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8

eEngineering 2009—2012

Digitising the product process

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Foreword

At the beginning of the 2010s **traditional heavy industry accounted for 75% of the total value of Finnish exports, up notably from 57% in 2000**. In addition to industrial production, the success of Finnish industry is based strongly on the design and engineering of devices, working machines, manufacturing plants, power plants, process machinery and ships for global markets.

Digitalization has become ever more vital to the success of industrial production and engineering. In practice, it has enabled the creation and exploitation of a digital continuum of engineering and operative computer-based systems. For instance, requirements analysis and conceptual design are carried out with the aid of specific computer-based tools. Product and system design are carried out by a multitude of different software tools, often referred to collectively as CAD (computer-aided design) tools, with each field of technology and engineering using its own specific tool sets. Engineering software has also steadily evolved into extensive product life cycle management (PLM) systems with CAD and product data management (PDM) subsystems at their core. Engineering is followed by manufacturing or construction and delivery, managed again by specific engineering or manufacturing control software. Thereafter, the product or system enters its intended industrial use and, depending on the case, effective operation is governed, for example, by sensor or actuator systems, machine or process control systems, wider automation, condition monitoring, or quality management systems. At a higher level, production planning, enterprise resource management (ERP) systems, and even cross-machine management systems and networked business management systems, may be used.

This continuum of engineering and operative computer-based systems provides the foundation for the digitalization of industry. Computers, software and ICT systems have long been used by all industries. Nevertheless, *it is more acute than ever to really talk dually about virtual plants or machines and real plants or machines.* The volume, value and importance of the digital, virtual realm is increasing dramatically compared to physical plants and machines.

Today, everything done in or for a modern plant is managed by or with the help of software and ICT systems. Therefore being competitive, efficient, flexible, innovative, experienced, professional or knowledgeable in the virtual realm are key competitive factors for modern industries.

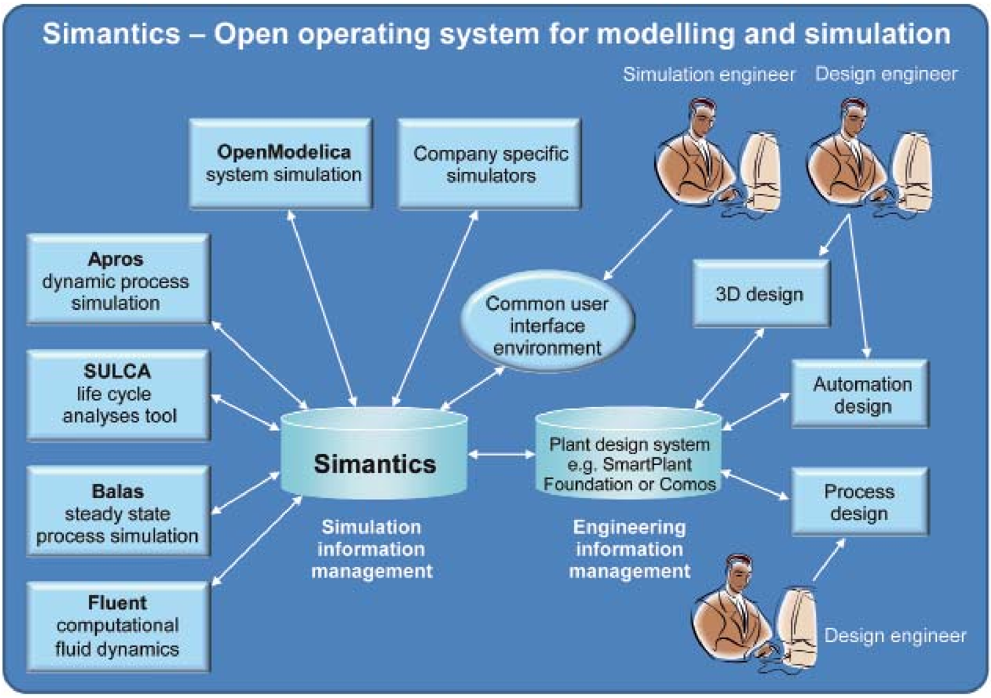
In VTT's eEngineering spearhead programme, 'Digital product process as a success factor for technology industries', success is defined as having: a) flexible and comprehensive design and engineering processes, b) faster deliveries and engineering throughput despite the increasing complexity and size of engineering contents, c) effective accumulation of engineering knowledge and reuse of proven solutions, d) efficient management of growing complexities, engineering projects, and processes, and f) ascertained quality. Meeting each of these key criteria to its fullest extent is an undertaking far beyond the scope of this research programme and requiring a vast range of digitalization tools and systems. The focus of the *eEngineering* programme was therefore limited to the following core areas:

1. Simulation-based engineering
2. Knowledge-based engineering, and
3. Interoperability of engineering systems.

The official programme period for eEngineering was from 2009–2012, although some projects are still on-going in 2013. The programme included around 100 projects in total, the majority of which were funded by VTT or jointly, for example by the EU or the Finnish Funding Agency for Technology and Innovation (Tekes), or partly or wholly by private companies. The programme had a total budget of around EUR 40 million, representing about 350 person years. This issue of Research Highlights focuses mainly on strategic areas of VTT funding within the programme.

By the beginning of 2009, VTT already had significant assets in digital engineering based on its long tradition in leading-edge modelling and simulation research. The successful APROS (Advanced Process Simulation Software) environment, for example, is the culmination of more than 20 years of dedicated research and development in dynamic process simulation by VTT and its partners. Based on R&D revenues alone, APROS has been VTT's single most valuable ICT software product. VTT's BALAS steady-state simulator developed primarily for the pulp and paper industry has also achieved similar success. For detailed process simulation VTT has used and developed a number of CFD (computational fluid dynamics) packages, and has also used a wide range of FEM (finite element method) software for mechanical analyses. In system-level simulation the Modelica family has been growing fastest, and VTT is a long-standing member of the Modelica Association. VTT has also been active in conducting life cycle analyses (LCA, carbon footprint calculations, etc.) and developing LCA software. For the machine industry, VTT has developed extensively instrumented virtual studios for conducting user experience simulations covering animations, acoustics, thermal comfort, safety, and ergonomics. Given this background, the programme implementation was targeted towards process and mechanical engineering and, furthermore, to their most challenging engineering tools, such as modelling & simulation and engineering tools co-use.

Product or system platforms are a modern means of building needed modularity and efficiency while at the same time enabling high flexibility and tailorability with respect to needs. Platforms also provide a means of accumulating knowledge, managing application complexity, and ensuring quality. As the eEngineering programme demonstrates, the benefits of platforms can also be realized in research, by enabling separate research outcomes, such as methods, algorithms, analysers, and simulators, to be effectively combined to produce synergistic applications. Information exchange across these applications can be made seamless and live, where changes in one domain can be effectively proliferated across tool databases, and where design items can be made readily available transparently or via transforms wherever needed. Single and isolated research tools may be interesting but greater value can be obtained from individual research tools by integrating them into strategic application platforms. In technical domains, the wider contexts of systems such as the CAD or open source tools mentioned above are also essential and multiply the value of research-based tools. Platforms are also middleware systems, meaning that many features that are necessary for most, if not all, tools need to be implemented only once as components of the middleware and be reused elsewhere.



Examples include graphical configuration editors, interfaces to third-party systems, support for multi-user editing, and security and privacy features. The use of simulators can be based on CAD system input or exchange of data, which is important for increasing user confidence and lowering the threshold for wider use of simulators.

The most significant achievement of the programme is Simantics, an extensive operating system providing an open, high-level application platform on which different computational tools can be easily integrated to form a common environment for modelling and simulation. The development of Simantics began under a previous VTT programme, Complex Systems Design, which provided the basic template for the current platform.

A core part of the eEngineering programme involved further developing the template version and directly building the elements of the Simantics platform. Alongside this, several existing simulator or tool components also needed considerable development in order to become fully integrated or compatible with the growing Simantics environment. Other separate simulator and tool development projects affiliated with the spearhead programme also contributed to the evolution and design of Simantics.

Despite a strong emphasis on the development of Simantics and its respective simulator components, the commercial Virtools™ environment remained the integration platform of choice for the majority of new engineering areas for virtual machine cabins, such as auralization (sound and noise experiences) and thermal comfort. The challenges related to the platform components and to our understanding of the interactions involved led us not to test Simantics compatibility during the early stages of the programme. The Virtools environment also served well as a means of interfacing with the virtual studio infrastructure.

In 2013, the advantages and potential of the programme have become evident, as summarized in the following:

- Process and automation designer's working environment extended by a powerful and versatile simulation environment, enabled by the Simantics platform.
- Extended workbench supports a wide range of simulation-based design stages and purposes, e.g.: a) Early process dimensioning aided by simple steady-state simulation, b) Detailed design iterations by dynamic APROS or even finer FEM or CFD, c) Early automation concept testing and later actual automation system testing against appropriate level simulators, d) Process simulator assisted operator training and system troubleshooting.
- Seamless and transparent bi-directional exchange of CAD and simulator data, allowing an iterative working approach across tools as engineering solutions evolve. Key CAD software features, such as version control, externally accessible to simulators (no need to implement separately in simulators.)
- Opens a range of possibilities for automatic generation of automation systems and generation of process details.
- Automation systems can be proven perfectly correct by proper methods, such as formal model checking, and based on commercially available design tools.
- Combination of design, simulation and life cycle assessment (LCA) opens new development possibilities. In addition to performing traditional analyses and benefitting from existing model libraries and LCA databases, gaps in LCA data can be compensated by simulated output of power plants, manufacturing sites, etc., and the weaknesses of light LCA systems compensated by CAD connectivity, advanced user interfaces, and other strengths of a combined environment.

eEngineering is built on and has benefitted greatly from previous VTT research programmes and projects, and this successful leveraging will continue to be applied in future programmes. One current example is VTT's Multidesign programme, which is aimed at developing a full chain of simulators spanning from fine atomic and material grid structures and the many levels of product structure to the industrial service business level. The Simantics platform offers a powerful means for implementing the necessary model interactions and integrations. Another example is the Smart Grid programme, which is conducting extensive research on distributed small energy production by wind turbines, solar systems, household energy sources, etc., and on advanced and more accurate energy use by consumers, vehicles, offices and industry. A wide range of simulator types are needed to study the challenges and scenarios presented by the smart grid concept. Simantics is an ideal platform for drawing all of these elements together.

During the eEngineering programme we had the opportunity to cooperate with many research and development organizations, enterprises and professionals in Finland and abroad. This cooperation has been mutually inspiring and productive. I wish to thank the funding organizations, most notably Tekes and the EU, and also our partner organizations, most notably the Finnish Metals and Engineering Competence Cluster (FIMECC). Last but not least, my sincere thanks to the project teams and outstanding individuals who have contributed so much to eEngineering.

Olli Ventä
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Simantics — an open source platform for modelling and simulation

Simantics – blurring the boundaries of modelling and simulation

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Simulation offers proven advantages as a tool for modern decision making. In industry, simulation is widely used in virtual prototyping, simulation-aided design and testing as well as in training and R&D. However, obstacles to wider utilization of modelling and simulation still remain.

Current modelling and simulation (M&S) tools exist as separate systems and are not integrated with other information management networks. They do not integrate well enough with commonly used software systems, such as CAD, PLM/PDM, ERP, or with control systems. Co-use of the simulation tools themselves is poor, and the modelling process as a whole is often considered too laborious.

The Software as a Service (SaaS) and Open Source business models, used widely in consumer markets, are also entering the modelling and simulation world. The closed source licensing model is considered problematic, especially in public decision making where the whole computational model should be as openly available as possible.

To address the boundaries between modelling and simulation, VTT developed Simantics, an integration technique and platform implementation which has been published as open source software.

Design (CAD) and simulation system integration

Design systems (CAD) and simulation systems have traditionally been separate in many areas of engineering. Notable exceptions include electronic circuit design and piece goods manufacturing processes, where simulation-aided design has long been in use. The reason for this is also evident. The more deterministic the target production process is, the easier it has been to utilize computational models.

In many engineering sectors – such as the process and construction industries – 2D and 3D CAD systems have already been used for decades, but these systems do not include integrated simulation features. Instead, numerous separate computational tools are utilized in different phases of the engineering process.

Common operating environment for combining M&S tools

There are many simulation solvers used both in academia and industry that have sophisticated computational algorithms, but lack an effective operating environment. There is a current need for common operating environments and pre- and post-processing capabilities as well as connections to other applications such as design and control systems.

Pre-processing capabilities include features such as 2D-fowsheeting support or 3D-geometry definition support, discretization support (meshing) as well as support for model validation, model structure browsing and editing, model component reuse, model documentation and searching, experiment

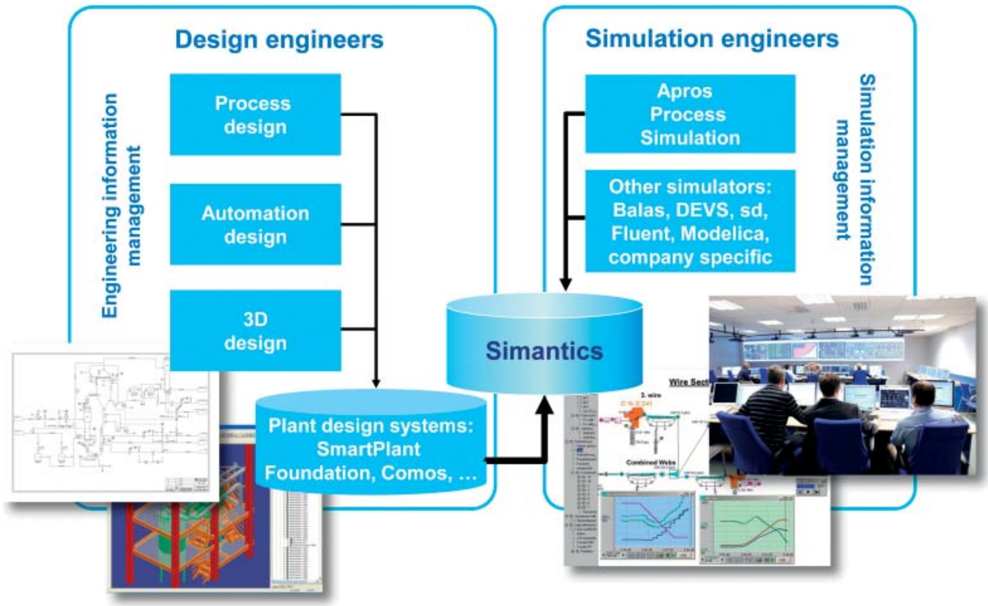

Figure 1. The Simantics platform demonstrates its strength in easing communication between different design and simulation disciplines by enabling smooth data transfer and information exploitation from design tools to simulation tools and vice versa.

configuration, model version control and team features.

Post-processing capabilities include features such as 2D-charts and 3D-visualization of results, 2D and 3D animation of results, and experiment control visualization. As these are generic requirements, it is inefficient for different parties to maintain their own individual operating environments. Instead, a single common framework could be implemented which could be jointly maintained and further developed.

Co-use between different computational tools

The need for co-use of different simulation models arises from the same need for design system integration explained above. The products and production processes modelled are complex. Heterogeneous multi-level models are needed which can be utilized across different engineering disciplines. In addition to supporting different levels of detail, users also need to combine optimization and model uncertainty assessment into their simulation experiments. In order to break the boundaries between different computational tools, configuration and simulation run-time integration is needed.

Team features in M&S

Modelling and simulation environments are used and developed by extremely heterogeneous user populations. Some users develop new, more efficient solvers and data structures, others design reusable model libraries or use these libraries to model real-world systems, while others simply use these ready configured models to support decision making. The team features of a simulation environment should not support any one user level alone, they are needed in and across all of these levels. The features should enable as efficient as possible reuse of model assets.

This requires an infrastructure for publishing and sharing model components with others within the same model, project or company, or even more publicly.

There has been a significant shift in the software business toward open source and software as a service business models. For example, in the US most software startups that are venture-funded utilize these business models. The same models are also penetrating the field of modelling and simulation. **It is likely that future modelling and simulation business will no longer be in platform solutions, but in simulation components and services running on open operating systems for modelling and simulation.** This openness also means that a neutral democratic forum for decision making on maintenance and further development has to be established.

VTT's Simantics platform has been published as an open source environment under the Eclipse Public License (EPL). To support democratic decision making, **VTT and partners have established a Simantics Division under the Association of Decentralized Information Management for Industry (THTH)**. At the time of writing, there are 25 company, university and research institute members in the association.

Main technological innovations of the Simantics platform

The cornerstone of the Simantics architecture is its open and extensible semantic data model, which is used to represent the operating environment and the simulation and modelling results. *The data model is semi-structured, which means that the data contains the rules regarding its own structure.* The approach shares similarities with W3C RDF and OWL, but is especially tailored for use with engineering and simulation models. The semi-structured approach allows the co-existence of different interlinked data models, which can also be augmented with new pieces of data when needed. This data-centric approach places an emphasis on high quality representation, which increases the usefulness of the produced results. Simantics comes with standard models developed for common simulation and modelling patterns. As an example, a generic conceptualization of hierarchical, connected and parameterized models can be used as a basis for different domain models. The data models are organized in layered conceptualizations, i.e. ontologies, which can be developed before or during modelling.

As an operating system for modelling and simulation, Simantics needs to be able to handle various data models related to different tools, computational methods and modelling methodologies. Successful co-use of these different domain services requires powerful integration and mapping tools between the different models. Simantics addresses these needs by supplying an ontology-based mapping framework for mapping and trans-

Whereas modelling and simulation is used widely in design and development, it has yet to gain a foothold in operational decision making. In this area, simulation models are connected to measurements from real systems and predictions are made to support actual decisions. Co-use of simulators and control systems sets requirements for the real-time communication, synchronization and simulation control facilities of the integration platform. If these are implemented in a neutral and efficient way, they can also provide a solid base for the communication and synchronization of different dynamic simulation tools or for the high-level parallelization of several simulation experiments. High-level parallelization here refers to process-level parallelization i.e. several simulator instances running in parallel, not to code-level parallelization of a single simulator. High-level parallelization is also useful in optimization and uncertainty quantification assessment cases.

forming models within Simantics. The general approach is to import domain models into Simantics as they are, and then transform the data further by using semantic mechanisms, which have been studied for some time [e.g. 1, 2, 3]. *The advantage of this approach is that each specific data model is kept clean and separate*. Elaborate data transformation mechanisms are also useful for generating models from other models. From the use case point of view, the mechanisms for mapping and transformation enable the co-use of different domain models as well as the co-use of models of different levels of detail. Simantics offers the user a special Simantics Constraint Language (SCL) for developing user configurable mappings and transformations. The same functional programming language can be used, for example, for semantic queries and model validation.

The use cases for modelling needs in a data-driven simulation and modelling system are highly versatile. In addition, the semantic data modelling approach is heavy performance-wise. To be able to fully establish a semantic data driven modelling approach, Simantics supports a wide range of mechanisms for extending the application range of the semantic data model. *Simantics offers seamless support for four levels of persistence of semantic data in a unified model.* Memory persistent parts of semantic data can be used to model quickly changing and transient structures, so that the structures only exist during a modelling session. Workspace persistent structures are only stored in the user's local hard disk and can be used to represent various cache or preference structures, which are generated or otherwise not publishable to all users of the distributed database. Database persistent parts of the data model are shared by different clients of a database server. Database persistent data is also fully versioned. Finally, database persistent data can also be published and synchronized between database servers, called team servers, across organizations.

The wide range of persistence levels and representations is common in simulation cases. For a semantically similar attribute we can have input values in engineering systems, permanent configuration values in simulation models, different sets of, for example, dimensioning values in simulation models, computed result values and time series, real-time dynamic simulation or measurement values, etc. The representation of values for the same attribute can be modelled in completely different ways or not at all. Some attributes have many values, some are time-dependent, some are persistently stored and some are not. To fulfil the integration goals the system needs to be able to represent and manage all these different pieces of data and, most importantly, to associate the data semantically together so that the data can be integrated. Simantics addresses these issues through semantic modelling of variables and their values and simulation experiments and by specifying a software interface to be used to obtain values for a given configuration of semantically modelled variables. The interface defines a semantic connection from a data value to the concepts of the data model while allowing free acquisition of values from any source. In many cases the obtained values are backed by the semantic data model, but can also be directly obtained from, for example, a simulator or measurement device. This framework for simulation data management makes Simantics unique among other data modelling platforms.

Simantics – an open operating system for M&S

The benefits to industry of modelling and simulation are clearly proven, yet two key obstacles to the use of simulation still persist – cost and timely availability of simulation models. These are both the result of model development not being integrated into engineering work flow and data management. Recent cases have shown that a sufficient system-level model can be created based entirely

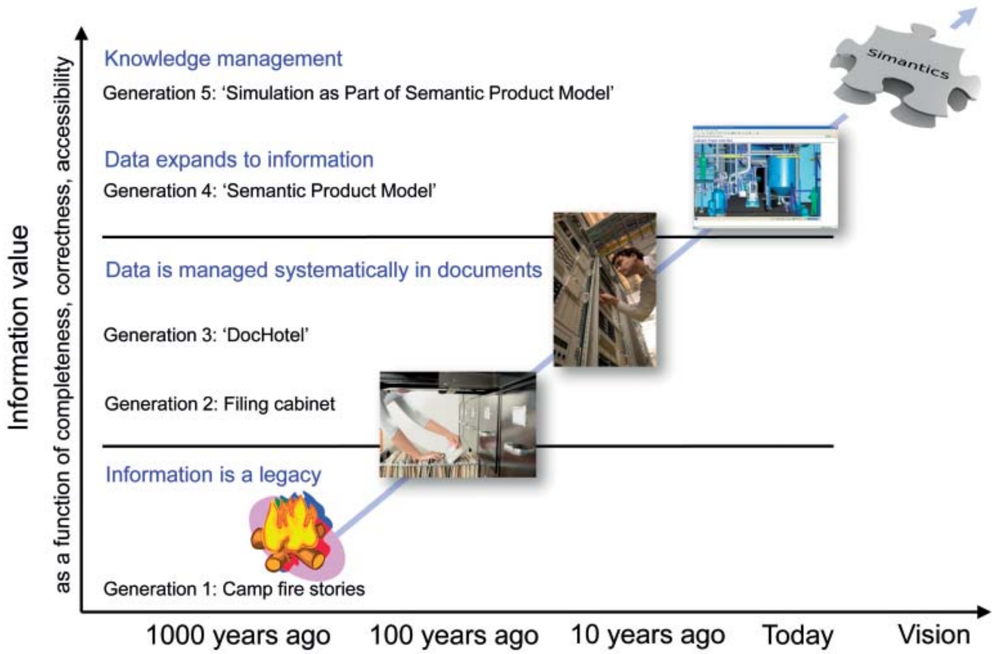

Figure 2. Evolution of information management.

on engineering data. These case studies are explained in more detail in the next chapter. It has been additionally concluded that the co-use of different modelling and simulation tools is currently insufficient. Multi-scale models combining different levels of detail would benefit from better configuration integration and run-time co-use of different simulators. Furthermore, the co-use capabilities of simulation environments and real-time systems, such as control systems, are inadequate. The challenge of integrating design system features, simulation features and real-time control and measurement features into the same software architecture has been identified. Current simulation environments also lack team features, which are essential in modern globally networked engineering projects.

VTT has introduced a solution that utilizes a semantic data modelling approach and combines this expressively powerful ontology-based design with fast accessibility to simulation, measurement and control data. This data-driven approach opens possibilities for automatic model validation, reporting, processing, annotation and linking. The layered ontology structure enables expandability and reusability. The heart of the integration solution is an ontology-based mapping mechanism that enables rule-based synchronization of different engineering and simulation models. **The idea is to integrate data from different background systems into the environment 'as is' using native data models**. The model mapping is done inside the platform using ontology-based mapping rules. To address problems of scalability and processing speed – key bottlenecks in the semantic approach – the developed solution has been optimized for industrial use. The platform has been published under an open source license and is maintained jointly with industry partners in the form of an association.

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Virtual plant combines engineering tools for the process industry

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Process plant deliveries consist nowadays of two plant components – a 'real' plant and a 'virtual' plant. The real plant is the actual nuts and bolts delivery, while the virtual plant comprises all of the digital material handed over to the customer. However, a lack of proper standards and harmonized procedures regarding the content and delivery of virtual plants poses a number of challenges for system integrators (EPC contractors) – to the extent, in fact, that virtual delivery may be more challenging than the actual plant delivery itself.

A live or executable virtual plant combines a virtual plant, i.e. piping and instrumentation (P&I) diagrams, 3D models, automation models and electrical designs, together with simulation models and other computational algorithms. The live virtual plant has a wide range of potential uses throughout the life cycle of the facility, from the early design phases through to commissioning and operation support. Some of the most time-consuming tasks involved in live virtual modelling include the collection of the initial data needed to create simulation models and keeping this data up to date throughout the life cycle of the plant. There have previously been no readymade work processes, standards or tools for efficient simulation model generation. To address this problem, VTT has developed information model integration techniques that enable seamless bi-directional data flow between engineering systems and simulation models, facilitating the development of efficient working processes. This article gives an overview of two key development efforts in this area.

VTT has been developing simulation tools for the process industry for well over 25 years. Apros – a software platform for dynamic modelling and simulation – has been one of the biggest success stories in this area [1]. Apros has been used for simulation-assisted automation testing [2], as a tool for automation modernization of the Loviisa nuclear power plant (see Figure 1), and in control concept development [3]. One of the main obstacles to wider utilization of these beneficial methods has been the amount of work needed to create and update simulation models. Now, there are new possibilities to solve the problem.

Accurate and up-to-date virtual plant models are becoming more common. EPC contractors have started to integrate EDMS (Engineering Data Management System) tools such as Comos or Intergraph SmartPlant as a part of their normal design procedure. Industry is also adopting more and more so-called intelligent CAD systems that provide online access to up-to-date databases that always contain the latest engineering data. **Meanwhile, VTT has been developing the Simantics integration platform [4], which can be used to connect databases and simulators together, providing the basis for creating live virtual plants.**

New techniques make it possible to take simulation into use earlier and use more detailed simulation models cost-effectively. Updating design data needed for simulation

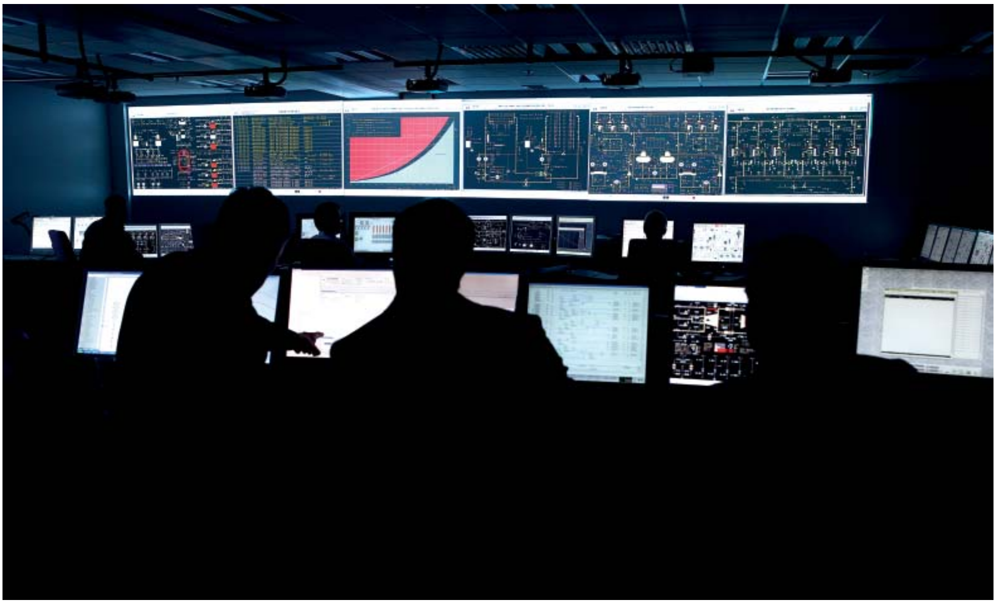

Figure 1. Simulation is widely used in the Loviisa nuclear power plant automation renewal, e.g. to develop and test the new automation system and for operator training.

can be done automatically several times during the design process and using real design data every time.

Recent work in this area has focused on automatically generating simulation models based on design data, and then transferring possible changes back to the plant engineering databases. The possibility of simulation-assisted preliminary planning has also been considered. In the latter case, the plant design database would be seeded with a design created in a simulator. A typical integration project would include a technical solution for transferring design data and, more importantly, finding correspondences between the data objects of the simulation model and the plant design database.

Case: Foster Wheeler Energia Oy – connecting Apros to Comos

Foster Wheeler Energia Oy (FWE) has been using Apros simulation software for modelling boilers and related automation. They have also integrated Comos [5] as a part of their boiler engineering process. VTT has been involved in the take-up process and has integrated dynamic process simulation as part of the engineering process by designing and implementing tools for integrating Comos and the Apros simulation tool. The developed tools transfer process and automation design data from the Comos database to the Apros simulator and generate or update the Apros model automatically.

The project began by analysing FWE's existing simulation practices. Based on this, the integration tool requirements were identified. Three potential levels of detail of the dynamic simulation model were considered. The first level – the conceptual level – contains the main process components and the pipelines between them and is usually tuned to match steady-state performance calculation. Simulation at this level was considered most beneficial in the FWE case and also in future cases in general. The second level of detail, referred to as the basic level, is more detailed, corresponding to the level of

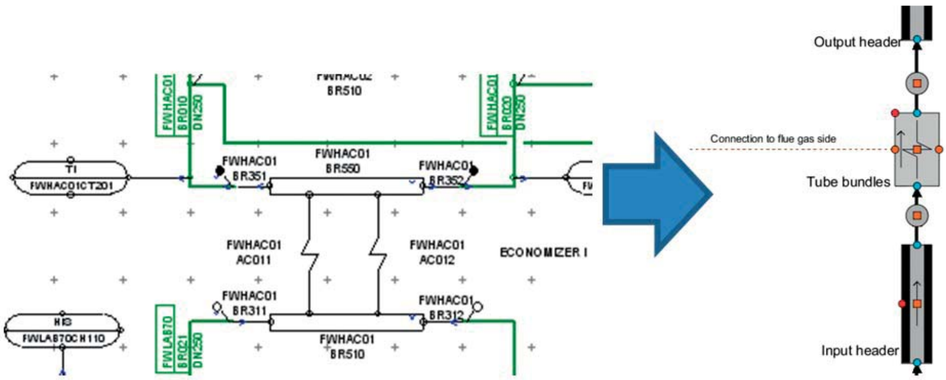

Figure 2. Economizer P&I diagram and corresponding conceptual-level simulation model. The heat surfaces, i.e. pipes, in the middle generate heat exchanger in Apros. Headers and pipes entering and leaving the system are combined together as heat pipes in Apros.

detail of a piping and instrumentation (P&I) diagram, with most pipes and similar heat surface groups described individually, and also including detailed automation diagrams. Simulation at this level is highly extensive and detailed, and has previously not been considered cost effective. The third level of simulation considered was the 3D level, in which even the smallest devices and pipes are modelled. This level of detail was not implemented.

Figure 2 shows the typical correspondence between a P&I diagram and a conceptual-level model. The P&I diagram on the left shows an economizer system and its header and pipe connections to other parts of the plant. Two pipe bundles are also described. The diagram shows only the water side (flue gas side is not shown). The corresponding Apros model is shown on the right. In the Apros model, the input header represents all input headers and pipes in the system combined and, likewise, the output header represents the output headers and pipes combined. Similarly, the pipe bundles identified in the P&I diagram are modelled as a single heat exchanger in the Apros model. The identification of system components is based on the KKS power plant classification system.

A key challenge brought to light by the FWE project was a lack of readily available data for simulation model generation. This underlines the importance of planning simulation tools and EDMS tools in parallel. For example, obtaining accurate elevation levels during the early design stages was problematic, as elevations are typically defined only later in the project during the detailed 3D design stage. It was also found that not all plant modelling practices were a suitable basis for simulation; for example, a P&I diagram might appear fully connected visually, but contain symbols that are not present in the plant model. When generating a simulation model, this results connections being missed. This shows that, in addition to appropriate and timely selection of tools, also further guidance of plant designers is needed.

'Dynamic simulation with Apros has been valuable tool for us when investigating boiler plant configurations. Verifying and optimizing plant design decisions is an important part of the work process. When we started to integrate Comos as part of

our design process, it was natural to also include connection to Apros as part of the Comos development.

Currently, we can develop the plant with our design tools, run steady-state analysis using our in-house dimensioning tool and then automatically generate Apros model for use in analyses requiring a dynamic simulation model. Connection to our own boiler model can also be generated automatically. If the design changes, the model can be updated or regenerated easily. Now we can virtually test more design alternatives in a shorter time than before.'

-Jenö Kovacs, D.Sc., Principal Research Engineer, Foster Wheeler Energia Oy

Case: Fortum – connecting Apros to SmartPlant

In another on-going project, the Apros simulation tool is being integrated with Intergraph's SmartPlant product family [6], particularly SmartPlant P&ID, SmartPlant Instrumentation, and SmartPlant Foundation. The project shares many similar features to the previous FWE case concerning data transfer between process modelling and P&I diagrams. The project's prime focus, however, is on simulation-based basic automation design and its integration with other SmartPlant engineering tools. Data transfer with SmartPlant is achieved through SmartPlant Foundation, which enables electronic management of all of the plant's engineering information, integrating data on physical assets, processes, and regulatory and safety imperatives. Apros is used as an automation design tool, while SmartPlant Foundation acts as an integration platform between automation, process and instrumentation planning. Typical automation design solutions and structural automation components are accepted and taken into use by other developers through SmartPlant Foundation.

The integrated solution enhances the use of SmartPlant products by adding control design and Apros-based testing features to it. The integration also benefits SmartPlant owner operators by extending access to engineering asset data, including dynamic plant performance versus as-designed engineering data. The solution also enhances the use of Apros by enabling use of SmartPlant engineering data to create dynamic models more efficiently.

'Fortum considers dynamic simulation as an essential tool in modern power engineering and foresees its role as clearly increasing in the future. Real breakthroughs can be achieved through seamless integration between engineering project tools and simulation software. Besides technical integration capabilities, also a willingness to move towards new working methods is needed. Further development is needed, but we see great potential here. Embracing this approach could bring a competitive edge to the Finnish engineering sector. Fortum wants to be on the front line of this development, firstly as a company with a strong engineering tradition, and secondly, as a committed simulation provider for the power industry.'

-Sami Tuuri, Product Manager, Fortum

Discussion

Dynamic simulation serves as a valuable tool in plant design and modernization, enabling, for example, automation and process design to be verified ahead of plant construction, and plant personnel to be effectively trained to operate the plant under normal and abnormal conditions.

This development provides a good basis for wider take-up of simulation in industry.

There is still work to do. The FWE/Comos integration project has progressed to the maintenance phase. The system has been successfully tested with completed engineering projects, but with the emergence of new projects alterations to the current generation rules are likely to be needed. Apros-Comos integrations also need to keep pace with the evolution of Comos. Deeper integration with SmartPlant is also currently under development ahead of the piloting phase. It should also be noted that as Comos and SmartPlant are intended to be used flexibly in different environments, a degree of tailoring is needed when applying the technology within new companies.

The Simantics integration platform developed by VTT has been successfully used (see case Foster Wheeler above) to integrate the Apros simulation tool with the plant asset management software Comos and, in an ongoing Fortum collaboration, the platform is also being used to integrate Apros with SmartPlant Foundation. An integration between Aucoplan and Apros has also been developed in an earlier case [3]. Automatically generated models are free of manual copying errors, faster to generate and can be more detailed than normally possible.

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Virtual machines smooth the way from traditional product development to seamless simulation-based life cycle management

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The use of computational tools in product development is now standard practice in mechanical engineering and design. The development of a modern, complex high-technology product, such as a modern passenger car, aeroplane, or diesel engine, would be practically impossible without computer-aided design (CAD) systems, computational analyses, and system simulation. These provide the tools for designers to gain valuable feedback about the behaviour and performance of products under development. Rapid advances in computer technology and decreasing computational costs have made it possible for even small companies to incorporate digital design and simulation into their product development. At the same time, the most advanced companies are taking steps towards the vision of fully digital product processes and digital management of all data, information, and even knowledge related to their product processes. The vision includes digital functional product models that can be used to virtually test products and their behaviour from multiple engineering perspectives as well as data management solutions that enable engineers, designers, and other doers in the process to efficiently utilize all of the information involved in the product process.

As the offering of different computational tools, design systems and data management solutions continues to surge, the need to separate data, information and knowledge from computational tools is becoming increasingly evident.

The mechanical engineering research carried out under the eEngineering research programme focused on the concept of a simulation-based product process covering the entire product life cycle and on the integration of data and engineering software applications into this process. One of the major findings of the programme was the importance of product information and related knowledge, and especially how data, information and knowledge are managed and in what form. Computational tools and systems often store data in forms that are not known or understood by their users, and not always even by the system managers – data simply goes into a database, and there it stays. **However, together with engineering knowledge, the information contained in this data is essential capital in the product process. This capital is often not systematically managed at all. The technologies developed in the eEngineering programme, such as the Simantics platform, provide means and practical tools for managing the valuable information and knowledge of the product process**. Another important insight was the need to expand the application of simulation beyond estimating the behaviour of physical systems to include non-physical systems and processes, such as the function of an organization or the markets. Even though these simulations may not be perfectly accurate or fail-safe, they provide a similar learning experience as the simulation of physical systems provides to an engineer or designer. The modelling phase of the target system helps the user to understand the structure, relations, and scale of the components and phenomena involved in the system. By simulating the model, the user gains understanding of the behaviour and dynamics of the system and the interaction of its components and subsystems. This applies to both physical and non-physical systems, and helps the user to design better products, processes and services.

The concept of applying simulation for estimating the behaviour of physical systems can be extended to non-physical systems and processes, such as the function of the organization or the markets.

From product development to simulation-driven life cycle process

VTT has an excellent vantage position for viewing the landscape of Finnish and international industry. As a neutral technology developer and know-how producer, VTT has a comprehensive understanding of the use of computational methods and tools in industrial product processes. The key challenge is strong case or conditions dependency. What is obvious to one industrial sector or company does not necessarily apply to others. We view a product process as a whole chain, including tools and systems, people and practices, the operating environment and the markets. A product process is not just about technology, but about everything related to the product life cycle.

Main advantages of applying computational methods in product development

Computational methods **speed up the development process** by providing quick answers to hard but yet critical questions, such as, what is the dynamic loading condition of the machine or what is the vibration behaviour of the system.

Modelling and simulation enables linking of different design domains, such as mechanical design and control system design, at an early phase of the product process. In other words, **the conditions are better for concurrent engineering and a faster overall design phase.**

Computational models are **safe and cost efficient ways of testing** different kinds of what-if scenarios of the product and its use.

Playing with the models and different use cases is a **fast and convenient way to learn the overall behaviour of the system** and how different physical phenomena affect the product.

Development levels in the simulation-based product process

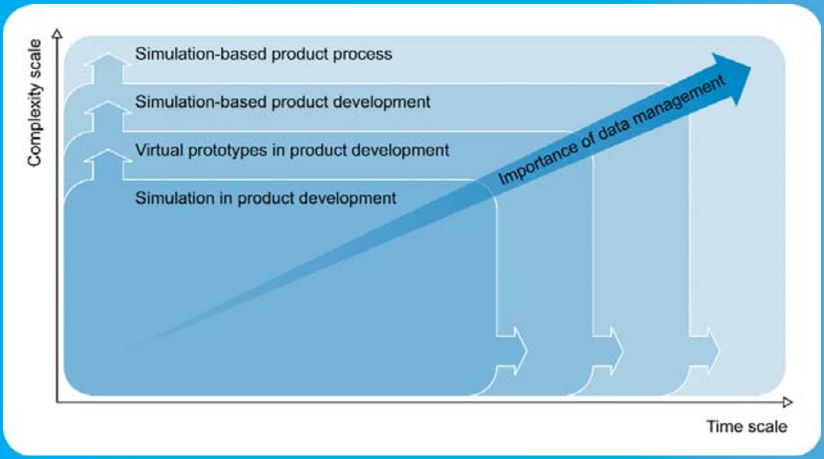

Figure 1. Evolution of simulation use in the product process and the increasing importance of data management. [2]

On the first level, *simulation in product development*, computational methods are used to study detailed and local phenomena (from the product perspective). At this level, computational methods typically have only a limited effect on product development, and most product development is carried out using traditional methods, i.e., engineering practices and established design principles. This is the prevailing practice in many mechanical engineering companies in Finland today.

On the second level, *virtual prototypes in product development*, the whole product or at least its main subsystems are modelled and simulated as virtual prototypes. This enables engineers to study the overall dynamics and behaviour of the system and gain important information at an early stage in the product process, before constructing any physical prototypes. Product development is still based on traditional engineering practices. Some companies in the mechanical engineering sector in Finland utilise this approach.

On the third level, *simulation-based product development*, similar computational methods are used as on the previous level, but now they are used systematically and form the basis of the design process. Before design work commences, the component, subsystem or product in question is modelled and simulated using a coarse model to gain understanding of the interactions and interferences involved. Based on this knowledge the design is then improved, and the procedure is continued iteratively until a design that fulfils the requirements is achieved. The challenge of this approach is in implementing this design process in practice. Only a few mechanical engineering companies in Finland operate on this level.

On the fourth level, *simulation-based product process*, the product modelling and simulation concept is also applied to the product process. This means that in addition to modelling the physical properties of the product, also the non-physical processes, such as the product maintenance business model and product development organization, are modelled and simulated. In addition, other important aspects, such as carbon and water footprint and other environmental effects, are analysed based on the available product data, and the life cycle performance of the product is optimized. This is still the future, although methods and tools to implement this level are already available.

VTT provides research and services in all key areas of the simulation-based product process concept.

VTT's long experience in applying computational methods and simulation in research and in industrial product development has provided a unique understanding of how the use and development of computational methods evolve within an organization. This evolution process can be roughly divided into four levels, as illustrated in Figure 1. The objective of modelling and simulation is to gain better understanding of the systems in the product process and, ultimately, to create a 'big picture' of not only the product, but the whole product life cycle. The different simulation methods and tools, optimization algorithms, and data integration solutions available are the pieces in this puzzle, which need to be collected, modified and combined in order for the big picture to be revealed.

The concept of the simulation-based product process, i.e., the use of computational methods for simulating and analysing the whole product life cycle, and different approaches to software integration through a centralized data management system, were studied together with the Finnish Funding Agency for Technology and Innovation (Tekes) in the joint-funded research project *Computational models in product life cycle – Codes* [1]. The project shed new light on the concept of simulation-based product life cycle management and the fact that the same justifications for utilizing simulation in studies of physical systems are also valid for larger-scale systems and processes. Another important finding was that we already have many of the pieces of the 'big picture' of whole life cycle simulation, and we have a good understanding of the parts needed to complete the rest of the puzzle. The project was carried out under VTT's eEngineering programme as part of the national *Digital Product Process* research programme.

Simulation-based design requires strong data management

As product processes become increasingly comprehensive, covering all process aspects and business perspectives, effective product life cycle management at the product development and manufacturing stages is also becoming ever more important. **Product data, information and related knowledge are the most valuable assets of the product process**. The software applications and systems used to produce, modify and store data during the process have a direct impact on the functioning of the process. For example, the engineering software applications used in product and manufacturing design influence the working efficiency of the design engineers and, in turn, the end quality of the design. This is emphasized in the simulation-based product process, where the design of the product and the manufacturing process are based heavily on the results provided by the system simulation tools used and on the understanding gained from them. Also, as simulation and design are carried out iteratively, the amount of data gathered is extensive, and effective data exchange and data integration become essential.

Computational methods provide a valuable tool for estimating the effects of design and strategy decisions in the early stages of the product process and thus enable overall optimization of the product and its related services. This requires strong solutions for product and design data management, especially in globally operating organizations.

Even though digital design and computational methods are widely used in mechanical engineering, design and simulation data exchange is still cumbersome in daily research and development work. Different design systems and simulation tools use their own data formats and internal data models, which are not well-supported by other software applications. Switching

CAD systems mid-project can be a formidable undertaking due to data exchange issues and should preferably be avoided. Exchanging data between simulation software is in some cases totally impossible due to a lack of common data formats. This means that the software applications used in the process have a strong effect on the daily work of the design engineer, and the choice of tools used determines many outcomes later in the process. As an example, if structural analysis modelling has been started with one commercial FEM software application, it can be very difficult to switch later in the process to using a different, preferred FEM application for computations. **In an ideal situation, modelling data would be independent of the computational tools used, and tool selection would be freely possible at the computational analysis stage.**

Separating the product data and the computational tools and systems ensures the preservation of product information and provides the freedom to choose the best computational tools.

The general concept of separating product and design data from the tools used to produce, modify, and process it is illustrated in Figure 2. The concept also includes the management of engineering knowledge in machine-understandable form. According to the concept, all data, information and knowledge related to the product process are managed and interpreted by a centralized system. This ensures that product information is preserved even if the computational tools used are changed. In addition, the concept provides the freedom to choose the right tool for each purpose, thereby enabling the use of computational resources to be optimized. The centralized data management approach allows all users to access up-to-date data, whether the organization is local or worldwide.

The vision of separating product data and computational tools, described above

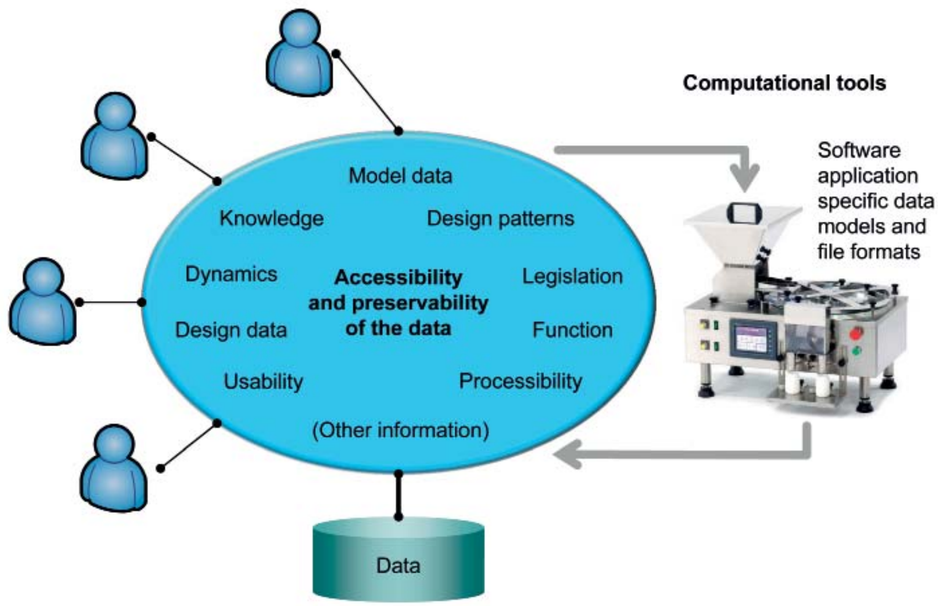

Figure 2. The concept of separating valuable computational product data from the tools that use it.

and illustrated in Figure 2, requires a range of skills, systems and methods. Each computational method requires specific expertise to be gathered in order to reliably model and simulate complex physical systems. Running large computational analyses also requires large computational resources and systems capable of utilizing these resources. The vast amounts of numerical data produced by large-scale simulations need to be managed and used efficiently in the product process. These are considerable challenges in themselves and represent a major combined undertaking, but the benefits are compelling. **The Simantics platform introduced in the previous article offers a solid basis for achieving these data management goals.**

Case: Data architecture and software application integration through a centralized data management system

The eEngineering programme studied and implemented the 'big picture', discussed in the previous sections, in a number of areas. A general architecture for data and software application integration into a centralized data management system, such as the Simantics platform, was designed, and selected software applications and formats were integrated to determine the effort required for its implementation and to understand the concrete process and its details. The data model and software application integration architecture is illustrated in Figure 3. The main design idea is that the data model of a software application or a file format, such as the Abaqus INPUT format, is created one-to-one in the Simantics platform as an ontology. The data from different software applications is integrated inside the Simantics platform using semantic data mapping based on general software application or domain ontologies (e.g., a generic FEM ontology). **This approach simplifies the implementation of laborious software application integrations and enables the utilization of data mapping features of the semantic data representation approach.**

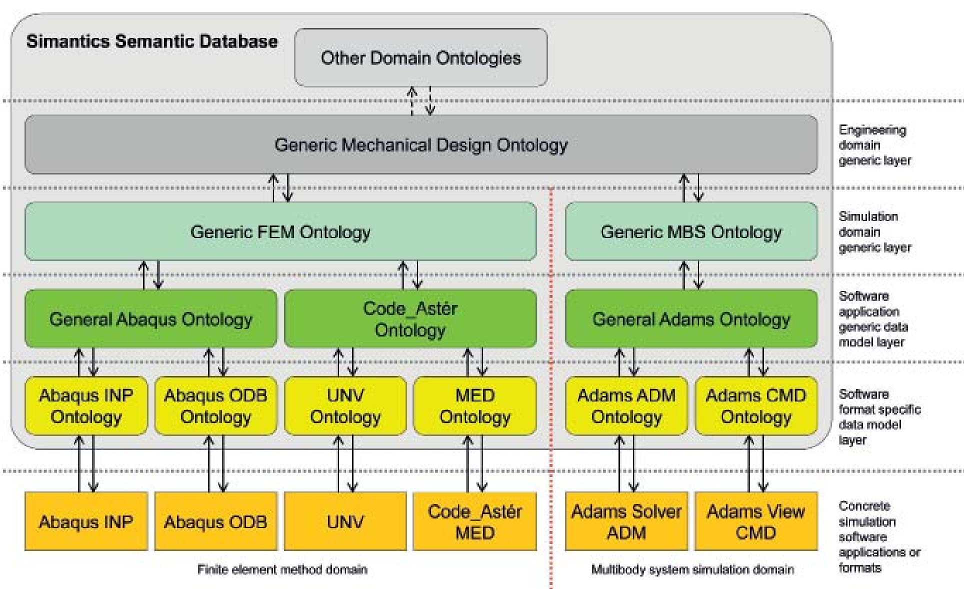

Figure 3. Architecture of the integration of the simulation software applications into the common data management solution.

Several data models, such as the Universal File Format (UFF) and the Abaqus FEM package's INPUT format, were created as ontologies in the Simantics platform, and the necessary file parsers were implemented. Based on new knowledge of the required effort and the process, the use of a parser generator (ANTLR3) was studied and a demonstrator implementation of a data parser was created. The conclusions of the work on data modelling and integration are:

- The concept of integrating engineering software applications according to the architecture presented in Figure 3 is valid. Data transfer from one software application to another is straightforward and software integration into the data management system is lossless, due to explicitly matching data types and structures in both systems (i.e., the engineering software application and the data management system). Data mapping from a software application specific ontology to another ontology is easy compared to mapping between separate software applications. This is due to the built-in data mapping mechanisms in semantic data representation.
- High-level software development tools, such as parser generators, can markedly improve the implementation of software and data integration and ease software maintenance and further development of the component.
- The amount of work needed for implementing all necessary software application integrations for the needs of a whole product process is large and cannot be carried out by one actor in a software or engineering eco-system. Thus, communication, architecture design, and standardization between data models and system interfaces are needed. This is an opportunity for software vendors and service providers to find new business areas.

Case: Implementing a demonstrator of a multibody system simulation environment

The advantage of the platform concept was highlighted during the execution of the eEngineering programme in a number of key ways. Platforms are a natural continuation of the vision of simulation-based product process and life cycle management discussed in the above sections, and the concept of separating valuable product data and computational engineering tools, as illustrated in Figure 1.

Practical examples concretizing the use and usefulness of the platform concept were studied and demonstrated in the eEngineering programme. The main features of the Simantics platform are described in brief below (more detailed description of the platform is presented in chapter *Simantics – blurring the boundaries of modelling and simulation*). The Simantics platform consists of a background data management system (a semantic database), a graphical user interface framework, and high-level software components on the framework, such as a 2D model graph editor and model structure browser. The availability of these high-level components markedly improves the efficiency of software implementation and also enables quick proof of concept testing of new ideas for software applications. In mechanical engineering, this was tested by implementing a 3D solid geometry modeller component on the Simantics platform and using the component to create a 3D multibody system (MBS) model editor, integrating an existing simulation environment as the computational backend, and implementing post-processing features, including simulation results animation and a plotting component (see Figure 4). For numerical solving of the MBS simulation, another platform, the OpenModelica Environment[1], was used. For the implementation, external high-level software components, such as the OpenCASCADE[2] geometry kernel for the 3D solid modelling, and the Visualization Toolkit (VTK)[3] for 3D graphics, were used to speed up the software

[1] OpenModelica project: www.openmodelica.org
[2] OpenCASCADE project: www.opencascade.org
[3] Visualization Toolkit software: www.vtk.org

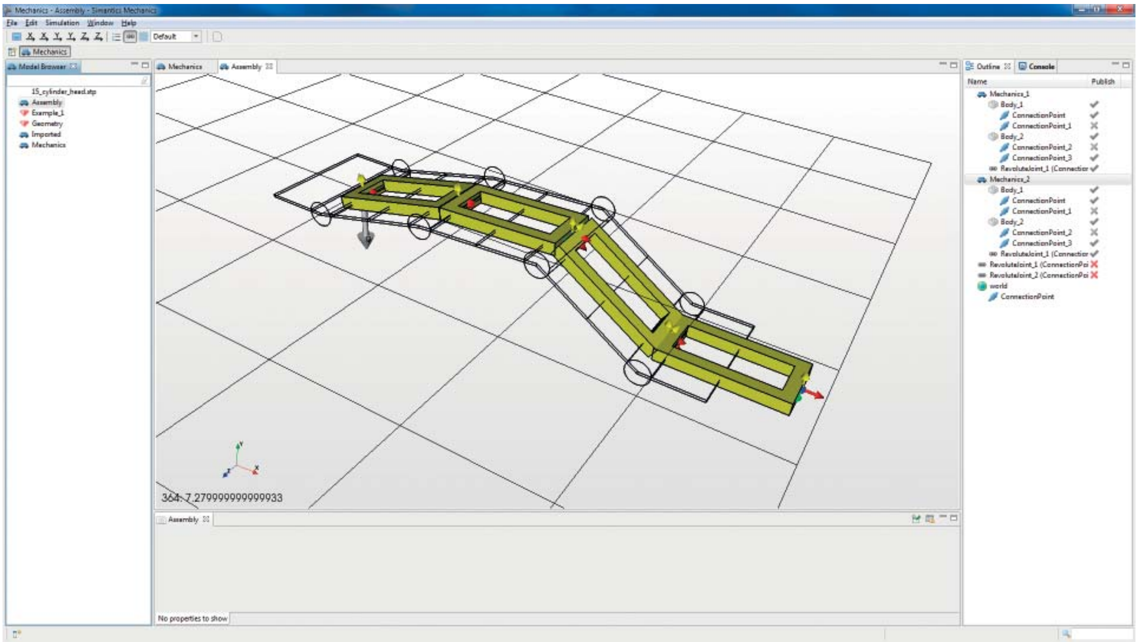

Figure 4. The graphical user interface of the MBS editor built on the Simantics platform, showing a test model.

implementation. The OpenModelica Environment is an open source implementation of the Modelica[4] simulation language environment. Implementing the 3D solid geometry modeller and the MBS modelling, simulation, and post-processing features on the Simantics platform required a total labour input of four man-months.

Based on the case study, the following conclusions were drawn regarding the application of platforms to build a data management system for a simulation-based product process and to improve software development efficiency:

- Centralized, open, and extensible data management systems are needed to implement the vision of a simulation-based product process and product life cycle process. A good proof of concept is the Simantics platform.
- The platform concept was studied, tested and proofed in mechanical engineering by implementing a 3D solid modeller and a 3D MBS model editor, simulation manager, and post-processing features within four man-months. This was enabled by the existing high-level software components and platforms.

Bringing the vision to reality

The old maxim *'knowledge is power'* has a new meaning in the context of product life cycle data management, but when it comes to the products and services in this business area, it has deep wisdom. The one who manages the data, information and knowledge in the product process, and can utilize it efficiently, has a clear advantage in the market. From the research point of view, the key question is what steps and actions must be taken to ensure that Finnish companies are at the forefront of this development and reap its benefits?

[4] Modelica simulation language project: www.modelica.org

The eEngineering programme has demonstrated the importance of data, information and knowledge management in the product process. The case studies and the lessons learned from them have provided understanding of the size of the challenge, the ways to implement the vision, and the importance of long-term work in the form of well-designed technologies and platforms. Implementation of the vision requires close cooperation between different parties: research, commercializers, service providers, and end users. The challenge is big, and must therefore be divided into manageable pieces, e.g., using standardization and open specification of required system and data interfaces, and several parties are needed to implement it. The development trend among vendors of big design systems is clearly towards a similar vision. End users who adopt the concept and the vision of the pioneers will reap the benefits. Players who wait for proof of concept from the market will most likely be too late.

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Analysing our environmental impact – real and virtual

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Life-cycle assessment — Life cycle inventory — Impact assessments — Software tools

Rising global population and material well-being present a multitude of global challenges, including biodiversity loss, climate change, ocean acidification and competition over scarce material and fossil energy resources such as phosphorus and crude oil [1]. To mitigate these impacts, we need to transform our societies, business concepts and industrial processes towards high energy- and resource-efficiency and reduced environmental pressure. Modelling and comparing the life cycle environmental impacts of different systems enables us to identify the hotspots in value chains with most improvement potential and enables selection of production pathways with smallest environmental impacts. A focus on the whole life cycle instead of partial optimization of single steps in the value chain ensures that no burden shifting through partial optimization takes place. VTT provides the know-how, technology and software tools for modelling and improving the environmental performance of our society and production systems, in parallel with economic and technical considerations.

Typically, engineering design is done using CAD systems and environmental assessment using LCA software. While these two worlds are strongly related – especially in ecodesign – they are not necessarily connected. CAD systems contain a wealth of information about different parameters of the product life cycle from which Life Cycle Assessment (LCA) can benefit. Stronger integration between CAD and LCA software system has been suggested by several researchers, for example, in [2] and [3]. **In the eEngineering spearhead programme we have implemented bridges between Simantics and Intergraph SmartPlant Foundation (CAD integration system) and Siemens Comos (CAD system). These bridges can also be utilized together with VTT's SULCA LCA tool.**

Life cycle assessment is a prerequisite for holistic environmental evaluation

Life cycle assessment (LCA) is a comprehensive and ISO standardized method (ISO 14040:2006 [4], ISO 14044:2006 [5]) of evaluating the environmental aspects and potential environmental impacts of products. LCA can also be applied in evaluating the impact of technologies and processes. An LCA study covers the whole life cycle of products, from raw materials acquisition to end use, recycling, or disposal. LCA provides information to support decision-making in product and technology development projects. LCA-based information is applied in eco-labelling and the production of environmental product declarations. An LCA approach can also be applied in the evaluation of eco-efficiency, material- and energy-efficiency, and eco-design and life cycle design.

Life cycle assessment has been developed in order to gain a better understanding of the potential environmental impacts of products. As an example, LCA can be used for:

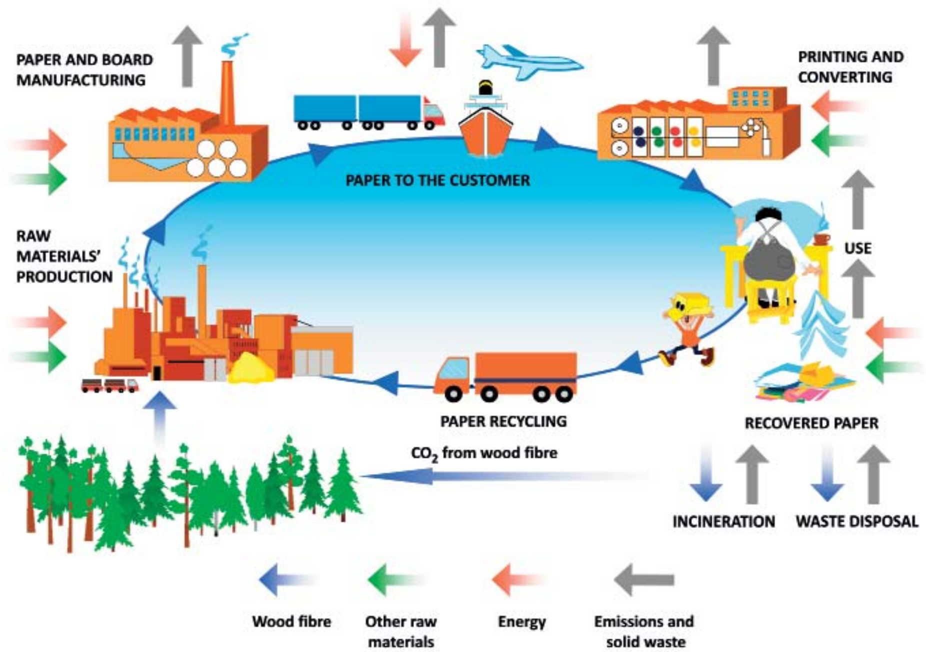

Figure 1. Life cycle of a fibre product, showing inputs and outputs.

- Identifying opportunities for improving the environmental performance of products.
- Informing decision-makers in industry, government or organizations.
- Selecting relevant indicators of the environmental performance of products.
- Marketing products (e.g., making an environmental claim or applying for an eco-label or background information for environmental product declaration) (ISO 14040:2006 [4]).

Each LCA study must be planned separately and involves large-scale information gathering. Thorough understanding of the processes and products being assessed is essential in order to enable evaluation of the correctness of the data used in the assessment as well as interpretation of the assessment results. All products have some impact on the environment, but improving one part of the life cycle can also cause deterioration in another. To be able to evaluate the sustainability of a product or technology, several indicators and extensive data collection are required. An example of the life cycle of a fiber product is presented in Figure 1, depicting the complexity of such evaluation. Figure 2 shows the four stages of LCA; goal and scope definition, life cycle inventory, impact assessment and interpretation of results.

Benefitting from more than 20 years of experience, VTT applies LCA in research and customer projects in several sectors of industry. VTT's researchers participate actively in the development of LCA methodology and tools in Finland and internationally. We actively participate in ISO standardization processes, including LCA (ISO 14040 series), carbon footprint (ISO 14067, 14069), water footprint (ISO 14067), eco-efficiency (ISO 14045) and social responsibility (ISO 26000).

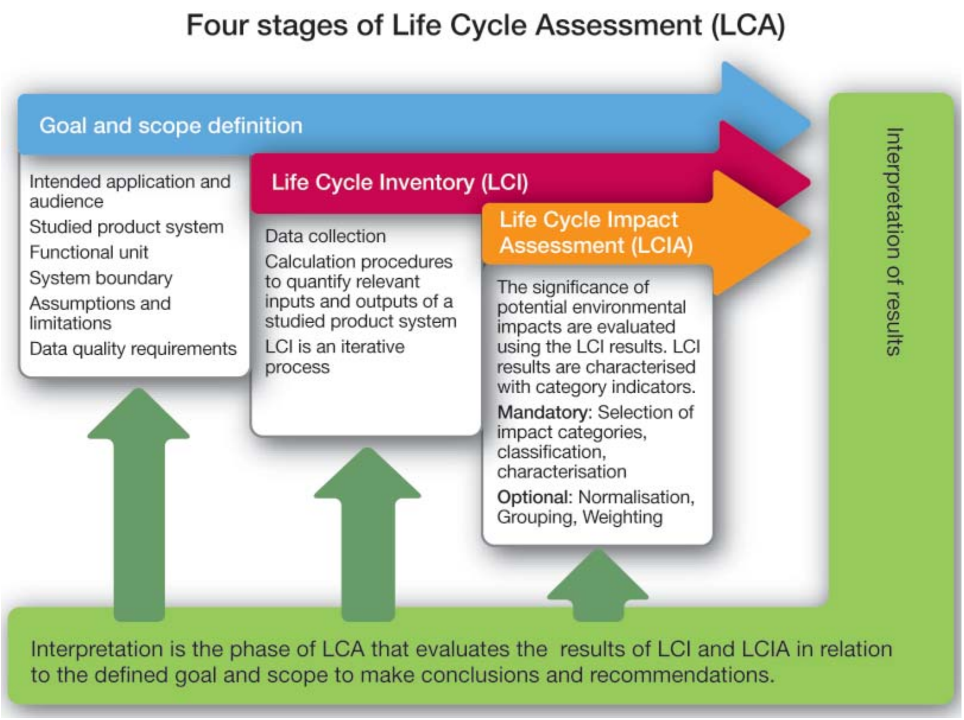

Figure 2. The four stages of LCA: goal and scope definition, life cycle inventory, impact assessment and interpretation of results.

Software for life cycle assessment

The SULCA software allows the user to perform life cycle inventory (LCI) and life cycle impact assessments (LCIA) and to present the calculation results in a clear, easy-to-use way using unique reporting features and configurable charts. Users of SULCA enjoy connectivity with public and commercial LCA databases, reducing the effort required for data collection. With this software calculation of carbon and water footprints is easy and fast. The software – SULCA4, sold internationally and currently in use in more than 15 countries – is employed by industry, universities, research institutes, and others.

SULCA facilitates wider use of LCA by lowering the level of effort required to conduct LCA studies. The tool is designed and built in close cooperation with VTT's LCA experts using agile software development methodologies to enable fast LCA modelling with less effort and lower cost. A key aspect of the requirements engineering process was the observation of LCA modellers in their natural work environment during a typical working day. As the end users tend not to be software designers, they are less able to explicitly describe their software needs. Instead, this knowledge is obtained by observing how users carry out LCA studies in practice. Observing the users enabled often used features to be distinguished from rarely used features and common usability flaws and user mistakes to be identified. This information is then used to prioritize software requirements so that the most important features of the tool are implemented first, in the early stages of development. This gives the users the opportunity to provide more feedback on the most commonly used features and allows the software developers to build a tool that better responds to the needs of LCA professionals.

SULCA offers the following:

- Third-party database integrations
- Effective data management
- Support for KCL-ECO 4 models
- Simple and easy user interface
- Separate presentation for transport-related elements
- Versatile configurability of flows allowing closed loop systems
- Structural modelling
- Module classification
- Automatic unit conversions
- Mathematical formulas
- Impact assessment

Key features of SULCA include effective data management, including sharing and re-using data, and connectivity to public LCA databases. Modellers are able to effectively combine data from various sources, including models from older software versions. Support for mathematical formulas allows building of configurable unit processes, reducing the need to store numerous static configurations. With global model parameters, users are able to build multiple scenarios for a single model for easy comparison. Transports are represented with material flows between processes to increase the clarity of the models. SULCA also includes a new intuitive user interface with improved model validation, structural modelling and automatic unit conversions. Advanced users can restructure the user interface by moving, detaching and re-attaching UI components. The large amounts of data connected with LCA model simulations are represented in an easily interpretable format. Modellers are able to quickly find the information they are looking for and make visualizations using the chart function. With the help of SULCA's module classifications, the user can easily identify which life cycle stages cause the most environmental burden.

LCA as part of an integrated design and simulation environment

One of the key application areas of LCA is the environmental impact assessment of emerging technologies. However, assessment is often limited by a lack of robust data due to the immaturity of these technologies. Process simulation offers an interesting potential solution to this problem. Process simulation mass and energy calculations can be combined with LCA to support strategic decision making regarding emerging technologies. This approach has been suggested, for example, by Liptow [6]. VTT has extensive experience in both process simulation and LCA. In the eEngineering spearhead programme we have integrated our process simulation tools Apros (www.apros.fi) and Balas (balas.vtt.fi) into a common operating environment shared with the SULCA LCA tool.

With the semantic data transformation mechanisms of Simantics we are able to transmit data from process simulation experiments to LCA experiments.

LCA is a widely-used technique for measuring the environmental costs assignable to a product or service. However, LCA takes a high-level view and often assumes a fixed supply chain structure and operation, with sensitivity analyses often restricted to scenario analysis of a limited number of possible choices within this structure. Supply chain design and practices can be a significant contributor to overall environmental impacts. An LCA approach typically considers the effect of supply chain design and practices in retrospect, with limited possibilities for ex ante analysis of detailed process design options. To overcome this problem, it has been suggested, for example in [7] that LCA could be combined with dynamic simulation. Using this approach, environmental impact indicators can be incorporated into a dynamic model of the supply chain along with profit and customer satisfaction, so that the sustainability of various design and operational decisions can be assessed comprehensively. VTT is utilizing system dynamics for modelling and simulation of business processes. *In the eEngineering spearhead programme we have integrated our System Dynamics tool (www.simantics.org) and LCA tool SULCA into the same operating environment. This will enable combined analyses in the future, as suggested above.*

Towards integrated toolsets

Growing pressure on natural resources and increased environmental awareness have created growing demand for evaluating the environmental aspects and potential environmental burdens of products and services. Against this background, the SULCA life cycle assessment tool, used for conducting LCA studies according to the ISO 14040:2006 and ISO 14044:2006 standards ([4] and [5]), has been developed in close collaboration with VTT's LCA experts to respond to their needs and to enable LCA studies to be conducted with less effort and cost.

Future work includes further usability improvements based on increased user feedback once the tool is deployed for production use. The new SULCA version is implemented in Simantics – an open-source integration platform for modelling and simulation tools. Simantics enables connectivity with a growing set of other modelling and simulation tools integrated into the same environment. Future research includes exploiting the potential of co-using LCA with process simulation, business process simulation, and with system dynamics and intelligent CAD environments. For example, in process simulation an integrated toolset enables environmental impacts to be considered earlier in the process design. Such advanced interdisciplinary research would not be possible without the intensive collaboration of various teams and knowledge centres at VTT.

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Error-free software through formal methods

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Anyone dealing with modern digital equipment is aware of the effects of inadequate software quality. Software in smartphones and set-top boxes has to be constantly updated – not to introduce new features, but simply to manage errors and issues as they emerge, to prevent them from acting up or freezing on the user. But the quality of the software of computer-based systems that are critical, for example, to the infrastructure of society, should be addressed in much more serious ways. **Almost everything making up our infrastructure, from road and rail traffic, supply chain logistics and communication networks to power grids and plants, is controlled, or at least monitored, by software-based systems.**

Although the design of industrial, critical software is based on completely different practices to the software in consumer electronics devices, the goal of 100% error-free software has nevertheless remained elusive. But the situation is changing.

Model checking finds hidden software errors

The process of analysing whether a system design meets its requirements and fulfils its intended purpose is called verification and validation (V&V). For industrial instrumentation and control (I&C) systems, V&V has traditionally been based on testing and simulation – of either an actual system or model replicas, i.e., running the target software and benchmarking the behaviour and outcomes against scenarios or test cases. Test runs are a valuable and necessary source of data, but testing and simulation alone cannot be relied on to prove that a system is 100% error-free. Test spaces easily grow to immense proportions so that, in practice, not all possible test cases or scenarios can be taken into consideration. Specific, advanced test automation tools are available, but conclusive analyses are impossible due to the sheer number of possible situations that a system can, in theory, and with the necessary critical approach, be shown to incur.

Model checking is a computer-assisted formal method that can prove conclusively whether a (hardware or software) design model acts according to its stated requirements in all situations. Both the system design and the requirements are presented in a format understood by a model checking tool, called a model checker, which will then thoroughly analyse whether a model execution that is contrary to the requirements is possible. *As a general principle, instead of looking at what happens in a given situation with given inputs, the idea is to define an undesired situation and see if it is possible to end up there.* Instead of excessively computing all combinations, a systematic search is carried out using a graph-like model, looking only at the combinations that are relevant to each stated requirement.

Since the 90s, formal model checking has been the key verification method in microprocessor manufacturing, and has recently found its way into ever more versatile domains. At VTT, we have been applying model checking in the V&V of critical I&C software, i.e., the logic that controls and monitors industrial processes.

Developing practical tools for industry

Versatile and mature model checking tools are available, but most are either too generic and abstract or aimed at a specific domain and, therefore, not suitable for the analysis of I&C software. So-called function blocks are one of the most common programming languages used to implement I&C systems. Instead of writing code, applications are constructed by selecting predefined standard blocks (e.g., AND, OR, delay, or a PID controller) and connecting ('wiring') them together in a graphical diagram to obtain the desired functionality or operation logic. Each block reads its inputs, updates its internal variables, and sets its outputs according to its internal logic. Block wiring then defines the data flow and the block processing order. Function block diagrams are favoured, since (among other benefits) they present clear input-output mapping, and it is relatively easy to understand and follow the processing flow.

Accordingly, VTT has been developing tools for model checking of function block based software. Our work has been based on Simantics, an open source platform for modelling and simulation. We have been specifying a Simantics plugin for the open source model checker NuSMV, and are now able to construct the NuSMV model by wiring blocks together in a 2D graphical view.

The expected benefits of such a graphical, dedicated toolset are clear. In the future, the model translation capabilities of Simantics are also expected to enable automatic model conversion from, for example, an existing Apros model of process control software.

Practical experience in evaluating industrial control systems

The majority of VTT's practical experience in applying model checking is in the nuclear industry (see Case: Nuclear on the next page) where very strict safety analysis procedures are an essential requirement. The approach is, however, also more generally applicable, and we have conducted small-scale pilots in diverse I&C applications in which different programming languages and environments from different vendors have been used. Successful pilots have been performed, for example, in factory, power plant, electrical and machine automation projects.

The model checking approach is most suitable for the analysis of relatively straightforward logic – the kind of logic that should be favoured for safety-critical applications – as the computational power of model checking is based on the use of fairly simple modelling languages. Conversely, more sophisticated and algorithmically complex control applications, such as those needed to run a modern paper machine, for example, cannot be effectively analysed, in which case, for example, simulation-based verification and validation are more suitable. Nevertheless, just because a system is straightforward does not mean that its analysis is simple: a binary circuit with 100 inputs and no internal memory will have 10^{30} different input combinations, and adding memory to the application only further complicates the analysis.

Solving the theoretical challenges

VTT has been working with Aalto University to solve some of the theoretical challenges related to model checking and, in particular, the evaluation of I&C software. The greatest challenge is the computational effort required due to the state explosion problem: as the number of possible model states grows exponentially with respect to the size of the model, the analysis task can become too complex for existing methods and computers. Model

CASE: NUCLEAR

With new-builds and modernizations, old analogue nuclear power plant technology is being steadily replaced by digital instrumentation and control (I&C) systems. Software-based control systems can offer higher reliability, better plant performance and new diagnostic capabilities. Nevertheless, the inherent complexity of digital I&C has justifiably raised questions regarding the correctness of both hardware and software design. The industry and regulators thus face important challenges in assuring that new systems meet their requirements.

At VTT, research on model checking began in 2007 under the Finnish Research Programme on Nuclear Power Plant Safety (SAFIR2010). Successful industrial pilot cases quickly proved the value of the approach. Finnish nuclear power companies and authorities have shown continued interest in formal methods, and research continues under the SAFIR2014 programme.

In addition to active research, the approach has been put to practical use. VTT has been consulting the Finnish Radiation and Nuclear Safety Authority (STUK) (since 2008) and the power company Fortum on evaluating nuclear I&C systems using model checking.

checking is a computationally very powerful method, but it, too, has its limits.

Specific topics for past and present research include:

- *Modular approach to analysis of very large models*: A technique has been developed to analyse systems that would otherwise result in models with a too large state space, based on the modular structure of the model. The model is first approximated by greatly abstracting the logic of some of the modules. An algorithm has been developed that iteratively searches for a composition of modules that at the same time is computationally manageable, and covers enough modules to prove the properties of the original model. The feasibility of the analysis results for the abstracted model is then reviewed in the context of the full model.
- *Analysis of asynchronous models:* For many model checkers, one of the necessary simplifications needed in order to make the analysis efficient is that the analysed system model has a unified, discrete time cycle. However, many real-world systems are physically distributed to several different processors that each behave according to their internal clock. Model checkers that can also handle asynchronous behaviour do exist, but in these cases the size of model that can be effectively analysed is clearly smaller. A new model checking tool is being developed that will combine the strengths of different types of model checkers.
- *Modelling system faults:* If the I&C software has a mechanism for dealing with faulty input data, the mechanism is taken into account in the model. However, if we wish to introduce failure modes of the underlying hardware architecture ('What if one of the processors the software is running on or the communication network fails?'), extra work is needed in defining suitable failure mechanisms. We are currently working on structured approaches for doing so.
- *Reliability through tool diversity:* When a model checker discovers no error, there is always some question whether the design actually is error-free. Errors in the modelling process are usually found, and most often result in a 'false negative' result. One way of increasing confidence in the results is to use several model checkers that do not share source code in their implementation. We are currently constructing a tool portfolio that will not only enable the evaluation of more versatile applications than before, but also add to the reliability of analysis results.

Summary and need for further work

Through model checking, we have been able to find hidden design errors in software systems that have already undergone verification and validation through more traditional means. Others have reported similar results in diverse application areas, such as aviation. The method is not, however, a one-size-fits-all solution, since it is only effective for the evaluation of fairly straightforward software applications (which safety-critical industrial control systems often are). Also, expert knowledge is always needed when applying formal methods.

VTT is currently working on the theoretical challenges as well as more practical issues related to the application of model checking in industrial contexts. **The Simantics platform enables us to bring model checking to the mainstream, as the dedicated, user-friendly tool makes it possible to implement model checking with less knowledge of the underlying theory.** Our current tool development approach is tied to function block diagrams as the programming language of I&C software, but other viewpoints are also needed, as, for example, the C language is often used in the industry, and model checkers for verifying C code are also available. On the theoretical side, new methods are needed to handle the specification of system requirements. Our ongoing research is nevertheless motivated by successful applications both in research pilot cases and in practical customer projects.

To date, practical application of VTT's model checking has been mainly within the context of nuclear power plants, as the nuclear industry is subject to rigorous legislative requirements regarding safety analysis. However, safety is not the only criterion driving strict V&V – cost is also an important factor. While the expertise needed for model checking does not come free of charge, the expenses caused by the downtime of industrial plants or infrastructure systems due to design faults can be immense.

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Designing user experience for the machine cabin of the future

Designing user experience for the machine cabin of the future

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In addition to safety, operator comfort has become an essential driver of product design and development in the mobile machine industry. Typically, the machine cabin designer focuses on one or, at most, a few properties at a time, such as physical ergonomics or machine feasibility during task execution. However, user experience (UX) and comfort are a combination of several different features. **A holistic UX and comfort evaluation includes aspects such as psychoacoustics, thermal comfort, vibrations within the cabin, musculoskeletal discomfort, and visibility from the cabin**. For many of these factors, UX vary greatly between individuals, tasks and working environments. New tools and methods are therefore needed to identify and optimize these factors to meet user requirements in design and to evaluate their feasibility in practice.

But how to evaluate human–machine interaction parameters and their combined

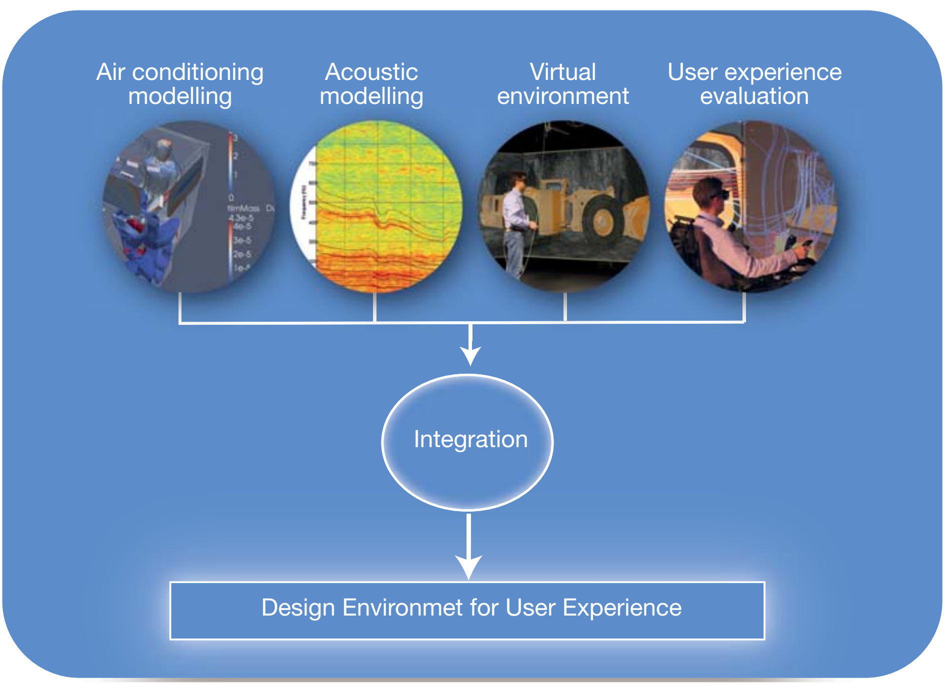


Figure 1. The multidisciplinary design environment enables designers to take key factors affecting user experience and comfort into early consideration in the design process.

effect on the UX in the early design phase, when physical prototypes are too costly to construct or not available? This can be achieved by using Virtual Environments (VEs), which combine design models and operation simulations to enhance the natural feel of a simulated work task, when evaluating a design. **With VEs that include a good visualization system, realistic motion platform, realistic acoustics, and air conditioning modelling, it is possible to assess the combined effect of these parameters, thus benefitting the user through improved design with respect to comfort, ergonomics, usability and safety**. In addition, machine manufacturing companies also benefit through reduced design costs, faster time-to-market, and better product quality, as requirements can be evaluated early and modifications can be made fast.

Virtual design environment enables holistic consideration of the user

The main outcome of this sub-project of the eEngineering programme was the development of a virtual, simulator-based design environment for the multidisciplinary UX design of machine cabins. The project had two main objectives: (1) Integration of various areas or systems, such as, acoustic modelling, air condition modelling, and UX evaluation into one design environment (such as VEs), see Figure 1. (2) Development of UX and comfort evaluation methods (psychoacoustics, thermal comfort, whole-body vibration, musculoskeletal discomfort and operator's field of view) to enable more holistic UX evaluation.

Holistic user consideration changes the entire product design and development process

Impacts on product processes were also studied during the project, with a focus on how use of the novel virtual design environment changes current product design and development processes, and how to bring the environment into normal practice within industry. Product or system design life cycles – from

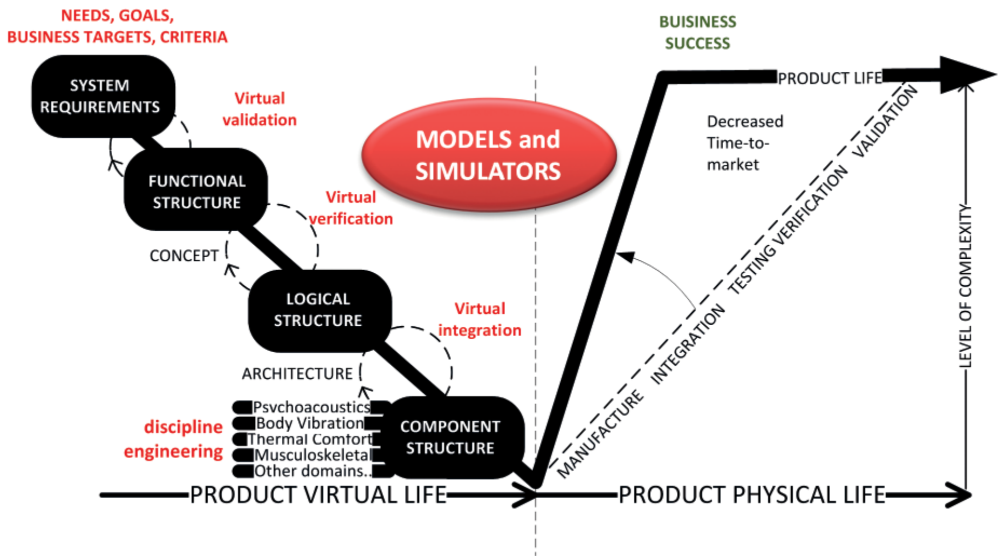


Figure 2. Impacts of the multidisciplinary design environment on virtual and physical product life. The left side illustrates the phases of the design process. The use of VE smooths the iterations and phases and eases communication across phases. The right side shows the effect of VE on time-to-market due to earlier and more effective requirements validation and verification and thus fewer engineering changes and interruptions.

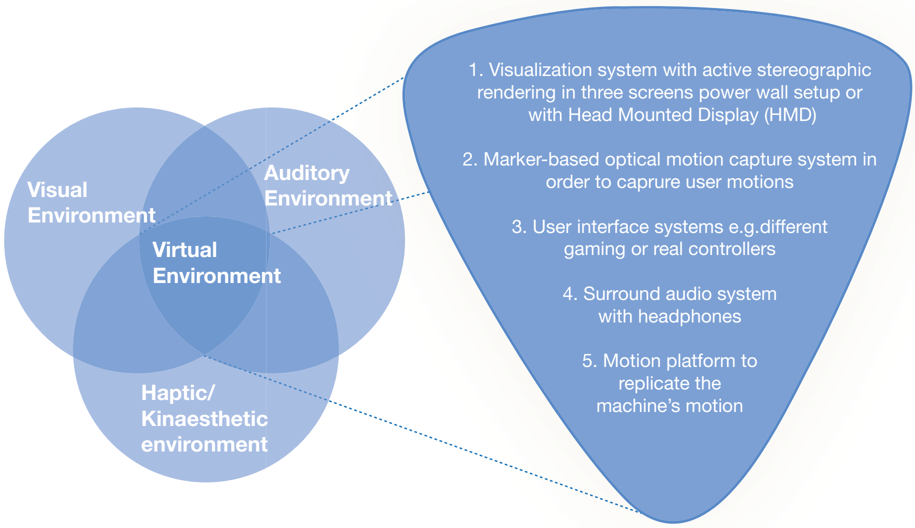


Figure 3. The creation of virtual environments through interaction between different sub-environments. The left side shows the relationships between the parts of the virtual environment (ref. [2, p. 6]), the right side shows the basic technology enablers for a virtual environment (also shown in Figure 4).

product specification and business targets to detailed verified technical solutions – are often described using the systems engineering V-model. Adapted V-model (see Figure 2) illustrates how integrated product development simulators bring improvements and significant changes to the product design and development process.

Figure 2 shows how the use of virtual simulators shifts the actual, physical system towards earlier commercial product launch compared to traditional engineering. It enables earlier and better decision making based on earlier evaluation and validation of user and other stakeholder requirements, and verification of combined multidisciplinary design solutions with less engineering changes during product development and, therefore, faster time-to-market. Experiences from our partners show that impacts are actual.

Capturing the user experience in the virtual environment

UX and comfort are essential factors in high quality cabin design. **UX can be defined as a person's perceptions and responses resulting from the use of a product, system or service.** Additionally, comfort is defined as a subjective, personal experience, affected by various factors (e.g. touch, sight, hearing, taste and smell) and reaction to the environment [1].

VEs help designers to get understanding of the UX and to design systems that take into account human needs while ensuring that the cognitive and physical potential of the user are utilized with respect to the overall goals of the system. In addition, it can ensure, during the design, the recognition of different users involved to product life cycle such as assembly, maintenance and operation. Another benefit of VEs and virtual reality (VR) technologies is that they enable fast comparison of radically different design

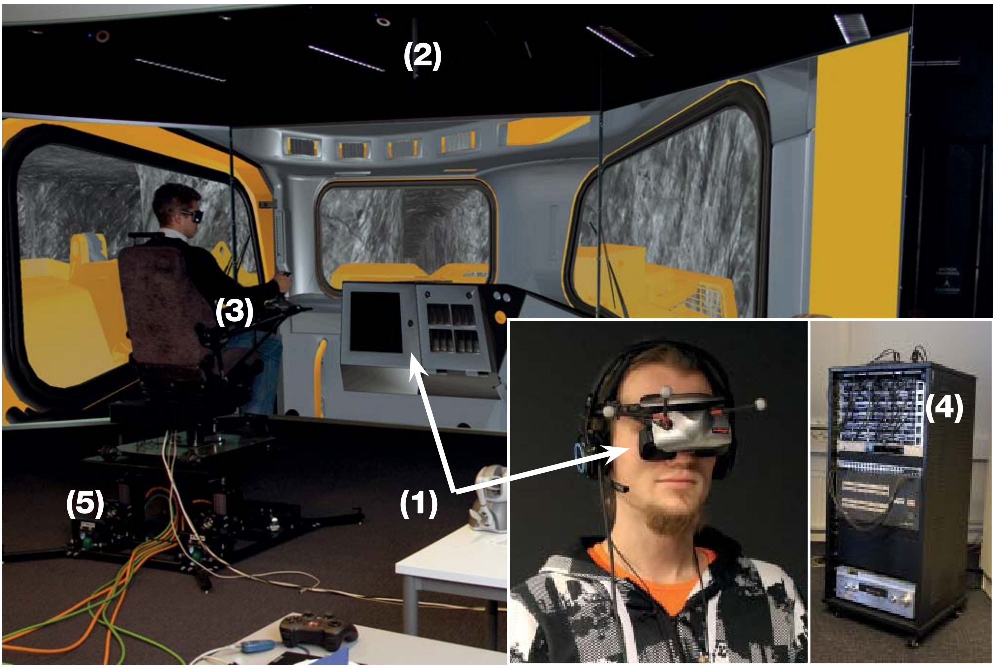


Figure 4. The virtual environment developed at VTT consists of five subsystems: (1) Main visualization system with active stereographic rendering in three walls setup plus secondary visualization system with head-mounted display (HMD); (2) Marker-based optical motion capture system to capture user motions; (3) User interface (UI) system combining different gaming controllers and basic keyboard interaction; (4) Ambient audio system with headphones; and (5) Motion platform to replicate machine motion.

solutions without the need for physical prototypes.

The main quality criteria for VEs have traditionally been the quality of 3D graphics and the generation speed and smoothness of visualization. High quality visuals are undoubtedly the single most important factor when aiming to create an effective and functional VEs. However, 3D graphics alone are not sufficient to produce a realistic illusion of an environment. In addition to vision, manipulation of the other senses is also required to create a convincing illusion of reality, i.e., VR. The key senses include hearing, haptic (touch) and kinaesthetic (body position and movement) senses, and to a lesser degree, taste and smell.

Figure 3 [ref. 2, p. 6], depicts how a VE consists of several simultaneously interacting sub-environments. **The visual, auditory, and haptic environments together form the VE. If any of these is missing, the VE is considerably less functional and realistic**. The VE created at VTT and its subsystems are illustrated in Figure 4.

Development of the UX and comfort evaluation methods was started by selecting key cabin design parameters, such as: psychoacoustics, thermal comfort, whole-body vibration, musculoskeletal discomfort and operator's field of view.

Psychoacoustic Experience Evaluation and Enhancement (PEEE) is a method for evaluating how human beings experience the acoustic environment and for improving key factors of the acoustic experience. Real or modelled sound events in a real or modelled

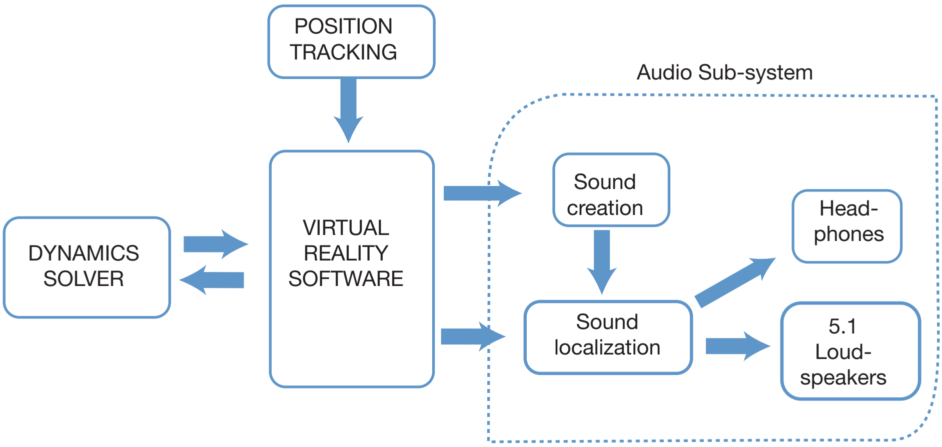


Figure 5. Modular sound generation for virtual reality. Position tracking follows the position and movements of objects (including the observer) in the VE. A dynamics solver creates the dynamic parameters for the model. This information is forwarded to the VR software, which translates them into an appropriate format for the sound creation block. Sound from the sound creation block is localized by the sound localization block, and then sent either to the headphones or loudspeakers.

acoustic environment are captured or generated in binaural form. Binaural signals are then used in listening tests or for extraction of individual psychoacoustic metrics, such as loudness and sharpness.

UX of *thermal comfort* is evaluated by applying Fanger's thermal comfort model [3, 4]. Additionally, window fogging and dust dispersion can be simulated. Air flows and other cabin air conditioning related phenomena can then be visualized in VEs enabling users to visually experience air flow streams, thermal comfort, window fogging and dust dispersion.

In order to measure the *whole-body vibration dose* experienced by the user, data based on standard acceleration is gathered from the motion platform or by collecting acceleration sensor data from the seat. The vibration dose is calculated based on standard ISO 2631-1 [5].

Subjective musculoskeletal symptoms of the user are collected via a computer-aided tool that enables the user to choose a body part from a body map and then indicate their severity of discomfort. Data on experienced musculoskeletal discomfort and degree of discomfort is gathered before and after performing the task in the VEs.

To increase the *use of real operators in field of view (FOV) evaluations*, a new method for calculating FOV in VEs was developed. The FOV analysis method is based on task-related visibility and occlusion evaluation of target objects in the operator's FOV. The method calculates (1) the percentage of visible target object pixels from all pixels in the operator's FOV, and (2) the percentage of occluded (by the cabin structure) pixels from the visible target object pixels in the operator's FOV. The results facilitate comparison of the impacts of alternative design solutions on visibility.

Auralization: the virtual hearing experience

Effective audio is key to building a convincing VR experience. In VEs, sound events and acoustics are simulated to sufficient accu-

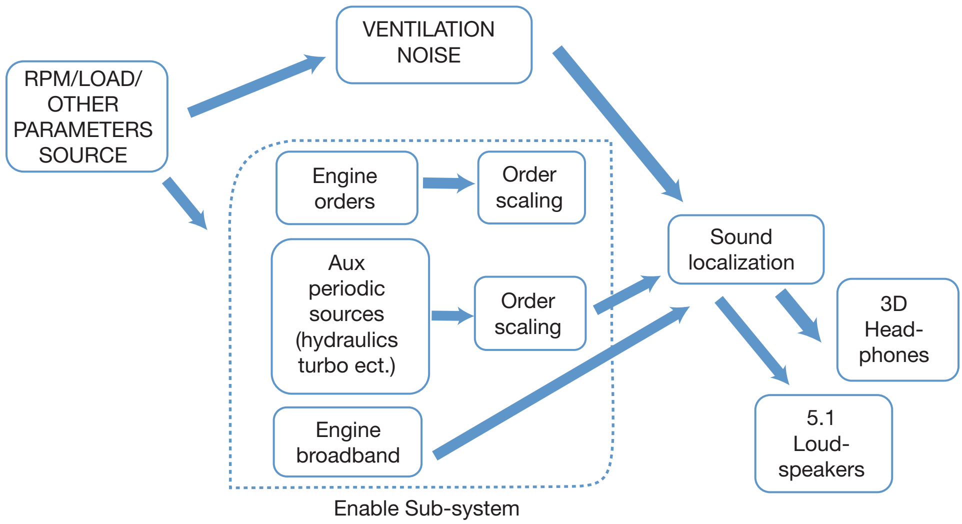


Figure 6. Audible Model Platform (AMP) tailored for the cabin noise model. The sources of noise are engine orders, hydraulics orders, engine broadband noise and ventilation noise. All of these are affected by various parameters coming from external VE source.

racy to create an immersive experience while not placing excessive demands on system resources. The most important requirement is real-time and concurrent operation of the audio simulator and visualization to preserve the illusion of immersion. Visualization events must be tightly synchronized with the auralized environment.

In general, sound events and acoustics form an audio sub-system itself, as illustrated in Figure 5. Sound events are generated in the Sound Creation block and are positioned accordingly in the Sound Localization block. A 5.1 loudspeaker setup comprising 3 loudspeakers in the front (left, right, and middle), 2 rear loudspeakers and a subwoofer, was used as the main sound source. Panned sound within these loudspeakers can also be converted to headphone use. Sound panning involves projecting sound in a certain direction by changing the level of sound in each individual loudspeaker. The audio subsystem gets its parameters in real time from the VR software, which generates the parameters based on position tracking and information from a dynamics solver.

Sounds can be created in the VEs in various ways. In many industries the common practice is simply to pre-record or sample noise signals and then play them back in the VEs. At the other end of the spectrum, audible models are being developed to generate sound and noise based on parameters such as tonal component levels, frequencies, relative phases, broadband noise frequency content, and level of amplitude modulation. Such audio models offer the potential to create truly virtual audio experiences and are therefore a key focus area of current research.

The Audible Model Platform (AMP) developed by VTT is a parameter-based sound and noise generation platform. The AMP is not directly based on the structural or mechanical physics of noise generating machinery, but rather the noise profile parameters are functions of angular velocity (rpm), load, listening position and other relevant factors.

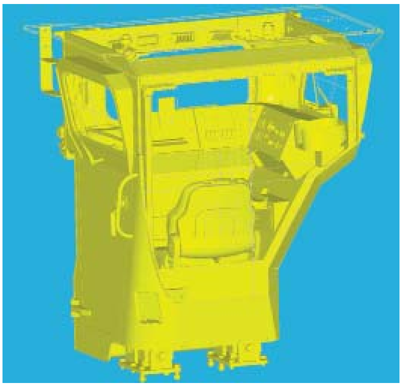


Figure 7. Computational fluid dynamics (CFD) simulation can be executed at the very beginning of the product development cycle to provide detailed information on air conditioning properties from the user's perspective even if no physical models of the cabin exist. The resulting air flows, thermal comfort, window fogging and hazardous silica dust dispersion to breathing zone of the operator can all be visualized in 3D.

The AMP is used here for cabin noise modelling, but it has also been customized for various fixed engine applications and even outdoor noise applications, most recently for noise modelling of wind turbines. AMP noise profile parameters include engine and other rotating mechanical system acoustical order structure, levels and phases, as well as, similar parameters for auxiliary mechanical systems, such as cooling, turbo and hydraulics. Furthermore, broadband noise is parameterized whenever applicable, and otherwise modelled based on a steady-state empirical model. **Due to the parameter-based design, changes in parameters also cause real-time changes in the rendered audio.**

The noise profile parameters can be extracted from the measurements or noise recordings. For this extraction, automatic and semi-automatic tools have been generated. Parameters from the numerical models can also be used if they can be generated. The AMP also visualizes engine orders and generated noise, and the visualization parameters can also be sent back to the VE. Each order contribution is visualized in real time, as well as the overall noise spectrum. Individual narrowband or broadband components can be turned on and off to evaluate their noise contribution.

An example AMP for cabin noise generation is presented in Figure 6. Here, the main sources of noise are engine orders, hydraulics orders, engine broadband noise and ventilation noise. All of these are affected by various parameters coming from external VE source, such as dynamics solver. The noise level and sound quality parameters are also calculated and are available in the model or as outputs to VR software.

Air conditioning in a virtual cabin – more than just temperature control

Detailed information on air flows and other cabin air conditioning related phenomena can be obtained using computational fluid dynamics (CFD). For example, **air flow patterns, thermal comfort, window fogging and dust dispersion inside the cabin can be determined computationally without a physical model of the cabin,** as demonstrated in Figure 7. The cabin geometry and details such as the location of supply air inlets can be varied and the effects of the

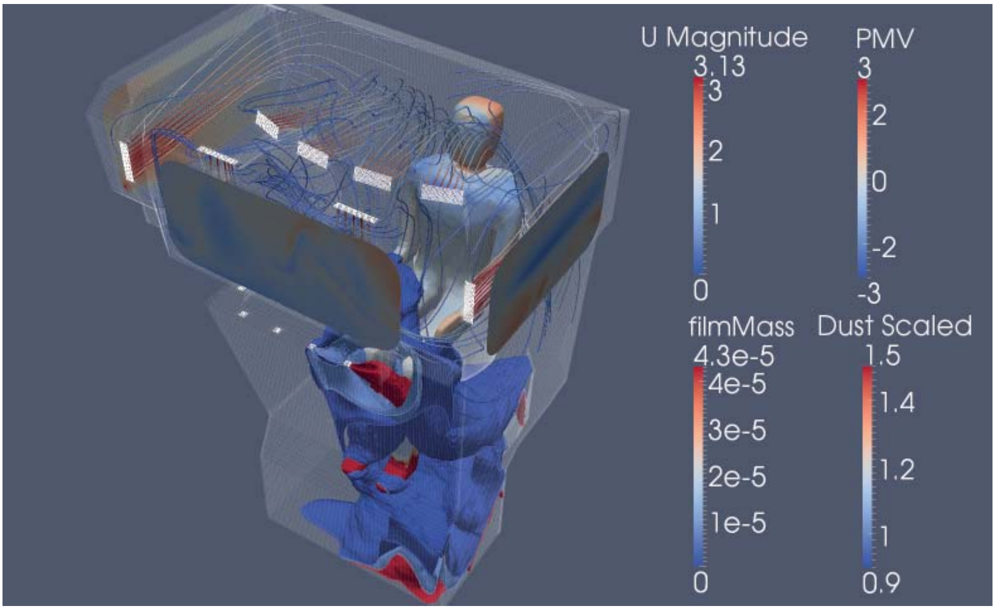


Figure 8. The result of an air conditioning simulation comprising the evaluation of thermal comfort, window fogging and dust dispersion from floor by air flows. The experienced thermal environment (average over a group of people) is represented by PMV (predicted mean vote) ranging from cold (-3) via neutral (0) to hot (+3). Humidity originating from the operator, wet floor and supply air inlets, dispersed and condensated on the windows, is visualized by the variable filmMass (kg/m²/s). The dust concentration dispersion from the floor is visualized by constant concentration contours. Instead of analysing absolute concentration values, the resulting concentration values are normed to the uniformly dispersed concentration; for example, a scaled concentration of *dust scaled* = 1 corresponds to the dust concentration if it would be uniformly mixed throughout the whole air volume of the cabin.

changes can be estimated. All of this can be carried out at the very beginning of product development, providing much more detailed knowledge of the system compared to what physical models alone would provide.

The UX related to air conditioning is highly dependent on cabin airflow patterns, which in turn are dependent on, for example, the geometry of the cabin. Detailed data on the steady-state flow field (i.e. velocity, pressure, temperature, etc., values in each spatial location) are obtained from the CFD calculation. In the standard procedure of CFD, the domain of interest, here a work machine cabin, is divided into a grid of small computation or control volumes over which the Navier–Stokes equations are solved numerically, resulting in 3D data for the flow field. The thermal comfort of the operator can be evaluated by applying this CFD data to Fanger's thermal comfort model. Thermal comfort is determined based on six parameters: air temperature, air velocity, mean radiant temperature, relative humidity, metabolic activity level and clothing of the human. The comfort indices are widely used and have reached the status of normative reference (ISO 7730). The classical comfort indices are suitable for representing conditions in an enclosed space provided that fairly uniform conditions hold. However, the airflow in a cabin environment does not satisfy the assumptions of uniform conditions. Contrary to Fanger's original method, heat exchange is modelled by CFD methods and the actual flow properties provided by the CFD calculation are used to determine the comfort indices. In addition, fogging of the cabin windows can be modelled by solving the dispersion of water vapour inside the cabin and by solving the condensation onto the window surface. Furthermore, the transport of hazardous silica dust into the breathing zone of the operator can be modelled by solving the dispersion of dust from the floor due to air flows. In some cases, such as an underground loader, the cabin floor can become covered with sand containing hazardous quartz (SiO2) dust particles. An example of air conditioning simulation is shown in Figure 8.

Empowering manual work with augmented reality

According to Eurostat [6], in 2012 15.7 million people[1] were involved in high-knowledge manual work in Europe, mainly as plant and machine assemblers and operators. Numerous industry sectors depend on the knowledge and skills – such as satellite assembly, nuclear reactor maintenance, operation of complex machinery, design and manufacturing of highly customized products – of their manual workers. In these sectors, manual work constitutes the core operations and cannot be off-shored or easily automated.

The EU-funded ManuVAR project coordinated by VTT [7, 8] developed a new system with the potential to significantly improve productivity and working environments across Europe. The project combined product life cycle management, ergonomics, and virtual and augmented reality (VR and AR) technology.

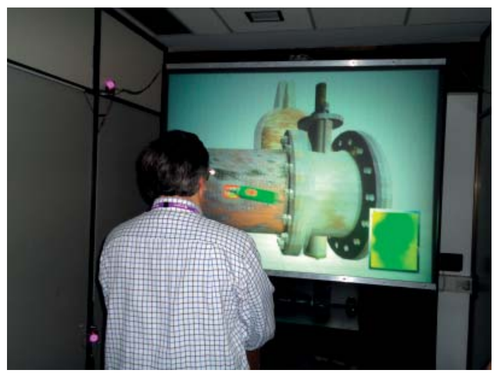
The following four main results were achieved by the project.

1. *Most prominent problem areas* faced by European industries in the context of high knowledge high value manual work:
   * Hindered communication across various actors throughout the life cycle.
   * Poor interfaces with complex CAD and information systems.
   * Inflexible design processes – feedback from later life cycle stages is difficult to utilize in design improvement.
   * Inefficient knowledge management – substantial employee know-how not utilized in system design and improvements.
   * Low productivity of manual work due to poor overall system design.
   * Lack of acceptance of supporting technologies, especially virtual and augmented reality technologies, in industrial contexts.
   * Physical and cognitive stress of manual workers, could be minimized by a better system design.
2. *Five industrial cluster cases* including performance criteria for the evaluation of laboratory trials and factory-floor demonstrations, business analysis, economic impact forecast, training and technology transfer plans:
   * *Cluster 1: Support of Spacecraft Assembly*. Develop and validate critical procedures in VR that can be used to support integration assembly activities through AR instructions.
   * *Cluster 2: Manufacturing design for SMEs.* Support assembly line workers by means of an automatic work load evaluation tool and reduce learning time by means of an operator navigation tool.
   * *Cluster 3: Remote support in train maintenance.* Support the maintenance of complex systems by exploiting the benefits of AR technology and reinforcing communication between actors involved.

[1] Total obtained for EU27 countries from the referred table "Employment by sex, age, professional status and accupation" as of 04-07-2013, by selecting industry category (ISCO) "Plant and machine operators, and assemblers", data for 2012.

Contextual instruction delivery: AR, tracking; remote and local versions

Ergonomics evaluation: automatic physical and cognitive load analysis, full body motion capture



Task analysis and procedure validation: hierarchical task analysis, VR with haptics

Motor skill training: VR with haptics, precision teaching theory

Figure 9. ManuVAR application tools. Source: ManuVAR consortium.

   * *Cluster 4: Training for industrial plant maintenance.* Training for metallographic replica activities using VR with visual, audio and haptic interaction.
   * *Cluster 5: Design and maintenance of heavy machinery.* Assembly and maintenance design reviews and instructions.
3. *System architecture* characterized by the following features [9]:
   * *Bi-directional communication* throughout the system life cycle (e.g. worker feedback to designers, designer recommendations to workers) is accomplished by means of a 'virtual model'. The virtual model plays the role of communication mediator – a single systemic access point to a variety of system data, information and models for all users in the life cycle – accessed as an integral system by 'virtual experiments';
   * *Adaptive VR/AR user interfaces* to the complex virtual model, suitable for all actors in the life cycle: from workers to engineers to managers. The VR/AR interfaces are implemented by component reconfiguration with low-delay middleware (haptics, tracking, VR/AR

visualization, application logic, connection to PLM systems);

* *Four groups of ergonomics methods* covering the principal ways of improving manual work from the system-cybernetics perspective: workplace design, ergonomics evaluation, instruction delivery, and training;
* *Knowledge management concept* based on Nonaka's organizational knowledge creation theory, with each modality of knowledge creation supported: externalization and internalization (adaptive and natural user interfaces with VR/AR), socialization (bi-directional communication and the virtual model), and combination (linking in the virtual model and connection to PLM systems).

4. *Four reconfigurable application tools,* which can be combined together via the virtual model to solve a given industrial case, were designed, implemented and evaluated in the laboratory and in the company environment, Figure 9.

The ManuVAR system was demonstrated in all five project clusters. Around 110 workers, engineers, managers and customers from 23 external companies were also included in the project. The feedback was constructive and indicated considerable interest from the industry:

- 'I think training could be performed in less time, reducing the "in-class" training of trainers, and so be much more efficient with ManuVAR'.
- 'Operators will be more open to recording and analysing their postures and movements. Giving immediate results and feedback will probably encourage them to change their postures and movements'.
- 'Connection to the company PDM would make it possible to use simulations and modify data models using an innovative recursive process rather than the normal waterfall approach'.

Towards user experience design

The multidisciplinary UX based approach to cabin design implemented in the eEngineering programme appears, based on the first version integration alone, to be highly promising. The results also appear generalizable to the transportation and manufacturing industries. In the future, finding ways for reliable evaluation of comfort continues to be challenging as well as overcoming technical constraints of virtual reality systems that may limit the realistic user experience. Nevertheless, the presented approach to cabin design is very beneficial due to its holistic approach to these complex socio-technical systems.

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Aromaa, S., Leino, S.-P., Viitaniemi, J., Jokinen, L. & Kiviranta, S. 2012. Benefits of the use of Virtual Environments in product design review meeting. International Design Conference, Dubrovnik, Croatia, May 2012, 21–24. 8 p.

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Impacts of eEngineering 2009—2012

Inputs	• The volume of the programme EUR 31 million, approximately 250 person years. o The annual budget varied between EUR 7-9 million. • The programme consisted of ca. 130 projects: o 43 contract research projects, with total revenue of 6,1 M€. o 63 public and jointly funded projects, totalling 18,4 M€ (13,6 M€ external funding and 4,8 M€ VTT's own funding). o 15 of the joint projects were funded by EU (with EU revenue 3,7 M€). o 11 of the joint projects were carried out in the context with SHOK's (Strategic Centres for Science, Technology and Innovation) and 9 projects in the context with SAFIR (Finnish public research programme on nuclear power plant safety), while others were funded directly by Tekes or Academy of Finland. o 30 projects self-funded by VTT with total revenue of 6,7 M€. o Included in the above figures, there were three multi-million project clusters of several industrial and university partners, each contributing with their own resources.
Out-puts	• Several successful technology transfer actions, for example, o 87 licensing agreements involving simultaneous process development with the client o Contracts with 5 big industrial customers, reflecting the commercial relevance of programme themes o Formation of 2 alliances of private and public partners • 5 invention disclosures • 1 start-up company (Semantum) • Altogether ca. 40 technical and scientific (10) publications, including peer reviewed scientific journals, international conference papers, and VTT publications. • Development and release of the SIMANTICS platform, an ontology based integration environment for modelling and simulation, that enables the linking and co-use of models of different levels of details through different viewpoints to the models and transformations between engineering (CAD) information and simulation models. • Simantics Constraint Language (SCL) for transformations between engineering and simulation components' data models within SIMANTICS. • Development and release of several other simulation and engineering tools • 2011 Automation award of the Finnish Automation Society to VTT's Simantics team • 2010 VTT Award to Research Professor Tommi Karhela for outstanding work on the Simantics platform

Highlighted examples	In terms of the SIMANTICS platform: • New release of VTT's Apros ver. 6 (software for modelling and dynamic simulation of processes and power plants) built on top of SIMANTICS 1.6. • Integration between the Siemens Comos engineering system and the Apros simulator via SIMANTICS. • Integration of the Intergraph SmartPlant design system and the Apros simulator. • Integration between an automation CAD program and the Apros simulator. • Integration of modelling and simulation capabilities utilising Modelica simulation language, especially for mechanical engineering purposes, to SIMANTICS. • Design and implementation of a multibody system (MBS) modelling and simulation environment demonstrator. The demonstrator utilises brings together the 3D geometry modelling and visualisation capabilities of CAD software and the OpenModelica language. • Integration of a best in class life-cycle analysis (LCA) software, KCL-Eco, to SIMANTICS. Due Thanks to SIMANTICS, additional capabilities are enabled, e.g., connections to process simulators, interfaces to industrial design systems and databases, possibility to use user-interfaces of other engineering tools, and multi-user support. In terms of virtual design environment: • Integration of model checking to SIMANTICS. A more efficient and reliable model checking enabled together with ability to verify the correctness of larger systems than before. • Implementation of the whole design chain of mobile machine cabins in comprehensive virtual environment; regarding visual appearance, thermal conditions, and sound or vibration experiences. • Modelling, simulation and control of the entire exhaust tube of a combustion-engine as a noise or vibration source, in all audible frequencies to manage better the noise properties and user experience.
People & networks	• The most significant industrial partners in the programme have been Fortum, Wärtsilä, and Metso. In joint projects the sphere of partners consists of dozens of firms. • The open source SIMANTICS platform is today hosted by Simantics Division of the THTH Association of Decentralized Information Management for Industry with 25 industrial and academic members . • Linkoping University and Modelica Association (Simantics, mechanical engineering) • Royal Institute of Technology (machine modelling) • Luleå University of Technology (automation, Artemis activities, ProcessIT. EU –strategy) • Steering Group of the programme: Rauno Heinonen, Risto Kuivanen, Tuomo Niskanen • Core team of the programme: Olli Ventä (programme manager), Ismo Vessonen, Riikka Virkkunen, Tommi Karhela, Timo Määttä, Teijo Salmi

Series title and number
VTT Research Highlights 8

Title	eEngineering 2009—2012. Digitising the product process
Author(s)	Kaisa Belloni and Olli Ventä (Eds.)
Abstract	In addition to industrial production, the success of Finnish industry is based strongly on the design and engineering of devices, working machines, manufacturing plants, power plants, process machinery and ships for global markets. At the same time, digitisation has become ever more vital to the success of industrial production and engineering and the volume, value and importance of the digital, virtual realm is increasing dramatically compared to physical plants and machines. At the beginning of the 2010s traditional heavy industry accounted for 75% of the total value of Finnish exports, up notably from 57% in 2000. To reduce the design and production ramp-up times by half, VTT's eEngineering spearhead programme (2009-2012) developed technology platforms for modelling and simulation, design knowledge management, life-cycle management, and human-technology interaction. The highlights of the research carried out during the programme are presented in this publication. The most significant achievement of the programme is Simantics, an extensive operating system providing an open, high-level application platform on which different computational tools can be easily integrated to form a common environment for modelling and simulation. Programme also enabled successful integration of user's sound and noise experience and thermal comfort modelling to the design of machine cabins in a virtual design environment.
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eEngineering 2009—2012

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