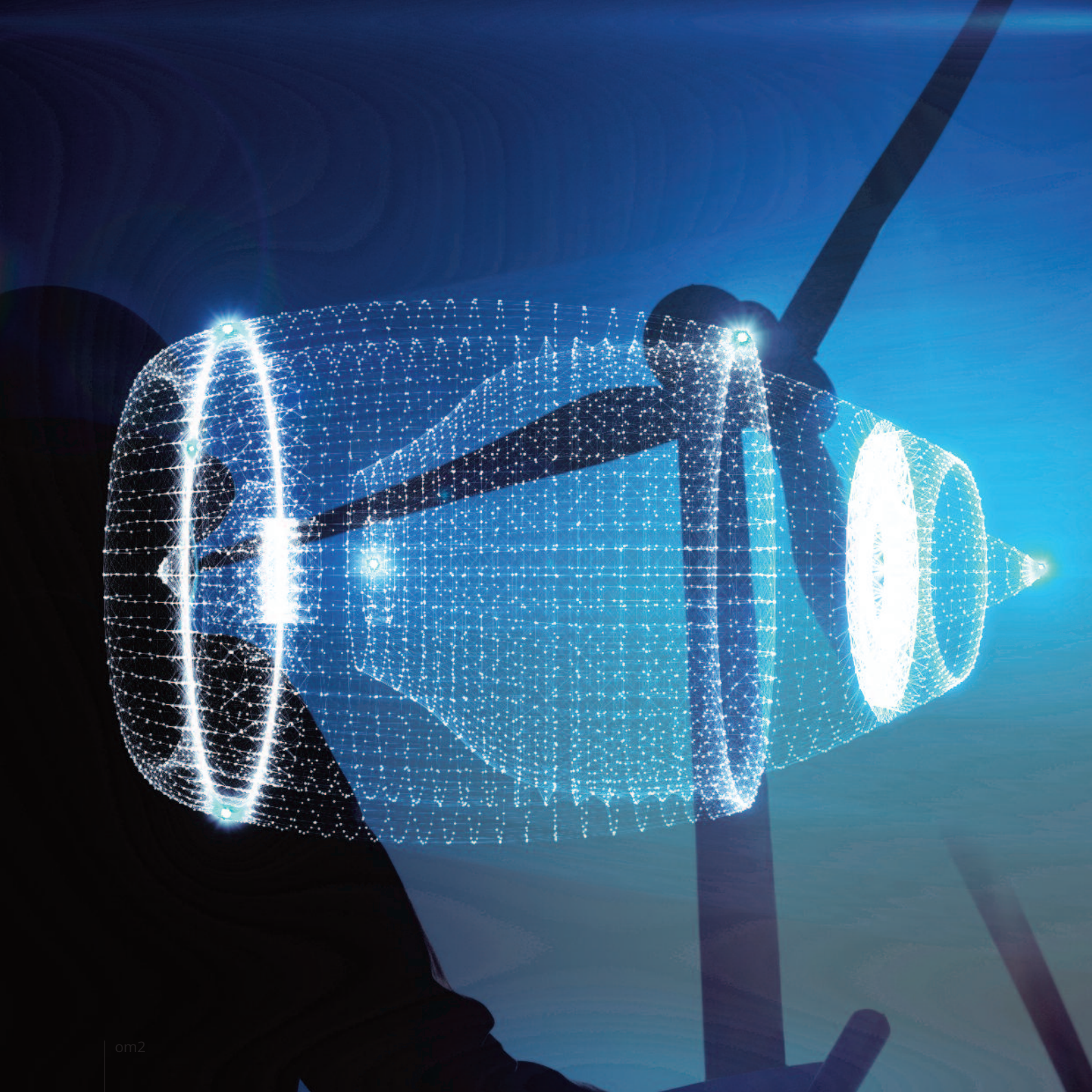
Modelling, Simulation & Optimization in a Data rich Environment

A window of opportunity to boost innovations in Europe

EU MATHS IN



Introduction

Modelling, Simulation & Optimization (MSO) remain the cornerstone for the development of most products in the fields of Industry, Health, Energy or even Finance. Although High Performance Computing, Data Analytics and Artificial Intelligence offer new opportunities, their impact on innovation and the improvement of products and services could remain partial without a massive effort on the axes of modelling, simulation and complex systems optimization. Major opportunities, in particular, the establishment of digital twins, rely on the connections at the interface between fields of expertise, domains, businesses and across the complete lifecycle of products & systems. At the same time, methods have outpaced computational power in terms of capability over the past decades. Our initiative is guided by the certainty that a high level approach on Modelling, Simulation & Optimization, enriched by data analytics and intensive computing, is a considerable economic asset.

Our core group represents a vast network of firms at the European scale, aggregated through the national communities into the EU-MATHS-IN organization. Beyond the size of the current network, we are proud of the presence aboard of major European Simulation firms (SIEMENS, ESI), of a living network of SMEs, and many firms grounding the performance of their products on mathematical expertise. We have definitely achieved successes by the construction of various national networks, which connect SMEs with academic expertise in order to deliver innovative approaches and eventually new business opportunities. In France, it has been named as the MSO Network. We are convinced our action, when really taken to the European scale, will increase the connection between competences, promote innovative ideas for SMEs as well as for Large Firms, offer business synergies at the interface between non-competing interests, and reinforce the scientific and technological European leadership. This is also underlined by recent studies predicting that Digital Twins relying on technological leaps in Modelling, Simulation & Optimization will cover a novel market up to 90 billion dollars by 2025.

The following pages detail the opportunity and witness concrete applications in alignment with the corporate strategies of the firms pertaining to the EU-MATHS-IN Industrial Core Team.

Several contacts are now established on the side of national research agencies and decision making European structures. We look forward to identifying the final structure of the initiative we advise in a collaborative state of mind, in order to achieve the stakes we envision.

MSO for Digital Twins (DT)

Novel Modelling, Simulation and Optimisation paradigms in a Data rich Environment (MSODE)

This document serves as a discussion paper on the technological challenges needed to implement, in a systematic and structured way, digital twins in industry and society and make these a business success. Many components to achieve this are in place, but there is missing capability on the side of mathematical modelling, simulation and optimisation as a key enabler, especially in data rich environments.

Vision for the initiative

On the one hand, the future development of industry and society exhibits strongly increasing complexity and at the same time ever-shorter innovation cycles. On the other hand, digitisation and the internet of things have led to an explosion of data and information. Without novel computational tools and paradigms we will not be able to manage these challenges. There is a clear need to strengthen European competitive advantage in industrial innovations and to start a new initiative to meet the associated societal challenges ahead of us.
For almost all domains of science and engineering and in almost all industrial sectors, model based approaches are well established. A multitude of commercial and open source software for modelling, simulation and optimization (MSO) based on mathematical models is available. At the same time increasingly large amounts of process and product data are available and strong artificial intelligence solutions have been developed to exploit these. All this is fostered by computers becoming more and more powerful.

These developments lead to the vision that in the near future holistic approaches can be achieved that combine all these developments. A complete industrial product or process in its whole life cycle can be accompanied by a virtual representation, often called digital twin that allows design optimization, process control, lifecycle management, predictive maintenance, risk analysis and many other features[1]. Digital twins are so important to business today, that they were named one of Gartner's Top 10 Strategic Technology Trends for 2017[2]. They are becoming a business imperative, covering the entire lifecycle of an asset or process and forming the foundation for connected products and services. Companies that fail to respond will be left behind.

To establish this vision or to even come close to it, several new developments that involve different scientific communities have to take place and many obstacles have to be removed. A core need are novel mathematical technologies, to describe, to structure, to integrate and to interpret across disciplines. Mathematics is the language of digital twins.

History[3]

NASA was the first to dabble with pairing technology – the precursor to today's digital twin – as far back as the early days of space exploration. How do you operate, maintain, or repair systems when you aren't within physical proximity to them? That was the challenge NASA's research department had to face when developing systems that would travel beyond the ability to see or monitor physically.

Michael Grieves at the University of Michigan first wrote of the concept using the digital twin terminology in 2002[4]. The digital twin serves as a bridge between the physical and digital world. The components are connected to a cloud-based system or a dedicated hardware that uses sensors to gather data about real-time status and working condition. This input is analysed against business and other contextual data. Lessons are learned and opportunities are uncovered within the virtual environment that can be applied to the physical world.

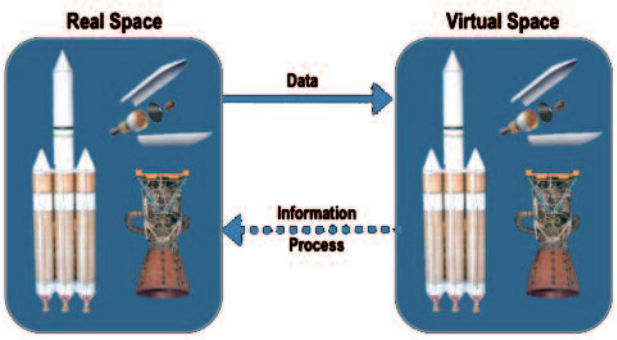


Figure 1. Concept of a digital twin
(picture taken from the reference in footnote 4)

Digital twins are powerful masterminds to drive innovation and performance. It is predicted footnote that companies who invest in digital twin technology will see a 30 percent improvement in cycle times of critical processes.

State-of-the-art

Although first successes are reported[5] and many claims are made[6], neither the classical MSO approaches based on mathematical models and their software implementations, nor the constantly improving techniques for data analysis and machine learning will be enough to achieve this visionary goal[7,8]. Even the rapid improvements in modern computing hardware and especially algorithms/software are not sufficient to achieve this. Currently, due to the high manual human effort[7], only major companies with large R&D departments can afford to build digital twins, but it would be desirable that companies on all scales can profit from the development. New generations of mathematical paradigms are required to convey today's highly fragmented approaches in the various disciplines.

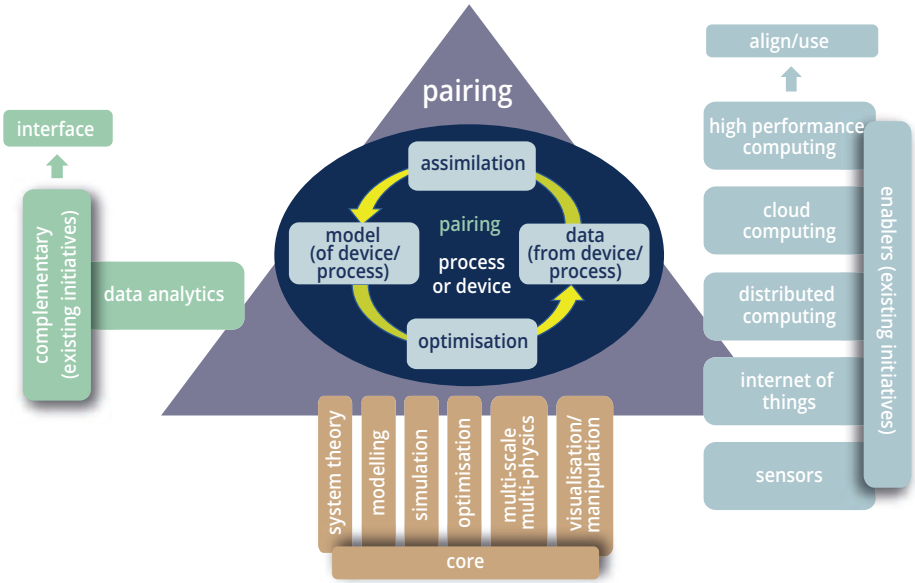


Figure 2. High level schematic of this initiative and its connection to other initiatives

Technology Challenges

Currently, models, methods, as well as software implementations and data sets are of highly different fidelity requiring many manual interactions. The figure above summarizes these interactions in a schematic way (including the interactions with existing initiatives). To meet the future challenges, it is necessary to develop novel MSO paradigms allowing a systematic MSO based approach to build highly automated modularized networks of model hierarchies (from very high fidelity physics based models to very coarse, surrogate, or even purely data based models), and that can deal with multi-physics and multi-scale systems. Key will be a convergence of artificial intelligence methods and first principle approaches typically used in MSO by laying down novel mathematical principles as the core language of digital twins.

Furthermore, the model hierarchies should

- be able to (automatically) evolve with the availability of new information, data, or even changes in the process,
- allow adaptive models and solutions with seamless choice of accuracy and speed,
- allow real-time and interactive simulation and optimisation,
- be made robust towards inaccuracies in the data and the model,
- be able to quantify the uncertainties and risks that come with the determined solutions,
- lead to the convergence of artificial intelligence and physics-based models,
- exploitation new computing architectures, e.g. combined cloud - edge solutions,
- be flexible for new user interaction concepts,
- allow the use of advanced black box solvers MSO software packages,.

Goal of the initiative

The goal is to accelerate the development and optimisation of industrial processes and devices extending current Model-based Systems Engineering (MBSE) concepts to model-based assistance along the complete life cycle. What is needed is a high powered multi-disciplinary effort to bring mathematical MSO methods together with techniques for the treatment of big data and artificial intelligence methods as well as to make them efficient on modern hardware environments. All results should be made available within a European Open Source Ecosystem[9].

European Strengths

In the development of high performance computer architectures, Europe was lagging behind, but due to new initiatives in the HPC and exascale area it is working hard to become one of the world leaders. A similar effort is needed in the MSO area. Europe is traditionally (for many centuries) very strong in mathematics, much stronger than it is in the HPC or exascale area, but bridging the gap between these strengths and industrial challenges as put forward in the Industry 4.0 initiative is a big challenge in itself. The situation is improving, as reflected by the fact that the MSO industry is focussing more and more in Europe, as exemplified by Siemens and Dassault who are quickly building up their MSO product portfolios. However, much more is possible when a major and concerted effort is developed to truly bridge the aforementioned gap, and unite the strengths of European mathematicians with Industry 4.0 and other initiatives of this kind to bring European industry to the forefront.

Approach of the initiative

Academia and industry should

- focus on new generations of algorithms and concepts combined with a focus on usability and transfer (technology driven research programmes),
- overcome the boundaries between disciplines as well as academic and industrial research by collaborative, co-located projects, e.g. creating joint research labs of mathematical (or MSO) technology between industry and academia, favouring long term relationships that ease the transfer of technology,
- develop new ways of collaboration of companies and public-private partnerships, to achieve fast track transfer and to support the formation of start-ups, e.g. by promoting funding opportunities for fast-track transfer projects from basic concepts to industrial scale solutions,
- promote new academic highly interdisciplinary education programs, and increase/create new possibilities for obtaining PhDs within a company in close collaboration with academia in mathematics,
- develop new business interactions through models (product co-development) and enhanced customer experience (embarked models, improvement of data assimilation), e.g. by enabling efficient R&D virtual interactions through multi-fidelity models owned by different parties, while protecting intellectual property.

Benefits for industries and business opportunities

There are large business opportunities in utilizing the power of models in combination with massive computing capacities, the increasing availability of rich

data sets, modern data analytics and Artifical Intelligence techniques. This is, in particular, the case within industrial partnerships whenever modelling concepts or hierarchical modelling need to be co-developed; mathematical MSO techniques become the cornerstone of predictiveness and innovative design.

Reference

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3 Summary of
https://www.forbes.com/sites/bernardmarr/2017/03/06/what-is-digital-twin-technology-and-why-is-it-so-important/#1ef8f9802e2a

4 http://innovate.fit.edu/plm/documents/doc_mgr/912/1411.0_Digital_Twin_White_Paper_Dr_Grieves.pdf

5 GE: https://www.ge.com/reports/scientists-built-a-digital-twin-of-a-car-battery-to-make-it-last-longer/

6 ANSYS: http://www.ansys.com/products/release-highlights/digital-twin

7 ORACLE: Digital Twins for IoT Applications
http://www.oracle.com/us/solutions/internetofthings/digital-twins-for-iot-apps-wp-3491953.pdf

8 Engineering.com: Mission Impossible: The Digital Twin:
https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/15919/Mission-Impossible-The-Digital-Twin.aspx

9 See also recommendations in the final report of the ESF Forward Look project on Mathematics for Industry:
http://www.eu-maths-in.eu/EUMATHSIN/wp-content/uploads/2016/02/2010-Forward-Look-MathIndustry.pdf

Industrial visions and innovation

In order to make the vision from the previous pages more concrete, here are some statements from companies describing related applications and stakes.

ESI

MICHELIN

NORS

REPSOL

SHELL

SIEMENS

AKSELOS

ECOMT

MAGWEL

SMART SAMPLE

VORTECH

ESI

Embracing Smart Virtual Prototyping, Factory of the Future, Hybrid Twin™, and Product Performance in its full Lifecycle

CAE 4.0 disruptive challenges in the age of the Internet of Everything

At its inception fifty years ago, CAE 1.0 (Computer Aided Engineering), together with CAD and CAM for Product design and manufacturing respectively, is part of PLM (Product Lifecycle Management). PLM covers overall product development and documentation, while CAE focuses on engineering analyses and simulation of validation testing.

Leveraging the exponential power of HPC (High Performance Computing) and ICT (Information and Communication Technologies), CAE 2.0 further provides a powerful digital backbone to accelerate the Product development cycle by incorporating Virtual Manufacturing and its impact on performance testing, including the details of the physics of materials, and therefore delivering a physically representative 'Virtual Prototype' all the way to pre-certification, real or digital.

In the context of the Outcome Economy, in which the customer Product itself is not the only objective, we cannot stay at the level of the pre-certification stage of the Product. Rather, we must address the experience and performance of the Product in its intended and actual operating environment. Building on our deep knowledge of the Physics of Materials complemented with the new technologies now available in recent years - including Artificial Intelligence (AI), Big Data, and Internet of Things we must change the way we approach Manufacturing of Products and, importantly, in the Performance Management during the entire Product lifecycle from launch to retirement.

It is also essential that we have an effective model development and assembly CAE Platform to enable and control the 'Art of Modeling' within proper 'circumstances and limits', on which we can develop CAE multi-model chains and processes to approach.

So the spectacular progress of AI (Artificial Intelligence) with Machine Learning (ML) and Deep Learning (DL), together with the Cloud and IoT (Internet of Things), are transforming the innovation focus from the Product development phase (PLM) to the Product Performance Lifecycle (PPL) in its operational phase, i.e. during its real life without failures or recalls, targeting intelligent/assisted/autonomous products, and managing predictive maintenance up to retirement and decommissioning.

This present expectation for CAE 3.0 is a fundamental 'disruptive' transformation into Smart Virtual Prototyping requires an augmented digital representation of the Product no longer in its 'nominal' certified state, 'but 'as

aged', possibly damaged, and 'as interacting' in its expected operational environment in service, i.e. represented, immersed, animated and interactively piloted as its Virtual Twin in its Virtual Environment..

Now the new frontier of CAE 4.0 arises when the theory based approach is updated by in-service 'real life' data from sensors and IoT. The Virtual Twin now becomes the Hybrid Twin ("HT"), combining the ML enhanced data driven model with the theory built Virtual Prototype ("VP"), for the best of both worlds.

Essentially limited to the Product development phase, the legacy PLM paradigm is waning, while the new "PPL" (Product Performance Lifecycle) is waxing. This fundamental evolution of the Product full lifecycle™ with its Performance follow up and the actionable Hybrid Twin ™ is at the core of the Smart Factory and of the Industry 4.0 grand challenge and huge promises.

Scientific and Technological Perspectives

As models involved in science and engineering applications become too complex (nonlinear coupled systems of partial differential equations) their analytical solution is often compromised and, more specifically, in those of practical interest involving complex geometries, models and boundary conditions. Fortunately, computers came to our rescue. However, computers are only able
to make very efficiently elemental operations.

Consequently, it was necessary to transform complex mathematical objects (derivatives, integrals ...) into simpler objects {elementary operations {and at the same time, to reduce the number of points and time instants at which the solution of the model was searched and from which the solution could be interpolated everywhere (in space and time). Such procedure is known as numerical simulation and constituted a true revolution at the end of the second millennium, being considered as one of the three pillars of the 20th century engineering, being modeling and experiments (for model calibration and validation purposes) the other two pillars.

In the previous (third) industrial revolution \virtual twins" (emulating a physical system from the accurate solution of the mathematical model expected describing it) were major protagonists, making accurate designs possible. Numerical simulation is nowadays present in most of scientific held and engineering domains, making possible the virtual evaluation of systems responses, alleviating the number of experimental tests on the real system that the numerical model represents. however, usually virtual models (virtual twins) are static, that is, they are used in the design of complex systems and their components, but they are not expected to accommodate or assimilate data so as to be done dynamic data-driven application systems. The reason is that the characteristic time of standard simulation strategies is not compatible with the real-time constraints compulsory for control purposes. Thus, real-time control was ensured by techniques based on the use of adapted representations of the system (adapted in the sense that they relate some inputs to some outputs, encapsulated into richer models for Hybrid Twin™.

Mastering the Hybrid Twin™ and associated technologies, platform and knowledge, will be a key success factor for the digital transformation and sustainable competitiveness.

Michelin

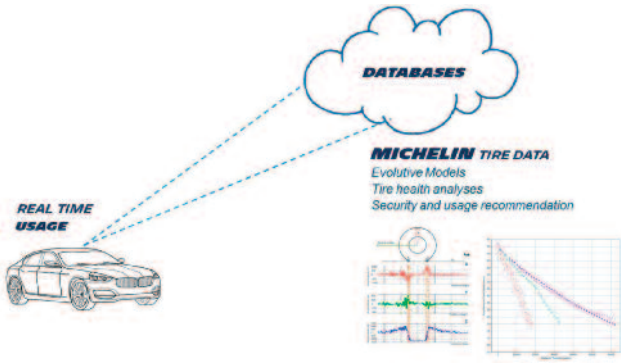
Advanced Modelling at the Service of Innovative Products and Services

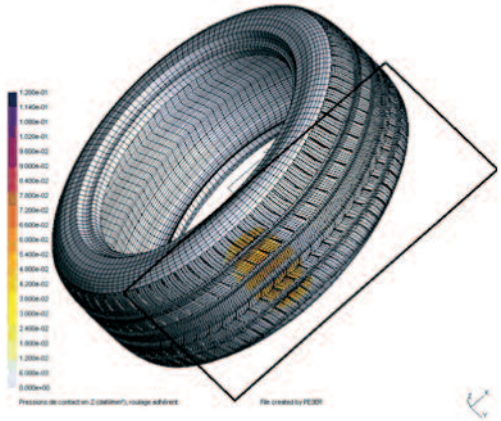
At the core of our tire design process is the quality of modelling. It not only underpins our long term worldwide technological leadership, but it also can create short term economic opportunities derived from enhanced methodologies in the conceptualization of tires.

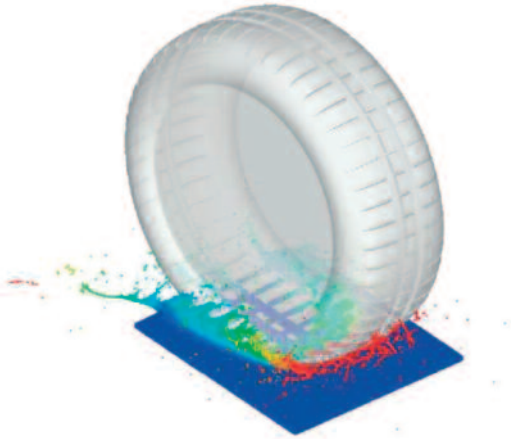
To give an example, the virtual homologation of tires on vehicles during their joint development phase has an important potential in terms of improving speed to market and efficiency. For this to be successful, it requires the availability of multi-partner simulation platforms where individual models can be shared and coupled in an efficient way, while simultaneously preserving intellectual property rights. In addition predictive capability must also be guaranteed by the adequate use of multi-fidelity models and the availability of validation data. Furthermore such collaborative platforms could benefit importantly from general multi-criteria optimization capabilities. This approach would clearly establish new standards for the automotive industry, and result in considerable efficiency gain for all the businesses involved.

A second opportunity lies in the constant improvement of models based on the collection & exploitation of real life data, well beyond the present capabilities available for data assimilation. Models of different nature and accuracy could be potentially combined to provide the right compromise between accuracy and efficiency.

The ultimate goal here is an increased predictive power in the assessment of the performance of our products. Eventually, once integrated into vehicles, such models will provide drivers with enhanced driving experience, and in turn enrich the understanding of tire usages in B2C applications. In B2B applications, these models will enable fleet operators to manage operations more efficiently, improving uptime through predictive maintenance and maximizing value creation from product designs better adapted to specific usages.







More generally models and data analysis support the development of innovative products. Multi scale and multi-physics analyses enable the identification of new technologies and provide deeper understanding at the smallest of physical scales. In modelling, extreme computational performances are needed to account for the unusual level of heterogeneities in the tire structure. This in turn requires dedicated work in domain decomposition and high performance computing and ultimately, sensitivity analysis will become increasingly necessary to optimize performances in a challenging framework where sophisticated contact states and complex material laws remain a challenge. In this way this initiative will strongly support the design of long lasting and environmentally friendly performances

Finally “Digital Twins” play a key role for Industry 4.0. With the help of simulation they allow for the development of a deeper understanding of product/process interaction. This understanding, in turn, enables better preventive maintenance and the adaptation of production tools in order to optimize quality and efficiency. These technologies can be used to support productivity improvement, all the way from early understanding and learning, up to real time decision making processes. Supporting industry with a long lasting framework for industrial twinning would allow for the experience, sorting and deployment of relevant technologies for the long run, without the need to change the working environment.

All these axes can lead to powerful scientific and technological advances that will ultimately deliver higher competitiveness to a wide range of industries. In this domain, partnerships are both welcome and necessary in order to generate significant value. This includes connecting to both public research units and start-ups.

Nors

Digital Twins in services Application in automotive industry aftermarket services

The Nors Group is a Portuguese group whose vision is to be a world leader in transport solutions, construction equipment and agriculture equipment. In its genesis are 85 years of history and activity in Portugal, which started with the representation of the Volvo brand in 1933.

Currently, the Nors Group is present in 17 countries across four continents: Portugal, Spain, Brazil, Angola, Botswana, Namibia, Mozambique, Cuba, Mexico, USA, Turquey, Austria, Czech Republic, Slovakia, Romania, Hungary and Croatia, with around 3.650 employees and a volume of business exceeding 1.5 billion Euros.

The automotive sector and its aftermarket business, repair and maintenance services, will work with a big amount of data in an ongoing updated approach. The existing information, either company history as well as new scenarios for this fast-changing environment, for example the self-driving and connected cars technology, will introduce new paradigms on the existing models (for instance the almost absence of car crashes will reduce some markets, the body parts sell out or the private automotive insurance) combined with external data will rise even more the importance of tailor-made models, adapted to each business changing-realities.

For example, when sensors collect data from a connected vehicle or device, the sensor data can be used to update a virtual and digital copy of the real car/truck/bus with the purpose of monitoring, diagnostics and prognostics the repair and maintenance services. In this field, sensory data can be combined with historical data, human expertise and fleet and machine learning to improve the prognostics.

A digital twin is a digital copy of a real car/truck/bus, including its systems that synthesizes the information available about the vehicle in a digital world. This allows any aspect of an asset to be explored through a digital interface, creating a virtual test bench to assess the safety and performance of a vehicle and its systems through its lifecycle and repair and maintenance needs.

In a near future when the aftermarket services business can access to the data that each vehicle generates and stores via telematics systems, building a digital twins platform, so each physical vehicle has a digital version, it will be a critical development to reach the aim of the industry - reduce cost, improve efficiency and deliver value to the customer.

Repsol

Industrial vision on Modelling Simulation and Optimization

Repsol is an integrated energy company committed to produce, transform and bring to market energy that is efficient, sustainable, and competitive for millions of people. Being engaged to innovation, Repsol welcomes the European Commission proposal on the construction of an e-infrastructure for Mathematical Modelling, Simulation and Optimization.

In the energy sector, achieving technological competitiveness usually involves developing precise mathematical models and simulations of industrial processes, as well as designing methods for optimizing decisions based on those simulation models.

Real industrial systems quite often involve modelling and solving complex coupled physical and chemical phenomena which require important development efforts in order to produce outputs of simulations with an adequate predictive quality in a short amount of computational time. In addition, these challenging simulation models are tightly connected to decisions concerning supply chain, production plans, logistics and maintenance that need to be optimized, thus resulting in big optimization problems with complex models at different levels and scales.

Moreover, industrial equipment modifies its performance and operation during its lifecycle while new information is gathered from the physical domain, so mathematical models need to be adapted and updated using historic offline and online data directly from industrial operations. This issue is present in the whole value chain of an energy supplier. To properly assimilate all the available data, to integrate rigorous mathematical models with techniques in the field of artificial intelligence and big data, and finally to take decisions at various levels based on those simulation models in real time still remains a challenge.

In this context, obtaining knowledge by using sophisticated simulations with adequate assimilation of data, aiming at real time decision making, will result in more competitive, energy-efficient and environmentally-friendly operation of European industrial assets.

Achieving this goal will require an important effort in the field of industrial mathematics, mainly aimed at providing collaborative environments and platforms among organizations in both industry and academia, as well as initiatives bringing together mathematical methods with techniques in the field of artificial intelligence and big data.

Royal Dutch Shell

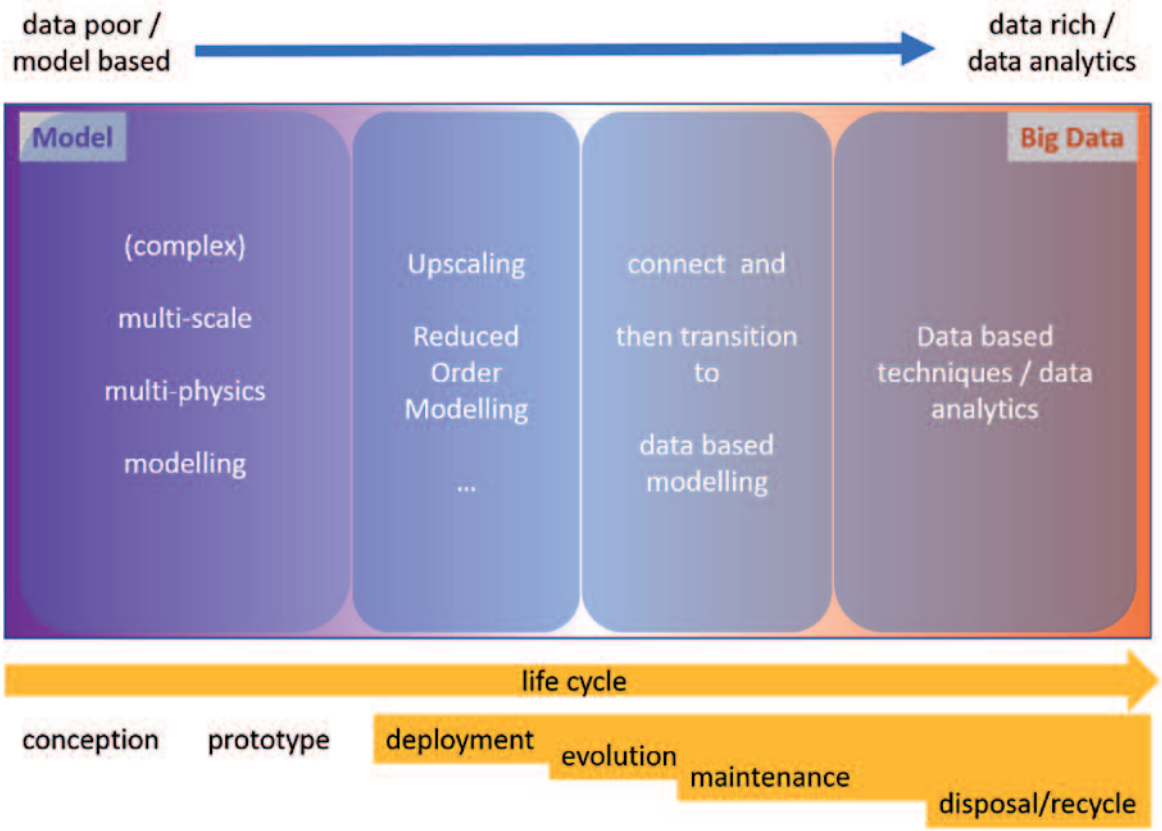
Digitalisation in all its potential is rapidly gaining ground within Shell. Data analytics has an increasing impact on our work processes, as more and more data is available. It adds value along the entire life-cycle of our products and processes. In addition, modelling, simulation and optimization (MSO) are successfully and ubiquitously used throughout the various business segments of Shell.

Particularly in the initial phases of a product, device or process, a model-based approach is used as insufficient data is available to support the many design decisions based solely on the data. Along the life cycle, data abundance will increase and slowly data analytics will gain prominence. Data analytics has made giant strides in the past decade and is finding its way into our processes.

However, we feel there is a need to strengthen the MSO community to allow us to accelerate the conception phase. This is particularly valuable in our efforts to support the energy transition as well as explore newer, greener chemistries. Many of the systems we are exploring are inherently multi-scale and require several different forces and drivers (mechanical, electrical, thermodynamic) to be assessed in an integrated fashion. These often constitute complex, multi-scale, multi-physics problems. Brute force methods alone (HPC) will not be sufficient. Only sophisticated, new mathematical approaches, together with HPC and data assimilation will be able to handle these problems.

Whereas in the past Shell largely relied on internal efforts to develop the technology it relies on, the last 10 years we are partnering more and more with third parties from industry, service companies and academia. The concept of a European Open Source Ecosystem, as described in this document, seems to us as the fastest route to innovation in the area of complex multi-scale, multi-physics problems, and hence progress in the fields described above.

The concept of Digital Twins is very attractive. We are already deploying them in several of our assets to optimize operations and maintenance. Once sufficiently powerful mathematical models are available as advocated above, we can move this powerful concept into our labs as well. This would truly give us the next generation laboratories that will drive future progress.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to
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modelling
Data based
techniques / data
analytics
life cycle
conception
prototype
deployment
evolution
maintenance
disposal/recycle

Siemens AG

Siemens AG (headquartered in Berlin and Munich) is a global powerhouse in electronics and electrical engineering. Operating in the fields of automation, electrification and mainly also digitalization, Siemens holds leading market positions in all its business areas.

The company has roughly 372,000 employees – of which 39,000 were newly hired in Fiscal Year (FY) 2017 and of which 115,000 or 30,9% are based in Germany – working to develop and manufacture products, design and install complex systems and projects, and tailor a wide range of solutions for individual requirements. For more than 170 years, Siemens stands for technological excellence, innovation, quality, reliability and internationality. In FY 2017, Siemens had revenue with business in more than 200 countries of €83.05 billion. Arising from Siemens software and digital services alone, €5.2 billion could be achieved (e.g. via MindSphere), making it a growth rate in this area of 20%.

Since 2007, Siemens is driving digital transformation with $10 billion investment in U.S. software companies[1] in the field of digital twins making it now one of the largest computational engineering and design tool providers. Combined with its MindSphere offering, no other IoT provider can drive closed-loop innovation through complete digital twins for products, production, and performance like Siemens.

Digital Twins

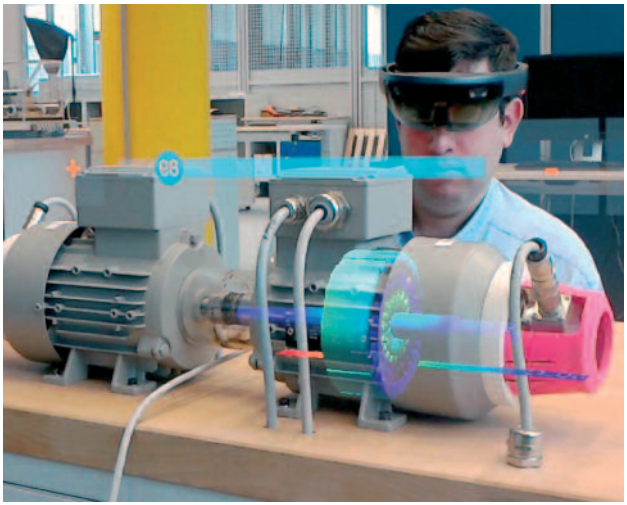
A digital twin is a cross-domain digital model that accurately represents a product, production process or performance of a product or production system in operation[2]. The digital twin evolves and continuously updates to reflect any change to the physical counterpart throughout the counterpart's lifecycle, creating a closed-loop of feedback in a virtual environment that offers companies the best possible design for their products and production processes. Digital twins are the epitome of the digitalization of plants and machinery – the virtual copy of a real machine or system. And the twin is indeed increasingly proving that it can help ensure optimized machine design, efficient commissioning, short changeover times, and smooth operation.

Siemens believes in a holistic approach that, with intelligent models and a closed-loop digital thread, leads to insight with actionable impact. By incorporating multiphysics simulation capabilities, the digital twin is a predictive analytics tool used to determine the performance characteristics of

products and production systems. The digital twin's end-to-end use can last through the design, manufacturing, operation, feedback, and updates until the physical counterpart's end-of-life. Products and production systems can be consistently optimized as the digital twin receives performance information from the field (product) or the factory (production system).

Example: Rethinking design

Simulation-tools today are expert centric and require long cycle times. Thus simulation is very often used only lately during the design process and performed not by the designer or the domain engineer but by separate simulation experts. These long iterative cycles lead to the fact that up to 80% of time-to-market is spent waiting[3].



A look through an augmented-reality headset at a motor allows a viewer to see an exact simulation of the motor in real time and its interior with a real motor superimposed over it.

Novel mathematical approaches developed in the last years allow rethinking these paradigms[4]. Providing very fast simulations tools, e.g. 3D mechanical or lumped systems simulations, allows interactively exploring design spaces manually or generating designs automatically by means of mathematical optimization and machine learning. In particular for additive manufacturing corresponding paradigm shifts are crucial, since available design spaces for products are exploding due to the disappearance of manufacturing constraints.

Apart from optimizing products and systems, in particular digital twins allow to realize novel operation and service offerings build on engineering knowledge in terms of executable models. In particular for small lot size products (e.g. gas turbines or large electrical drives), fault detection, or operation close to the feasible limit, artificial intelligence or statistic based applications are confined due to the available amount of data. Reusing existing engineering models in terms of digital twins allows addressing novel solutions and services for these kinds of scenarios. Corresponding applications are spanning the complete Siemens portfolio from large gas turbines to complete trains. At the same time Siemens is providing corresponding infrastructure via its IoT operating system MindSphere[5].

Example: Reinventing operation of large drives

Let us consider an example of large drives[6]. If they were repeatedly started, their interior temperature could shoot to as much as 800°C, thereby potentially causing serious damage. The motors must therefore

be allowed to cool before being restarted. The temperature in critical areas of the motors' interior cannot be directly measured. Normally, experts build in a safety buffer that rules out the possibility of damage. This frequently results in down times of up to 12 hours that are much longer than actually needed.

Technology leaps in the mathematical sciences allow today to reuse engineering models during operation. Using complexity reduction methods, corresponding models can be speed up by orders of magnitude, allows running a simulation parallel to the operation and by means of the simulation to estimate temperatures in the rotor. The direction of temperature changes can now be monitored in real time and predicted. Such an optimized process that can prevent motor overheating and reduce the downtimes required during the cool-off phase can save up to €210,000 per hour.

The age of simulations and digital twins is just rising. According to the German Association for Information Technology, Telecommunications and New Media (BITKOM), every digital twin in the manufacturing industry will have an economic potential of more than € 78 bn by 2025. However, this potential can only be achieved if future systems are not only networked, but are also capable of seeing, understanding, and self-optimizing by building on digital twins in order to adapt to future changes[7].

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Akselos

Top Predictive Power for Digital Twins

Akselos is a digital technology company headquartered in Switzerland, with operations in Europe, the USA and South East Asia. Akselos is powering digital transformation in heavy industry with top predictive digital twins.

The company has created the world's fastest and most advanced engineering simulation technology, to protect the world's critical infrastructure today and tomorrow. The technology has the power to revolutionise how we build and manage our critical infrastructure, and pushes the boundaries of what modern engineering and data analytics can achieve. Developed by some of the world's best minds, the MIT-licensed technology builds something far beyond the capability of a conventional digital twin – a Digital Guardian that allows operators to not only monitor an asset's condition in real time, but helps them to see the future.

Challenges of Digital Twins

The concept of a digital twin isn't a new one; there are numerous versions on the market. But they all have one limitation in common – scale. Digital twins that use Big Data only are not capable of providing accurate predictive maintenance, especially for critical large assets. For digital twins to achieve high predictive power they have to be trained on a large set of failure data, which is currently not available for assets like FPSOs, oil rigs, and wind turbines. We need a physics-based take on Big data to achieve accurate predictions of how assets behave in real life.

The science behind the traditional simulation tech – Finite Element Analysis – can't model assets of a large scale in the level of detail needed to enable condition-based monitoring and predictive maintenance. The science behind Akselos' technology changes this. It has the power to model assets of limitless scale. This leverages the power of the Industrial Internet of Things for heavy industry in a way that has been impossible until now.

Benefits of Digital Guardian

The Digital Guardian is game changing technology that combines engineering simulation software with sensors, machine learning and big data analytics to monitor and protect large mechanical assets. It can do this by creating a learning virtual replica of a structure or asset. The model, or Digital Twin, is calibrated based on sensor data to create a Digital Guardian which will help structural engineers understand the

condition of the asset, and make predictions about its future condition – allowing them to fix things before they break.

By using Digital Guardian technology, operators would be making use of some of the most advanced digital technology in the world to:

- Gain entire visibility of the condition of an asset
- Understand structural capacity to support Asset Life Extension
- Data that helps businesses make smarter, informed decisions
- What if? Virtual scenario planning
- Optimize maintenance schedules enabling a move towards zero unplanned downtime.

ECOMT

ECOMT (www.ecomt.net) is a company dedicated to the development of technology, software and services to control and manage the procedure, equipment and installation in the industrial, energy and logistics fields. Our ultimate objective is to help our clients to better manage and ensure the most efficient use of energy. We provide the guidance and equipment necessary to guarantee a sustainable environmental economy of the business.

During the past few years, cost reduction and technical access to technology and information have gained popularity through by the application of diverse techniques. The management of enormous quantities of data trough mathematical and statistical algorithms and heuristics. These tools have become a strategic element in our business which allows us to offer highly competitive products and services. It is for these reasons that the use of and proliferation of these tools and techniques in the industrial field is of such relevance to ECOMT. Specifically, ECOMT has been a very active participant in developing expert systems such as OTEA software, whose inference drives employ statistical models or systems in other neuronal or Bayesian networks which are especially useful in the decision-making process in areas where the level of attention of qualified personnel may be low, such as the use and maintenance of installations of businesses with multiple site optimization of energy usage per installation.

Applying Artificial Intelligence, machine learning, classifying and data filtration, mining and other techniques to solve regulation as well as control problems in the industry such as detecting anomalies and defects are part of what ECOMT does for its clients on a day to day basis. The creation of expert systems of different range, generalizing conversion bots, applying advanced mathematics to solve optimization problems, applying statistics for application ranging from the measurement of indirect methods to classifying information, clustering or automated resolution proposal of incidents and decision making are areas in which our business is strategically vested along with the need to collaborate with public agencies and organisms who hold pertinent scientific knowledge derived from formal science.

Given the nature and quantity of data provided by our clients, it would not be possible to generalize the use of these methods and technologies without counting

on the high-performance computing with which we habitually work.

Finding public and private entities like those associated to MATHS-IN with which to collaborate to generate and increase the value for our clients and to facilitate the transfer of technology and knowledge from our researchers to the industry is part of our business strategy.

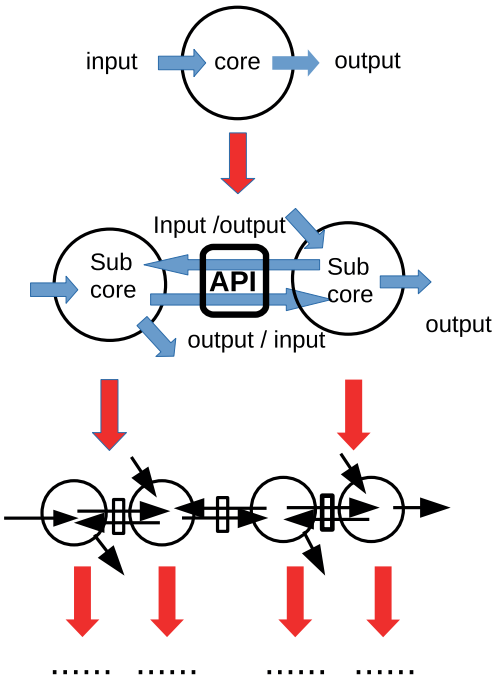
MAGWEL

The key success of modeling simulation and optimization is found in the predictability level of the underlying core modules that mimic the real world actors in a digital clone. The digital representation is composed from a series of ingredients. In a top-down perspective the core modules require input data and generate results. At the input side there are the models which in a condensed way describe physical response to external stimuli. (See top graph of Figure1).

The results that are produced serve as input for design decisions for the object under development. The figure represents this high-level perspective. Over the last decade a zoom-in of this figure shows that there exists a self-similar hierarchical substructure of the core modules. A core module is a collection of sub-core modules that process subsets of problems.

Interoperability of a collection of sub-cores, dealing with design challenges in the semiconductor industry has become a key feature of MAGWEL's business. The interfacing between (sub-) cores requires the development of dedicated application-programming interfaces (APIs), modifications of the (sub-) cores to access data structures inside the cores and upgrading the core's states. With the increasing demands of complexity it becomes critical to design the cores with having the interoperability already in mind. MAGWEL has applied above software model to electronic-designautomation (EDA) tools for development of chips in the automotive industry, chips design for data

Figure 1. Self-similar MSO software design view.



servers by combined compute kernels for the electrical and thermal characterization of the chips.

Another area of application is the design of RF chips for near-field communication by coupling an electromagnetic field solver with a circuit simulator using tight interfacing (holistic coupling) between the cores. More recently a similar approach we applied for the development of the MAGWEL tool ESDi that analysis the chip's robustness against electrostatic discharge (ESD) failure. The successes of these applications demonstrate that the APIs will play an increasing important role in for the MSO practice. The actual construction of APIs is a challenging task that requires combined expertise from mathematicians, software engineering and field-application engineering. However, once having the APIs in place their use increases the predictive power of the core modules tremendously. In figure 2, a chip the layout of an integrated circuit is shown. As an illustration, in figure 3 a typical result of a holistic coupled set of the electrical and thermal core solvers is shown for a chip section of which the layout is shown in figure 2.

Figure 2 View of a chip.

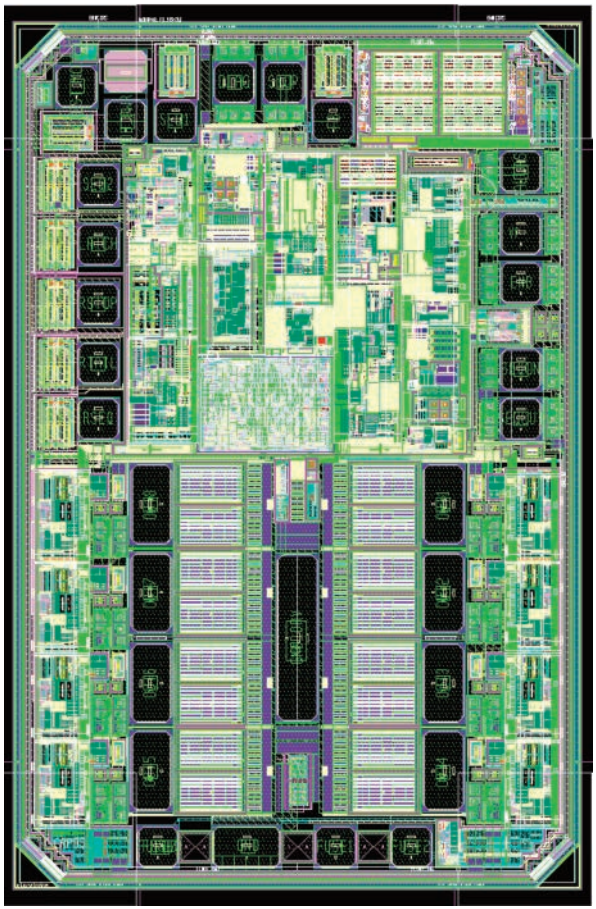
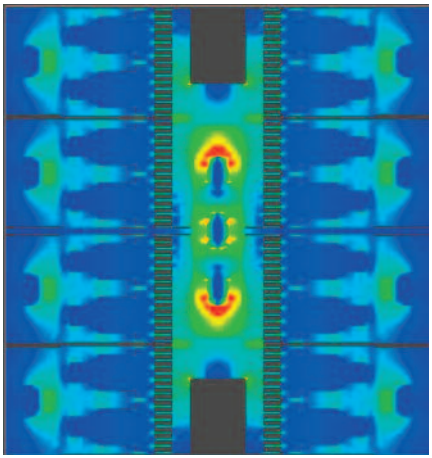


Figure 3: Thermal map of the driver shown in Figure 2 (lower part).



Smart Sample

Over the past decade, medical imaging has been truly revolutionized by the development and adoption of compressed sensing, a methodology that enabled a drastic reduction of the number of data points necessary for reconstructing the 3-dimensional shape of an organ or a tissue, thereby reducing patients' exposure to radiations and demultiplying the number of examinations in a day that can be performed with the same device.

This sensational example reminds us that the acquisition of information has a cost, which should not be overshadowed by the immense momentum acquired recently by scaled up data processing systems, also known as « Big data ». Destructive assays performed to develop novel materials, artificial evolution procedures executed to obtain enzymes of industrial interest, perturbations of a marketing scheme to assess the response of the demand, or the estimation of dose-response curves in the pharmaceutical domain are just a few more illustrations of the diverse realities behind the term cost here. Irrespective of the modelling task at hand, the optimisation of spendings in data acquisition towards a maximal gain of information is paramount to securing the full benefits of advanced modelling and simulation techniques.

From a formal standpoint, it is essentially straightforward to follow the Bayesian paradigm and define a predictive information gain over the full range of the control parameters governing the physical counterpart of a digital twin, integrating the knowledge composing it and the data already acquired. As more observations come in, its repeated optimization designates to the experimenter the values of the control parameters to be assessed next, resulting in the training effort to be concentrated on information-rich areas of the parameter space.

In practice, the construction of a Bayesian training scheme for a digital twin is a demanding expert task specific to the system under scrutiny. Yet, it results in a probabilistic abstraction of the training process where otherwise unrelated physical systems may converge, so that a limited number of algorithms may suffice to guide the training of a broad range of digital twins.

The performance of such approaches depends critically on sharing statistical strength locally in the parameter space, resulting in massive averaging

operations that cannot be executed without carefully optimized algorithms, efficient programming and high-performance computational infrastructures.

The advancement towards a cost-effective training of digital twins will find its fastest pace within a network of diverse players, who will be able to take advantage of the versatility of the mathematical methods involved and to contribute jointly to the development of a solid toolkit.

VORtech

VORtechs mission is to assist our customers in developing the best possible modeling and simulation facilities. Our customers come from a wide range of sectors, including water management, oil and gas, the process industry, traffic management and environmental management. We see it as part of our mission to stimulate the development of new modeling- and simulation technology that will benefit our customers. As an SME, we do not have the resources to do or pay for research ourselves, but we can support cooperation between academia and industry.

In the last years, we have noticed a convergence of approaches in the field of modeling and simulation. First of all, where modeling and measuring used to be separate activities, the combined use of models and observations is considered to be essential in many sectors. Secondly, we see that modern users put ever higher demands on the interaction with models: they come to expect real time interaction and advanced graphics, often through web-interfaces. But fancy graphics is obviously not enough: users also expect the physics behind the simulation to be reliable. Finally, now that the initial hype in machine learning is over, many have come to realize that machine learning and first principle modeling are synergetic: data science will not replace traditional modeling but will augment it in very useful ways.

All these aspects come together in the concept of digital twins. This makes the digital twin an excellent focus point for future developments.

The elements of digital twins are mostly there already: we have advanced first principle models for many processes; we have wonderful graphics; we have a wide range of data-assimilation methods and we are quickly learning to manage and analyze large datasets. However, putting these elements together raises the issues such as those that are addressed in the EU-MATHS-IN initiative. It will create a need for faster models, it will put much stronger demands on the data assimilation methods, it will heighten the requirements in terms of robustness and usability of modeling and simulation systems. Developing generic technology to address such issues will provide immediate benefits across many different industries.

An example of the potential benefits that we see is in the utility sector. In distribution systems for water, gas

and electricity, there is a strong interest in having a real-time view of the entire distribution network with online facilities to analyze events and with the possibility to perform what-if simulations in the mitigation of problems. In water distribution networks, the ability to quickly detect and localize pipe bursts is seen as important to avoid customer complaints and to limit the damage from such an event. Power distribution networks will come to exhibit a much stronger dynamic as renewable but fluctuating energy becomes a larger part of our energy supply. Being able to handle and manage this dynamic is seen as a major challenge for power distribution companies. Given the complexity of distribution networks, things like these just cannot be done without the technology that is proposed by the EU-MATHS-IN initiative.

Regarding the initiative as such, we feel that the initiative should not only focus on research but make a real effort to make the results operational in industrial settings. This is essential for making sure that the right knowledge is developed and that the technology that is developed is actually applicable in practice.

The value of mathematical sciences

The value of mathematical sciences (MSO) for the European economy

Mathematics, more specifically MSO (mathematical modeling, simulation and optimisation), is an essential asset for addressing tomorrow's challenges: knowledge, innovation and competitiveness. Although the excellence of European research in mathematics is world renowned, its interaction with the industrial world still lacks clarity. Yet, industry and the business world abound in mathematics more or less explicitly (models, statistics, algorithms, numerical simulation, optimization, etc.):

"The domains that mobilize advanced mathematics are today considerably more numerous than twenty years ago. They are also more strategic. (...) Today we see new professions appearing and new economical models, in which statistics and data analysis play a major role. The collection, structuring, transformation and exploitation of collected data traverse high-level mathematical processes. (...) In the new paradigm, marked by the continuity between fundamental and applied mathematics and by the presence of fundamental mathematics at the heart of the economical world, the question of communication is central."

Jean-Pierre Bourguignon, President of the European Research Council, « Un nouvel âge d'or pour les Mathématiques en entreprise ? » (2014)

This tendency has been confirmed by an ensemble of reflections led over the past few years by mathematics communities all over the world. The Forward Look project of the Europan Science Foundation entitled "Mathematics and Industry" was carried out in 2009-2010 (see page 40). Besides giving a number of important recommendations, this report concludes:

"The basic message of this report is that if Europe is to achieve its goal of becoming the leading knowledgebased economy in the world, mathematics has a vital role to play. In many industrial sectors the value of mathematics is already proven, in others its potential contribution to competitiveness is becoming apparent. The benefits resulting from a dynamic mathematics community interacting actively with industry and commerce are considerable and certainly far outweigh the rather modest costs required to support such a community.

Nevertheless, such benefits will not be realised unless action is taken to develop mathematics and a coordinated community of industrial and applied mathematicians needed for the future success and global competitiveness of the European economy and prosperity."

In the following sections, we give an impression of the power of the mathematical sciences/MSO, with often surprising facts that are unknown to the larger public.

Studies into the economic value of the mathematical sciences

In 2012, 2014 and 2016, studies were carried out into the economic value of the mathematical sciences in the UK, The Netherlands and France, respectively. Summaries othe these reports are provided here.

UK report (Deloitte UK):

"The report reflects the excellence of the UK mathematics research base, and the impressive and far-reaching impact of the mathematical sciences. The report looked at mathematical science occupations, defined as occupations which either entail mathematical science research or which use tools and techniques derived from mathematical science research. The report estimates the contribution of mathematical science to the UK economy in 2010 to be quite remarkable: 2.8 million in employment terms (around 10 per cent of all jobs in the UK) and £208 billion in terms of Gross Value Added (around 16 per cent of total UK GVA). Productivity (as measured by direct GVA per worker) is significantly higher in mathematical science occupations compared to the UK average (approximately £74,000 versus £36,000), and as such the direct GVA impact of mathematical sciences research is proportionately higher than the share of direct employment.

In addition to these direct impacts, mathematical research activities by organisations and employees have impact across the supply chain (indirect effects) and also affect household spending (induced effects). There are also wider impacts and benefits generated by organisations using the research. Sectors contributing to this impact include Computer Services, Finance, Aerospace, Telecommunications, Research and Development, Pharmaceuticals, Public Administration and Defence. The impact of data analytics, and its contribution to innovation and new investment, is particularly noted."

Dutch report (Deloitte Netherlands):

"The full time equivalent of about 900,000 highly educated employees use mathematical sciences in the Netherlands. They include scientists who use mathematics all the time, as well as bankers, who spend some of their time computing the value of assets, and physicians, who use maths to interpret medical tests.

These 900,000 jobs not only generate direct income for the employees involved. People who work in industries that supply organizations where mathematical sciences practitioners work and in businesses where these practitioners spend their own income benefit as well. Based on standard input-output analyses of the Dutch economy, these so-called indirect and induced effects are estimated to create another 1.4 million jobs, resulting in mathematical sciences contributing for up to 26% to

total employment. Because these are high income jobs, the economic contribution of mathematical sciences is even higher, representing around 30% of Dutch national income."

French report (CMI):

"This study emphasizes the very strong and growing impact of mathematics for the competitiveness and growth of the French economy:

- The jobs affected by mathematics have a strong added value (15% of GNP and 9% of employment) and are increasing in number (+0.9% per year from 2009 to 2012 vs. +0.5% for overall employment)
- It turns out that 44% of key technologies, identified as such by government reports, are strongly affected by progress in mathematics.
- The mobilization of 5 major competency fields of mathematics (signal and image analysis, data mining, modelling-simulation-optimization (MSO), high performance computing (HPC), computer system security and cryptography) will increase in numerous activity sectors, in particular energy, health, and telecommunications.

The employability of mathematics students is excellent: businesses (both large ones and SME's) are progressively becoming aware of this impact but are still somewhat ill-organized for managing in-house mathematical expertise."

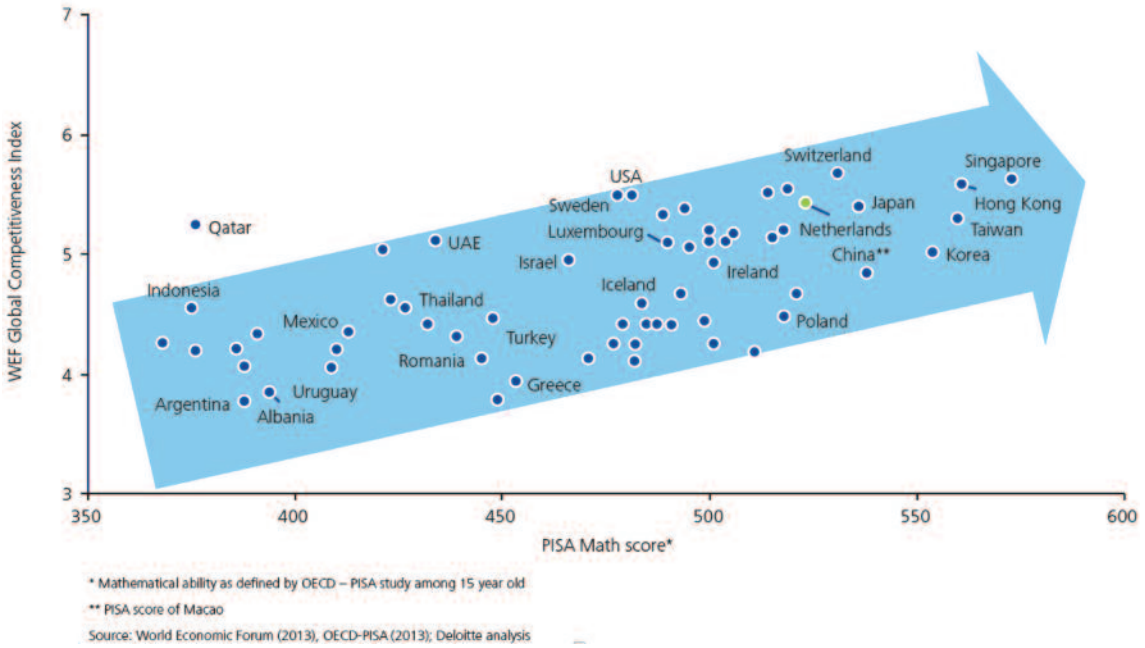
The correlation of mathematical skills and country competitiveness

A strong mathematical sciences foundation is critical to the success of any advanced economy. Better mathematical skills correlate with a more competitive economy and a higher standard of living. Moreover, with the revolutions in computational science, big data, statistics and business analytics the importance of mathematical sciences to society is likely to increase substantially in the coming decades. These revolutions are driven by ever more powerful computers, the data explosion, and improved algorithms (see next section).

The World Economic Forum describes three types of countries: factor-driven economies which compete on low-skilled labour and natural resources (like Angola), efficiency-driven economies which rely on good education and well-functioning markets (think of Bulgaria) and innovative economies where businesses must compete with new products, technologies, processes and business models. These economies, many of them in Europe, require an exceptional level of sophistication to maintain their high standard of living.

The Figure on the next page shows the relation between the mathematical abilities of pupils per country, as measured by the OECD in its PISA study, and the Global Competitiveness Index for that country as defined by the World Economic Forum. The most competitive nations generally have populations with strong mathematical skills.

Figure 1: Relation between mathematical ability and country competitiveness



The power of MSO in comparison with Moore's Law

Algorithms outperforming machines

Everyone knows Moore's Law, stating that the number of transistors in a dense integrated circuit doubles approximately every two years. As more transistors fit into smaller spaces, processing power increased and energy efficiency improved, all at a lower cost for the end user. This development not only enhanced existing industries and increased productivity, but it has spawned whole new industries empowered by cheap and powerful computing.

Less known or even virtually unknown, at least to non-experts, is that the development of (mathematical) algorithms has shown a development similar to that of Moore's Law, and in all cases it turns out that algorithm improvement outperforms machine improvement, sometimes by significant factors. The following figures prove this statement for various areas in mathematics: solution of linear systems (a core activity in all simulation software), methods for optimisation (both the traditional linear programming and the more recent mixed integer programming methods), and methods using particle simulations (to stay closer to the physical formulation).

Figure 2. Algorithm improvement for solving linear systems

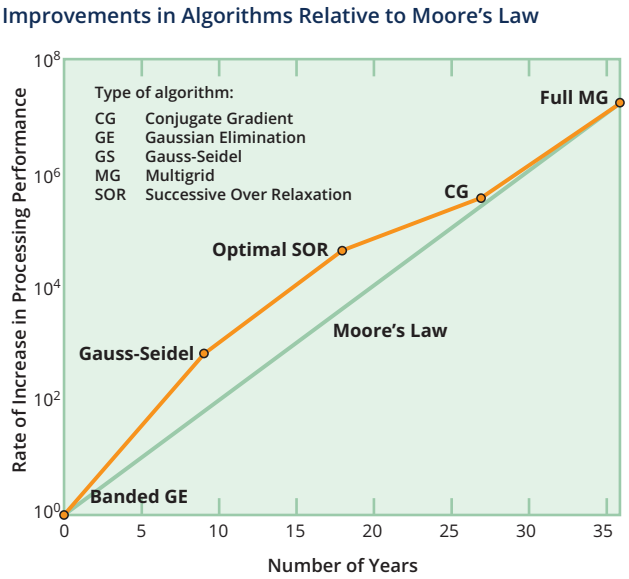


Figure 3. Algorithm improvement in the area of Linear Programming (optimisation)

Progress in LP: 1988-2004

(operations Research, Jan 2002, pp. 3-5, updated in 2004)

Algorithm (machine independent):	3,300x

Primal versus best of Primal/Dual/Barrier

Machines (workstations -> PC's):	1,600x
NET: Algorithm × Machines:	5,300,000x

(2 months/5300000~=1 second)

Figure 4. Algorithm improvement for particle simulations

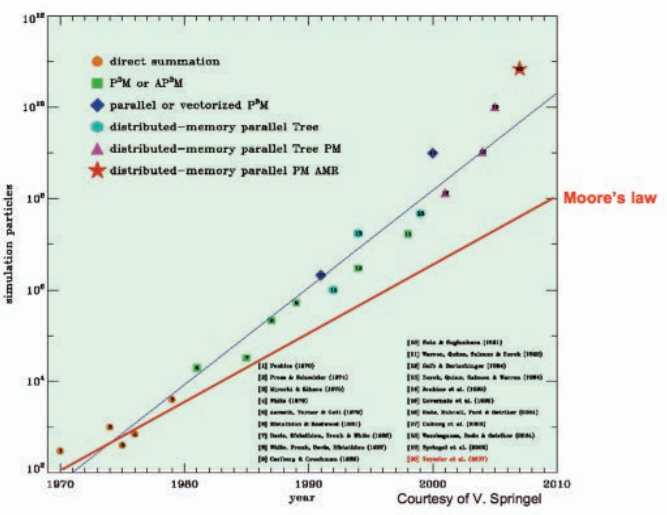


Figure 5. Algorithm improvement in the area of Mixed Integer Programming (optimisation)

Overall improvement: 1990-2014

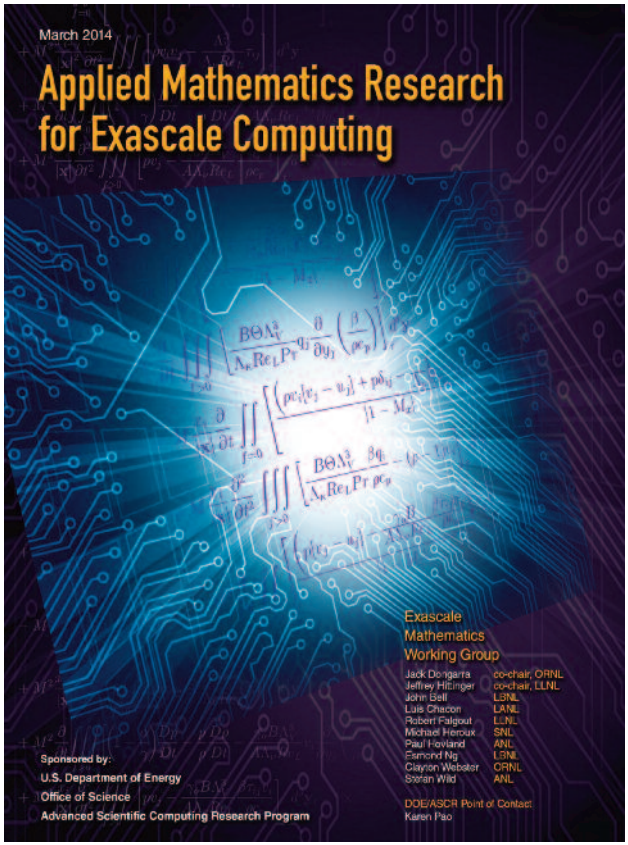
Algorithm:	870,000x
Machines:	6,500x
NET: Algorithm × Machines:	5,600,000,000x

(180 years/56B~=1 second)

Applied mathematics research for exascale computing

Recommendation: invest in applied mathematics research

A few years ago, the US Department of Energy (DOE) asked a working group of renowned researchers from academia and industry to report on the needs regarding applied mathematics research for exascale computing. In March 2014, this report was published.



Quoting from the executive summary:

"High fidelity modeling and simulation of physical systems is a critical enabling technology area for the U.S. Department of Energy (DOE), required for addressing some of the most challenging problems in energy, the environment and national security. The importance of continued advances in this area cannot be overstated. As a result, DOE is aggressively pursuing an exascale computing program that includes applied mathematics research focused on the unique challenges and opportunities present at this scale."

The report contains a detailed study of the needs with respect to applied mathematics, and also contains numerous examples of fields where progress needs to be made. The necessary actions are summarized in five key recommendations, associated with an Advanced Scientific Computing Research Program to be set up:

1. The Advanced Scientific Computing Research Program should proceed expeditiously and with high priority with an exascale mathematics initiative so that DOE continues to lead in using extreme-scale computing to meet important national needs.
2. A significant new investment in research and development of new models, discretizations, and algorithms implemented in new science application codes is required in order to fully leverage the significant advances in computational capability that will be available at the exascale. Many existing algorithms and implementations that have relied on steady clock speed improvements cannot exploit the performance trends of future systems.
3. Not all problems require exascale computation,

and yet these problems will continue to require applied mathematics research. Thus, a balance is needed in the DOE Applied Mathematics Research portfolio that provides sufficient resources to realize the potential of exascale simulation while preserving a healthy base research program.

4. An intensive co-design effort is essential for success, where computer scientists, applied mathematicians, and application scientists work closely together to produce a computational science discovery environment able to exploit the computational resources that will be available at the exascale.
5. The Advanced Scientific Computing Research Program must make investments to increase the pool of computational scientists and mathematicians trained in both applied mathematics and high-performance computing.

Future and emerging mathematical technologies for Europe

In December 2017, a workshop was held at the Lorentz Center in Leiden, a national center for international workshops in all scientific disciplines. The guiding philosophy is that innovative research thrives on interaction between creative researchers. Lorentz Center workshops focus on new collaborations and on interactions in highly diverse groups of researchers – international and with different scientific viewpoints as well as seniority, gender, and culture.

For the workshop held from December 11-15, 2017, the aim and objectives were formulated as follows: "The current and future technological and economic

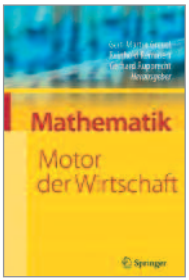
development of the industrial Europe is characterized by a steadily growing complexity of modern products and processes, as well as ever shorter innovation cycles. Principal issues which must be addressed are the scarcity of resources, recycling, climate change, assessment of the risks to the environment and society, as well as increased automation and a holistic view of the life cycle of a product. The long-term and sustainable solution to these problems is only possible through an intensive support of the

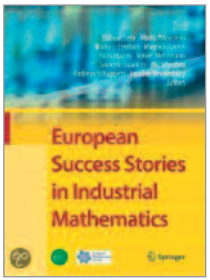
development procedures of new products and production processes via a holistic mathematical Modeling, Simulation and Optimization (MSO) approach, where in each case parallel to each product or process a virtual product or process (the digital twin) is generated. On this basis a simulation of functionality and design, as well as of long-term effects and risks, one is able to design optimized products and sustainable process controls. In addition to the classic areas of mechanical and vehicle engineering in which a modularized and component-based development on the basis of mathematical models is already established, this approach is also essential in the development of Industry 4.0 as a key technology and a decisive competitive advantage. This procedure also plays a central role in all other fields of science, economy and society and the aim must be to strengthen the leading position of Europe in this system- oriented approach. Success of the above mentioned approach relies heavily on the further advancement of Mathematical Technologies. Mathematical Technologies play already an essential role in almost all areas of industrial and societal relevance. As numerous success stories show, Mathematical Technologies, in particular Modelling, Simulation and Optimization tools, provide real and production processes, analysing data, enabling virtual prototyping of new products and reducing costs. Mathematical Technologies find application in a wide range of scientific and technological fields, and it is expected that in the coming years, with the increased use of technology and availability of ever more powerful high performance computers, the impact of MSO tools will become even more significant.
There is a clear need to bring together the existing European National Networks of Research Centres for Industrial and Applied Mathematical Technologies, to ensure a common effort towards one main and shared objective: providing the industrial and scientific communities with a single coordinated and comprehensive infrastructure for Mathematical Modelling, Simulation and Optimization, and resulting research programs.
The workshop is organized under the auspices of EU-MATHS-IN – a European Network of Mathematics for Industry and Innovation. This network is a collaboration of national organizations from 17 European countries. The promoting partners of EU-MATHS-IN are the European Mathematical Society and the European Consortium for Mathematics in Industry. The primary objective of the meeting is to discuss success stories and share experience and best practices of organizing collaborative research projects with industry, as well as to discuss and brainstorm about joint future activities. One of the major obstacles to be addressed is the low visibility of mathematical technologies in European programs. We will also discuss measures facilitating awareness about existing expertise in Europe and knowledge transfer."

Mathematics: engine of the economy
(original German title: Mathematik: Motor der Wirtschaft)

During the Year of Mathematics in Germany (2008), a workshop was held in the Oberwolfach Mathematics Research Institute where 20 captains of industry presented their view on the importance of mathematics for their companies. The resulting book "Mathematik - Motor der Wirtschaft" came about in close cooperation

between the Oberwolfach Foundation and the Mathematisches Forschungsinstitut Oberwolfach and features articles by renowned business figures. It was presented by the German Federal Minister of Education and Research, Annette Schavan, at a gala event. In their articles, various heads of major German companies - Allianz, Daimler, Lufthansa, Linde, and TUI, to name but a few - sum it up in a nutshell: Mathematics is everywhere, and our economy would not work without it. SAP's CEO, Henning Kagermann, puts it like this: "Corporate management without mathematics is like space travel without physics. Numbers aren't the be all and end all in business life. But without mathematics, we would be nothing." The list of authors in the Springer book reads like a Who's Who of German DAX companies. The book (in German, except for one contribution in English) is published by Springer Verlag Heidelberg.





ESF Forward Look project "Mathematics and Industry"

In 2009-2010, a Forward Look project of the European Science Foundation was undertaken to investigate the role of mathematics for industry. The project issued 2 reports, viz. a report with recommendations and findings, and a book of success stories:

The first recommendation reads:

Policy makers and funding organisations should join their efforts to fund mathematics activities through a European Institute of Mathematics for innovation.

The second recommendation reads

In order to overcome geographical and scientific fragmentation, academic institutions and industry must share and disseminate best practises across Europe and disciplines via networks and digital means.

Roadmap implementation:

- Researchers in academia and industry must adapt their mentalities to the different mathematical and scientific domains they interact with. and disseminate best practises.
- The mathematical community in collaboration with industry should create a journal devoted to industrial mathematics and contribute to a European Digital Mathematics Library.
- Academic institutions and industry must facilitate the employment mobility between academia and companies.
- The mathematics community and industry should work together on real opportunities in applicationthemed competitions.

and has led to the foundation of the organisation EU-MATHS-IN (http://www.eu-maths-in.eu) whose mission is "to leverage the impact of mathematics on innovations in key technologies by enhanced communication and information exchange between and among the involved stakeholders on a European level."

Roadmap implementation:

› EU and National funding agencies should coordinate cMsters of excellence in industrial mathematics and create a European Institute of Mathematics for Innovation (EIMI) for mathematicians and users of mathematics.

› EU and European governments should set up a Strategy Taskforoe for Innovation and Mathematics (STIM) in order to develop a European strategy for mathematics.

› Policy makers should put in place a Small Business Act in Mathematics (88AM) to encourage spimoff companies explicin using mathematics.

› EU must identify industrial and applied mathematics as an independent crosscutting priority for the Framework Programme 8.

This remains a very important recommendation, also in view of the previous sections where the importance of mathematics for European competetiveness and prosperity is demonstrated.

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