Simulation-Based Engineering Science: a heritage to cherish and invest in for a sustainable future

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Numerical simulation, also known as mathematical modelling, refers to the use of computer models to study the behaviour of engineering systems (even complex ones) and to predict physical events.

A significant and broad pool/spectrum of scientific, mathematical, computational, and engineering knowledge and methodologies has been used to develop numerical simulation, of which the engineering part is one of the most frequented applications/uses, although the methodologies are valid for all applied sciences.

Computer simulation is an extension of theoretical science in that it is based on mathematical models that attempt to characterize the physical predictions or consequences of scientific theories. However, simulation can become so much more because it can be used directly to explore new theories and to design new experiments to test those theories. Simulation is a powerful alternative to experimental science and observational techniques in cases where phenomena cannot be observed or where measurements are impractical or too costly.

Simulation-Based Engineering Science (SBES), defined as the discipline that provides the scientific and mathematical basis for the simulation of engineering systems, is embedded in the context of numerical simulation. These engineering systems range from microelectronic devices to automobiles, from coffee machines to photovoltaic systems, from electro-medical devices to remote surgery equipment, from aircraft to oilfield infrastructure and urban agglomerations (villages, towns, cities).

This means that SBES combines knowledge and techniques from traditional engineering disciplines – electrical/electronic, mechanical, civil, chemical, aerospace, nuclear, biomedical and materials engineering – with knowledge and techniques from fields such as computer science, mathematics, physics, medical and social sciences. As a result, SBES will enable engineers to better predict and optimize systems affecting many aspects of daily life, work, environment, safety, health, and the design/engineering/production/use processes of everyday products. SBES is therefore critical to advances in biomedicine, nanotechnology, microelectronics, energy and environmental sciences, and the use of advanced materials.

Although the use of computer simulation in engineering science began over 70 years ago (in this sense, SBES is a well-known method from

the past), it is only in the last 20 to 25 years that scientific theories and simulation technologies have had a tremendous impact on all areas of engineering. This remarkable change has been driven largely by developments in the fields of computer science and information technology, and by rapid advances in electronic processors and computer systems.
And it is precisely because of these developments (which have also affected interaction and graphical visualization tools to the extent that the SBES approach is essential) that solutions are gradually being found to problems of multiscale and multiphysics modelling, real-time integration of simulation with measurement, model validation and verification, and the management and processing of big data.

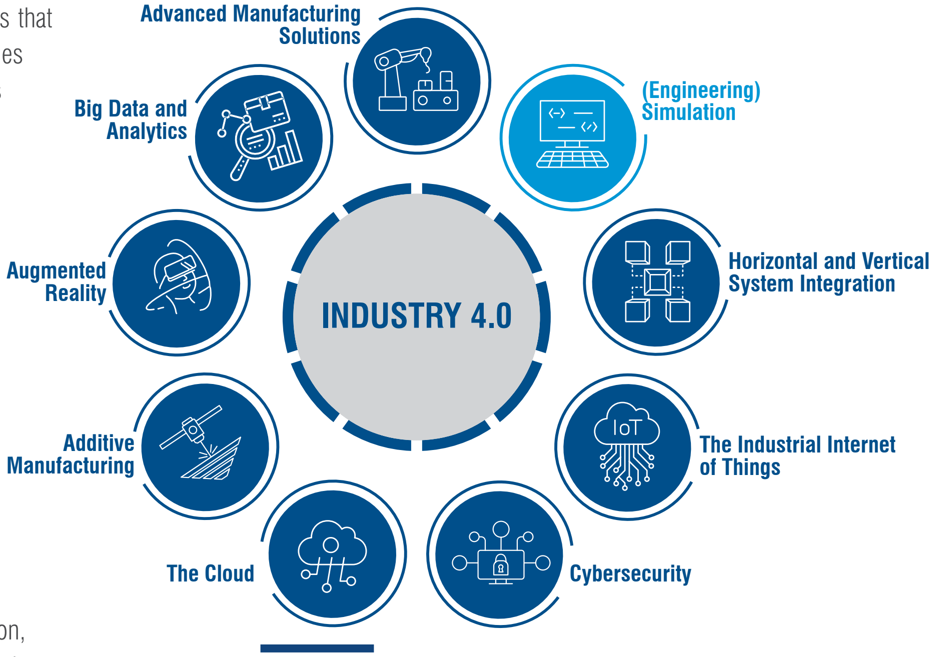


Fig. 1. The nine industry 4.0-enabling technologies.

Industry 4.0 speaks the language of SBES

In industry, the signal for this "revolution" was (and is) nurtured by the European Industry 4.0 initiative, which identified nine core technologies capable of innovating processes, products, and services in all economic sectors of human activity, thereby increasing the value of the production system chain.

The nine enabling technologies (see Fig.1) are briefly described below:

- **Advanced manufacturing solutions,** the main component of which is “collaborative robotics” also known as cobots, that is, humans and robots sharing a workspace safely and efficiently thanks to the artificial intelligence of machines that sense the environment around them.
- **Additive manufacturing,** a technology that creates a product by depositing material in layers, as opposed to traditional manufacturing, which creates products by removing material from a rough workpiece.
- **Augmented Reality,** which integrates additional information in any form (text, graphics, sound, etc.) into the physical environment in real time, with the aim of streamlining the user's activities and enhancing their interactions with the real world.
- **(Engineering) Simulation,** now widely used in design and production processes to analyse and test controlled virtual models of real products to be produced by specific processes, with the aim of reducing installation times, increasing product quality and establishing/improving product functionality.
- **Horizontal/vertical integration,** which uses networked technologies to analyse large volumes of data and creates open systems to share them in real time with all members of the value chain, from suppliers to end customers (vertical integration), to define common working standards and objectives, and with the business units (horizontal integration) that contribute to defining a product's life cycle.
- **The Industrial Internet** is the term used to describe the application of technological components and devices (the Internet of Things or IoT) inside physical items, such as machines, making them "intelligent" and enabling them to communicate and interact with one another and with the surrounding world via the Internet and a standardized language.
- **The cloud** is a shared, flexible, and open IT infrastructure for the sharing of data, information, and applications across the Internet beyond the boundaries of the enterprise, to support the transformation of business models with the necessary capacity.
- **Cybersecurity,** the set of technologies (processes, products, and standards) designed to ensure that, in today’s fully connected world, an organization’s information systems are protected from attacks that could result in the loss or compromise of business-critical data and information.
- **Big Data and Analytics** is the process of collecting and analysing (with appropriate management tools) large data sets containing a variety of data types from many different sources to uncover hidden patterns, unknown correlations, trends and preferences to enable organizations to make better decisions in every business process, from finance, marketing and sales to supply chain, design, production and maintenance.

Of these nine Industry 4.0-enabling technologies, engineering simulation can be seen as the key enabler of the growth of the other functions because of mutual interactions that enables production to move from single automated cells to fully integrated (and automated) organizations capable of communicating with each other, with consequent improvements in flexibility, speed, productivity and quality.

The fact that engineering simulation has become central to the enabling technologies of the Fourth Industrial Revolution is demonstrated by the sharp acceleration in the adoption of SBES methodologies.

However, this increased use is accompanied by the complex dynamics typical of change that depends on new orientations and new metrics. Faced with such a highly innovative approach, the growth prospects are indeed enormous, but companies need to generate (and support) the appropriate skills to adapt the path to their own reality without losing valuable opportunities.

One thing is certain, however: there is an overwhelming consensus that numerical simulation is fundamental to the advancement of engineering and science. Rarely have so many independent studies from experts in different disciplines agreed that computational simulation has had and will continue to have an enormous impact on all areas of engineering, scientific discovery, and efforts to solve major societal problems.
Therefore, if these advances are to be taken seriously and incorporated into everyday social and industrial life, further efforts are needed in the field of research, in the training of academic institutions that produce new generations of engineers, technicians and scientists, and at the level of corporate culture, which must rethink the way it views SBES, recognizing it as an asset rather than as a product/commodity to obtain other products or other goods.

Furthermore, if we have a look at the simulation engineering market, although dominated by general-purpose technologies promoted by large system suppliers, it receives a significant growth contribution from so-called “vertical” products/sectors, i.e. applications that enable the solution of specific/specialized problems that require specific skills and a strong determination to find the best solution. EnginSoft excels here, especially when it comes to the real and measurable added value for the customer.

EnginSoft and SBES

To put it frankly, EnginSoft has been following the evolution of the disciplines related to SBES since the first pioneering applications in the late 1970s/early 1980s, often anticipating their industrial exploitation, in the conviction (confirmed by today’s scenario) that the potential of the virtual approach went far beyond what was gradually being achieved in production contexts – at that time often only experimentally or as research.

The company's success is the result of this longstanding conviction, but also of the skills of its employees, acquired in the course of a journey together with the producers of innovative numeric technology and with customers who have increasingly relied on EnginSoft to help solve their problems and challenges.

EnginSoft's mission has therefore always been to provide cutting-edge solutions and innovative technological services aimed at improving the competitiveness and productivity of engineers and companies involved in design and production, as well as increasing the quality, safety and efficiency of processes and products.

SBES by definition encompasses areas such as Virtual Prototyping (understood as the creation of a virtual prototype of a product and/or structure) and Computer Aided Engineering (CAE), which includes FEM (Finite Element Method), CFD (Computational Fluid Dynamic), MBD (Multi-Body Dynamics simulation), crash/impact simulations, as well as multiphysics and thermo-fluid-structure interaction issues.

Validation and verification

The primary and ultimate goal of numerical simulation lies in predicting physical events or anticipating how engineered systems will behave.

Prediction is the key to engineering design, the foundation for scientific discovery, and the primary means by which computer science is able to move beyond the "realms" of experimentation and physical observation.

It is therefore natural to ask whether specific decisions can be based on the expected outcome of an event. In other words:

- How accurate are the predictions of a computer simulation?
- What level of confidence can be assigned to a predicted outcome, given what is known about the physical system and the model used to describe it?

Science, technology and, in a different way, philosophy (understood here as the activity of thinking that guides the criteria for the determination and quantification of reliability and — why not? — ethics of computer simulations and their predictions) have become known as the V&V (Validation and Verification) process, the methods of which are fundamental to the success and progress of SBES.

To understand the objectives of the V&V process, it is worth analysing how simulation begins.

The analyst (or engineer or scientist) implements/designs/realizes an appropriate mathematical model based, on the one hand, on the conceptual understanding of certain physical events of interest (including social events) and, on the other hand, on the scientific theories that explain the real phenomena or engineering systems to be studied.

The mathematical model is a set of mathematical “constructions”, equations, inequalities, constraints, etc. that represent abstractions of reality and are dictated by the theories that characterize the event or describe how a system behaves. The analyst then develops a computational model. This is a discretized approximation of the mathematical model developed to describe the event, for the purpose of implementing the analysis on a computer.

Validation is the stage of V&V that determines how accurately the mathematical model describes the actual physical event. Verification, in contrast, is the stage that determines the accuracy with which the computer model represents the mathematical model.

Simply put, validation asks: "Are the right equations solved?" or “Has a product/system been built with the right requirements?” whereas verification asks: "Have the equations been solved correctly?" or "Has the product/system been correctly implemented?"

A trivial example of a V&V process concerns the (numerical) solution of the equation:

$$M\ddot{x}(t)+C(x)\dot{}(t)+K\,x(t)=F(t)$$

which governs the dynamic behaviour of a system that is subjected to a set of forces as a function of time.

Validating the numerical model means (for example) fine-tuning the distribution of concentrated and/or distributed masses so that it corresponds to the real one, together with the distribution of damping and stiffness. (i.e. equations written in terms that are consistent with the phenomenon to be simulated/analysed).

On the other hand, again referring to the example, verification consists of ensuring that appropriate methods for solving the differential equations (e.g. Newmark's time integration method for linear transient response systems) are applied to correctly solve the problem.

Many aspects of V&V remain in the grey area between the philosophy of science, the theory of subjective choice, mathematics, and physics. The philosopher of science Karl Popper noted that a scientific theory cannot be validated, it can only be invalidated. Therefore, the mathematical model of a physical event as expressed in a theory can never be validated in the strict sense, it can only be invalidated.

To a certain extent, therefore, all validation processes are based on a pre-established set of acceptance criteria. Consequently, the analyst (or engineer or scientist) judges whether the model is invalid in the light of physical observations, experiments, and criteria. He/she (analyst/engineer/scientist), combining in-depth expertise with analytical skills, generates insights and recognizes/identifies patterns useful for the validation process itself.

The verification process, on the other hand, is already more clearly defined since it is based on mathematical and computational aspects. It involves the use of software engineering protocols, error detection and control, scientific programming methods and, most importantly, a posteriori error estimation.

Ultimately, the most "confounding" ("confounder" in the statistical sense) aspect of the V&V process has to do with the uncertainty in the data that characterizes the robustness of the mathematical models used to represent phenomena.

In some cases, the parameters that define and/or support the models are determined by observations, laboratory tests and field measurements. However, the measured values of these parameters vary from sample to sample or from observation to observation.

In addition, there may be ambiguities or inaccuracies due to uncontrollable factors (so-called noise) or calibration errors in the experimental equipment used to obtain the data. Moreover, some phenomena have little quantitative information or an incomplete or approximate understanding of the physical processes governing them.

Uncertainties may thus result from the variability of the data, which in turn is due to immeasurable or unknown factors, including incomplete knowledge of the underlying physics governing or characterizing the phenomena on which the prediction studies are to be performed.

Developing reliable methodologies — algorithms, data acquisition and management procedures, appropriate software, specific theories — to quantify the uncertainty associated with computational predictions from numerical simulations is therefore one of the major challenges for advancing SBES.

The benefits of simulation and its democratization

As already mentioned, the trends defined by the Fourth Industrial Revolution have marked — and are still marking — a significant change in the way in which industrial equipment (but not only) is designed and manufactured.

Thanks to the technological advances that have been made, it is now possible to carry out numerical analyses on three-dimensional prototypes, even complex ones, considering the interaction of two or more physical phenomena.

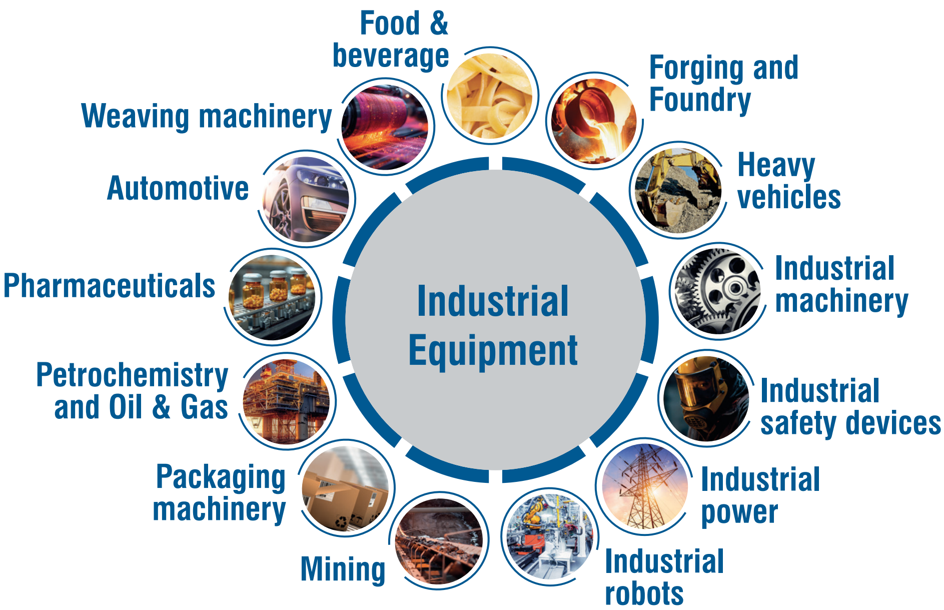
This allows the static, dynamic, fatigue, fluid dynamic and electromagnetic behaviour of a product or component to be simulated virtually at the design stage, using software solutions that are much more agile and intuitive than in the past and, above all, much easier to use.

Emerging technologies are therefore providing advanced and, in some ways, disruptive solutions that are leading to the design, manufacture and supply of sophisticated and efficient machinery and components in all sectors of the Industrial Equipment industry, some of which are graphically summarized below.

We are therefore moving into a phase of democratization of virtual prototyping. This will be accompanied by widespread availability of digital simulation solutions.

This democratization (and, of course, a conscious and appropriate use of the simulation tools available) will bring significant benefits in terms of cost reduction and, at the same time, increased reliability of the products/components designed and manufactured.

Consequently it is becoming becoming routine to be able to digitally simulate the operation of a product or machine in all its aspects and to be able to identify any critical functional and/or cost issues in advance, to make the appropriate corrections, update the model and repeat the simulation during the design phase until the prototype meets the specifications of the final product.
It is clear, therefore, that the greatest opportunity to improve product/component performance and/or reduce costs is in the early stages



of the development process based on numerical simulation, which therefore has the greatest impact when implemented early in the process itself (see Fig. 2).

If we focus on CAE, we can see that, together with CAD (Computer Aided Design), it has become indispensable in manufacturing at all levels, since the simulation software to which CAE is related makes it possible to reproduce on a digital scale what would be obtained by experimenting, sometimes destructively, on real prototypes. CAE thus enables a true virtual prototyping process, not limited to FEM analysis and structural calculations or stress analysis but covering various engineering aspects involving different physics (thermal, vibro-acoustic, fluid dynamics, electromagnetic processes), up to specific areas of predictive and preventive maintenance of products/components, as well as production management and optimization.

And it is the concepts of virtual prototyping and numerical analysis and testing that underpin the Digital Twin: a finished product with all its physical, functional, aesthetic and usability characteristics in a virtual context in which it can be "lived" and experienced, and its behaviour can be examined — even before the "physical twin" is ever manufactured.

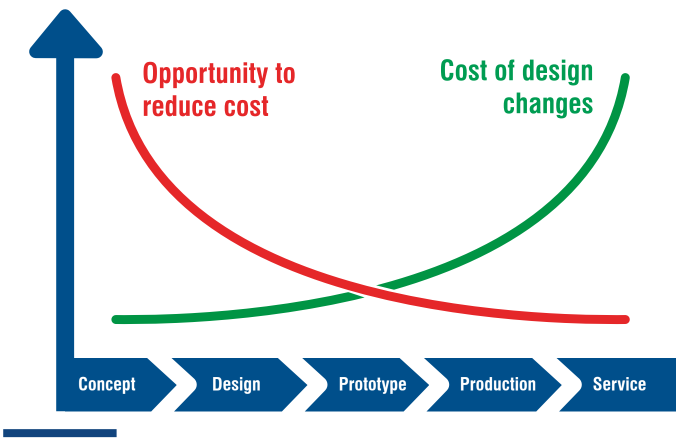


Fig. 2. Variation in the cost of a product depending on the stage of development

The act of "designing" undoubtedly involves the very act that profoundly characterizes the engineering profession: thinking ahead to imagine the product and to anticipate the steps required to calculate, realize and assess its compatibility both with users and with the physical reality that will surround this product during its use and/or operational life.

It is clear, then, that the growing democratization of (numerical) simulation cannot be separated, in terms of the reliability of the design/production process based on virtual prototyping, from a solid knowledge of the theoretical fundamentals on which the specific numerical methods of CAE are implanted.

While the "push-button" approach has made it easier to use tools such as FEA or CFD, putting these tools into the hands of a growing number of engineers and designers and significantly reducing set-up time, it has also introduced several unknowns, mainly related to the hypotheses, formulations and simplifications used to represent the underlying physical and engineering problem.

Inaccurate boundary conditions, choice of finite element type and discretization execution left to the simulation software (perhaps with a meshing phase that is not even guided, thus free to avoid what is considered to be an unnecessary waste of time), inappropriate shape functions for determining (e.g. for the mechanical-structural domain) stress gradients in regions of high geometric discontinuity: this is the way that algorithms can produce inaccurate or even incorrect results.

Democracy thus demands the ability to critically analyse decisions and choices, since it is not (merely) the automated entry of commands via keyboard or mouse (which carries the risk of reaching erroneous or hasty conclusions), but rather an awareness of the potential of numerical simulation when used with skill, wisdom and a certain willingness and curiosity to understand what lies behind the menus proposed on the screen.

A selection of application cases

It was previously noted that areas such as virtual prototyping and computer aided engineering (in its various "offshoots" — FEM, CFD, MBD, etc. — as discussed previously) are, by definition, part of SBES.

To demonstrate the essential role of engineering simulation for implementing projects to produce functional and reliable products in a sustainable manner, we will present a few reference cases, some of which were developed by combining different physics where necessary.

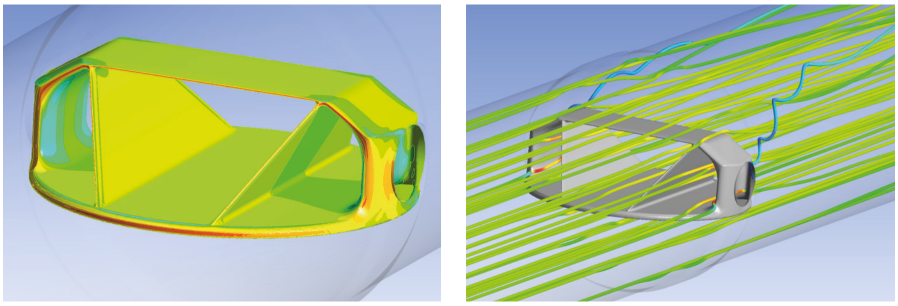


Fig. 4. Fully open disc: right) Disc pressure distribution, left) Flowlines.

FEM and CFD: fine-tuning a project

This project concerned the design of butterfly valves installed in the Kargi Hydropower Plant in Türkiye. The valves were manufactured by CIB (Carpenteria Industriale Bresciana) in electro-welded steel and had a circular fluid passage section with a diameter of 4,100mm and a weight of approximately 750kN (75 tonnes) each. They were installed at the end of the hydroelectric plant's pressure pipe to interrupt as necessary the flow entering the turbines, which can reach the considerable flow rate of 84,000l/s under severe conditions.

The valve design, entirely developed by EnginSoft, found a synergy between different physics, specifically between fluid dynamics and mechanics, as well as hydraulics for managing the disc opening and closing control.

The shape of the disc used to laminate the flow of water entering the turbine was designed to minimize pressure losses when the valve is open, while at the same time ensuring the necessary rigidity and tightness when the valve is closed. Obviously, these requirements are completely contradictory, but the "rational" use of numerical simulation (CFD and FEM) made it possible to satisfy both.

The morphology of the disc profile, which was specifically optimized to meet the stringent design requirements for pressure drop, required targeted interventions to achieve shape optimization (see Fig. 3) and thus obtain a highly efficient hydrodynamic profile from a raw component. The hydrodynamic behaviour was simulated by CFD for different sectioned partitions (see Fig. 4).

The structural validation of the valve body, disk and shaft was conducted by transferring the actions experienced by the disk during valve closing (see Fig. 5) from the CFD model to the FEM models (implemented on the basis of geometries obtained from preliminary calculations) and by carrying out appropriate numerical analyses capable of returning the deformations (see Fig. 6) and stress fields for subsequent functional and strength checks of the components (valve body, disk, shaft, opening and closing mechanism).

Standard EN 13445-3 (Unfired Pressure Vessels — Part 3: Design), in particular Annex C — Design by Analysis — Method based on Stress Categories, was used to develop the code verifications required to qualify the safety levels of the various components against specific objective requirements. This standard classifies the stresses calculated by elastic analysis into categories and limits them by allowable values, which are set conservatively so that plastic collapse does not occur.

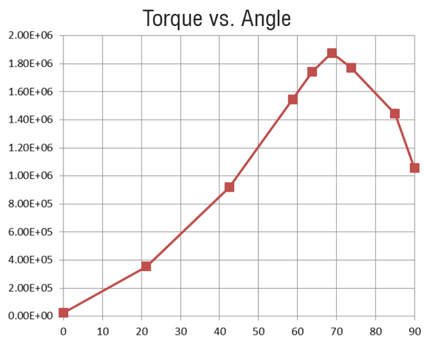


Fig. 5. Pin torque versus angle in closed state.

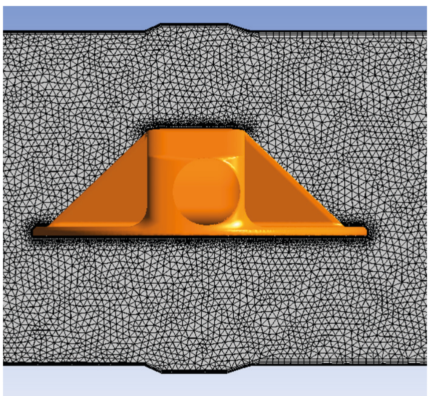
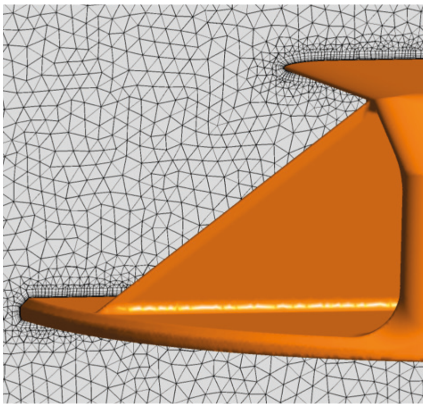


Fig. 3. CFD model for open disc pressure drop analysis.



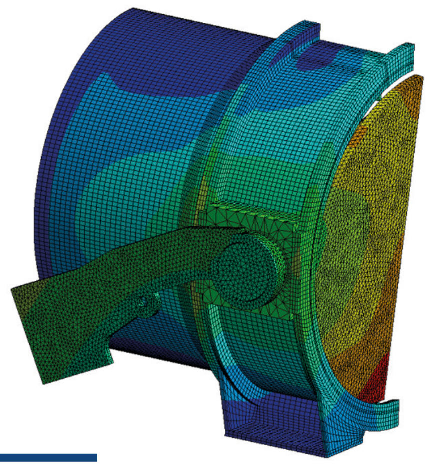


Fig. 6. Displacement range for valve in closed position.

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The generous plasticity of steel

Analysis and verification methods for pressure vessels, alternative to the linear elastic approach used for the validation of the structural resistance of the valve body and disc of the project described above, refer to the lower and upper limit theorems of the plasticity limit analysis:

- **Lower limit theorem (static theorem):** The structure will not collapse or can be kept in a state close to collapse if an equilibrium moment distribution can be found that balances the applied loads and is everywhere less than or equal to the plastic moment.
- **Upper limit theorem (kinematic theorem):** The structure will collapse if there is a compatible model of a plastic failure mechanism for which the work per unit time of the external forces (external power) is equal to or greater than the work per unit time of the internal dissipations (internal power).

The lower limit theorem states that, if possible, the structure will adapt to resist the applied load. It gives the lower or safe limits of the collapse load. The maximum lower limit is the collapse load itself.

The upper limit theorem states that if a plastic failure mechanism is present, the structure will not hold. It defines the upper or unsafe limits of the collapse load. The minimum upper limit is the collapse load itself.

It is on these theoretical argu-ments (supported by ASME VIII Div. 2, Part 5 – Limit Load Analysis Method and Elastic Plastic Stress Analysis Method) that the stress analysis of a specific pressure component used in the Oil&Gas sector (see Fig. 7) was based and on which EnginSoft conducted significant calculation and verification activities.

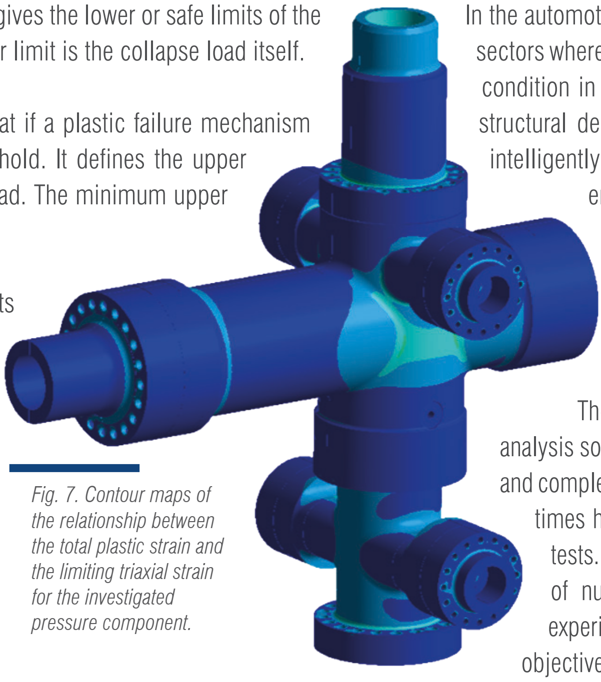


Fig. 7. Contour maps of the relationship between the total plastic strain and the limiting triaxial strain for the investigated pressure component.

Starting from the design geometries, a finite element model was implemented with an adequate degree of detail, fully considering the elasto-plastic behaviour of the material to determine the limit load condition (combination of internal pressure and external loads) beyond which the component itself would collapse by exceeding the resistance capacity defined, in addition to the non-convergence of the numerical analyses, by a very specific limit (ε_L) on the plastic deformations that accrue during the application of the design/ calculation actions.

This limit is given by the following relationship:

$$\varepsilon_L = \varepsilon_{Lu}\, e^{-\left[\left(\frac{\alpha_{sl}}{1+m_2}\right)\left(\left\{\frac{\sigma_1+\sigma_2+\sigma_3}{3\,\sigma_e}\right\}-\frac{1}{3}\right)\right]}$$

where:

- ε_{Lu} is the uniaxial strain limit
- α_{sl} and m_2 are parameters as defined in ASME VIII Div. 2, Part 5
- the term $(\sigma_1+\sigma_2+\sigma_3)/3\sigma_e$ is the triaxiality index of the local stress field, where σ_1, σ_2, σ_3 are the principal stresses of the local stress field and σ_e is the equivalent von Mises stress of the local stress field.

The approach adopted (specifically the elastic plastic stress analysis method) allowed the extension of theoretical formulations (theorems) to virtual realities (numerical models) in order to find the limit beyond which the essential component analysed presents a risk of collapse, using all due safety margins and without the need to carry out a "design by experiment", which is much more costly than "design by analysis".

Impact: a numerical solution to a dynamic problem

Understanding what happens during a vehicle collision or impact is necessary for improving the safety of a vehicle and, consequently, the chances of survival for its occupants.

In the automotive sector (as well as in aeronautics and other sectors where impact phenomena constitute a dimensioning condition in the design process), the main interest of the structural designer is to create bodies/frames capable of intelligently participating in the dissipation of impact energy so that each part contributes to energy absorption, to avoid damage to people from structural collapse and, when relevant for safety and related costs, to avoid damage to the payload.

The development of kinematic and dynamic analysis software capable of producing ever more complex and complete calculation models in ever shorter calculation times has significantly improved the success of crash tests. In fact, the systematic (and competent) use of numerical simulation to predict the results of experimental tests is key to achieving the design objectives, and considerable savings in all respects.

The advantage lies precisely in predicting the actual course of the experiment without unnecessarily destroying the vehicles (or components) being analysed.

In industry, for example, the cost and development time of new designs has been significantly reduced thanks to the widespread use of numerical methods based on the finite element method, an approach that has become indispensable for creating efficient and robust models for simulating dynamic problems in structures with non-linear behaviour.

The term non-linear refers to all dynamic phenomena where structures are subjected to:

- large displacements and small deformations or large displacements and large deformations also known as geometric non-linearities.

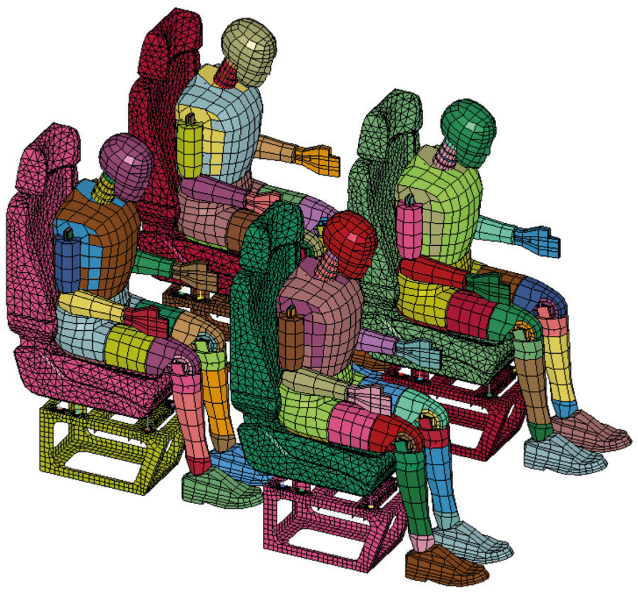


Fig. 8. Hybrid III 50th percentile male LSTC virtual dummies positioned in the cabin of a special vehicle.

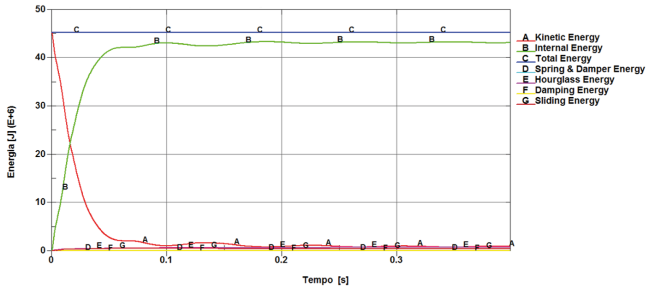


Fig. 9. Energy balance of a frontal impact on the cabin of a special vehicle.

- plasticization phenomena or material non-linearity.
- contact problems, where non-linearity is related to the nature of the external and/or internal constraints, i.e. non-linearity of contacts and self-contacts.
- the impulsive nature of the acting loads, which includes the non-linear behaviour listed above.

In (non-linear) dynamics, the equilibrium equation is obtained from the static case by adding the inertial and viscous terms; the time variable must also be considered, which involves a workload proportional to the duration of the integration over time.

The system of second-order differential equations, in matrix form, is as follows (see also the earlier report on V&V):

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=F(t)$$

where the various terms are familiar.

There are two possible approaches to the solution process: the implicit method and the explicit method. In the implicit formulation, a step-by-step calculation method is used in which an appropriate convergence criterion allows the analysis to continue or not, possibly reducing the time increment and depending on the accuracy of the results and the achievement of an equilibrium condition at the end of each step. This method requires the inversion of the stiffness matrix, which makes it computationally expensive for very complex models with many degrees of freedom.

The explicit method was developed as a particularly efficient computational tool for solving highly non-linear structural dynamics problems characterized by many variables (large-scale problems) but defined over very short time intervals. In this case, the analysis is not conditioned by a convergence criterion, and the time increment, which is defined at the beginning of the analysis, remains constant during the computation.

The choice of such a time step is constrained by the stability or CFL (Courant-Friedrichs-Lewy) criterion; this condition implies that a mechanical wave propagating through the material cannot move more than the smallest characteristic dimension of all mesh elements in a single time step.

In the simplest case, the maximum allowable Δt equals

$$\Delta t = \frac{d_{min}}{c} = \frac{d_{min}}{\sqrt{E/\rho}}$$

where

- d_{min} is the minimum distance between two nodes in the mesh,
- c is the velocity of sound propagation in the material,
- E is the Young's modulus of the material in which the perturbation travels,
- ρ is the density of the material through which the perturbation travels.

Therefore, the size of the finite element discretization used to implement the model will determine whether this criterion is met.

As mentioned above, fast dynamics applications are common in the automotive sector when it is necessary to simulate crash phenomena in relation to specific requirements, such as avoiding any damage to the occupants of the vehicle.

A specific case analysed by EnginSoft (among many that have been addressed and solved) concerned the study of the impact behaviour of the cabin of a special vehicle.

The aim was to evaluate both the structural resistance of the cabin itself under crash conditions (crash verification according to ECE-R29) and the preservation of the vital space of the occupants during the crash, simulated using Hybrid III 50th percentile male LSTC virtual dummies (see Fig. 8) placed inside the full cabin model.

Fig. 9 shows the energy balance of the frontal impact on the cabin. The reliability and accuracy of the simulation can be seen from the fact that the total energy, which remains constant for the duration of the impact (0.3s), is gradually converted from kinetic energy to internal dissipated energy.

EnginSoft also applies fast dynamics to domestic appliances (e.g. refrigerators, washing machines, dishwashers) to assess their impact behaviour as a result of accidental dropping during loading/unloading from the bed of a lorry or from a forklift truck.

Since the equipment is supplied with packaging protection for such scenarios, and in situations where it is fully represented in the calculation models, the numerical simulations also make it possible to evaluate the effectiveness of this protection and, if deemed necessary, to carry out optimization measures to reduce its cost while maintaining the level of effective protection.

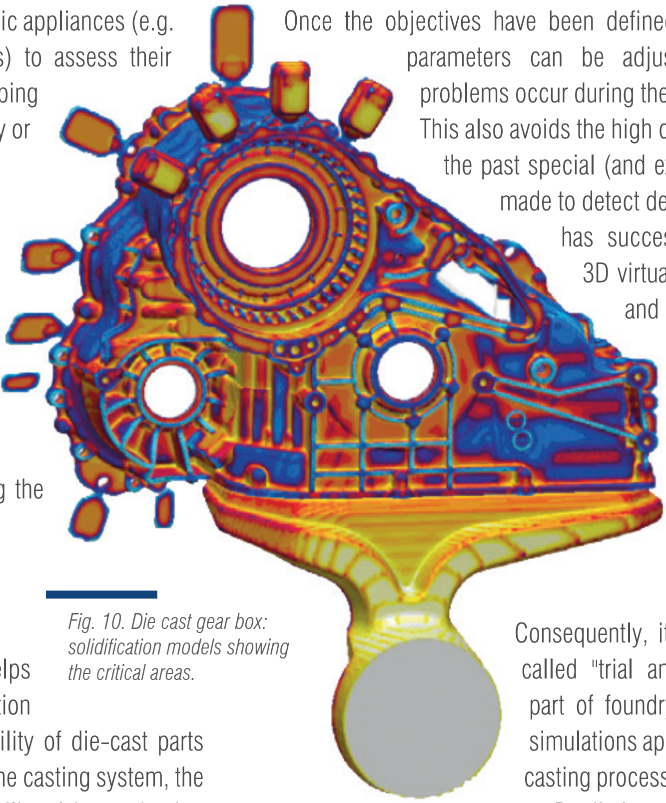


Fig. 10. Die cast gear box: solidification models showing the critical areas.

Casting simulation prevents expensive prototyping

Another area where numerical simulation helps to improve product quality and reduce production costs is the foundry. The quality and profitability of die-cast parts depend on the design of the tool, the layout of the casting system, the thermal control of the mould and the reproducibility of the production conditions.

In other words, determining the correct casting configuration to consider during the die casting production phase is a relatively complex process, the results of which can only be known in advance by relying on virtual prototyping guided by practical experience and knowledge.

Numerical simulation applied to casting and die-casting processes makes a significant contribution to the overall design of the processes themselves and to the quality of the cast components.

In fact, it is estimated that more than 90% of casting defects are typically due to design errors and only 10% are due to real production problems. Many design errors can thus be avoided by using predictive simulation.

Once the objectives have been defined, the design or process parameters can be adjusted to ensure that no problems occur during the production of the casting. This also avoids the high cost of defective casting. In the past special (and expensive) prototypes were made to detect defects; nowadays this stage has successfully been replaced by 3D virtual prototyping. The casting and die-casting simulations developed almost daily at EnginSoft provide a high degree of process safety, prevent technical problems, and ensure that a project is not delayed.

Consequently, it can be said that the so-called "trial and error" process is now part of foundry history. The benefits of simulations applied to the casting and die casting process are briefly outlined below:

- Predicting turbulence or laminar flow of the liquid metal during melting
- Detecting possible inclusions
- Predicting the timing and nature of solidification
- Predicting residual (tensile) stresses and deformations during cooling and/or heat treatment of the casting
- Improving product quality
- Significantly reducing scrap
- Reducing production times
- Identifying areas of the casting where porosity and/or cracking may occur
- Providing information on critical temperature and pressure ranges for mould design.

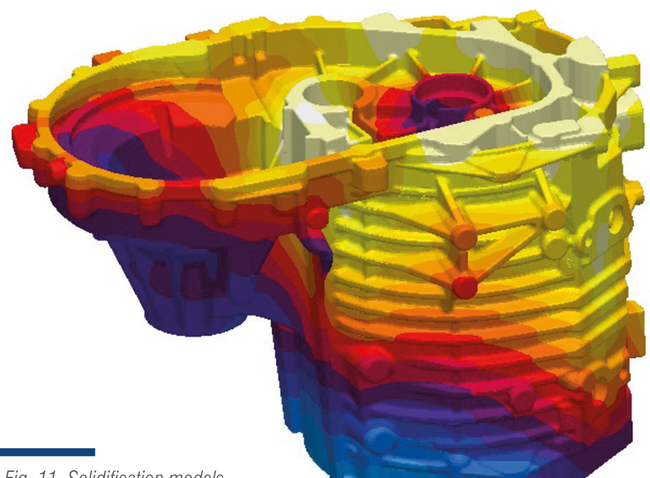


Fig. 11. Solidification models of a die-cast electric motor housing.

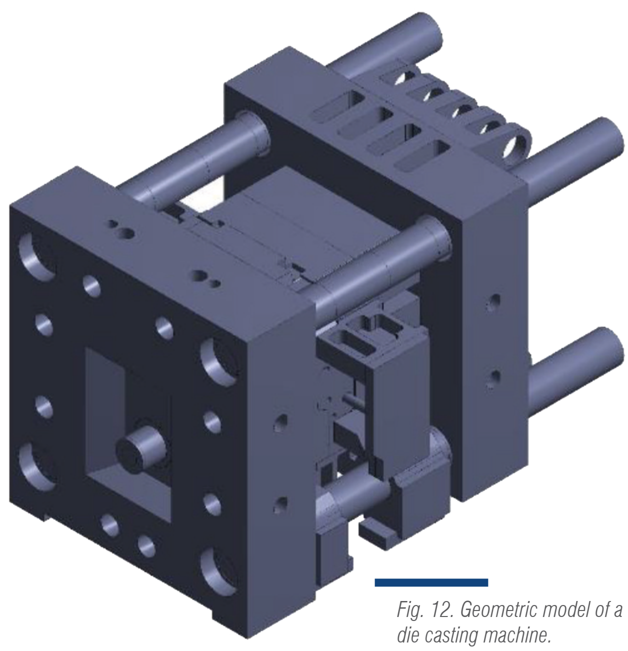


Fig. 12. Geometric model of a die casting machine.

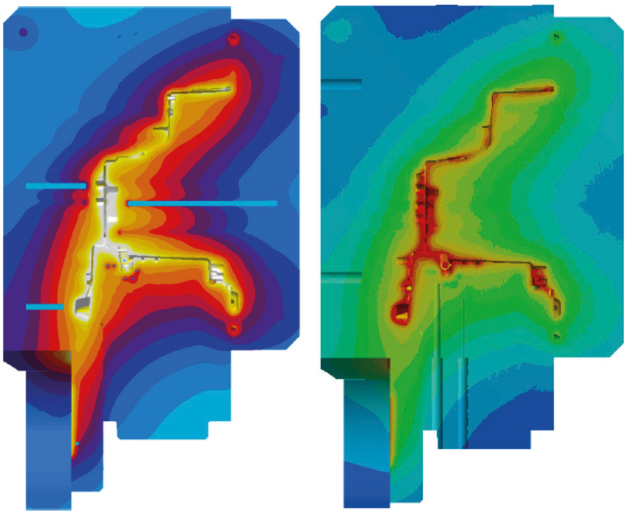


Fig. 13. a) Temperature distribution at cavity transferred from casting simulation to b) Structural simulation to assess the thermal steady state stress analysis.

As can be seen from the last item in the brief list above, in addition to quality control of the die-cast product, simulation of the die-casting processes also provides useful information for the development of the mechanical-structural design of the moulds.

In fact, it is possible to perform thermo-structural analyses on specific FEM models of the entire mould structure based on the distribution of temperature and the pressure fields in the cavities of the mould into which the molten metal is injected to obtain the relevant product/casting component (see Fig. 12 — the model is composed of the various parts that make up the mould assembly, such as tie bars, cover holder, cover cavity, ejector holder, ejector cavity, columns, cover holder block, ejector holder block, slide supports, ejector box, side supports, side cavities).

Once the temperatures obtained from the analysis of the casting process have been transferred to the FEM model of the die (see Fig. 13), taking into account the prestressing applied to the tie bars, the thermal fields over the entire die, as well as the stress and deformation states of the sensitive/significant parts of the die itself, are determined in relation to resistance and fatigue aspects (stress states — see Fig. 14) on the one hand, and to aspects relevant to flashing that could occur if there were excessive gaps between parts (e.g. between ejector cavities and side cavities) on the other hand.

Obviously, to obtain reliable results, all parts of the mould that are not in structural continuity but in contact with each other are placed in contact, which means that numerical analyses are performed in geometric non-linearity (specifically defined as the presence of non-linear contacts).

Meshless CFD

In the changing landscape of product design and development, the engineer is challenged to optimize performance, reduce costs and minimize time to market. As already mentioned, the creation of traditional physical prototypes, while essential, can be time

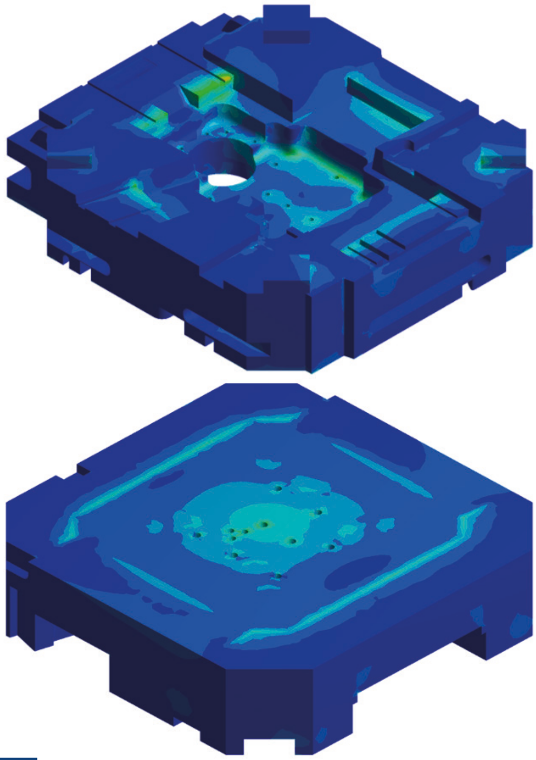


Fig. 14. Von Mises stress distribution in some structural components of the die casting tool.

consuming and expensive. As a result, virtual models and digital simulations are becoming the foundation of innovation, especially for complex processes.

Digital twins, which bridge the gap between the conceptual and physical worlds by allowing rapid iteration and informed decision-making, have already been mentioned, but the importance of making numerical simulation reliable when it replaces all or part of physical reality must be reiterated. It is therefore essential to validate the results obtained from digital models against the corresponding results obtained from experimental tests, to find paths that are minimally affected by the approximations introduced at the method (computation) level.

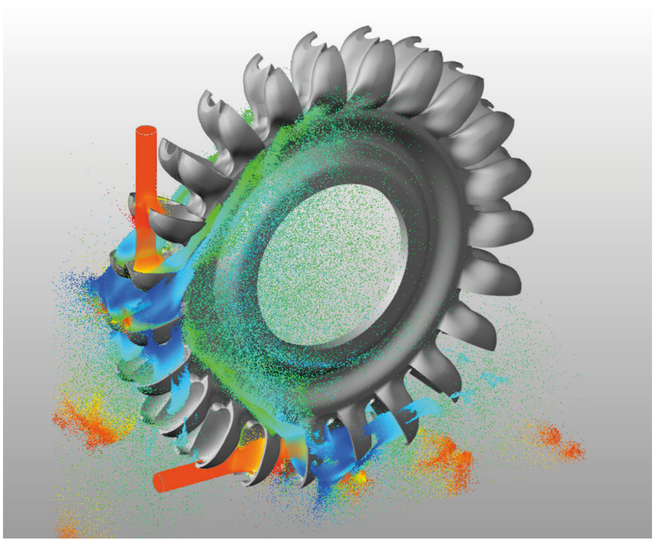


Fig. 15. Application of MPS to optimize power generation from Pelton turbines.

This is the case with moving particle simulation (MPS), historically known as the moving particle semi-implicit method.

This is a more intelligent approach to CFD, applicable to the simulation of incompressible free surface flows.

Where traditional CFD, by means of a fixed mesh throughout the domain, uses the Eulerian approach of solving the Navier-Stokes equation to calculate fluid flow, the MPS method instead uses the Lagrangian approach by representing the fluid with particles, eliminating the need for a computational grid. Its mesh-free nature makes the simulation mesh independent, simplifying and accelerating the process, especially when dealing with complex geometries and moving parts.

The MPS approach has been widely adopted in the automotive sector in recent years, mainly for powertrain applications such as the simulation of oil mist and lubrication of engines and transmissions, accompanied by the determination of operating temperatures to allow the correct design of the cooling system.

The advantage of this method is its ability to simulate free surface flows and fluid jets in very complex geometries, such as an entire gearbox or engine, in a short modelling and simulation time. This is made possible by the meshless nature of MPS.

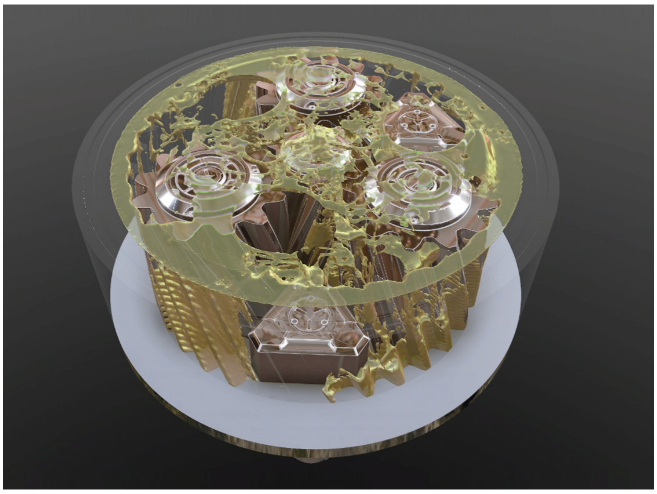
Conclusions

Summing up, SBES is a discipline that focuses on the computer modelling and simulation of complex, interconnected engineered systems, and the acquisition of information that enables these systems to meet specific standards of accuracy and reliability. SBES takes advances in scientific understanding and uses computer simulation to translate them into innovative approaches to solving engineering problems.

There is no doubt that over the past 50-odd years, developments in mathematical modelling, computational algorithms, and technologies for processing enormous amounts of data/information have led to significant improvements in industrial productivity, safety, quality of life and health.

But the acceleration of scientific research over the last half century has also led to the current phase in which the enormous expansion of the capacity to model and simulate an almost unlimited variety of physical phenomena has become apparent. This potential has profound implications, some of them ethical.

Firstly, computer modelling and simulation make it possible to study natural events and engineered systems that for too long have relied largely on experimental methods. In effect, empirical assumptions are replaced by computational models grafted onto scientific approaches and findings. Modelling and simulation extend the ability to address problems too complex to be solved by traditional analysis. These include problems involving micro and macro scales (both



space and time) or problems involving several physical processes simultaneously (multiphysics).

Secondly, modelling and simulation enable design and production to be more scientifically based, with less trial and error and shorter design-production cycles, resulting in greater sustainability (including environmental sustainability) and less waste. In other words, modelling and simulation improve the ability to predict outcomes and optimize solutions, allowing the right resources to be allocated to specific projects and/or the right strategic decisions to be made.

Thirdly, modelling and simulation introduce tools and methods into everyday life that are applicable to all engineering disciplines (electrical, computer, mechanical, civil, chemical, aerospace, nuclear, biomedical), allowing each to benefit from advances in optimization, control, uncertainty quantification, verification and validation, design decision-making and real-time response.

As to the ethical implications, the great "power to do" that is available today must be governed by the "ability to foresee" the effects of formidable technical intuitions/ideas. To approach an ethics that guides technology and directs it towards a safe and sustainable future, we need to recover and pay due attention to the virtues of "those who see in advance".

This ability cannot be and must not be lost. It is essential to tap into the wisdom of imagining and anticipating the ultimate effects of action. Lest we lose the hope of expanding our capacity to understand and perceive the “infinite” that surrounds us. Lest, in the age of automation and artificial intelligence processes, technology itself, from being a rational tool to support and safeguard human life, be transformed into an autonomous and self-sustaining power apparatus, emptying human labour of content.

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