting virtual prototyping. Even by 2001, Thomke [1] states that "Toyota has slashed development costs and time by 30-40% and solves 80% of all problems before creating initial physical prototypes" and "Using many computer simulations – and two physical ones – BMW conducted a total of 93 car-crash tests that transformed its understanding of car performance and improved side impact safety by 30%".

In the context of assessing the functional performance, safety, reliability, etc, of a design, the virtual prototype defines a simulation, which is by definition a *prediction* of how the design will behave in given situations. Since both economic performance and the safety of human lives and environment will depend on the behaviour of the design, the reliability of this prediction is of crucial importance. This can be understood in terms of an assessment of the *fitness for purpose of the design analysis procedures*. The issues surrounding this and the actions being taken by NAFEMS to facilitate the use of fit-for-purpose simulations across a range of industries, are the topics of this paper. The simulation methods that are considered are typically 'mesh based': mostly finite element (FE) modelling, but for some applications boundary element (BE) methods may be more appropriate, or even others such as finite difference techniques; and in fluids applications mesh-based numerical solutions of Navier-Stokes problems, namely computational fluid dynamics (CFD). More generally, we address any modelling method using numerical solutions of partial differential equations: these remarks are quite general and can be applied to many different scenarios.

2. FITNESS FOR PURPOSE – WHAT IS THAT ?

When using any computer-aided engineering (CAE) tool, we make a mapping from the real world into the virtual domain, simulate the real-world behaviour, draw conclusions regarding the design (perhaps with modifications, iterations, and optimisation) and then map back to the real world – where the final 'verification' will take place. The digital simulation must therefore represent *to a sufficient degree* the real world situation. It must generate results of *sufficient accuracy* to be valid and provide useful design guidance (and potentially 'sign off'); those results must be of *sufficient quantity and detail*, to identify risks and/or beneficial design changes; and they must be provided within a time-scale that means they are *relevant* to the overall 'business process'. What then does it mean to have a simulation that is *fit for purpose*? For an engineer in one industry, the answer will be very different from another: to take two extremes, someone modelling Formula 1 race-car aerodynamics will require results as rapidly as possible, to assess the benefits of small design changes during race activity (and is perhaps not too concerned with absolute accuracy); whereas a nuclear plant engineer will require a result with the highest-possible confidence when assessing safety cases. With the increasing use of simulations embedded within a larger digital product design system (CAD) or product data management (PDM), the user of the simulation tool may even be unaware of all the issues surrounding its application – an issue to which we will return later.

The rise of the virtual prototype has largely been driven by questions of *value* (fewer expensive and time-consuming physical tests, faster design cycle times, reduced time to market, optimised products, etc). However, if a simulation process is used badly, *this value will be destroyed*: product re-work and re-design will be required, in the limit even product recall or very serious scenarios of failure. Whilst a 'business case' can be made for increased used of simulation, then, a parallel case must also be made to ensure this is fit-for-purpose. The specific values attached to different aspects of these business cases will, of course, vary from industry to industry and product to product.

2.1. Assessing Fitness for Purpose: Verification and Validation

Leaving aside the economic aspects such as speed, required resources and similar factors, assessing the fitness for purpose of a simulation is a matter of verification and validation. Useful definitions highlighting the difference between these two terms, in this context, have been adopted by AIAA [2] and ASME [3]:

Verification: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.

Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

As Schwer states [4]: "Verification provides evidence, or substantiation, that the conceptual model is solved correctly by the computer code in question. … [T]he conceptual model, sometimes called the mathematical model, is typically defined by a set of partial differential or integro-differential equations, along with the required initial and boundary conditions. The computer code solves the computational model, *ie* the discrete-mathematics version, or mapping, of the conceptual model. The fundamental strategy in verification is to identify, quantify, and reduce errors caused by the mapping of the conceptual model to a computer code. Verification does not address the issue of whether the conceptual model has any relationship to the real world, *eg* physics. Validation, on the other hand, provides evidence, or substantiation, for how accurately the computational model simulates the real world for system responses of interest."

Figure 1 (after [3], [4]) shows a flow-chart of an analysis – and a parallel physical test – with the points at which verification of the mathematical model and its implementation in a computer code can take place, together with validation based on the outcomes of the process.

We can consider how these issues apply and the risks and opportunities that exist in three main aspects of the simulation: the programs (*ie* software); the process; and the people who use them.

2.1.1. Programs – verification

Computer code needs to be verified, to know that the mathematical model and the solution algorithms work correctly; and the calculation procedure needs to be verified, to know that the discrete numerical solution is accurate. With most large-scale simulation programs now extending to many hundreds of thousands (if not millions) of lines of code, with sub-routines linked together at multiple levels, and with many different options for choices of algorithms and specific parameters, these tasks are not trivial. Software developers have to devote significant resources to them, if their end-users are to be confident. Furthermore, every new release of the software (which probably adds further features and complexity) also requires repeated testing, along with implementations on different hardware (with different numerical precision, parallel computing, etc) and different operating systems or compilers. This can be brought into focus when realistic problems involving ill-conditioned numerical problems are attempted, particularly with such cases as material or geometric non-linearity. Sometimes an embedded routine written many years ago can be the source of problems when software is migrated to a new environment.

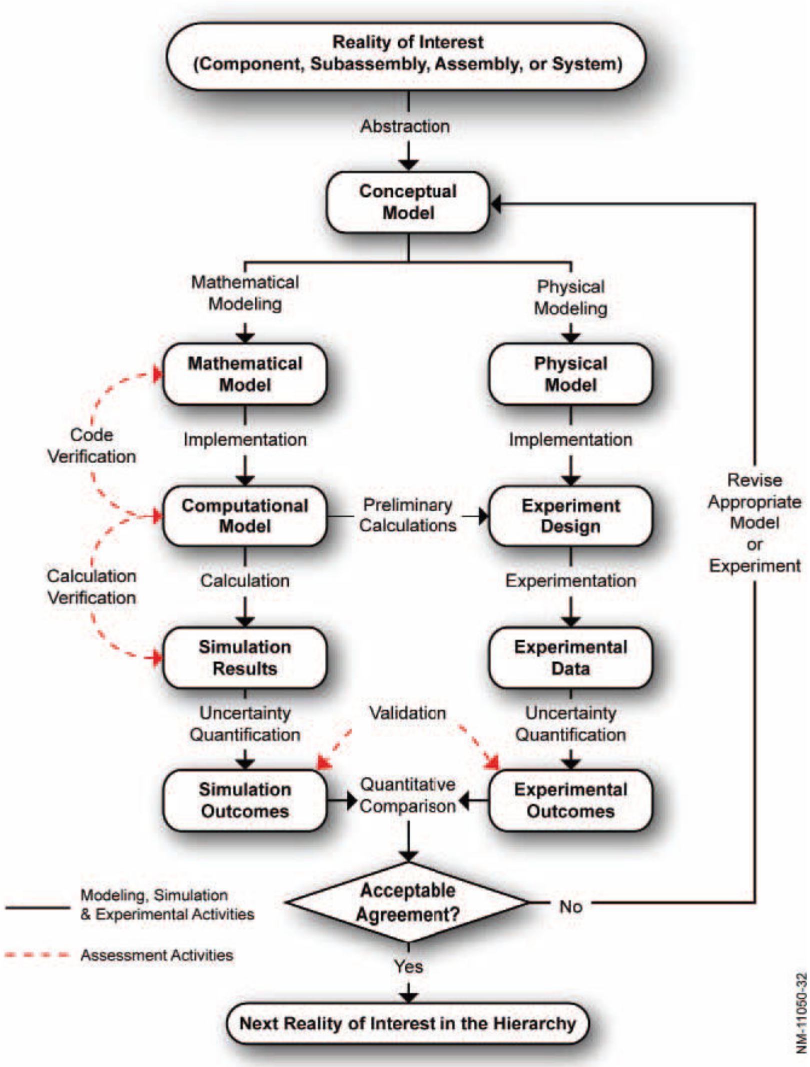

Figure 1: Numerical and physical modelling processes

It is self-evident that software should be tested, but since many simulation programs are commercial codes, several issues arise – notably the need for transparency in the testing, open publication of results, and the need for external standards.

2.1.2. Processes – validation

Using a verified simulation code will only bring valid results if the overall process is accurate – that is to say, the application of the correct simulation methods and modelling assumptions with the right input data. The choice of linear or non-linear behaviour is an obvious question but may not have an obvious answer until more experience is gained on the specific application; dynamic or quasi-static conditions may be chosen, boundary assumptions etc. Whilst guidance may be provided in software, with increasing use of 'wizards' (similar to other standard office/PC tools) the use of generic embedded expertise ('expert systems') is unlikely to replace the development of application-specific methodologies – which implies that each user (or his organisation) needs to establish processes and procedures that aim to ensure fit-for-purpose simulations.

Independent standards for quality assurance procedures, especially the ISO 9000 series, have been widely implemented in many industries in recent years. The validation and benefits of those systems is outside the scope of this paper. But we can note that ISO 9000 has a Supplement for its application to engineering analysis [5].

A major issue in the overall simulation process is often the acquisition and selection of correct input data: both in the sense of its accuracy (correct geometry, finding and using correct material properties etc) and its timeliness (relating to the current state of the design, after all changes made by other design personnel). In recent times, embedding or linking simulation into a wider CAE process, indeed into a PDM system, has become increasingly popular. There are many business benefits to be gained from this, in terms of speed, data management and so on; and to some extent this can also assist in overcoming the accuracy and timeliness issues of the simulation data, through automatic transfer of data, less rework, reduced errors etc – and even notifying users of the need to perform re-analyses if design data have changed, or automatically doing re-analysis and notifying key changes in results. However, automation also carries weaknesses: the lack of user intervention may mean that results are accepted unquestioningly, assumptions are embedded into the data-transfer and analysis processes that are not scrutinized by the users, or technical issues in the transfer (such as CAD to FE geometry conversion) can affect the accuracy. The overall process as well as the details of the simulation methodology must be tested with realistic scenarios.

2.1.3. People – education and certification

Despite the steps taken over the years of development of CAE software and systems to build in automatic checks, warnings and so forth, these systems are nevertheless used by people – who make assumptions, gather and input data, choose one method or algorithm over another, choose one program over another, read and respond to program warnings (or ignore them) – and generally have a large influence on the outcome of a simulation. One may ask if our numerical analysis capability now exceeds our ability to make effective use of it. "This brings up many issues concerning the requirements for training the wider pool of personnel who are to utilise simulation" [1]. A university education, even to the highest level, which may include some exposure to the use of CAE methods or even the development of computer code, may not of itself provide the right sort of training in the overall process of performing fit-for-purpose simulations. There is a need to train personnel, better to understand the fundamentals of the simulation methods they may be called upon to use, how to select the right options and assumptions and how to control the complete process so it is 'fit for purpose' and produces results that are robust and relevant.

2.1.4. Case studies in verification and validation

Errors and other problems brought about by failures of programs, processes or people are often not publicised, for obvious reasons, such as high commercially sensitivity! However, the reader probably knows some cases. One form of 'test' which is done in a more open way is the so-called 'round robin' exercise: in such a test, all of the above-mentioned factors come into play, since often the exercise is set up as a comparison of different programs as well as different teams of modellers. Although the framework of such round-robins is often unrealistic compared to real-life analysis work (they are artificial exercises, the resources devoted are often limited, the real-life pressure to 'get it right' may be absent…) they do serve to illustrate the very large variation in results that can result from what should be the same modelling objective. Two examples are shown in Figures 2 and 3.

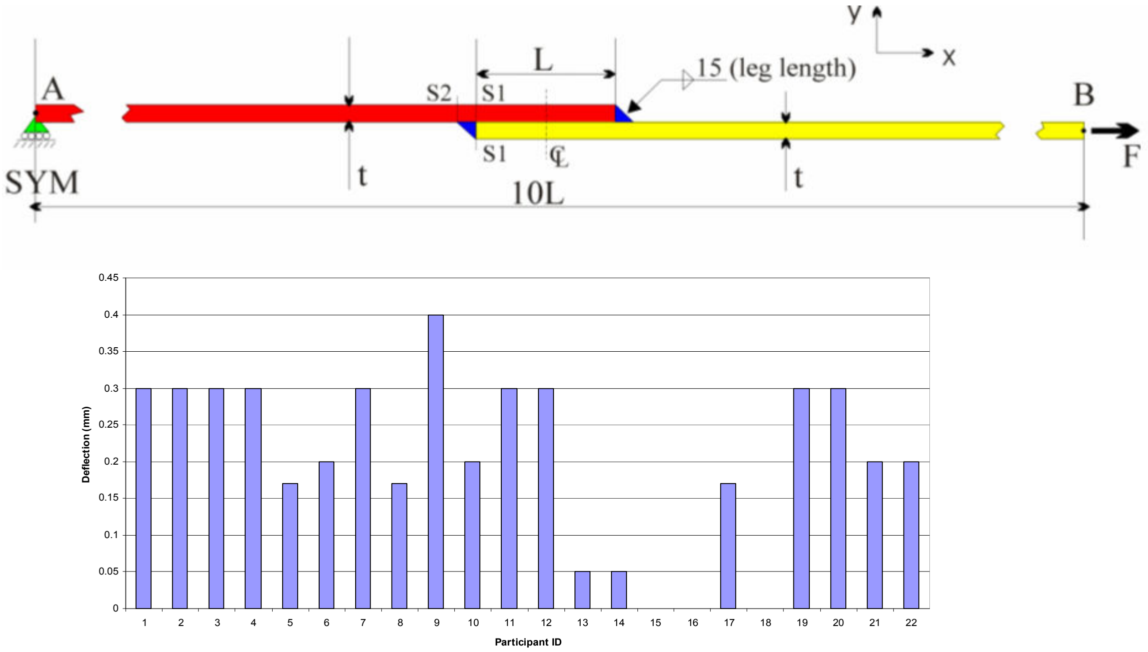

Figure 2: Round-robin computational mechanics study – NAFEMS benchmark for lapped joint
Results for X-deflection at loaded end, from various codes/modellers.

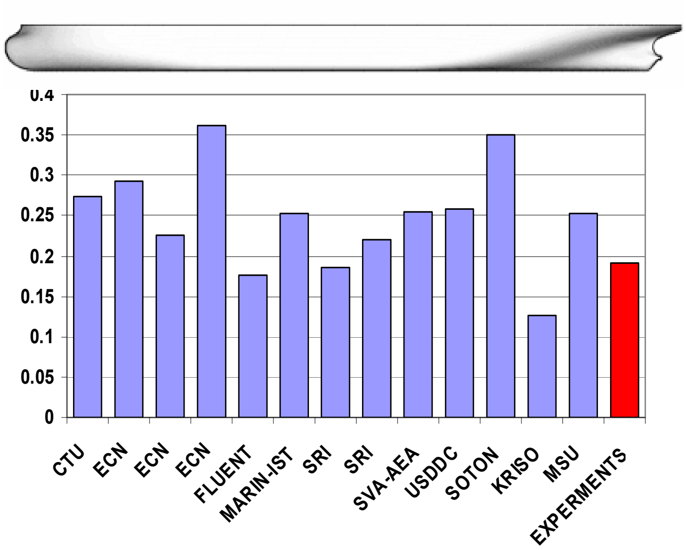

Figure 3: Round-robin CFD study (Workshop on CFD in Ship Hydrodynamics, Gothenburg 2000)
Form factor prediction for the KRISO 300K tanker hull.
Different results from the same code and turbulence model, different results from different turbulence models, variation increased at full scale…

2.2. Historical Perspectives on the Adoption of CAE Technology

Simulation using FE has been available for several decades, as has CFD (though adopted later) but it is the exponential growth in available computing power of the last decade or so that has led to the widespread adoption of CAE processes. Westphal [6] reviewed the historical development of the assessment or verification of simulations: a timeline is given in Table 1.

Time Period	Analysis Methods
Pre 1960s	Hand calculations (99% of analysts time spent on developing pre-processing – mesh generation/cleaning, boundary conditions, loading, etc)
1960s	Customized Programming on large main frames with simple manual made models (95% of time for pre-processing)
1970s	Customized Commercial Programs on large main frames with more complex manual made models (90% of time for pre-processing)
1980s	Introduction of PC/Workstations based analysis programs. Importation of CAD geometry (75% of time for pre-processing). "Make and break" verification.
1990s	Linkage (one-way) of CAD designs for analysis (60% of time pre-processing). "Model and simulate" verification.
2004+ (the future)	Optimization (full linkage of design and analysis). Multiphysics. Automatic pre-processing of the CAD design.

Table 1: Historical perspective of CAE methods

The organisations demanding (and acting to achieve) verification and validation of simulations have in the past been mostly governmental, military, or those responsible for safety-critical cases such as power and process industries, but in more recent times a strong commercial case has been made in many different industries, due to the increasing reliance on simulation within the design process and the increased risks of failures. This is apparent in the attendance at relevant technology seminars and conferences.

The level of adoption of simulation technologies varies in different regions and in economies at different stages of development. In particular, there are differences between so-called developed and developing economies: the latter typically have much higher growth rates but based usually on low-cost manufacturing of various sorts, with design (and consequently the related need for design analysis) only following later. There may however be some divergence between the level of adoption of design analysis technologies in commercial applications, and the level of academic education available in such so-called developing economies, which is very advanced in many cases. For one view on this, see for instance Pant [7].

3. NAFEMS

3.1. Overview of Organization and Activities

NAFEMS ('the international association for the engineering analysis community') exists to promote best practice in the use of simulation technologies in engineering and related disciplines. Originally established as a section of the UK government-run national engineering laboratory, it was subsequently re-constituted as an independent, not-for-profit membership association. This means that all its activities are run on a commercial basis, without underlying subsidies, but that it has no obligation to generate financial returns for investors or shareholders, and so is free to serve the best interests of its members and industry at large. NAFEMS has a small permanent staff and is led by a board of directors who are senior industrialists. Technical Working Groups, composed of specialists from industry and academia, are focussed on specific technologies or topics. Regional Steering Groups, composed of leading figures from industry, software vendors and academics, direct activities on a local basis and provide feedback from the membership. From its origins in the UK, NAFEMS has grown over the past 25 years to have a worldwide presence with activities in many countries in Europe and North America, and now looking at further regions where its services would be of benefit to the engineering community. A simple form organisation chart is shown in Figure 4.

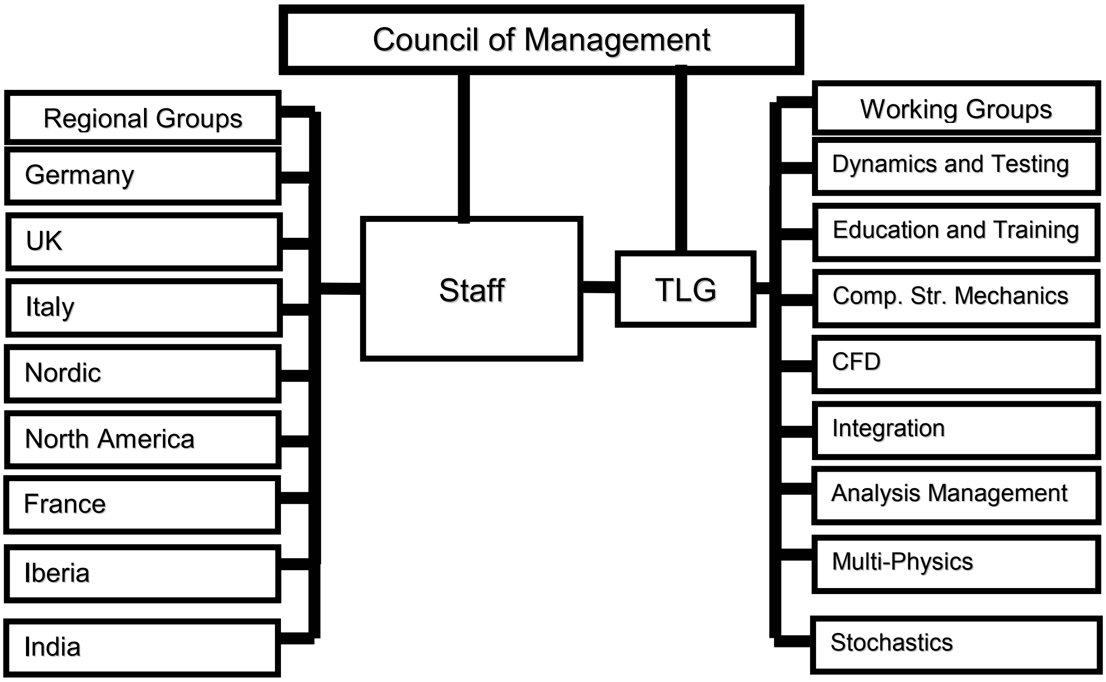

Figure 4: NAFEMS organisation structure

NAFEMS activities mainly comprise communications and education, through publications and seminars, and in recent times an important role in qualification through the certification of competent personnel.

3.2. NAFEMS and program verification

In its early days, NAFEMS focussed to a large extent on software benchmarking of various sorts. This activity is still going on, although it nowadays has somewhat less prominence within the whole scope of NAFEMS' activities, reflecting the developments in the use of simulation technologies and the needs for validation and verification.

NAFEMS' aim has not been to carry out benchmarks as such (that is, not to assume the role of a 'testing laboratory') but to coordinate agreement amongst relevant specialists about the content of benchmark tests for a wide range of software features – especially finite element algorithms and methods for modelling particular design features and details; to publish these standardised benchmarks; and to disseminate the results of testing exercises when these are done in a coordinated way. The current index of NAFEMS Publications [8] includes over 100 different benchmarks. It should be noted that these are often related to the application of FE or CFD to specific problems (such as modelling a joint) rather than the more 'internal' aspect of program testing (such as an element 'patch test').

The close involvement of many software vendors with the activities of NAFEMS is a positive aspect of this process. It is clearly not in vendors' interests to have their software misused (and perhaps therefore criticised) due to wrong choices when modelling a particular benchmark case.

3.3. NAFEMS and processes

NAFEMS addresses two main aspects of simulation processes: the overall operational procedures and related quality assurance principles and systems; and technical issues regarding the integration of simulation into product design systems and product data management. Various publications have been released on these topics and past and future seminars see researchers, software vendors and industrial practitioners addressing the issues.

Two NAFEMS Working Groups – on CAD/Integration and on Analysis Management – address these issues, guiding the production of further publications, organising seminars and collating inputs from practitioners, including coordination with national and international standards bodies such as ISO.

3.4. NAFEMS and people

Throughout its existence, NAFEMS has placed a strong emphasis on assisting individuals and organisations to develop the knowledge and skills to make effective use of FE and other simulation technologies. These activities are complementary to the work of educational establishments such as universities, where the emphasis can be more on the theory and development of algorithms and software. NAFEMS' focus is more on the practical application of the methods.

3.4.1. General education and dissemination

Two groups of people are addressed by NAFEMS' general education and dissemination activities: managers, who may not carry out modelling projects themselves but need to understand the benefits and potential problems of using simulation; and engineer/analyst end-users, who need to develop relevant and up-to-date skills and knowledge.

These client groups are addressed by way of seminars, both 'physical' and (increasingly) on-line 'webinars', and by publications. Speakers at these events are frequently real practitioners and managers from industrial companies, software vendors, institutes and academia, who are able to share state-of-the-art experience from a wide range of industries. The publications are also usually written by practitioners – such as the popular 'How to do … analysis' and 'Why do…' series (see Hellen [8] or www.nafems.org).

Every two years, NAFEMS organises a World Congress, which is a major event in the calendar of international symposia on engineering simulation, attracting some 400 delegates, all specialists in numerical modelling. In May 2007, the 11th Congress took place over 3 days in Vancouver, Canada, with over 130 papers.

3.4.2. Training courses

NAFEMS' own staff do not themselves present training courses on FE, CFD and related simulation methods, but in partnership with academic institutions and commercial training companies, NAFEMS coordinates and promotes a variety of practically-oriented courses on simulation, ranging from basic FE and applications to advanced methods. These events are publicised through NAFEMS communications, on its website, in mailings to members and others and in *Benchmark* magazine.

3.4.3. Certification and the Registered Analyst

As well as the general activities raising levels of awareness and knowledge in the end-user community, NAFEMS also recognised the need for a specific ‘certification’ that could be achieved by individual practitioners. This provides an independent verification of each individual’s level of expertise and experience. Therefore the Registered Analyst scheme was established. It is important to note that this is not ‘academically’ based but oriented to verifying the practical experience and responsibility exercised by the individual. This is done by a reporting and review process, carried out by suitable, local, experts, who in turn are authorised by their peers, coordinated by NAFEMS. The registration process currently has standard and advanced levels of attainment, and is open to experienced analysts through two alternative routes to verify his expertise, and to trainees through a mentored development route.

Registration is attractive to the individual, since it ‘certifies’ his level of competence (and is a portable element of his CV). It is attractive to his employing organisation, since it demonstrates a verified level of competence amongst their staff – whether for internal verification of quality or as a demonstration to external clients of the standard of personnel brought to their projects. It can form a useful part of relevant Continuing Professional Development.

3.5. NAFEMS Activities and Locations

The aim of NAFEMS’ activities is to be highly focussed on the simulation user community and meet the real needs of those in this area. NAFEMS’ independence of vendors and other commercial organisations means that those who attend seminars, read publications or use the benchmarks can be confident that they are getting unbiased comment and advice. In fact, some events provide the opportunity for end-users to make comparisons between different programs and methodologies.

The quality and independence of NAFEMS’ work has also been recognised by governmental/inter-governmental organisations, especially within Europe, where NAFEMS’ has been awarded the project management and coordination role in two major European Union ‘framework’ projects – FENET and AUTOSIM. FENET ran from 2001 to 2005 and included 110 participating organisations from 12 European states, looking at the current state of the art in FE, barriers to the uptake of technology, the drivers for development and future needs. Distinctions were made between the ‘state of the art’ and the level of readiness of specific technologies (that is, the outcome of research in methods development) and the ‘state of practice’ (that is, the maturity of their industrial deployment) and ranking different needs. These assessments were processed by sectoral groups across a range of industries from aerospace to consumer goods, process and manufacturing, against several technology themes. More information can be found at www.fe-net.org. AUTOSIM is a coordination action that builds on the success of FENET, in the automotive sector. It is addressing issues such as the need for suitable personnel for simulation work, integration of simulation methods into the supply chain, difficulties in obtaining correct data, especially for materials properties, and other gaps in the development or deployment of simulation technologies. More information can be found at www.autosim.org.

NAFEMS’ now has a wide geographical presence, with local groups in Germany/Austria/Switzerland, UK, Italy, Nordic countries, France, Spain/Portugal and North America – and recently in India. Further expansion into other regions is being considered. In each region, the mode of operation is adapted to suit local conditions, the key players from commercial, industrial and academic worlds, and the best partnerships to engage with and to complement existing actions.

4. CONCLUSION

The ever-increasing use of simulation technologies leads to great opportunities, but also risks. The effective, robust and safe deployment of these technologies into industrial practice requires attention to the quality, verification and validation of software, systems and processes, and the personnel who use them. For the future, industry continues to need robust simulation technologies, reliable software and processes and input data, and competent personnel.

NAFEMS was established many years ago to address these issues, and its continued and expanding activities indicate that the issues are not closed and NAFEMS continues to address these needs. As a membership organisation, NAFEMS is able to be independent and to fulfil its primary purpose: to help those who are using engineering analysis to achieve better collaboration with others in the industry, better innovation in the products that they develop, raised productivity in their engineering design processes and reliable, high-quality simulations.

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RESUME (for chairman to introduce C McCulloch as speaker, if required)

Colin McCulloch received the degree of MA in Mechanical Engineering from Cambridge University in 1976. His professional career has included work in engineering design and consultancy, related to metals-processing machinery; automotive vehicles and systems; aerospace structures and components; marine and offshore engineering; and machinery and consumer-goods industries. Much of his professional career has been as a consultant in the application of Finite Element and related methods, with particular application to structural analysis, dynamics, fatigue and vibro-acoustics, and working extensively with several software companies; corporations such as Ford, Boeing, GM, Cummins and Airbus; and government and other research centres. He is a member of the Institution of Mechanical Engineers and the Institute of Acoustics. In recent years he has developed a personal and professional interest in China and received an MSc in Chinese studies from Sheffield University in 2005. He was involved in some of the earliest meetings that led to the establishment of NAFEMS and has been associated with it, and all aspects of quality assurance, throughout his career.