THE THIRD WAVE OF CFD

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W H I T E P A P E R

M E C H A N I C A L   A N A L Y S I S

SUMMARY

In the history of the simulation of flow, heat and mass transfer processes for the development of products and processes, several phases can be observed: an early phase of the first commercial codes from the 1960s to the 1980s, and a subsequent era of unstructured grid-based methods, approximately starting from the beginning of the 1990s and lasting until the mid-2000s, which was characterized by the introduction of CFD into the research and development departments of large companies. After these two big waves in the development of commercial CFD software a new, third wave appeared. This current phase is characterized by a new paradigm shift in the use of CFD simulations in industrial product development. This paradigm shift relates to the changing development processes within companies towards simulation-driven design, which has resulted in a sharp increase in the responsibility being placed on simulation engineers as simulation results become the sole basis for making decisions that have serious business and financial implications. In turn, this is translating into pressure on the manufacturers of CFD simulation software, who must, beyond the traditional focus on improvements in physical models and solver performance, respond to the changing demands of industry with new concepts for integrating CFD simulations into the product development process, new business models for licensing and use, and innovative usability concepts.

Aspects like process integration, reliability, modeling safety, and reproducibility are becoming the center of attention for the industrial use of CFD, and will eventually displace the historical vendor-driven focus on result accuracy and solver performance improvements as key drivers for software development. Excellent and consistent simulation result quality, obtained using the latest computer hardware, system software and mathematical algorithms, is simply considered as a basic, given prerequisite. This new 'third wave' in the development of commercial CFD software is fueled by the continuing dramatic improvements in the performance of computing and graphics hardware that continue to produce dramatic improvements in the price-performance ratio for appropriate hardware configurations. This development is, in addition to the advances in CFD technology and new demands for excellent User Experience (UX), the third pillar of the current third wave.

In this paper, the three phases of the development of commercial CFD software for product development are analyzed in a historical context and the challenges and opportunities for the further development are discussed.

1. THE THREE WAVES OF COMMERCIAL CFD

In recent years, many papers have been published on the history of flow simulation. Many early CFD pioneers like Brian Spalding, David Tatchell, Ferit Boysan or Michael Engelman have talked or written about their memories. This pool of historical facts, technical information and personal impressions give a remarkably consistent description of the way engineering simulation software evolved from academic research codes towards the modern CFD products we know today, being developed and supported on an industrial scale by multinational software companies. Closely linked to the performance of available computing hardware, this development was, particularly in the early stages, driven primarily by research and development projects for aerospace and defense, but latterly also increasingly by interest from civilian industry. Looking back, three major phases of the development of CFD software for industrial applications can now be recognized:

- The First Wave: The beginnings of commercial CFD software in the 70's and 80's.
- The Second Wave: In the 90's, CFD enters the research and development departments of large industrial enterprises.
- The Third Wave: After the millennium, CFD becomes an indispensable part of the product development process.

A good overview and an extensive bibliography on this subject is contained in, among others, Hanna & Parry (2011). Interesting eyewitness reports are also given by Runchal (2008) and Tatchell (2009).

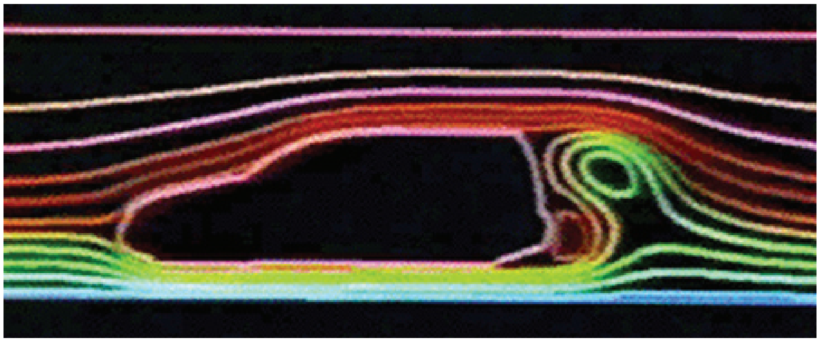

Figure 1: Fluid flow simulation in the 1980's, taken from Hanna & Parry (2011)

1.1. *THE FIRST WAVE:* THE BEGINNINGS OF COMMERCIAL CFD SOFTWARE

The codes of the CFD software engineers in the first phase had its roots in the work of the Fluid Dynamics Group T-3 at the Los Alamos National Laboratory (USA) since 1958, and the research activities under Prof. D. B. Spalding at Imperial College in London in the 1960's and 1970's.

In the late 1960s, Concentration, Heat and Momentum (CHAM) Ltd., founded by Prof. D. B. Spalding, and initially located at Imperial College in London, dealt with consulting work. The era of commercial CFD software began in 1974, when CHAM Ltd moved to its own offices in New Malden near London. Initially, the development of customized CFD codes was central to the business activities of CHAM. That became too time-consuming and inefficient, so CHAM decided to develop general-purpose CFD package for in-house consultancy work, and released this as a commercial product, PHOENICS, in 1981. This may well be regarded as the birth of the CFD software industry (see CHAM Ltd, 2008). Others quickly followed suit. Fluid Dynamics International (USA) followed in 1982 with FIDAP, a FEM-based CFD package, and in 1983 Creare.Inc (USA) released the finite-volume CFD code, Fluent. In 1980, Dr. C. W. Hirt founded Flow Science (USA) as a spinoff of the Los Alamos National Laboratory and in 1985 released Flow-3D. Many more CFD packages followed, including, for example, Flow3D from the UK Atomic Energy Authority Harwell (UK) in 1987 and in 1989 TASCflow was released by Applied Scientific Computing (Canada) - both now incorporated as ANSYS CFX. Computational Dynamics/ADAPCO (UK/USA), co-founded by Prof. David Gosman, another professor at Imperial College in London, released StarCD in 1989.

In the early 90's, the workstation manufacturer Silicon Graphics listed in its software catalog as many as 18 commercial CFD packages that were compatible with its hardware products, all vying for a share of the ~$30m CFD market (Boysan et al., 2009). The basic technologies behind most of these CFD packages had been created by former employees or guest scientists of the two aforementioned research institutions in London and Los Alamos, or were based on their scientific publications. But there were also other developments of CFD technology: in the 1980s alternative approaches for CFD simulation emerged as part of the military and civilian aviation and space program of the former Soviet Union, largely unnoticed by the Western scientific community due to the political situation. Their technical tasks for CFD simulations were similar to those in the West, but the available computing resource for their solution was much more limited. Conversely, because of the high political priority of these research programs, very extensive experimental data for numerous fluid flow and heat transfer phenomena, especially in the near-wall area, were generated. This situation led to the development of alternative CFD methods, which, building on known methods for Cartesian grids as published in the scientific publications in the West, were based on a combination of numerical, analytical, and empirical data. This innovative approach yielded high-quality simulation results in virtually arbitrarily complex computational domains while maintaining the low resource requirements and the effectiveness of methods using Cartesian grids. With the gradual economic liberalization in the Soviet Union in the late 1980s, several teams of scientists have commercialized this CFD technology and, since the early 1990s, sold their products and services in Europe and Asia. The best known products of this kind were Aeroshape-3D by Prof. V. N. Gavriliouk and team (Petrowa, 1998 & Alyamovskiy, 2008) and FlowVision by Dr. A. A. Aksenov and team (Aksenov et al. 2003).

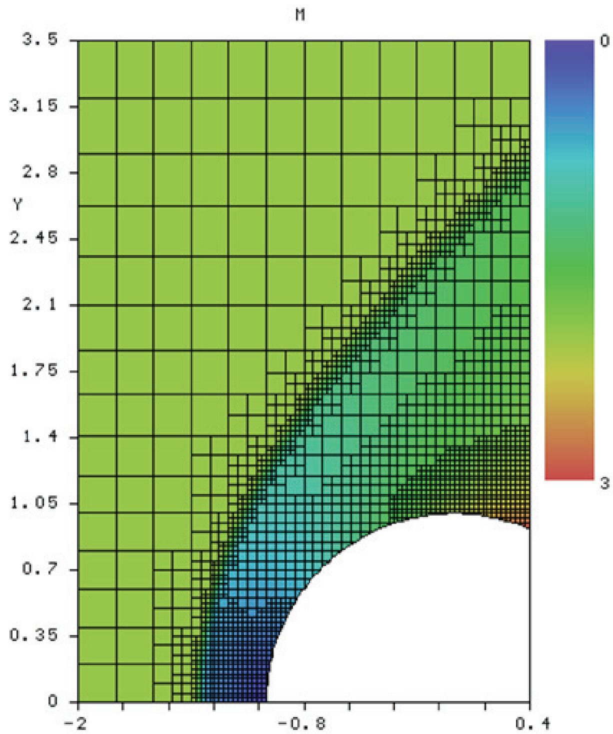

Figure 2: Result plot of Aeroshape-3D (Parry et al., 2012)

Characteristic for this first phase in the development of commercial CFD software was, by today's standards, a very primitive user interface for data entry, rudimentary graphics and very modest computational resources, particularly the available RAM memory always being too small, painfully limiting the maximum model size. These limitations led to very high demands on the user with respect to modeling of geometry and physics, as the real task had to be analyzed, simplified and entered into the software, all in a very laborious way. The uncertainties involved in the selection and configuration of the physical models and the risk of mistakes during data entry very high, and thus the need for comprehensive evaluation and testing of the simulation results was a regular step of the workflow. This required extensive knowledge of numerical techniques, the fundamentals and limitations of the physical models and their implications for the CFD model. Therefore, the users of CFD technology at this time were almost exclusively scientists or scientifically-trained engineers who practically had to validate each simulation result partially or completely with experimental studies. Characteristic of this period was, however, that due to their limited experience with applications of CFD simulations for industrial projects and intensifying competition in the CFD software market, vendors tended to strongly oversell the suitability of their products for the solution of industrial problems. This, coupled with the mixed experience of the first industrial users regarding the quality of CFD results achievable at an acceptable cost, earned CFD simulations the reputation of being too slow, too expensive, and the results too vague to be useful. This bad reputation persisted within the general engineering community for over two decades, but improved over the course of the current third phase of CFD software development, when CFD simulations became a daily routine for a new generation of users.

From the beginning of the 1990s, the conditions for CFD software and simulations changed quite rapidly. Computer hardware, mathematical methods and physical models all experienced huge performance gains. CPU speed and RAM size grew and got cheaper rapidly, providing, industrial users with new and more easily accessible hardware such as UNIX workstations and workstation PCs, and later, with the advent of affordable workstation clusters, access to high performance computing (HPC). These new capabilities on the hardware side of course also fuelled developments on the software side. Numerical methods such as unstructured Finite Volume methods, multi-grid methods, sliding mesh, etc., suitable for complex geometry and optimized for HPC, became commercially available as well as more reliable, more flexible and more broadly applicable physical models. Thus, new application areas for CFD appeared. CFD technology became much more practicable, and for the first time quite realistic model sizes for real industrial applications were possible. Hanna & Parry (2011) analyzed this development and found a direct correlation between Moore's Law for computing power and, for example, the model size for automotive racing CFD simulations. These new capabilities heralded a new phase in the usage of commercial CFD software - entry into the research and development departments of industry across the board.

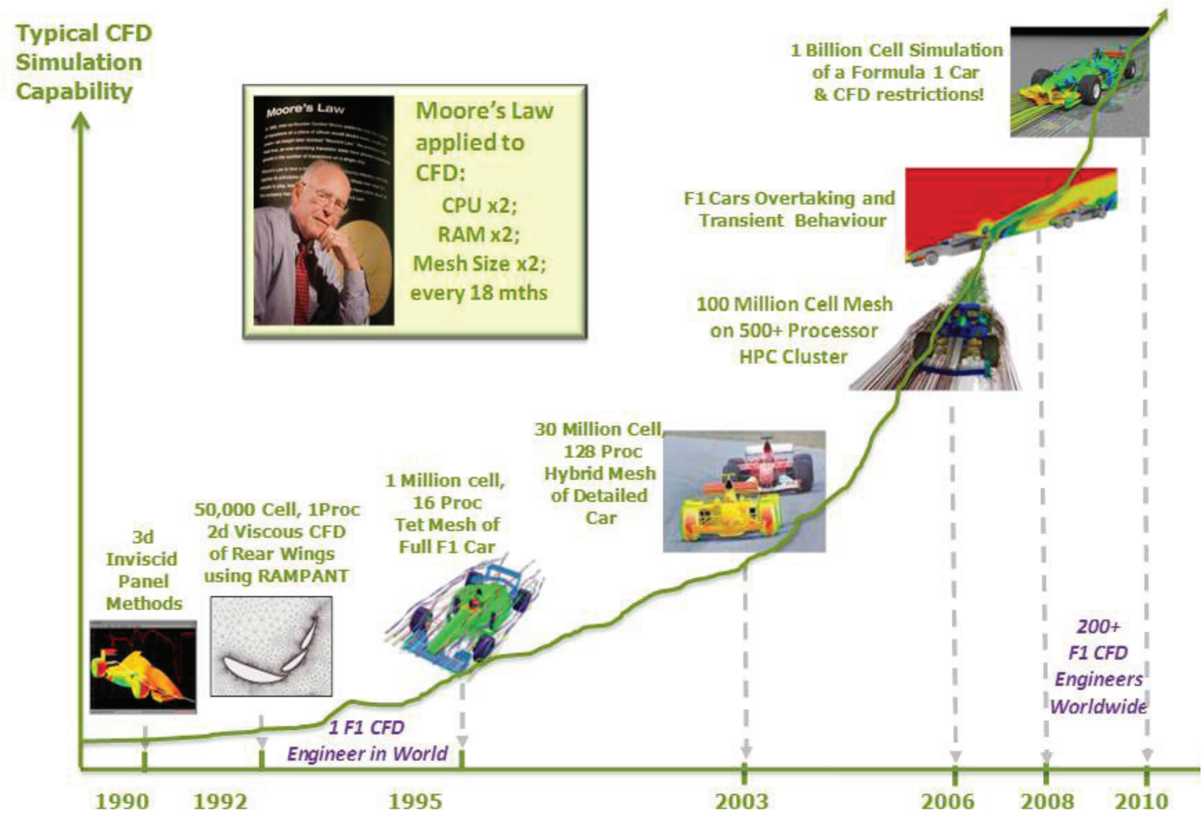

Figure 3: CFD has grown on the back of hardware advances – illustrated by Formula 1 Motor Racing CFD trends 1990 – 2010 (Hanna & Parry, 2011)

1.2. *THE SECOND WAVE:* CFD ENTERS THE RESEARCH AND DEVELOPMENT DEPARTMENTS OF THE INDUSTRY

Using technology typical of the first phase, Flomerics Ltd., founded in 1988 by David Tatchell and Harvey Rosten in Kingston-upon-Thames (UK), played a pioneering role in marketing CFD software developed exclusively for industrial applications with its software package FloTHERM, first released in 1989. Both founders worked for CHAM Ltd in senior positions before leaving to found Flomerics, with the aim of "providing good science to industry" (Tatchell, 2009). FloTHERM was a first paradigm shift in the CFD industry, away from the focus on complex CFD technology itself towards the solution of engineering tasks in industry as the central goal. This also meant that from then on engineers working in product development and not only scientists were the main target users of this type of CFD software. However, the available CFD technology and computer hardware and operating systems imposed certain limits on such an innovative approach. Therefore Flomerics concentrated initially on only two application areas: electronics cooling (with FloTHERM) and built environment HVAC (with FloVENT). The requirements of engineering-oriented CFD software for these application areas were relatively clearly defined and, more important, also just feasible.

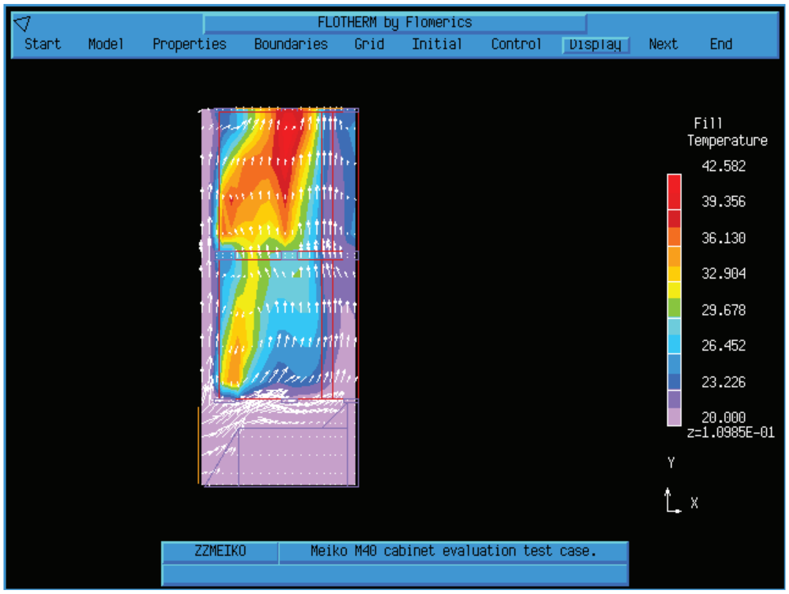

Figure 4: Early version of FloTHERM (Hanna & Parry, 2011)

This concept opened up completely new market opportunities, because for the first time, a much larger group of users with a common industrial background and application requirements could be addressed. It was also the time when engineers in product development without special knowledge of numerical methods and without extensive CFD experience were first empowered to employ CFD simulations as a development tool. The solution of a technical engineering task became the center of attention, while the underlying CFD technology was more or less just means to an end.

Obviously, other CFD providers also recognized the beginning of this paradigm shift and especially the new business opportunities associated with it, responding to this trend with their own product offerings. There was, for example, MixSim, a mixing-specific user interface for the Fluent solver, released in 1996 for use in modeling industrial mixing processes. The company Fluid Dynamics International entered the electronics cooling CFD market with Icepak, based on the FIDAP solver, and CD Adapco offered various special engineering tools for the automotive industry. New companies such as Exa Corporation (with PowerFlow) and Blue Ridge Numerics (with CFdesign) saw new opportunities and entered the market with new CFD products specifically designed for industrial applications. Overall, huge investments from all CFD software vendors in better user interfaces, robust solvers and reliable physical models could be observed, with the clear objective of entrenching CFD into the research and development departments of large industrial enterprises and thereby to attract a new generation of CFD users.

This second wave of development of CFD software for industrial applications lasted from around the beginning of 1990s until the mid-2000s. It is characterized by the combination of the availability of useful CFD simulations, utilizing cheaper and more powerful computing hardware. This produced a dramatically increased demand for CFD simulations, especially from large companies, and prompted CFD software vendors to further democratize CFD technology. However, many users noticed another trend during this period with understandably mixed feelings: The start of consolidation in the CFD software industry through acquisitions and market exits. Many established CFD systems became dated and required high development investments. For major CFD software suppliers, organic growth at the rates they were accustomed to was no longer sufficient. Sharp rises in development costs and increasingly tougher competition forced companies to combine forces to remain competitive and tackle the challenges of the future. During this phase, the foundations were laid for the numerous acquisitions that lead to CFD companies eventually being acquired by large software houses with thousands of employees, which now dominate the CFD software market.

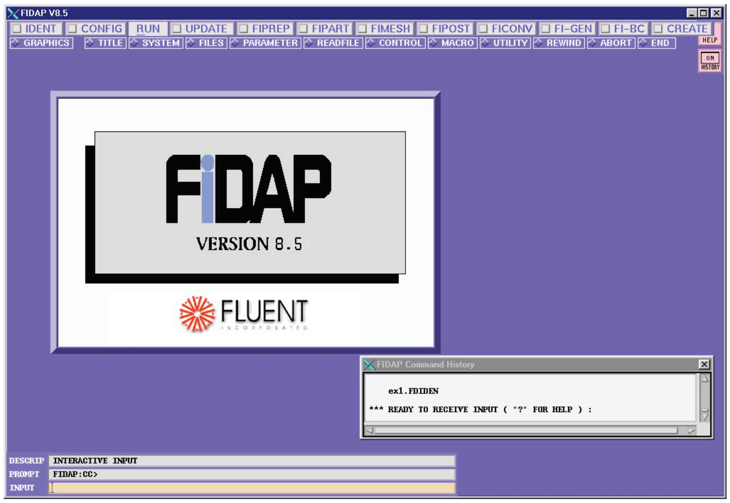

Figure 5: FIDAP User Interface in the late 1990s (University of Delaware, 2007)

After establishing CFD as a successful tool for the functional design, verification and optimization of product designs, features, processes and physical effects in large industrial companies in the early 2000s, the reputation of this technology amongst engineers improved significantly. Hundreds of case studies had proven that, provided the user employs reasonable care during the modeling process, the use of commercial CFD software on appropriately powerful hardware could deliver savings in development time and costs. As a result, the demand for CFD simulations showed strong growth, especially in medium-sized and small companies keen to reduce the costs associated with physical prototypes, the creation of which often had to be outsourced. However, the cost of CFD simulations relative to the cost of physical experiments at the beginning of the 2000s was a very serious hurdle. These costs were dominated primarily by the staff costs associated with hiring and training a highly-qualified user, a relatively long post-training learning curve to become proficient, very tedious modeling processes (especially if complex geometry was involved), and the comparatively high cost for the software licenses themselves. Another important aspect was the need to integrate CFD simulation into the regular product development process, as these companies usually had no dedicated simulation department (yet). This meant that qualified engineers from product development or design groups should perform the simulation themselves, and that the efficiency with which simulation projects were conducted had to be increased so CFD results would be available sufficiently in sync with the product design cycles for the results to help guide proposals for design improvements.

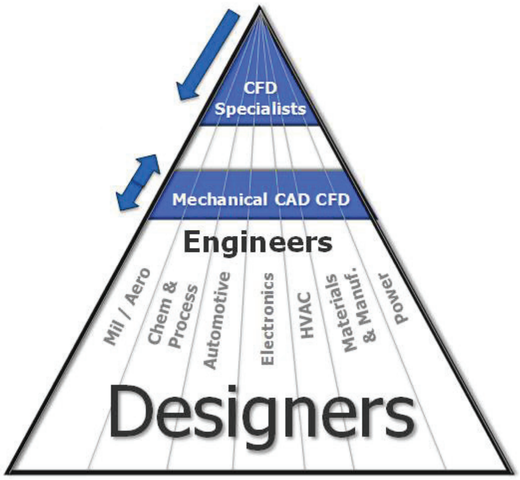

Figure 6: Pyramid of CFD Usage (Hanna & Parry, 2011)

The handling of industry-level geometry played a key role. At that time this was already being provided as 3D CAD data which should, of course, be used with as little simplification and modification effort as possible to be useable by the subsequent and preferably fully-automated mesh generation step. The CFD software market responded to these demands with many new and improved products – and a third wave of CFD software for industrial product design began and continues to this day.

1.3. *THE THIRD WAVE:* CFD BECOMES AN ESSENTIAL ELEMENT OF THE PRODUCT DESIGN PROCESS

The major CAD and PLM vendors play a key role in this third phase. Since the 1990s, they have been successfully introducing the concept of Product Lifecycle Management (PLM), which encompasses CAE. As a result, customers have put pressure on commercial CFD software vendors to conform to this concept and to take steps to integrate their products into the major PLM systems. Therefore, in the 2000s, virtually all CFD software providers upgraded their systems with, at the least, CAD import interfaces. Many have developed bi-directional links with major CAD/PLM systems and a few have even embedded their CFD technology directly into the 3D CAD systems themselves.

CAD system manufacturers supported these developments in order to be able to offer a complete solution in the framework of a PLM system, by providing support for external, specialized module developers. During this timeframe, products such as Fluent for CATIA (Fluent Inc), CFdesign (Blue Ridge Numerics) and FloWorks (NIKA GmbH) all emerged. New CFD techniques to support these new requirements were also developed, partly from scratch, and partly as enhancements of existing technology. For example, since 1999 CD-Adapco has been successfully employing an innovative, object-oriented approach to the development of STAR-CCM+. The company NIKA GmbH, founded in 1999 as a German-Russian joint venture, was a typical example of a new commercial CFD software vendor emerging at the start of this third wave. NIKA exclusively developed, based on the above mentioned Aeroshape-3D technology, CAD embedded CFD software, which is now offered as dedicated versions for several major 3D CAD systems (Fig. 7).

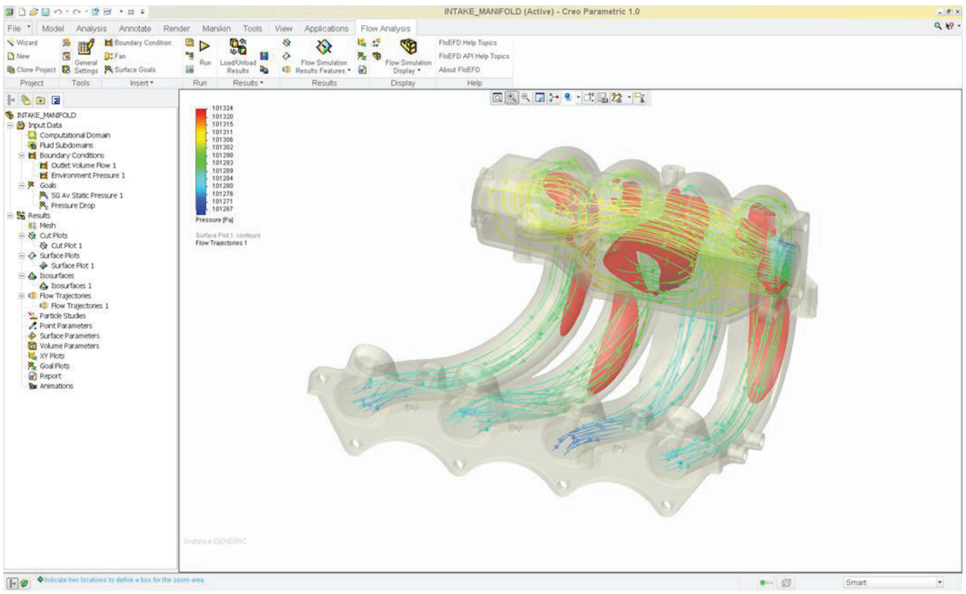

Figure 7: FloEFD for Creo by Mentor Graphics

In response to these changing market conditions, Blue Ridge Numerics adjusted its CFdesign package for use as an 'Upfront CFD' system. The PLM vendors themselves also increased (through acquisition) their activities in the area of CAD-integrated CFD software to better support the product development process. Representative of this market segment are Dassault Systèmes with SIMULIA's Abaqus/CFD, and Siemens PLM with their NX Advanced Flow and Femap Flow Solvers. Autodesk has also strengthened its CFD software portfolio with the acquisition of Blue Ridge Numerics' CFdesign complementing their Algor suite.

The current third wave has allowed newcomers from other areas opportunity to enter the CFD market, refreshing it with new disruptive technologies. An example is XFlow of Next Limit Technologies (Spain), which brings not only an alternative CFD technology with roots in the movie industry, but also a user interface more like that of animation software to the engineering community. Autodesk's Project Falcon brings gaming elements to the world of CFD.

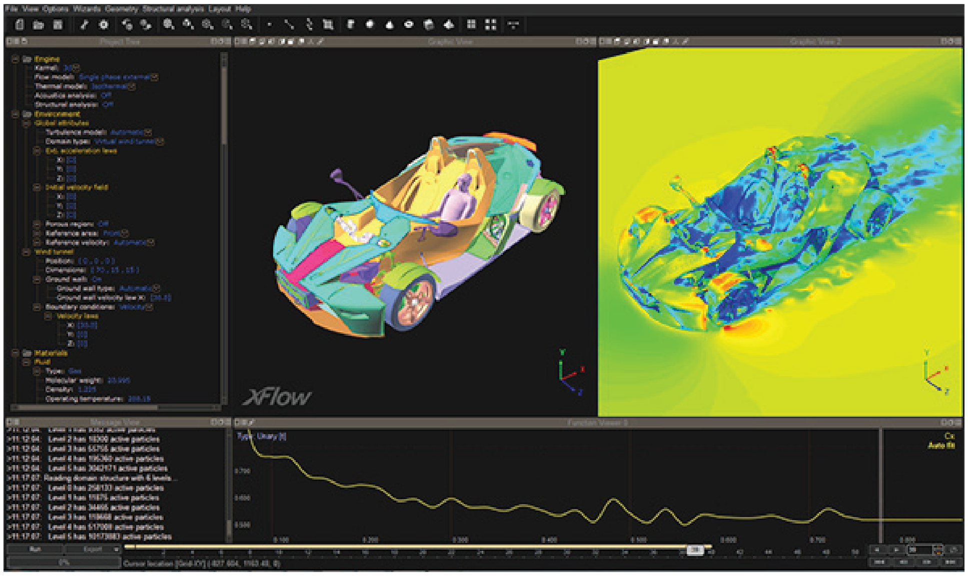

Figure 8: User Interface of XFlow by Next Limit Technologies (MSC Software, 2011)

This exposes what is perhaps a new trend: the CFD software market is becoming more diverse, through new, innovative, unconventional approaches, especially in the area of User Experience (UX) and usability. But all have one thing in common: The industrial user, with his or her need for easy-to-use, task-oriented, automated, reliable, efficient and readily-available CFD software as an indispensable tool for digital prototyping is the focus. This is caused by changing development processes and, as a consequence, the changing role of the simulation engineer. Aspects like process integration, reliability, modeling safety, and reproducibility are becoming the center of attention, and influence purchasing decisions for CFD software. The further development of CFD software based around these requirements will bring exciting new technologies and products to market. Therefore a new fourth wave may be expected to follow soon…

2. WHAT'S NEXT - A VISION

Hanna & Parry (2011) described their vision for the future as follows: "In the author's opinion the 'Holy Grail' of CFD, that is: real-time, push-button, automated, easy-to-use, CAD-embedded, bi-directional, multi-physics enabled CFD is still to be reached. Some CFD codes come closer to these ideals than others today, and many factors will feed into creating this nirvana in the next 20 years, not least, hardware, algorithmic, physical modeling and coupling advances in the industry".

Such a long-term goal, however, can only be achieved gradually. Along the way, many challenges remain, as the authors themselves note. Perhaps this ultimate goal may need to be adjusted from time to time, because design environments may also evolve along this way – CFD is after all iterative! In the following sections, a few selected milestones on this road to the 'Holy Grail', are discussed from today's perspective.

2.1. MULTIPHYSICS

An important aspect of the 'Holy Grail' of CFD is more realistic representation of complex physical reality, without the artificial 'boundaries' that exist today arising from the historical development of CFD, computational structural mechanics, multibody dynamics, kinematics, etc. as separate disciplines using different numerical techniques. The first signs of this are already visible, in what has become commonly known as 'multiphysics' simulation. However this often means little more than taking the results of one simulation (e.g. a thermal analysis) as an initial condition or boundary condition for another simulation (e.g. thermo-mechanical stress).

Some software vendors like ANSYS and COMSOL have chosen multiphysics to be a central aspect of their product philosophy and offer a respectably wide range of simulation capabilities. However, today the focus of multiphysics applications is still on mastering the functions and the technical challenges of having the individual components working together properly, because each component may have its own historical and technical background, which may be not compatible with others. Help with this problem comes from software frameworks that provide the necessary infrastructure for collaboration. These frameworks can be the result of the internal development efforts of a multiphysics software vendor, or supplied by independent third-party developers as middleware. One example for this is the Fraunhofer MpCCI Framework.

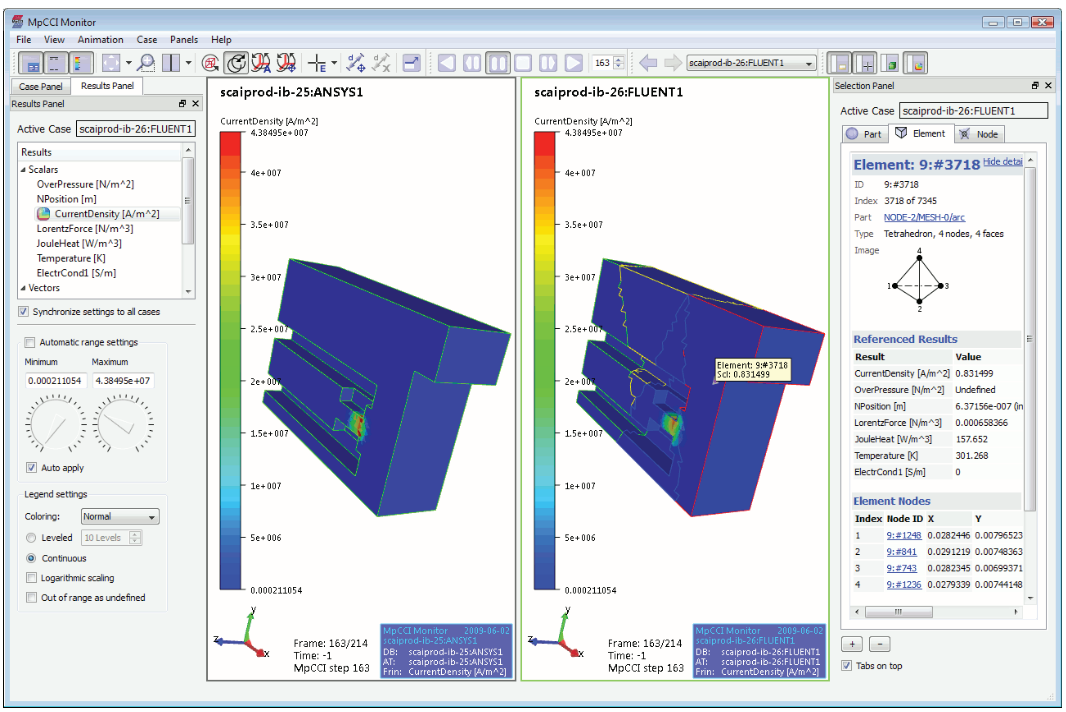

Figure 9: MpCCI Visualizer by Fraunhofer SCAI (Fraunhofer SCAI, 2012)

Another limiting factor of today's multiphysics approaches is providing the correct representation of an actual complex physical situation for the individual solver modules required for a given simulation project. In order to ensure that the results of one simulation can be used as input to the next, it frequently becomes necessary to have a 'white box' model that captures the geometry without simplification and requires all relevant physical effects to be simulated in complete detail, with the attendant simulation overheads. 'Black box' models that may provide considerable simulation efficiency but are limited to just one aspect of the problem (e.g. a thermal model of an electronic component) do not fit this paradigm.

Today, the selection of appropriate modules, the configuration and arrangement of the simulation workflow is the sole responsibility of the user, and the actual workflow is determined by the combined requirements of the solver modules and not on the physics of the actual engineering task. 'Multinumerics' may therefore be a more descriptive term.

A prerequisite for future success of such an approach will be not just to link, but rather to merge the separate solvers into a single, consistent solution methodology that allows the user to focus on the physics (albeit complex, there is only one physics) and have the simulation environment bring to bear whatever numerical techniques are required in a self-consistent way. It must be complemented by a UX-based design approach which shifts attention from simple feasibility to efficient solution of the engineering task as the most important criterion.

2.2. SIMULATION METHODS

If the idea of a general physics solver is pursued in terms of a possible realization, one is inevitably faced with unifying several very different and incompatible numerical methods. This variety of methods is of course useful, because the nature of the various physical aspects of the product's behavior are very different, and for each one or more favored numerical methods exist, that provide desirable combinations of result accuracy, computational resource requirement and solution efficiency.

It is certainly not a desirable objective to sacrifice this great advantage and to try to develop a single process for all possible physical applications that will work in many areas but might be considerably less efficient than each of the best individual solutions. Rather, the aim should be to develop a solver infrastructure that uses the currently available best methods for each situation automatically, combined and bi-directionally coupled within the same simulation model and across model boundaries. This means that very different methods will need to be integrated: discretization methods such as Finite Volume for internal flows, coupled with particle methods such as Smoothed Particle Hydraulics for areas with multiple phases and phase change, and 1D methods for large flow systems, to mention just fluid dynamics. Many elements of such an approach are already available as mature, reliable components. The task is to overcome the historically-based segregation of solver modules in favor of a single simulation engine that combines the best available methods based on the simulation task. The great advantage of such an approach is that it provides the opportunity to completely remove from the engineer the burden of defining the entire numerical workflow by offering a workflow that is exclusively focused on the engineering task and its solution. In this respect we see as a real possibility to go a long way towards this 'Holy Grail' of CFD.

2.3. USER EXPERIENCE (UX) AND USABILITY

Undoubtedly, the needs of the engineer as user will drive future developments of simulation software. The software will need to adapt to the working environment of the user, his needs and his individual intellectual capacity, and not vice versa. This affects the overall concept as well as every single detail of the software. This also relates to the process of product specification and code implementation employed by the software vendor. Already today, many software companies have introduced modern development processes such as Agile Development. This supports in a natural way the process required to employ user-centric design principles and is a prerequisite for the effective implementation of usability requirements with the sole objective to create and maintain an outstanding UX. Smart investments in this area will undoubtedly lead to attractive unique selling points in the CFD software market.

The working environment of development engineers and designers will also continue to change. New input techniques that better reflect the natural human movements are in development and others are already making their way into the workplace. As examples, augmented reality or touch screen operation should be mentioned. Likewise, new visualization technologies will be available for an ergonomic, exact presentation of the simulated physical situation. For example, just the age-old communication between engineers, technicians and workers based on 2D sketches and print has already been complemented by communication on the basis of solid 3D prints. This will continue, as the engineer will, for the foreseeable future, continue to play the central the role as final decision maker in the development process. This trend, also picked-up and actively supported by simulation software, will gain in importance. Visualization and communication of simulated results in the context of an ever-growing reliance on virtual prototyping for cost-effective product development is tightly connected to the increasing responsibility of simulation engineers for their conclusions.

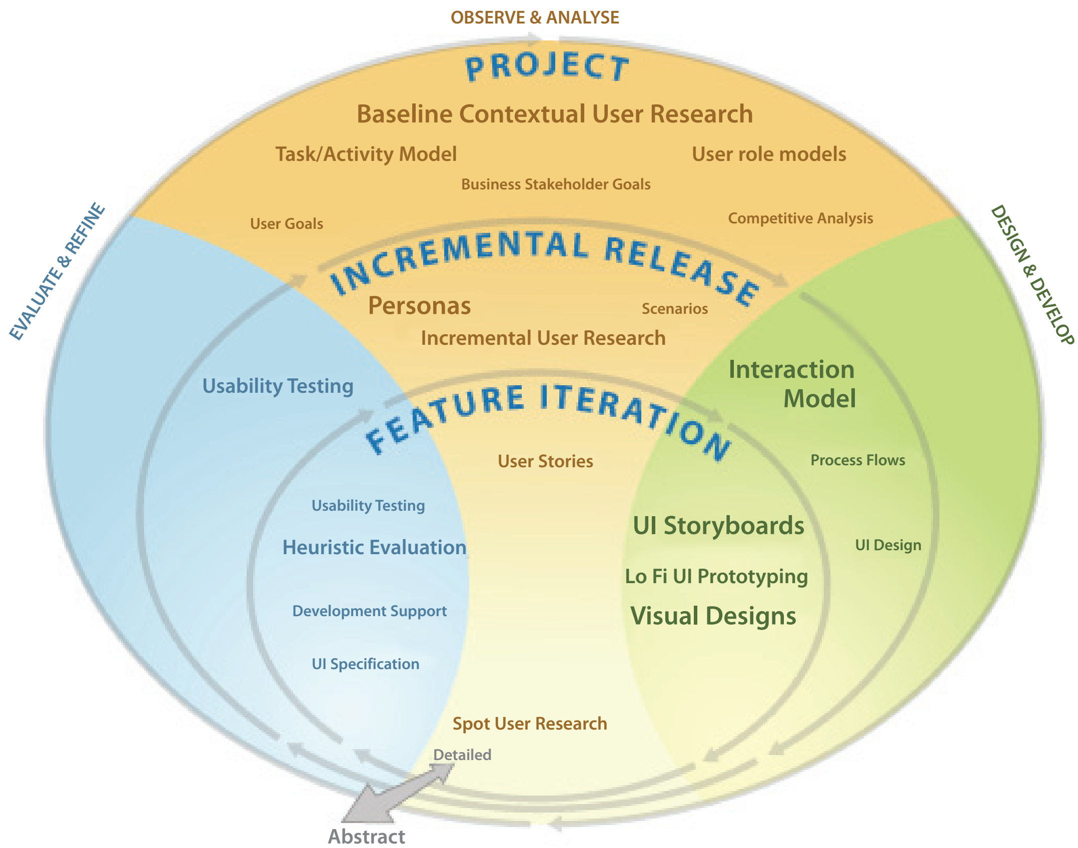

Figure 10: User Centered Design activities seamlessly employed at any given level of the Agile development methodology (Limina Application Office, 2012)

However, it is not only on the abstract, conceptual level that UX and usability will play a much more important role as a decision criterion for tool selection. Every detail of the user interface will require attention. Many user interface elements of today's CFD software date back to the early days of software development, even if they have been replaced by new, visually-appealing surfaces. The problem is not just with the surface detail, but is often located deeper in the software and its behavior. Beginning in 1990, Jakob Nielsen developed what has become quite a popular list of general principles for the design of user interfaces – the so-called "10 Usability Heuristics" (Nielsen et al., 1993). Here is an attempt to briefly comment on the application of these rules in the context of future requirements for simulation software, both in concept and practical detail:

Visibility of system status: The system should always keep users informed about what is going on, through appropriate feedback within reasonable time.

- *Concept:* Real-time simulations are the ultimate goal, so this is also a very important aspect of the 'Holy Grail' of CFD.
- *Detail:* Particularly during long-duration activities such as solver run, geometry checks, data transfers, a real-time feedback of the current status to the user is essential. This aspect becomes especially important when remote activities are carried out. The emerging cloud computing trend has particular implications for developers and special attention will be needed to ensure compliance with this rule.

Match between system and the real world: The system should speak the user's language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.

- *Concept:* This rule applies directly to complex workflows such as considering multiple coupled physical phenomena within one simulation. As already outlined elsewhere, the software must fit to the workflow, the work context and the individual's capability, and not vice-versa.
- *Detail:* Many CFD user interfaces still use terminology only familiar to CFD experts. Focus should be on terms from the particular engineering area, and not only in the user interface but also in all documentation, online help and tutorial material.

User control and freedom: Users often choose system functions by mistake and will need a clearly marked "emergency exit" to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.

- *Concept:* The emerging cloud computing brings the danger that such an emergency exit may not be quick enough, be very expensive, or is simply unreliable due to user control being one level removed. Developers will also need to pay special attention to this.
- *Detail:* Undo/redo has been an indispensible function for Office software for decades, but many of today's CFD software still do not comply with such a basic usability requirement.

Consistency and standards: Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform conventions.

- *Concept:* Numerous CFD software tools have a long history, worked on by generations of product managers and developers. Software modules may have been acquired or licensed, making this task harder still. It must be a high priority to develop appropriate user interface guidelines and apply them to all parts of the software.

Figure 11: Front cover of "Usability Engineering" by Jakob Nielsen (Nielsen, 1993)

- *Detail:* Platform conventions are often ignored for the sake of development cost reduction for multi-platform software packages. This does not only apply to the visual appearance of the interface, but importantly to many standard activities such as file load/save, print, search etc.,… and of course undo and redo.

Error prevention: Even better than good error messages is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.

- *Concept:* This requirement is a major challenge for CFD software, due to the complexity of the underlying physical models, numerical methods, etc. Actually, some sort of artificial intelligence will be needed to address this challenge properly. In future this aspect will play a distinguishing role regarding UX, because this is the critical factor for ensuring that non-expert users can successfully use CFD software to produce reliable, high-quality answers.
- *Detail:* It seems to be easy to try to build in warnings for every possible situation, but this is not the solution. Focus on critical situations only, and provide an undo/redo function.

Recognition rather than recall: Minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.

- *Concept:* Key to the conceptual design of a good user interface is to understand the user, his work context, and his workflow(s), and design the software usage based on this research in a way that it feels natural to him.
- *Detail:* Modern interactive User Interface concepts are already based on this principle. But many details can improve usability dramatically, such as recent file lists, status information, wizards, etc.

Flexibility and efficiency of use: Accelerators -- unseen by the novice user -- may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.

- *Concept:* Again, this leads to the requirement that the software must fit to the workflow, the work context, and the individual capability of the user, and not vice-versa. The software needs to help the user grow in expertise and adapt to that growth.
- *Detail:* Windows already has the concept of keyboard shortcuts that many users are familiar with, so let's use this concept. Touch interfaces have the concept of gestures, which should also be utilized, even if by mouse movement. Scripting capabilities will help experienced users to setup their own automation functions at relatively low cost.

Aesthetic and minimalist design: Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.

- *Concept:* The quality of usability is not measured by the number of buttons in the user interface. If the software is designed well, it knows the user, predicts his next steps correctly and presents exactly those functions which are relevant for this next step.
- *Detail:* For feature-rich products like CFD software, often less is more. Only present the available options and functions rather than gray out the unavailable functions. Automatically provide access to context-sensitive functions close to the object of activity.

Help users recognize, diagnose, and recover from errors: Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.

- *Concept:* Particularly the latter (constructively suggesting a solution), seems to be a major area for improvement. Again, error handling has the same priority as error prevention as a distinguishing factor for UX and related purchase decisions.
- *Detail:* An absolutely important requirement is to trap possible user errors and software malfunctions with dedicated, not universal, error messages - it's not a lot of effort to at least provide a proper description of what went wrong.

Help and documentation: Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.

- *Concept:* Help doesn't mean some textual and graphical explanations only; it must employ all available communication means. This includes short videos, direct access to internet resources, links to user communities and vendor technical support, etc.
- *Detail:* A picture paints a thousand words: This principle applies particularly to engineers as the main CFD users.

3. CONCLUDING REMARKS

Commercial CFD software for industrial applications has already celebrated its 30th birthday. Three decades of successful CFD simulations by hundreds of thousands of scientists, engineers, and students have made this technology an indispensable tool, and it is becoming embedded in the product design process across virtually all industries today. While classic CFD technology has matured to a great extent, new exciting concepts and technology to address the challenges of future CFD applications are approaching fast. After two main waves of commercial CFD, each with their own paradigm shifts, we are currently experiencing the third wave, again a paradigm shift towards embedding CFD software into the design process. There will certainly be a next, fourth wave of CFD simulation software to come. The authors anticipate this will be a step on the road to the 'Holy Grail' of CFD: real-time, push-button, automated, easy-to-use, CAD-embedded, bi-directional, multi-physics enabled CFD… leaving behind the classical CFD software of the second wave.

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