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Towards a simulation-based product process

SIMPRO research project final report

Juha Kortelainen (editor)

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Preface

Digital design and virtual engineering are nowadays the means for efficient machine design and product development. However, the full potential of the simulation-based approach has not been exploited.

At the time of writing this SIMPRO project final report, Finland is going through a period of economic recession, and all the sectors are trying to find ways to correct the situation. Industrial production and its challenges have been found to be one of the causes but probably also the cure. The overall system around commercial products and goods is complex and somehow touches all aspects of society, including public research and development. Research and development do not alone provide solutions for the economic recession, but are valuable tools in the solution, which will require actions in many areas of society. Investing in what we are already storing, adopting the latest methods, tools, and processes, and thinking more "outside the box" could be the ways to start the healing process. A digital design and virtual engineering approach is an opportunity for the Finnish mechanical industry, but also for the software and service providers, to find the way to success together.

The SIMPRO project was a multi-dimensional and multi-layered research effort. The project group contained several research parties and companies from industry, as well as from the service and solution providers sector. From the research topics point of view, the same multi-dimensional approach continued and the project focused on research on topics from small details in computational engineering to large product life-cycle processes. The idea behind this approach was to go into detail in some areas of the computational approach, to accelerate the development and to gather information about the development needed to achieve the industrially applicable level, and, at the same time, to illustrate the big and still forward-looking vision of the simulation-based product process.

This SIMPRO final report is just one of the deliverables of the research project and does not try to cover everything done in the project. We hope that the report will serve as an introduction to the research themes in the project, and as a reference source for detailed information.

Juha Kortelainen,
The project manager of the SIMPRO project

Contents

List of abbreviations

3D	Three dimensional
ACO	Ant colony optimisation
AI	Artificial intelligence
ANSI	American National Standards Institute
BCG	Bond/causal graph
BEM	Boundary element method
BF	Bacteria foraging
CA	Cultural algorithms
CAD	Computer-aided design
CAE	Computer-aided engineering
CAN	Controller area network
CFD	Computational fluid dynamics
CPU	Central processing unit
CSA	Clonal selection algorithm
DA	Dimension analysis
DACE	Design and analysis of computer experiments
DACM	Dimensional analysis conceptual framework
DAKOTA	Design analysis kit for optimisation and terascale applications (Dakota optimisation toolkit)
DC	Deterministic crowding
DE	Differential evolution
DEM	Discrete element method
DM	Decision maker
DMM	Domain-mapping matrix
DNS	Direct numerical simulation

DOE	Design of experiments
Dof	Degree of freedom
DRMS	Distributed resource management system
DSM	Design structure matrix/complexity management
DUAL-HS	Dual memory harmony search
ERP	Enterprise resource planning
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FSI	Fluid-structure interaction
GA	Genetic algorithm
GIM	Generic Intelligent Machine
GMRES	Generalised minimal residual method
GNU	“GNU's not Unix”
GPL	General Public License
HIL	Hardware-in-the-loop
HNIC	Hybrid nature-inspired computing
HPC	High-performance computing
HS	Harmony search
IFC	Industrial foundation classes
IHA	Intelligent Hydraulics and Automation
I-SIBEA	Interactive simple indicator-based evolutionary algorithm
JYU	The University of Jyväskylä
KE	Knowledge engineering
LAMMPS	Large-scale atomic/molecular massively parallel simulator
LIGGGHTS	LAMMPS improved for general granular and granular heat transfer simulations
LSA	Latent semantic analysis
LUT	Lappeenranta University of Technology
M&S	Modelling and simulation
MAC	Modal assurance criterion
MBS	Multibody system
MBSE	Model-based systems engineering

MC	Memetic computing
m-HS	Memetic harmony search
MLFMA	Multilevel fast multipole algorithm
n-HS	New harmony search
NIC	Nature-inspired computing
NL	Natural language
OBL	Opposition-based learning
PBIL	Population-based incremental learning
PC	Personal computer
PLM	Product life-cycle management
PSO	Particle swarm optimisation
R&D	Research and development
ReqIF	Requirements interchange format
RMP	Reusable modelling primitives
R-NSGA-II	Reference point non-dominated sorting genetic algorithm-II
SA	Simulated annealing
SBSE	Simulation-based systems engineering
SDM	Simulation data management
SE	Systems engineering
SEAModel	Systems engineering artefacts model
SLM	Simulation life-cycle management
SLURM	Simple Linux utility for resource management
SVD	Singular value decomposition
TIM	Traceability information model
TS	Tabu search
TUT	Tampere University of Technology

1. Introduction

SIMPRO research project
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This is the final report of the Tekes research project *Computational methods in mechanical engineering product development* – SIMPRO. The Tekes project type of the SIMPRO project was "*public research networked with companies*". Tekes defines the objectives of this project type as: "*The aim of public research networked with companies is to achieve competence and results that can be used as a springboard for the companies' own research and development projects*" [1]. The SIMPRO project combined basic and applied research, focusing on new openings, as well as transferring the existing research results to be applied in industry and business. In addition, the project provided a good framework for researchers to gather more understanding of the operating environment of both the industry and within the software and service providers' layer.

1.1 Background

The application of computational methods and tools has been a common practice in industry for several decades. Digital design and engineering, generally known as computer-aided design (CAD) and computer-aided engineering (CAE), are well-known concepts, and the variety of software applications and systems for these is wide and solutions from low budget to demanding, and thus usually expensive, software applications and systems are available. However, the extensive utilisation of these methods is not very common in Finnish industry, even though there have been several large public research programmes in Finland, such as the Tekes VÄRE [2], MASINA [3], and MASI [4] programmes. Reasons for the slow application of extensive utilisation of the computational approach in product design and engineering has been deliberated in several research projects, but no single reason has been found. Possible reasons for this include fast development of the software applications and systems, and, on the other hand, slower development of the processes of applying a computational approach in organisations.

The benefits of using a computational approach both in research and development (R&D) and in design and engineering are numerous. Often, the main motivation is to save money in product development or to get the necessary new knowledge about the system under development without building a prototype. Others include improving the ability to implement a concurrent engineering process or gaining more knowledge about the details of the product or system under development. A computational approach, including modelling, simulation, and computational analyses, provides a good means of optimising a multi-objective challenge in a product process: to design high-quality products, to get them to the markets quickly, and to minimise the design and engineering costs.

The software application and system offering for computational engineering is wide, and typically there are several similar options for one modelling and simulation task. For example, for structural analysis and multibody system simulation, there are more than ten commercial software products available. In addition, there are several dedicated software applications for structural analysis pre-processing. A natural conclusion from this is that the individual modelling and simulation technologies for, for example, structural analysis or multibody system simulation are already mature. This is, indeed, the situation with many leading software application solutions in the engineering markets. The maturing of the engineering tools indicates that the modelling and simulation technologies for product development are saturating – the technology s-curve has reached its later slow development phase (see Figure 1). On one hand, the SIMPRO research project aimed to show that numerous mature technologies and software applications exist for most of the practical areas of computational engineering, but on the other hand, the project aimed to illustrate the directions where more focus should be put and which are most likely to become the central areas of future technology progress in computational engineering.

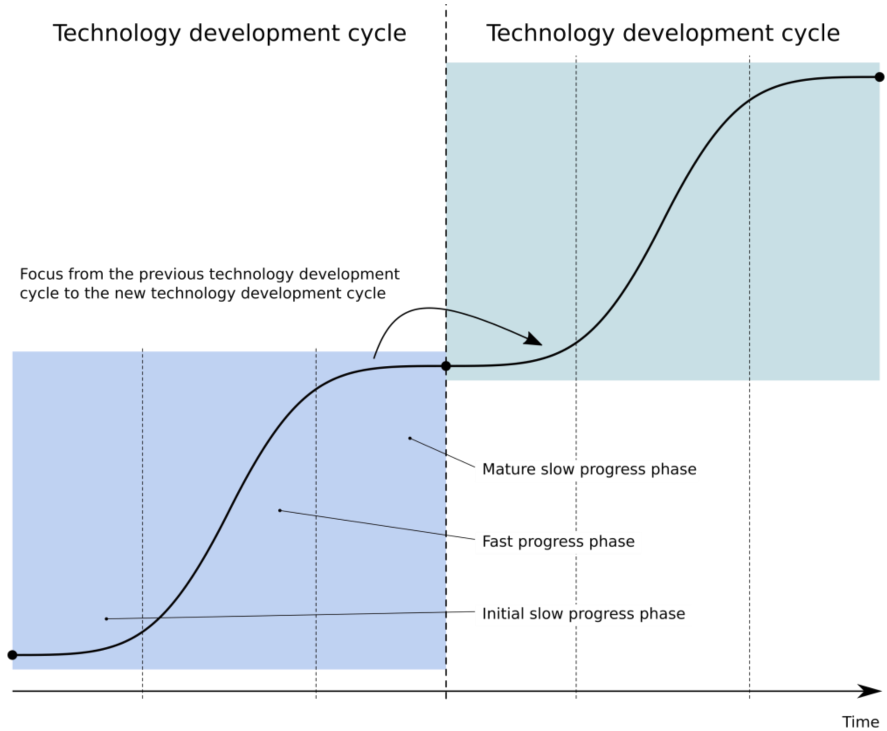

Figure 1. Technology development progress s-curve. Moving from a mature technology development cycle to a new one.

The evolution of the application of simulation in the product process is illustrated in Figure 2. In the first phase, modelling and simulation are used in the product process for solving specific problems in some product detail, but the product development is done following traditional design methodologies. In other words, simulation is used in product development, but the development is driven by other factors. In the second phase, the whole product or large sub-systems of the product are modelled and simulated, and so-called virtual prototypes are used in the process. This phase increases the requirements of the simulation technology compared to the first phase, but the design is still driven by factors other than the application of computational methods. In the third phase, the modelling and simulation technology used in the process may remain the same compared to the second phase, but the process itself is changed. Instead of applying traditional product development methodology, a simulation-based approach is used. In this approach, the product is first modelled and simulated using relatively coarse models, and then designed based on the information received from the simulations. This simulation-based approach often requires major changes in the process and is thus difficult to implement. The fourth phase is the application of the simulation-based approach to the management of the whole product life-cycle. In addition to applying modelling and simulation to the product development, the influence of the design decisions on, for example, the environment and the selected business model are also estimated. The development trend from using simulation in product development to the simulation-based product life-cycle process sets high demands on computational systems, including both hardware and software systems, and data management. On the other hand, connecting optimisation methods to the simulators enables efficient use of the available computational resources and may be the key to success and superior position in the markets, due to shortened time-to-market in product development, more efficient utilisation of resources, and better understanding of the product life-cycle aspects [5].

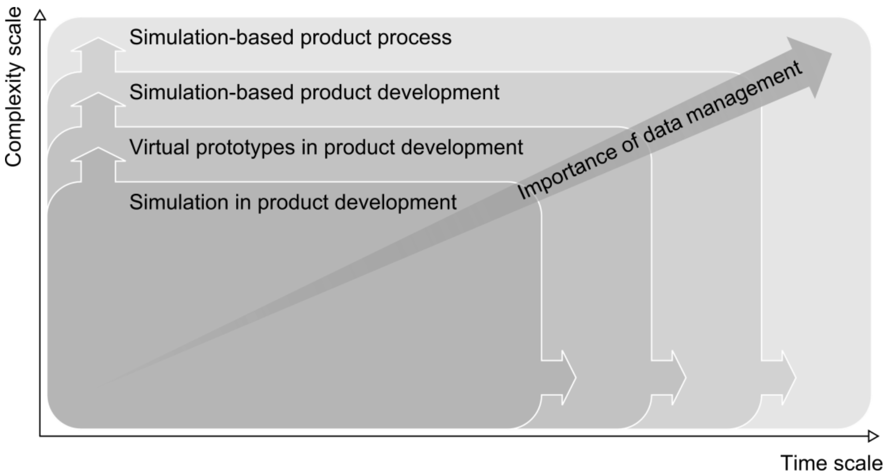

Figure 2. Evolution of the application of simulation in the product process and the increase in the importance of data management [5].

1.2 Objectives and scope

The main objective of the SIMPRO project was to lower the step to utilising computational methods – including single complex simulations and analysis, and large series of computations – in large-scale computations using efficient and convenient computational systems, tools, and practices. In other words, the project aimed to provide high-performance computing (HPC) for every design and research engineer in the office. This is necessary for implementing simulation-based product design at full scale. In addition, the project aimed to study how the product process should be changed and how the computation approach could be utilised in such a way that it provides optimal added value for the whole product life-cycle.

The SIMPRO research project focused on the different aspects of the simulation-based product process, including:

1) **High-performance computing in mechanical engineering:** In this topic, the focus is on computational infrastructure, including hardware systems, compu-

tation management systems, software applications for HPC, and useful tools and utilities.

2) **Optimisation, design studies, and analyses:** Optimisation is the natural next step in automating product design phase analyses. In this topic, using automated analyses, such as optimisation and parameter studies, is the main focus. These types of computational analyses typically require a large number of individual analyses to be run.
3) **Requirement- and customer-based product development:** Computational methods are well suited when applying a requirement and user-based development approach. In this topic, utilisation of modelling and simulation, both offline in multi-domain simulation and in real time in virtual environments, is the main focus. In addition, the application of a requirement-based design process with a simulation-based approach is studied.
4) **Modelling and results data management:** Large-scale application of computational methods in product development and in the product process in general leads to the challenge of managing the modelling and simulation data and integrating computational tools and systems. In a distributed operating environment, such as a subcontracting chain, this may become a complex challenge. This inevitable area in the simulation-based product process is the main focus of this topic.

The scope of the project was very wide, which made it challenging to keep the “big picture” clear for the project participants during the active research phase. The project was able to cover many important detailed topics in the overall scope, and thus provide knowledge about the building blocks of the “big picture”. The development of the “big picture” will take more time, and industrial-level applications and solutions of it are to be available after several years of development and productising.

1.3 Project structure

The project was organised in a similar manner to research programmes, meaning that the project contained several relatively independent and clearly bounded subprojects that focused on one or more of the SIMPRO project’s main focus areas. The SIMPRO subprojects were:

- **Subproject Aalto 1** (Aalto University): *Analysis and validation of requirements as networks and an enterprise search engine for product development*.
- **Subproject Aalto 2** (Aalto University): Hybrid nature-inspired computing methods in optimal electrical machine design.
- **Subproject Aalto 3** (Aalto University): *Enhancing finite and boundary element methods for efficient high-performance computing*.
- **Subproject JYU** (University of Jyväskylä): *Enhanced multiobjective optimisation algorithms for computationally expensive problems*.

- **Subproject LUT** (Lappeenranta University of Technology): *Development of a generic description of the structural flexibility for real-time multibody simulation*.
- **Subproject TUT 1** (Tampere University of Technology): *Structural optimisation in automated product design*.
- **Subproject TUT 2** (Tampere University of Technology): *Utilisation of simulation data to support the maintenance of mobile work machines*.
- **Subproject VTT** (VTT Technical Research Centre of Finland Ltd.): *Computational methods in mechanical engineering product development*.

The subprojects covered many of the main areas of the product life-cycle, but because the project life-cycle itself is a large concept and the variety of approaches is very wide, only some glimpses of the overall product life-cycle could be covered. Even so, the project gave a good conception about the possibilities of the computational approach in different phases of the product life-cycle.

1.4 Report scope and structure

This final report of the SIMPRO research project is an overview of the research topics and a reference to the detailed research results. The structure of the report follows the structure of the project so that each subproject has its own section with a brief description of the research focus and methods, and the highlights, discussion, and conclusions of the research results. The report is organised as follows:

- **Introduction:** Illustration of the background and a general introduction to the topics, objectives, and scope of the SIMPRO research project.

- **Analysis and validation of requirements as networks and an enterprise search engine for product development (Aalto 1):** The main topics are 1) supporting the requirement engineering process via modelling, analysis, and search for contradictions and conflicts within requirements, and 2) increasing productivity in product development via knowledge extraction, classification, and mining leveraging in a commercial enterprise search engine.

- **Hybrid nature-inspired computing methods in optimal electrical machine design (Aalto 2):** The focus is on the hybridisation of various nature-inspired computing (NIC) methods and the applications of these methods in design and engineering.

- **Enhancing finite and boundary element methods for efficient high-performance computing (Aalto 3):** The focus is on the enhancement of the existing finite and boundary element methods for solving wave problems, mainly in acoustics, and coupled problems in mechanical engineering.

- **Enhanced multiobjective optimisation algorithms for computationally expensive problems (JYU):** The focus is on studying the existing algorithms and approaches for applying multiobjective optimisation in design and engineering, especially in computationally expensive cases.

- **Development of a generic description of the structural flexibility for real-time multibody simulation (LUT):** The focus is on studying existing methods and techniques and implementing a research prototype for method testing.
- **Structural optimisation in automated product design (TUT 1):** The focus is on the development of procedures for automated product design using various optimisation techniques together with structural analysis.
- **Utilisation of simulation data to support the maintenance of mobile work machines (TUT 2):** The focus is on fault identification by utilising the simulation data created in the design phase of the machine.
- **Computational methods in mechanical engineering product development (VTT):** The focus is on all four topics in the project, including 1) computational tools and systems, 2) optimisation and large computational studies, 3) requirements engineering in a simulation-based design process, and 4) simulation life-cycle data management.
- **Discussion:** A general discussion of the research themes of the SIMPRO research project and conclusions of the results. Discussion of the possible future research and development work towards the implementation of the concept of the simulation-based product process.

The project's official research deliverables are referenced in this report, and most of the deliverables are publicly available, either on the project's public website (http://www.vtt.fi/sites/SIMPRO) or from the scientific publishers' websites. The reference list for each subproject section is located at the end of the section, and the SIMPRO project deliverables are marked explicitly. The authors of the report sections are listed, together with their affiliations, at the beginning of each section.

1.5 References

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2. Analysis and validation of requirements as networks and an enterprise search engine for product development

SIMPRO subproject Aalto 1
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2.1 Introduction

Analysing the needs of stakeholders and, later on, managing them properly in a system development project is probably one of the most strategic parts of the system engineering process [6, 7]. Failure to achieve those goals puts the entire project at risk due to the inadequacy of the end result to meet user needs. In this context, the assistance of prototype tools can be precious for keeping attributes such as coherence and consistency within the needs, documented as requirements specifications. Tools for the analysis of requirement quality [8] and specifications should consider criteria such as similarities, hierarchy, and contradictions [9, 10] between requirements, among many other important criteria [11]. The subproject has tried to answer this need by developing approaches to analysing requirements presented in a natural language format [12] and tracing them [13].

The second aspect of interest in this subproject is going more into the detail of the data saved in enterprise resource planning (ERP) systems. In order to develop advanced search capabilities between technical data in an ERP system, interconnections between data has to be considered. The data are often technical data represented by their names, their units, and their position in a certain product architecture. The idea was to make use of this information to generate connections between those data. A framework has been developed in this report to answer this problem. The approach is intended for the specification of Reusable

Modelling Primitives (RMPs), building on Dimensional Analysis (DA), Bond/Causal Graph (BCG), and Design Structure Matrix/Complexity Management (DSM) formal methods.

The following sections present in more detail the research approaches and results obtained in this subproject.

2.2 Research methods

The first part of the subproject proposes a natural language processing [14] approach to analyse requirement quality [15], links, similarities, and contradictions [16, 17, 18], and to cluster them into the most common categories used in system engineering. After reviewing metrics and tools for the linguistic analysis of requirement quality [19, 20], this work presents a combined methodology, integrating different methods, able to automatically cluster requirements in different categories, and able to suggest the nature of relationships between requirements, represented in the form of a network. Two different methods for requirement clustering are compared and combined in this work (i.e. LSA, using a keywords matrix, and a cosine matrix). The authors claim that the proposed methodology and network presentation not only support the understanding the semantics of the requirements, but also help requirement engineers to manage requirements [21]. The prototype tool supporting the methodology is exemplified through a case study of requirements for an air defence system. This work concludes with the relevance of such prototype tool support for analysing requirement models and presents future research developments.

The second part of the subproject is developing a model specification framework. The framework paradigm is demonstrated using a rudimentary system exemplar (the legacy model), for which a set of model intended uses are declared. Reuse of the framework is demonstrated similarly using an alternative exemplar and model intended uses that take advantage of the RMPs from the legacy model.

The framework analyses early design problems and transforms the problem step-by-step into a set of DSM and DMM matrixes populated by numbers that reveal knowledge gaps. Those matrixes constitute a “finger print” [22] of the problem space and conceptual design (i.e., conceptual model) of the solution space (i.e., simulation environment). DA is used to extract the behavioural laws of the conceptual solution under investigation. Causal graphs are used to model the architecture of the system. An ontology has been developed to capture the knowledge associated with the modelling process.

The “finger print” [22] of the problem space [23] can be used to specify the requirements of the problem in a compact manner. It can be used later to validate the solution produced. The framework is developed upon three fundamental pillars: dimensional analysis theory, bond graph, and DSM. Those pillars are briefly presented below.

2.2.1 Dimensional analysis theory (DA)

Dimensional analysis proposes an approach for reducing the complexity of modelling problems to the simplest form before going into more detail with any type of qualitative or quantitative modelling or simulation [24, 25]. Dimensional analysis theory (DA) has been developed over the years by an active research community that includes prominent researchers in physics and engineering [26, 25]. The fundamental interest of dimensional analysis is to deduce from the study of the dimensions of the variables (i.e. length, mass, time, and the four other dimensions of the international system of unit) used in models, certain constraints on the form of the possible relationship between variables.

For example, in the most familiar dimensional notation, learned in high-school or college physics, force is usually represented as M.L.T-2. Such a dimensional representation is a combination of mass (M), length (L), and time (T). The Newton law $F = m \cdot a$ with *F* (force), *m* (mass), and *a* (acceleration) is constrained by the dimensional homogeneity principle. This dimensional homogeneity is the most familiar principle of the dimensional analysis theory and can be verified by checking the dimensions on both sides of Newton's law. This is exemplified in Table 1 below.

Table 1. Dimensional homogeneity principle.

Newton's law	***F***	**=**	***m · a***
Dimension homogeneity principle	[MLT-2]	=	[M].[LT-2]

The other widely used result in dimensional analysis is Vashy-Buckingham's Π-theorem, stated and proved by Buckingham in 1914 [24, 26, 27]. This theorem identifies the number of independent dimensionless numbers that can characterise a given physical situation. The method offers a way to simplify problem complexity by grouping the variables into dimensionless primitives. Every law that takes the form $y_0 = f(x_1, x_{2,} x_3, \dots, x_n$ can take the alternative form:

$$\Pi_0 = f(\Pi_1, \Pi_2, \dots, \Pi_n) \tag{1}$$

Π_i are the dimensionless products. This alternative form is the final result of the dimensional analysis and is the consequence of the Vashy-Buckingham theorem.

A dimensionless number is a product that takes the following form:

$$\Pi_i = y_i \cdot \left(x_1^{\alpha_{i1}} x_2^{\alpha_{i2}} x_3^{\alpha_{i3}}\right) \tag{2}$$

where $x_i$are called the repeating variables, y_i are named the performance variables, and α_{ij} are the exponents.

Equation 2 presents the dimensionless form of the primitive (i.e. Reusable Modelling Primitives, RMPs) used intensively to develop the framework presented in this research work. Examples of those primitives are present in multiple domains of science. For instance, the efficiency rate, the Reynolds number, and the Froude number are some examples of famous dimensionless primitives. The approach can also be used to model and simulate the behaviour of complex systems, [28]. The dimensionless groups are computed following the Szyrtes and Butterfield approaches [29, 30]. Coatanéa has further developed the approach in his work [31]. The approach can also be used in other fields, such as economics [32].

2.2.2 Bond graphs (BG)

The bond graph modelling approach is a method conceived by H.M. Paynter from MIT in the 1950s [33, 34]. The bond graph approach is a domain-independent graphical description of the dynamic behaviour of physical systems. The system models are constructed using a uniform notation for all types of physical systems, based on energy flow. This is a powerful tool for modelling engineering systems, especially when different physical domains are involved. A bond graph is a form of object-oriented physical system modelling. The bong graph elements are decomposed into nine types of elements, listed in Table 2 below. More specific bond graph elements exist, not integrated into the table below.

Table 2. The nine most common bond graph elements and their connections.

Bond graph elements	Number of input connections	Number of output connections
Resistor dissipating (R)	1	1
Source of effort (Se)	1	1
Source of flow (Sf)	1	1
Capacitor storage element (C)	1	1
Inertia storage elements (I)	1	1
Transformer (TF)	2	2
Gyrator (GY)	2	2
Effort junction (Ej)	3	3
Flow junction (Fj)	3	3

To conclude this introduction to bond graph modelling language, the current research is using three fundamental elements of bond graph theory to develop the framework:

- the fundamental list of bond graph elements presented in Table 2 above
- the three fundamental categories of generic variables presented above
- the set of causal rules developed in bond graph theory.

2.2.3 Design structure matrixes (DSM)

A design structure matrix (DSM) is a manner of representing a graph. A good overview of DSM usage is provided by Eppinger and Browning [35]. A DSM is especially used to model the structure of a system or process. A DSM lists all the constituents of a system or the activities of a process, and the corresponding information exchange, interactions, or dependency patterns. The DSM was created by Stewart in the 1960s [36]. DSM compares interactions between elements of a similar nature.

A DSM is a square matrix (i.e. the same number of columns and rows). A DSM maps elements of the same domain. In the context of this report, a DSM can be used to represent a graph in a compact format [37].

Inside a DSM, different types of markings can exist to represent information. A connection can be represented by a cross “x” or by a “1”. Other markings can be used, for example, to represent other types of interrelations using a DSM. For example, a numeric scale can be used. This can represent the strength of a connection or a weight given to a connection.

Another kind of interrelation can also be analysed using matrixes. The mappings can also be done between elements of different natures, such as functions and components. Those interrelations are represented via another type of matrix, named a domain mapping matrix (DMM). A DMM is used to map elements belonging to different domains, for example function and physical sub-systems. A DMM is represented by a rectangular matrix and not by a square matrix. This difference later results in different issues to be solved if we want to use the battery of tools from linear algebra to process a DMM. Before processing a DMM, it is necessary to find approaches to transform it into square matrixes.

All those pillars are combined with the Design of Experiments in the DACM framework [38].

2.3 Results and research highlights

This short report summarises the results obtained in subproject 1 from Aalto. The first part describes the progress made in the different tasks of this subproject:

- task 1: modelling requirements as a network
- task 2: deployment of an enterprise search engine to support product development
- task 3: interoperability analysis.

2.3.1 Task 1: Modelling requirements as a network

This work proposes a process for analysing a set of requirements, where requirements are expressed in natural language (NL) [39, 40]. This work focused on the use of computational linguistic approaches applied to the field of system engineering. This is followed by a process representing requirements in graph form. Those graphs analyse similarities and contradictions within requirements [41]. This similarity process includes the coherent combined use of methods such as cosine similarity, singular value decomposition (SVD) [42], and K-means clustering [43]. The contradiction analysis [10] process includes a rule-based approach forming one of the contributions of this work. Finally, the combined results are presented as a graph, which unveils semantic relationships between requirements. This graph helps users to capture more easily semantic relationships between requirements in a document. It leads to efficient support during the requirement management phase. The proposed processes are validated using a case study, reflecting different levels of requirements abstraction (i.e. operational, capability, and system-level requirements). The nature of links (i.e. contradiction and similarity) is also visualised. Those elements form another contribution of this work. This case study was initially documented in IBM DOOR, and then this model was imported into our prototype tool. In the prototype tool, the methodology developed in this work was applied and the results presented in a graph. Finding and defining links between requirements requires data mining multiple sources of texts. A combination of multiple methods gives more accurate results, because it creates interdependencies and comparisons between processes. In this work, the authors start with a requirement elicitation process because, in a company, the sources of requirements and the forms of their documentation are multiple (i.e. email, notes, standards, etc.); and collecting those requirements on the same platform is an issue.

Considering the practical constraint related to the different sources of data, the process of this methodology (see Figure 3) starts with gathering requirements from different platforms (i.e. existing requirement management tools, Word documents, etc.). Requirements developed without any guidelines are more prone to defects. It is easier to analyse existing links between error-free requirements. Therefore, eliciting of requirements is followed by quality analysis. After quality analysis, the next steps of the proposed methodology of this paper consider three of the main requirement management qualities. These are listed below.

a. A requirement should be located in a relevant requirement category.
b. A requirement should not contradict other requirements describing the system for development.
c. Links or interactions between requirements should be considered and used during the requirement management process.

Other criteria related to requirement management can be added to this list. However, in this article, the focus is given to the three aspects listed above. The article contribution is based on those criteria. In order to implement those elements, the proposed methodology (Figure 3) includes the following steps:

- Step 1: Extraction of requirements from the documents.
- Step 2: Quality analysis of requirements document.
- Step 3: Semantic analysis of requirements and creation of links.
- Step 4: Graphical representation of requirement models.

Each of these processes, presented in Figure 3, is described in detail in the following sections.

The final step of the approach developed in this work consists of combining similarity analysis and contradiction analysis links and representing them in a common graph. In this graph, each node represents a requirement.

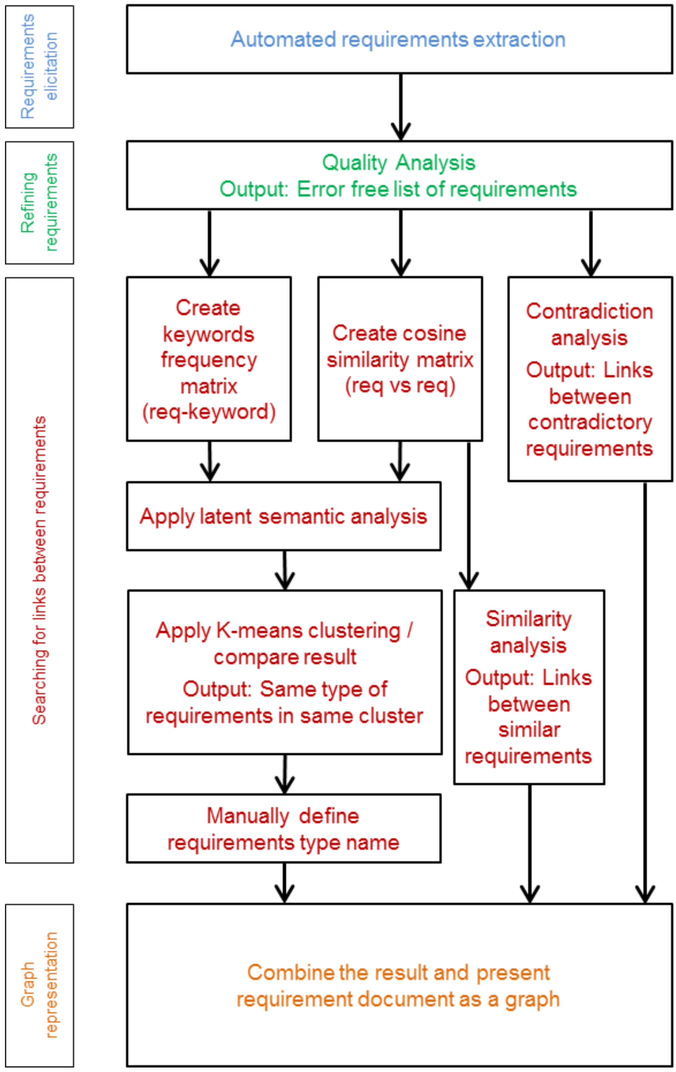

Figure 3. Block diagram representation of the proposed process (left: part of the requirement engineering process; right: the analysis process method proposed in this work).

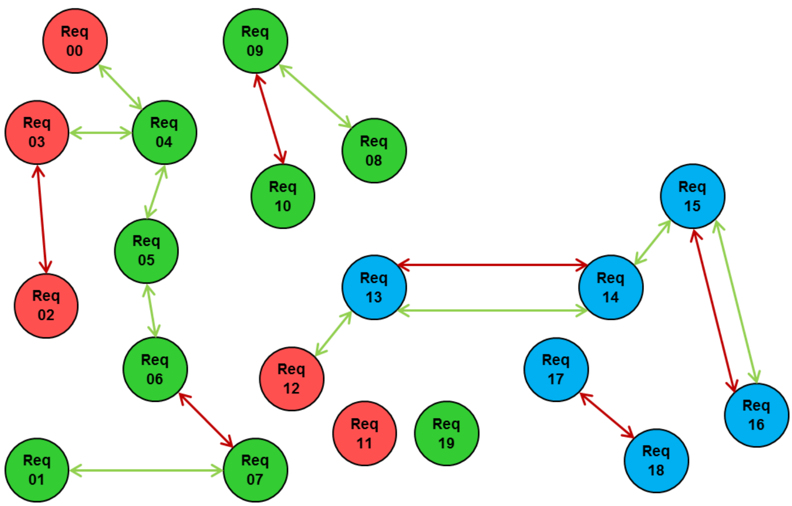

Figure 4. Graphical representation of requirements [44, 18, 37].

Figure 4, above, presents two types of links: similarity links and contradiction links. In the figure, each node (requirement) belongs to a certain group, represented by colours, representing the key clusters discovered with the K-mean approach.

2.3.2 Tasks 2 & 3: Deployment of an enterprise search engine to support product development and interoperability analysis

A benefit of the framework approach is as an enabler of expeditious high-level conceptual models that can be considered economically early in the planning phase of a project for the purpose of analyses of alternatives. A high-level conceptual model produced by the framework enables M&S systems engineers to locate and specify areas of the solution model where supplementary simulations or experiments are needed to increase the knowledge of the system under investigation. It is also possible to rank the specifications by impact level on the model.

A by-product of the framework investigation was the realisation that conceptual models produced in this manner reveal the significance of problem space variables in such a way that not only can the order of significance be determined, but design conflicts that restrict the solution space can also be identified.

The framework process may be summarised to include the following fundamental steps:

- description of the modelling and simulation problem context and objectives
- development of a functional representation of the problem
- mapping of the functional representation in a bond graph representation
- extracting the fundamental descriptive variables of the problem
- creating a causal ordering graph of the modelling and simulation problem
- generating the governing laws of the problem

- generating five categories of specifications for simulation models in a compact DSM format.

A proof-of-concept of the framework was demonstrated using two exemplars. Several prototype computer-aided tools were developed during the project, to support and automate the framework. The list of the tools and their functions is presented in Table 3 below.

Table 3. Different tools associated with the DACM framework produced in this work.

Tools names	Functions
Framework ontology	Capturing the knowledge associated with the framework and supporting the automatic extraction of problem variables
Causal ordering tool	Generating causally ordered graphs of problems
Pi number computing tool	Generating governing laws of complex systems
Problem comparator and extractor	Comparing simulation reusable model primitives (RMP) presented in the form of DSMs and a DMM

The framework developed in this research work has to fulfil three important characteristics:

1. being able to favour the slow and reflective mode of the brain [45]
2. using the natural tendency of the brain to classify the information in the form of cause-effects relationships [46, 47]
3. offering mechanisms to organise and simplify the complexity of the problem representation [48–50].

2.4 Discussion and conclusions

This short report summarises the results obtained in the Aalto 1 subproject. The tasks that were allocated to the Aalto 1 subproject were the following:

- task 1: modelling requirements as a network
- task 2: deployment of an enterprise search engine to support product development
- task 3: interoperability analysis.

Task 1 has generated multiple results. The project has enabled the automatic creation of a network of requirements presented as English sentences. The project has developed, tested, and validated approaches and methods to create clusters of requirements, and also to link automatically requirements by similarity and by type of conflict between requirements. The work has also enabled the development of an efficient new approach to supporting the automatic scheduling of tasks in a project [51].

Tasks 2 and 3 have focused on the modelling and analysis in form of complex networks. Variables stored in enterprise ERP systems can be organised in the form of networks with causal relationships for the variables belonging to common systems, or for variables sharing similarities with other projects. The automatic creation of causal relationships [37] and the comparison of projects commonalities have been the objectives developed in those tasks. It has also been decided to represent the data in the form of design structure matrixes in order to facilitate the computational treatment as an analysis of the data. The interoperability analysis has been developed by proposing a generic approach for comparing project similarities and also by creating generic categories of DSM representations that can be systematically implemented in ERP systems. The generic framework developed for Tasks 2 and 3 is named DACM, for Dimensional Analysis Conceptual Framework. We discovered during the course of the project that the scope of this framework is more important than initially considered. Indeed, the framework enables simulation and innovation and can be used as a specification framework.

The research work in general proposed in this subproject has been innovative and provides a totally different viewpoint compared with current research on modelling requirements, interoperability, and search engine approaches. The current work provides foundations for a complete renewal of the approach and perspective. It has, in addition, proved the feasibility of the approach. The DACM framework provides a totally new way to see specifications and to organise specifications in a computer. Requirements as a network and the DACM framework offer a new way to consider the classification and search of technical data such as requirements [37].

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3. Hybrid nature-inspired computing methods in optimal electrical machine design

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3.1 Introduction

During recent years, nature has been a rich information resource, inspired by which numerous intelligent computing methodologies have been proposed, developed, and studied. The Nature-Inspired Computing (NIC) methods use nature as a metaphor, inspiration, and enabler. The typical NIC methods include Genetic Algorithms (GA), Tabu Search (TS), Particle Swarm Optimisation (PSO), Ant Colony Optimisation (ACO), Bacteria Foraging (BF), Differential Evolution (DE), Clonal Selection Algorithm (CSA), Harmony Search (HS), Cultural Algorithms (CA), Simulated Annealing (SA), and Memetic Computing (MC). They have been successfully employed in such fields as optimisation, machine learning, data mining, and fault diagnosis. Unfortunately, each NIC method has its own strengths and drawbacks, since they are based on only certain phenomena in nature. Moreover, the standalone NIC methods are usually not efficient at handling uncertainty and imprecision in practice. Therefore, fusion of these NIC methods can offer us competitive solutions to practical problems. Subproject Aalto 2 targets combining the existing NIC methods so that they can benefit from each other and achieve superior performance. The study and development of the hybrid NIC methods with applications in the optimal design of electrical machines are accomplished in this subproject.

Design and construction of rotating electrical machines, such as electrical motors and generators, involve highly developed computational and simulation methods. One standard approach is to use the Finite Element Method (FEM) to construct an accurate model of the machines. FEM models enable very detailed analysis of the machine behaviour and its dependence on the varied parameters, such as materials used and geometry. However, tuning the parameters optimally is always a complex problem with multiple objectives. For example, the weight of the machine is to be minimised while the magnetic field in the air gap of the machine should be as strong as possible at the same time. Our NIC methods have been applied in subproject Aalto 2 in order to improve the accuracy and convergence speed of the optimisation of motors.

3.2 Methods

In this subproject, we have extensively studied a number of existing Nature-Inspired Computing (NIC) methods, such as Harmony Search (HS), Differential Evolution (DE), Particle Swarm Optimisation (PSO), Ant Colony Optimisation (ACO), and Cultural Algorithm (CA). On the basis of the fusion of these NIC techniques, we have proposed, developed, and studied a few Hybrid NIC (HNIC) algorithms, such as HS-CA and HS-DE. The details of these HNIC methods are explained as follows:

1. A new HS method with dual memory, namely DUAL-HS, is proposed and studied. The secondary memory in DUAL-HS takes advantage of Opposition-Based Learning (OBL) to evolve so that the quality of all the harmony memory members can be significantly improved. Optimisation of 25 typical benchmark functions demonstrates that, compared with the regular HS method, our DUAL-HS has an enhanced convergence property. DUAL-HS is further applied for wind generator design, in which it has also shown satisfactory optimisation performance [52, 58].
2. A novel hybrid optimisation approach, HS-PBIL, is developed by merging the HS and Population-Based Incremental Learning (PBIL). Some typical nonlinear functions and the same optimal wind generator design problem as explored in [52] are used to verify the effectiveness of the proposed method. It can be observed that the employment of PBIL in HS-PBIL indeed results in an enhanced convergence performance. Compared with the original HS, better optimisation results are obtained using HS-PBIL [53].
3. A hybrid HS method is investigated, in which the HS is merged with Opposition-Based Learning (OBL). The modified HS, HS-OBL, has an improved convergence property. Optimisation of 24 typical benchmark functions, as well as an optimal wind generator design case study, demonstrates that HS-OBL can indeed yield a superior optimisation performance over the original HS method [54].
4. A so-called HS-CA, based on the fusion of HS and Cultural Algorithm (CA), is developed in our subproject, which has the interesting feature of embedded problem-solving knowledge. The belief space of the CA is updated based on the information provided by the HS. On the other hand, the mutation operation of the HS is efficiently controlled by situational knowledge and normative knowledge from the CA. Some simulation examples of nonlinear functions and engineering optimisation using HS-CA have been demonstrated. The same optimal wind generator design problem is also deployed to further verify the effectiveness of the proposed method. It has been clearly illustrated that

the employment of CA in HS-CA indeed yields an improved convergence performance. Compared with the original HS, better optimisation results are obtained by HS-CA. It also has promising potential in coping with a large variety of engineering optimisation problems [55].

5. A new HS method, n-HS, for multi-modal optimisation, including a representative niching technique, Deterministic Crowding (DC), is introduced to maintain the useful diversity of the harmony members in the original HS algorithm. The efficiency of n-HS is examined using the practical wind generator design problem. Simulation results have demonstrated that it can successfully find multiple optimal design solutions [56].
6. A memetic HS method, m-HS, with a local search function is developed. The local search in m-HS is inspired by the principle of bee foraging, and performs only for selected harmony memory members, which can significantly improve the efficiency of the overall search procedure. Our m-HS has been tested in the numerical simulations of a total of 16 selected benchmark functions, and it has been shown to yield a significantly enhanced optimisation performance [57].

3.3 Results and highlights

3.3.1 Research results

The principles, behaviours, and effectiveness of the aforementioned new NIC methods have been carefully analysed and verified. They are also compared with the standalone NIC counterparts using the standard nonlinear functions benchmarks and typical engineering design problems. Numerical simulations have demonstrated their superior performance in dealing with challenging nonlinear, multi-dimension, multi-objective, multi-modal, and constrained optimisation problems. The proposed HNIC methods have been further applied in the optimal design of wind generators. A few different simulation models are used in this application case study. The experimental results have clearly illustrated that they are indeed competitive solution candidates to cope with the demanding problems of electrical machine design.

3.3.2 Collaboration

We have actively collaborated with two partners in the SIMPRO project: the University of Jyväskylä and VTT. In our collaboration, the proposed HNIC methods have been employed and compared with the optimisation techniques studied at the University of Jyväskylä, so as to handle the optimal design of the wind generator models provided by VTT.

3.3.3 Conferences and visits

We have attended the following four conferences during the period of subproject Aalto 2:

1. 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, November 2013.
2. 2013 Finland-Japan Joint Seminar on Soft Computing Methods and Applications, Muroran, Japan, June 2013.
3. 20th Automaatio Seminar, Helsinki, Finland, May 2013.
4. 2012 IEEE International Conference on Systems, Man, and Cybernetics, Seoul, Korea, October 2012.

Supported by subproject Aalto 2, the participant Dr. Xiao-Zhi Gao has also paid a few academic visits to the Harbin Institute of Technology, Beijing Normal University, and Shanghai Maritime University in China. His visits have significantly enhanced the collaboration with these universities and benefited the development of our subproject.

3.3.4 Deliverable results

a. A few novel HNIC methods for solving difficult optimisation problems.
b. A set of ready-to-use/flexible MATLAB-based software for the HNIC-based optimal design of wind generators.
c. Optimised parameters of various wind generator models.
d. As the outcome of our subproject Aalto 2, there are a total of four and three papers published in peer-reviewed journals and conferences, respectively. A book has also been published by Springer [59].

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4. Enhancing finite and boundary element methods for efficient high-performance computing

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4.1 Introduction

The capability to accurately and reliably predict acoustic wave propagation with numerical simulations plays an important role in many industrial research and development tasks. Simulations based on accurate numerical approximations of physical phenomena can provide a considerable alternative to tedious prototyping and measurements. In acoustics, a linear wave equation is an acceptable model for sound propagation in many fluids, such as air and water. If the acoustic field is periodic, time-harmonic, the wave equation reduces to a Helmholtz equation. This essentially simplifies the solution process, but on the other hand requires separate solutions for each frequency.

The finite element method (FEM) is a widely applied numerical method for finding solutions of a Helmholtz equation. The method has great flexibility in geometrical and material modelling. On the other hand, FEM requires volume meshing, and for exterior problems, where the computational domain extends to infinity, special techniques are required to truncate the mesh. An inherent challenge in FEM is that the resulting matrix is typically very ill-conditioned and difficult to solve with iterative techniques.

The boundary element method (BEM) provides an alternative solution strategy for FEM. Instead of solving Helmholtz directly as in FEM, in BEM an equivalent integral equation on the surface of an object is considered. This has the great advantage of requiring surface mesh and unknowns only, and therefore significantly reduces the number of degrees of freedom and simplifies the meshing procedure. Another benefit of BEM is that it satisfies the necessary radiation conditions at infinity, and is directly available for exterior problems. In most cases, BEM also leads to a much better conditioned matrix than FEM. The price one has to pay when using BEM is the dense matrix equation that arises from discretisation of an integral equation. The time and memory needed to solve the linear system scales very badly, preventing the use of conventional BEM solvers in the case of problems with a high number of degrees of freedom. Therefore, to solve large-scale problems with BEM, special fast solvers that significantly reduce the high computational load are of paramount importance.

The main goal of subproject Aalto 3 was to enhance the existing fast acoustic boundary element solver developed at Aalto University [60–62]. This solver, called CompA, utilises a multilevel fast multipole algorithm (MLFMA) to speed up the computations. It can be used to predict sound pressure levels for time harmonic acoustic scattering and emission from structures modelled with an acoustic surface impedance. The solver is able to consider large-scale exterior acoustic problems on a broad range of frequencies, from a couple of Hz up to tens of kHz.

The subproject was divided into three subtasks. The first one focused on the acoustic BEM modelling and methodology development, the second one on the techniques enabling more efficient large-scale and high-performance computing, and the third one on the utilisation of the developed methods in industrial applications.

4.2 Research methods

4.2.1 Boundary element method

The boundary element method (BEM) is an attractive technique for solving acoustic wave problems involving unbounded domains. The method is based on the equivalence principle, where the solutions of a Helmholtz equation are expressed in terms of Dirichlet and Neumann boundary values of an acoustic pressure. Applying an acoustic impedance boundary condition, an integral equation on the surface of a structure is obtained. This surface integral equation is solved using Galerkin's method with a linear piece-wise continuous basis and testing functions. A combined integral equation formulation is applied to avoid fictitious spurious resonances.

One of the major drawbacks of BEM is its high computational cost. Both the memory and time needed to solve the system increases very rapidly as the size of the problem increases. Iterative Krylov subspace techniques, such as the generalised minimal residual method (GMRES), can be used to solve larger problems, but for BEM with a dense matrix, this usually is not sufficient, and still the computational load can be too high to allow efficient solutions of the problem.

4.2.2 Multilevel fast multipole algorithm

The multilevel fast multipole algorithm (MLFMA) is one of the most powerful and versatile methods to accelerate the solution of the BEM matrix equation. This algorithm is based on the iterative solution of the matrix equation. The matrix is divided into two parts, where the near field interaction part is computed as in conventional BEM and the far field interaction part is treated with MLFMA. The algorithm utilises oct-tree like data structures, where the geometry is enclosed by a cube and the cube is recursively divided into smaller subcubes. Special aggregation, translation, and disaggregation techniques are used to compute a joint field of all sources within a cube, to transform and distribute that joint field to all targets within another cube. Figure 5 illustrates these three fundamental steps of MLFMA.

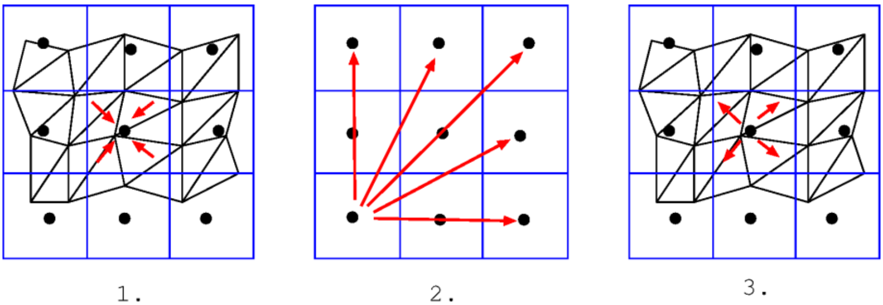

Figure 5. The three steps of MLFMA: 1. aggregation, 2. translation, 3. disaggregation.

4.3 Results and research highlights

Next, we discuss the main results and result highlights obtained during the SIMPRO project.

4.3.1 Conforming BEM

A fundamental requirement for any numerical software is that the solution should converge towards the correct solution as the number of degrees of freedom is increased. However, to obtain a BEM that satisfies the rigorous mathematical theorems concerning convergence of the solution is not trivial. In general, discretisation of an equation with so-called conforming finite element spaces guarantees convergence of the solution in the norm of the numerical solution space. The nontriviality here is that for some integral operators, this requires the use of special dual functions defined on the barycentrically refined mesh [63].

4.3.2 Calderon preconditioning

The combined Helmholtz integral equation, providing unique solutions for all non-zero frequencies, contains an unbounded operator. The spectrum of that operator is also unbounded, having a negative effect on the conditioning of the matrix and leading to challenges in the convergence of iterative solvers. To avoid this problem, we have investigated Calderon preconditioners [63]. In these methods, a problematic integral operator is multiplied by another operator so that the spectrum of the resulting operator (operator product) is bounded. Numerical implementation of the operator products requires the use of above-mentioned dual basis functions [63].

4.3.3 Extension of BEM

We have also developed methods for modelling different acoustic boundary conditions [63]. With these methods, it is also possible to model, in addition to the previously available Neumann and impedance boundary conditions [61], Dirichlet and transmission conditions.

4.3.4 Improved broadband MLFMA

Traditionally, MLFMA has separate algorithms for static (low frequency) and dynamic (high frequency) cases. The fundamental problem with these conventional methods is that they do not work efficiently on both the low and high frequency ranges, or in cases when the structure contains a lot of small geometrical details. To avoid these problems, we have been working with a broadband version of MLFMA [60]. This method can be applied to arbitrary mesh densities and to a broad range of frequencies. Figure 6 demonstrates the capabilities of the broadband MLFMA for modelling a large structure with about 100 000 surface elements at two very different frequencies.

During the SIMPRO project, we made several technical improvements to the broadband MLFMA engine. For example, optimisation of the spherical harmonics evaluator, rotation operators, and translators has been considered. New algorithms for computing MLFMA translators more efficiently have also been developed [64].

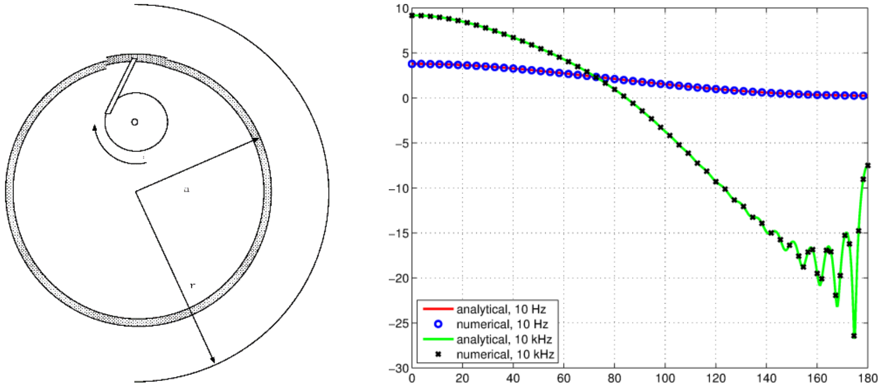

Figure 6. The model, a vibrating piston on a spherical object (left) [65], and computed sound pressure levels at 10 Hz and 10 kHz.

4.3.5 MLFMA with combined local and global interpolators

Interpolation is a vital part of an MLFMA algorithm that is needed to maintain the accuracy and efficiency of the algorithm when data is aggregated and disaggregated from one level to another. To obtain highly accurate and error-controllable interpolators, we have developed global interpolators based on trigonometric polynomials [66]. In addition to high accuracy, global interpolators allow a significant reduction of the number of samples in the field representations. The main challenge, however, is that these methods do not allow efficient distributed memory parallelisation.

To avoid this challenge, a new version of the MLFMA was developed [67–69]. This version combines a Lagrange interpolating polynomial-based local interpolator with the global one, utilising trigonometric polynomial expansions in the same algorithm. The resulting algorithm combines the best properties of both approaches: it enables storage of components of radiation patterns with a small number of samples, and should also make it possible to develop an efficient version for distributed computing systems. The key innovation is the developed interpolation process for the global interpolator, which is the standard process in disaggregation, with the MLFMA utilising a local interpolator based on Lagrange interpolating polynomials.

4.3.6 Fast evaluation of the source term

Although the MLFMA is a very powerful technique to solve BEM matrix equations, there are cases where this is not enough and the solution of the problem may still require too many computer resources. This can occur, for example, when the source acoustic wave is generated by a vibrating surface and when the surface is so large that its modelling requires a high number of elements. Since computation of an acoustic sound source due to a vibrating surface scales similarly to the solution of the BEM matrix equation, computation of the right-hand side of the system easily becomes very costly in terms of central processing unit (CPU) time and memory. To remove this bottleneck, we have applied the MLFMA to accelerate evaluation of the source term. This has significantly improved the efficiency of the algorithm and has speeded up the simulations.

4.3.7 Pressure evaluation speed-up

After the surface pressure has been found as a solution of the matrix equation, we are usually interested in the sound pressure levels outside the surface. This information is computed from the surface pressure using numerical integration as a post-processing step. As the size of the problem is large, and the number of points where the sound pressure is evaluated is high, this step may take even more time than solving the actual linear system. Here, too, the solution to the problem is provided by the MFLMA. The MLFMA has been found to be particularly effective for computing the sound pressure far from the surfaces. As the field point approaches the surfaces, the algorithm is not as effective, and further enhancements may still be needed to obtain a numerically robust and efficient method.

4.4 Discussion and conclusions

Initially the aim of subproject Aalto 3 was to consider both BEM and FEM and their combinations to find solutions for coupled acoustic-mechanic problems using domain decomposition approaches. During the SIMPRO project, however, it became evident that a brute force coupling of acoustic BEM and mechanical FEM gives sufficient accuracy in most practical situations. In this approach, first mechanical vibrations on the structure are found using a FEM solver, and that information is then given as an input (source of a sound wave) for the BEM solver to find the acoustic field. The approach was verified by Kuava Oy in several practical situations. Since our contribution to this task was rather small, the focus of the subproject was moved more to enhancing the acoustic BEM only.

The previous version of the MLFMA-BEM solver is integrated with Kuava's Waveller cloud solver [70], and its usability has been demonstrated in tens of industrial applications. For this reason, some of the work allocated to studying real-world applications was reallocated to methodology development. Consequently, the main contributions of subproject Aalto 3 were related to the enhancements and improvements of the fast MLFMA-BEM solver.

During the SIMPRO project, we also performed theoretical analysis on BEM modelling of acoustic problems. The previously developed BEM solver [61] was extended to enable modelling of different types of acoustic problems [63]. Advanced discretisation and preconditioning techniques were studied [63], too, to improve the accuracy of the solution and the conditioning of the matrix. However, verifying the advantages of these methods in real simulation problems will still require further study.

Several technical improvements to the efficiency, stability, and robustness of the previously developed MLFMA [60] have been carried out during the SIMPRO project [64]. As an outcome of this, a more efficient and robust simulation tool was developed. From a scientific point of view, the most significant result was the novel combination of the local and global interpolators [67–69]. This combination utilises the best properties of both techniques, has excellent error control and, most importantly, opens a door for high-performance distributed memory parallelisation. From a practical numerical simulation point of view, the most important result was the utilisation of the MLFMA to speed up the computation of the BEM source term in the case of large vibrating surfaces and in the evaluation of the sound pressure levels in cases of a high number of field points. These improvements remove the two major practical bottlenecks of the previous version of the solver, and have significantly improved its efficiency.

To summarise, in SIMPRO subproject Aalto 3, we have improved and streamlined our previously developed MLFMA-BEM solver, CompA, to have a faster and more robust simulation tool for large-scale acoustic simulations. The present version of CompA is able to solve problems including objects that are modelled with an acoustic surface impedance, and whose meshing leads to a high number of degrees of freedom. The simulations can be performed on a broad range of frequencies, from a couple of Hz to tens of kHz, with arbitrary mesh densities. The method is particularly well-suited to exterior acoustic problems where high accuracy is needed, such as in audio acoustics. It can also play an important role in designing machinery with low acoustic emissions.

Not all the developments and improvements made during the SIMPRO project are yet fully implemented in the CompA solver. These implementations are underway.

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5. Enhanced multiobjective optimisation algorithms for computationally expensive problems

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5.1 Introduction

Multiple conflicting objectives for optimisation typically arise in engineering design problems. Researchers and practitioners formulate such problems as multiobjective optimisation problems in which the goal is to minimise/maximise several conflicting objective functions simultaneously; for example, for a cantilever beam problem with a given load, minimisation of end deflection and minimisation of weight are two possible design objectives. In multiobjective optimisation, usually there is no single optimal solution, but a set of solutions called Pareto optimal solutions, which are all mathematically equally good. Decision-makers who are experts in the domain of the problem need to understand the trade-offs between the objectives, and choose a solution from among several solutions for implementation. Several methods have been proposed in the literature for solving multiobjective optimisation problems. Among them, heuristics-based methods such as nature-inspired algorithms are very commonly used. The applicability of such heuristics-based methods to practical multiobjective optimisation problems is the main focus of this research.

In practice, when a practitioner has a multiobjective optimisation problem at hand, they can face several challenges to solve it. Foremost, evaluation of objective and constraint function values in a multiobjective optimisation problem can be computationally expensive. Often, heuristic algorithms require thousands of function evaluations to converge for optimal solutions, thus making them unusable in practice. The literature contains a plethora of algorithms to solve computationally expensive problems, but they are widely distributed among several journals from diverse fields. Hence, a concise summary of methods that enables one to know what kinds of algorithms are available and ultimately to choose an appropriate one is missing.

Next, most nature-inspired algorithms aim to approximate the entire set of Pareto optimal solutions using so-called non-dominated solutions. When the number of objective functions increases, several algorithms stagnate and do not converge to optimal solutions. In addition, approximating a high-dimensional surface when a large number of objectives is involved would require a very large number of solutions. Computing such a large number of solutions is impractical, as it is computationally intensive and most of the solutions can be undesirable to the decision-maker.

Finally, most developers of evolutionary multiobjective optimisation algorithms do not consider decision support for the decision-maker. Helping the decision-maker to find their most preferred Pareto optimal solution is as important a task as computing Pareto optimal solutions. The entire task of solving a multiobjective optimisation problem can be considered as a failure if the decision-maker who chooses a solution for implementation does not find a suitable solution that matches their preferences, even though such a solution exists.

In this subproject, we have considered each of these challenges and addressed them effectively, so that by the end of the SIMPRO project, industrial practitioners are empowered with information and tools that enable them to solve multiobjective optimisation problems, including finding preferred Pareto optimal solutions easily.

Collaboration among practitioners and researchers to exchange knowledge about methods and experiences was emphasised in SIMPRO. In the JYU subproject, we established a joint collaboration with VTT by identifying a multiobjective optimisation problem of the design of a permanent magnet synchronous generator. In this study, the main focus was mainly to showcase the potential of using interactive multiobjective optimisation in the design of permanent magnet synchronous machines involving several objectives.

5.1.1 Research methods

In this section, we discuss the ways in which the challenges mentioned in the introduction were individually tackled. It must be noted that to address most of the challenges in this subproject, extensive emphasis was laid on collaboration with different researchers (both within Finland and abroad), so that the proposed approaches to addressing challenges and knowledge generated comprehensively consider all relevant aspects of problems.

First, let us consider the first challenge of preparing a comprehensive survey of algorithms/methods available in the literature to handle computationally expensive multiobjective optimisation problems. With a broad survey of the methods available in the literature, three distinct paths were identified, namely methods that are independent of the underlying optimisation algorithm, methods that are based on nature-inspired algorithms called evolutionary algorithms, and methods that use additional computational resources such as parallel computing to handle computationally expensive multiobjective optimisation problems. All the above surveys were prepared in joint collaboration with the Industrial Optimization Group.

The survey of methods that are independent of the underlying optimisation algorithm [71] considers 20 articles written in English and published in scientific journals before 2013. In this survey, the main focus is on so-called surrogate-based methods used to solve computationally expensive multiobjective optimisation problems. The methods were compared according to four aspects: (1) ability to handle black-box functions where explicit formulations of objective and constraint functions are unavailable, (2) capacity to generate any Pareto optimal solution, (3) effective working space of the algorithms with respect to the limits in the number of objective and constraint functions and decision variables, and (4) the role of the decision-maker.

Nature-inspired algorithms such as evolutionary algorithms are commonly used in the literature. Previously, some researchers have made an initial attempt to present a survey of methods/algorithms available to handle computationally expensive problems using evolutionary algorithms, but the survey was limited to articles published before 2008. In our survey [72], we extended the survey further by considering 34 methods published between the years 2008 and 2014 in different journals and conference proceedings written in English. In this survey, we maintained an identical classification as used earlier, so that this survey can be used as an extension to the previous survey. Since different researchers presented several algorithms, a formulation of a general function approximation framework was emphasised, apart from the efficacy of different methods in handling computationally expensive multiobjective optimisation problems.

Recently, there has been tremendous growth in the availability of parallel computing resources in industry. Parallelisation is a natural choice to quickly reduce computational time. There are some surveys in the literature that summarise the algorithms/methods that utilise parallel computing. In a recent literature survey, algorithms were considered from 2008 until 2012 based on the parallel models that are used in the literature. We have extended this survey from 2012 until 2014 [73].

Enhancing the efficacy of evolutionary algorithms for solving multiobjective optimisation problems was achieved using two different algorithms, meaning the development of an interactive simple indicator-based evolutionary algorithm [74] with colleagues from the Industrial Optimization Group, and Synchronous R-NSGA-II: An Extended Preference-based Evolutionary Algorithm for Multi-objective Optimisation [75] with researchers from the Institute of Informatics and Mathematics, Vilnius University. Both algorithms involve decision-makers who provide preference information and finally generate only preferred solutions. The main difference between these two algorithms lies in the working of the evolutionary algorithms and preference information handling by the algorithms.

A new decision support system for complex multiobjective optimisation problems was proposed in [76]. This research was a joint collaboration with researchers from the University of Malaga and based on a previously proposed NAUTILUS method by Miettinen *et al*. [77]. The enhanced NAUTILUS method (E-NAUTILUS) is directed at decision-making when a computationally expensive multiobjective optimisation problem is at hand. This algorithm considers psychological aspects of decision-making such as anchoring, and helps a decision-maker to progressively find their preferred Pareto optimal solution. The original multiobjective optimisation problem, involving computationally expensive function evaluations, is considered only before and after a decision-maker is involved in decision-making. This is done so that the decision-maker does not have to wait for solutions when they provide preference information in the decision-making stage. In addition, E-NAUTILUS can also act as a decision support tool to choose the best of the non-dominated solutions generated by evolutionary multiobjective optimisation algorithms.

When considering the joint study with VTT and JYU about the design of a permanent magnet synchronous generator [78], we first formulated a multiobjective optimisation problem involving six objective functions, three constraints, and fourteen design variables. Subsequently, the IND-NIMBUS software developed in the Industrial Optimization Group, University of Jyväskylä, was used to help the decision-maker (DM) to find their preferred Pareto optimal solutions. In this way, we demonstrated the potential of an interactive approach when solving such a problem.

5.2 Results and research highlights

The main outcome of the JYU subproject of SIMPRO can be summarised (Figure 7) as empowerment of practitioners, who have a computationally expensive multi-objective optimisation problem with:

- knowledge about the methods available to solve it, so that one can choose a method based on recorded past experiences of other researchers and practitioners, and
- novel methods that bring a decision-maker within the solution process by either generating Pareto optimal solutions that satisfy their preferences or providing a decision support system backed by psychological aspects of decision-making for them to choose a Pareto optimal solution from among several solutions with little cognitive load.

The research results and knowledge generated within this subproject have been published in leading academic journals and conference proceedings. Some knowledge has also been gathered as technical reports of the Department of Mathematical Information Technology, University of Jyväskylä, pending submission and/or different stages of the review process in academic journals.

In what follows, we present a brief overview of different research articles written within the JYU subproject of SIMPRO. To be concise, we split the summary of the articles into three research themes, namely literature surveys, novel methods developed for generating non-dominated solutions using nature-inspired algorithms, and a decision support system for computationally expensive multiobjective optimisation problems.

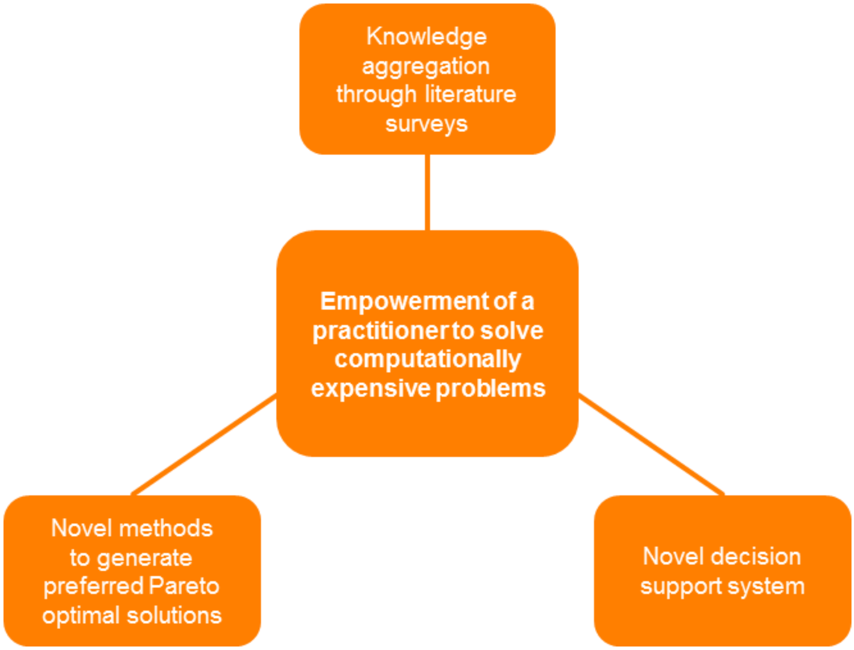

Figure 7.The summarised outcome of the SIMPRO subproject JYU.

5.2.1 Knowledge aggregation through literature surveys

Three survey articles were written. The findings can be summarised as follows:

1. *A survey on handling computationally expensive multiobjective optimization problems using surrogates: non-nature inspired methods* [71]*:*
   a. Surrogate-based methods, which substitute a computationally expensive problem with an inexpensive problem, often using surrogate models such as kriging.
   b. The accuracy of the surrogate model is important and must match as closely as possible with the original model to generate accurate enough Pareto optimal solutions.
   c. Methods proposed in the literature can be broadly classified into sequential and adaptive frameworks. On one hand, in sequential framework-based algorithms, an accurate surrogate model is built first and subsequently used to find Pareto optimal solutions. On the other hand, in adaptive framework-based algorithms, the surrogates are progressively tuned to increase their accuracy during the algorithm run.
   d. Adaptive framework-based algorithms are promising, as interesting regions containing optimal solutions are more accurate than other regions.
   e. In most research articles, the benchmark problems used are not computationally expensive. Hence, the relevance of the methods proposed to practical problems remains to be tested.

f. Most of the benchmark problems considered for testing the methods proposed have a low number of objective and constraint functions and decision variables. To be more specific, the number of objectives is usually three, the number of constraint functions is usually less than five, and the number of decision variables is usually less than eight. There are only a few studies with more objective and constraint functions and decision variables.
g. Noisy black-box functions with different function values as output for the same set of decision variables, due to some uncertainties, have not been considered.

2. *A survey on handling computationally expensive multiobjective optimization problems with evolutionary algorithms [72]:*
    a. Algorithms proposed using evolutionary algorithms can be broadly classified based on the types of approximations used as function, problem, and fitness approximations.
        i. In function approximation, computationally expensive functions are replaced by less expensive surrogates.
        ii. When the original problem, which is computationally expensive, is replaced by a simpler problem, such as when a 3D model is replaced by a 2D model, this is termed problem approximation.
        iii. Finally, fitness approximation is used when the objective function value corresponding to a solution is estimated from the previously evaluated objective function values of its neighbouring solutions.
    b. Function approximation is the most commonly used to reduce computation time.
    c. We introduced a new unified function approximation framework that presents the big picture of most function approximation-based algorithms proposed in the literature.
    d. Most algorithms proposed are independent of the types of metamodels or surrogates that are used in the articles.
    e. Neural networks and Kriging are most common metamodels used. However, no specific reason for their widespread use is typically mentioned in the literature.
    f. Different types of evolutionary algorithms called evolutionary multiobjective algorithms are used. Dominance-based algorithms are common.
    g. Promising concepts that can be used are an ensemble of metamodels (more than one metamodel used in an algorithm) and hybrid methods involving all three types of approximations.
3. *A survey on handling computationally expensive multiobjective optimization problems with evolutionary algorithms and parallel computing [73]:*
    a. Evolutionary algorithms are scalable and can be easily parallelised. The algorithms usually involve a set of solutions in any generation or iteration, and each of the solutions can be evaluated in parallel.

b. Parallelisation is used not only to speed up computations but also to enhance the search capacity of the algorithms to find optimal solutions.
c. Sometimes parallelisation is the only option to solve computationally expensive multiobjective optimisation problems, such as when function evaluations take days.
d. Distributed algorithms outperform traditional master/slave approaches. Distributed algorithms involve multiple subpopulations that sample different regions, and co-ordinate by sharing information about their search spaces with other regions; and the master/slave involves a single population, in which multiple solutions are computed in parallel.
e. Further research is needed in terms of diversity preservation among non-dominated solutions in parallel evolutionary algorithms, and the scalability of parallel algorithms with processors and numbers of objective and constraint functions and the decision space.

5.2.2 Novel methods of generating preferred Pareto optimal solutions

Most evolutionary multiobjective optimisation algorithms aim at generating a set of solutions that approximates the entire set of Pareto optimal solutions, also known as the Pareto optimal front. However, for computationally expensive problems, it is difficult to generate an approximation of the entire Pareto optimal front, especially when a decision-maker is interested in only a subset of solutions. Because of these reasons, and to keep a decision-maker involved, we have proposed two algorithms. These focus on two different classes of evolutionary multiobjective optimisation algorithms, namely indicator and dominance-based ones. The research highlights are mentioned below:

1. *An interactive simple indicator-based evolutionary algorithm (I-SIBEA) for multiobjective optimization problems [*74*]:*
   a. I-SIBEA is a preference and indicator-based algorithm that considers the decision-maker's preferences in generating only preferred solutions for them. Indicator-based algorithms maximise a quality indicator, in this case a hypervolume. Indicator algorithms perform well even when a large number of objectives is involved.
   b. In this algorithm, the decision-maker's preference information is expressed as preferred and/or non-preferred solutions. Non-preferred solutions help the algorithm to avoid uninteresting regions in subsequent iterations, thereby speeding up the convergence.
   c. The decision-maker has the flexibility to indicate how many solutions they wish to investigate and how many times they wish to interact with the algorithm to provide their preference information.
   d. The performance of the proposed algorithm was compared against a recently proposed algorithm. The results obtained were either equivalent to or, most often, better on a set of test problems.
   e. The potential of the algorithm was also demonstrated by involving a real human decision-maker in the solution process.

2. *Synchronous R-NSGA-II: an extended preference-based evolutionary algorithm for multi-objective optimization [*75*]:*
    a. The proposed algorithm is based on the R-NSGA-II algorithm proposed by Deb *et al*.
    b. The decision-maker provides a desirable objective vector, also called a reference point, as preference information.
    c. The main idea is to use multiple functions, all using the same preference information of the decision-maker, to generate a subset of Pareto optimal solutions desirable to the decision-maker.
        i. When different functions are used, usually different Pareto optimal solutions are obtained.
    d. The experimental results when tested against the R-NSGA-II algorithm on a set of benchmark problems provided an enhanced set of non-dominated solutions that reflect the preference information provided by the decision-maker.

5.2.3 Novel decision support system [76]

1. A novel decision support system based on the previously proposed NAUTILUS method [77] was called E-NAUTILUS.
2. E-NAUTILUS involves a three-stage approach for solving computationally expensive multiobjective optimisation problems.
    a. **Pre-processing stage:** A set of non-dominated solutions is calculated using, for example, an evolutionary multiobjective optimisation algorithm, using the original computationally expensive multiobjective optimisation problem.
    b. **Interactive decision-making stage:** The decision-maker is involved in this stage, where they interactively and iteratively improve all objective function values to find the most preferred solution available.
    c. **Post-processing stage:** The solution chosen by the decision-maker is ensured to be Pareto optimal.
3. E-NAUTILUS is aimed at avoiding the undesired anchoring effects that may take place in interactive solution processes. It also avoids the necessity of trading-off between iterations, as the decision-maker can gain in all objective functions without sacrifices in any of them.
4. It progressively proceeds to the most preferred Pareto optimal solution from the worst solution, called the nadir point, taking one step closer to the Pareto optimal set at each iteration, and effectively handles computationally expensive multiobjective optimisation problems.

5.2.4 VTT-JYU joint collaboration on the design of a permanent magnet synchronous generator [78]

The multiobjective optimisation-based design of a permanent magnet synchronous generator considered in this study is most likely the only study using up to six objective functions in this area. This provided an opportunity for the decision-maker to consider the design problem as a whole, understand all the relevant trade-offs, and ultimately find her preferred solutions. At the end of the decision-making process, the decision-maker involved was extremely satisfied both with respect to the solution process and with the solution she selected finally as her most preferred solution.

5.3 Conclusions

The SIMPRO project entitled Computational Methods in Mechanical Engineering Product Development aimed to lower the threshold for utilising computational methods. The idea was to enable efficient product development and a systems engineering approach. In the spirit of the focus of the entire project, the JYU subproject has also focused on efficient computational methods. Optimisation, especially multiobjective optimisation, is a cornerstone of product design. Addressing selected challenges in multiobjective optimisation will greatly advance innovation, shorten product design cycles, and enable efficient product design. This shall ultimately lead to greater resource efficiency.

In this subproject, we empowered practitioners or researchers with information about methods available in the literature, and involved a human decision-maker in the solution process for multiobjective optimisation. This is a non-trivial task, as decision-making is complex and supporting a human decision-maker in finding a most preferred solution is challenging when solving a computationally expensive problem involving a large number of objective and constraint functions. This subproject addressed these challenges.

The JYU subproject has generated novel algorithms, which are ready to be used to solve industrial complex multiobjective optimisation problems. Furthermore, we have found a number of areas where there is a need for further research. These areas include bringing machine learning techniques within multiobjective optimisation and decision-making to solve computationally expensive multiobjective optimisation, using visual analytics techniques to enhance the experience of a decision-maker when choosing preferred solutions, and visualising and understanding trade-offs when a large number of objectives is involved.

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6. Development of a generic description of the structural flexibility for real-time multibody simulation

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6.1 Introduction

Flexible bodies in multibody systems are commonly defined using the floating frame of reference formulation [79]. Body deformation is enlightened with respect to the reference coordinate system, whereas a finite element approach can be used [80]. The motion of deformable bodies can be detailed with translations and rotations of the reference coordinate system. The deformation of the body and the motion of the reference coordinate system are coupled together with the descriptions of elastic and inertia forces. The use of the reference coordinate system in the description of deformation allows for the use of modal reduction techniques [81]. This leads to a computationally efficient approach that makes it possible to describe structural flexibility in the case of real-time simulation [82]. It is noteworthy, however, that real-time simulation models that are currently in use suffer from the lack of a generic description of the structural flexibility.

This project extends real-time simulation based on multibody simulation dynamics to cases where one or more bodies can experience significant deformation. To achieve this, the finite element method (FEM) and multibody simulation approaches will be combined using the floating frame of reference formulation. A finite element model often results in a large number of degrees of freedom (dof), and simulation of these complex models is computationally intensive. To make the FEM approach practical for real-time simulation, the model must be simplified using model reduction techniques, as exemplified in Figure 8.

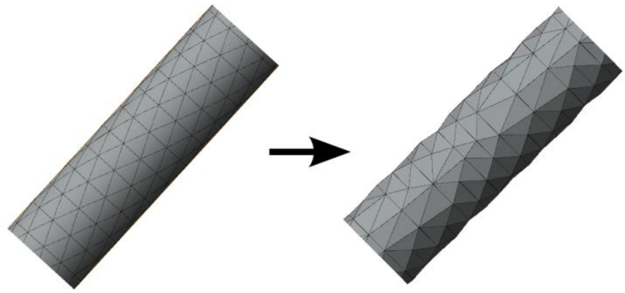

Figure 8. Removing nodes from the original finite element model.

Figure 8 shows a simple example of how nodes can be removed using model order reduction. Removing selected nodes will decrease the number of dof involved in the model. The model reduction techniques used to simplify the finite element model are critical to computational efficiency and to successful real-time simulation. Fewer dof can reduce the computing time that needs to be considered in real-time simulation. Once the model has been simplified, body deformations can be defined using the assumed deformation modes.

6.2 Objectives

This project studies various finite element model reduction techniques in the framework of real-time simulation. Using the appropriate techniques, the accuracy of real-time simulation can be improved considerably. This improved accuracy makes the real-time simulator perform more like the actual machine and offers the user a more realistic feel.

Real-time simulation technology can also be utilised in product development. Real-time simulation makes it possible to account for the machine user early on in the concept development phase. Furthermore, the methods that will be developed will enable faster-than-real-time simulation with flexible bodies, which will make possible the straightforward development of embedded and integrated machine intelligence.

In short, the project objectives can be summarised as follows:

1. Identify the potential for boosting computing time to enable faster-than-real-time simulation. This can be used when integrated and embedded machine intelligence is considered.
2. Account for the user early in the concept phase of the product development.

6.3 Research highlights

The code is developed to become like third-party software or a software plug-in that has been developed in ANSI C, in order to provide flexibility to different operating systems and computer architecture. The main idea of this development is to provide selective data from finite element software that can be used in the real-time simulation software with reasonable results. This is a crucial point from the modularity point of view. The solver was developed using several reliable GNU General Public License (GPL) libraries, which are comprehensively used by other well-known software applications, such as Matlab. This solver consists of several programming languages, such as Fortran, C++, and C [83]. This makes the programming process slightly challenging in order to pass the data through different languages.

The code is developed based on three numerical methods in model order reduction, which are the Craig-Bampton method, the Guyan reduction method, and the Krylov subspace method. These three methods can be alternated based on user preferences. In order to obtain a correct and accurate result, an experienced user is needed who is familiar with all three methods.

The input format to the solver should be standard and possible for the commercial software to provide. The output file also should be capable of being accepted by other software. It was found that most finite element software can provide the essential data in the sparse standard format, which is Harwell-Boeing format. Therefore, this format has been chosen for use in the developed code. A brief explanation of how the developed program work can be explained is given in Figure 9.

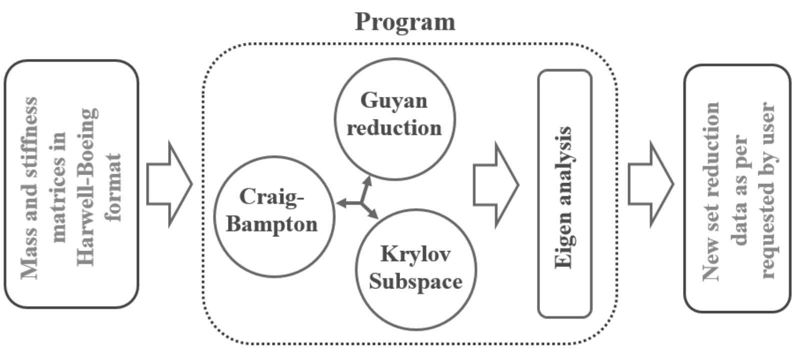

Figure 9. Input data and execution process in the program.

Figure 9 shows the Harwell-Boeing format is used as input data into the program. The types of data needed are the stiffness and mass matrices. The program will do its job based on the user settings, such as number of dof to be removed and type of output data [84]. As a rule of thumb, a high number of dof may increase the computing time to produce required results such as eigenmode.

6.4 Conclusions

Competition in real-time simulation is rapidly becoming more intense. Therefore, describing mechanical flexibility represents a unique capability that gives a competitive advantage to a simulator company, helping it stand out from among its rivals. This is particularly important in the case of user training simulators [85].

Efficient modelling of mechanical flexibility enables the development of detailed and accurate real-time simulators for research and product development purposes. In turn, this enables mechanical engineering concerns to develop software with the aid of real-time simulation, significantly speeding up the product development process.

To position this development in the big picture, this development can offer an alternative way to reduce the full finite element model system, which designs in commercial finite element software using third-party software, and return the new values and required specific input data format into the real-time simulation software. This is important in the real-time simulation software, whereas normally the full finite element model is not simulated to obtain the eigenmode. The real-time simulation software only needs numerous specific data from the FE model in order to make it able to process in real time. Therefore, this should be done separately and the new reduction values will be used in the simulation processing. This process can be explained better in Figure 10.

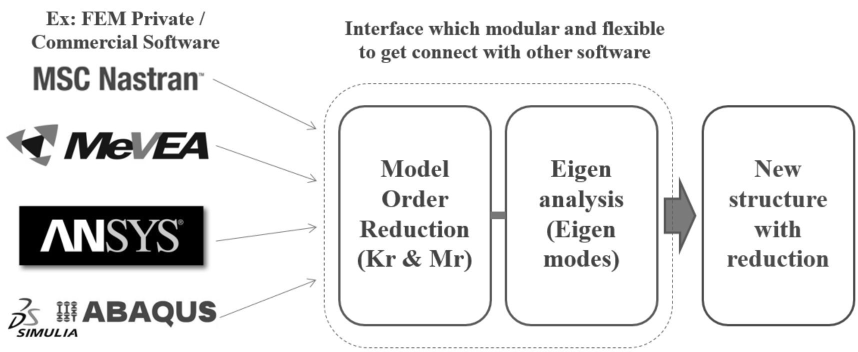

Figure 10. Implementation of the developed code as a third-party software application or a plug-in.

Figure 10 shows the application of the developed software, whereby the extracted model data from the commercial software can be used by the program and the produced new reduction model. The new data can be synced with other software or a real-time simulator. This development expands the capabilities of previously developed simulation techniques towards supporting arbitrary structures modelled using arbitrary elements.

6.5 References

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7. Structural optimisation in automated product design

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7.1 Introduction

Throughout the history of industrial optimisation, the main focus in a majority of the research projects has been the search for a global optimum using various strategies. This massive research has resulted in many fine-tuned and robust optimisation algorithms for different types of problems. In some problem categories, even the finding of the global optimum can be guaranteed. The main goal of this subproject is to set up a robust modelling, simulation, and optimisation procedure that produces an optimised product with the minimum amount of user control. In other words, the existing best optimisation algorithms are used to accelerate and automate the product design process.

Automated product design has many advantages: (i) routine work such as finite element model generation can be avoided, (ii) structural optimisation is carried out systematically and (iii) the designer can handle multiple design cases simultaneously. Especially in cases where the product is not limited to certain standard types and depends on the customer's requirements, the automated design process is extremely efficient.

The project research task is two-fold. First, a platform for setting up the optimisation problem controlling the automated design process is constructed; and second, the platform is used in industrial design cases. The platform construction was carried out in a Master of Science thesis [86] and the platform was applied to various cases, as reported in [87–90].

7.2 Research methods

In the project, we chose to use a surrogate model-based optimisation method due to its generic nature. The platform (design software called SimPro) was used to formulate the optimisation problem, while the simulations could be carried out using some black box solver, and the generated optimisation sub-problems could be solved using the best available optimisation algorithm libraries. The work-flow of the platform is depicted in Figure 11. In the optimisation problem formulation, the original simulation problem is replaced sequentially by polynomial-based metamodels. In the project, the HPC architecture generated by Techila Technologies Ltd was also adopted successfully, as was reported for example in [89].

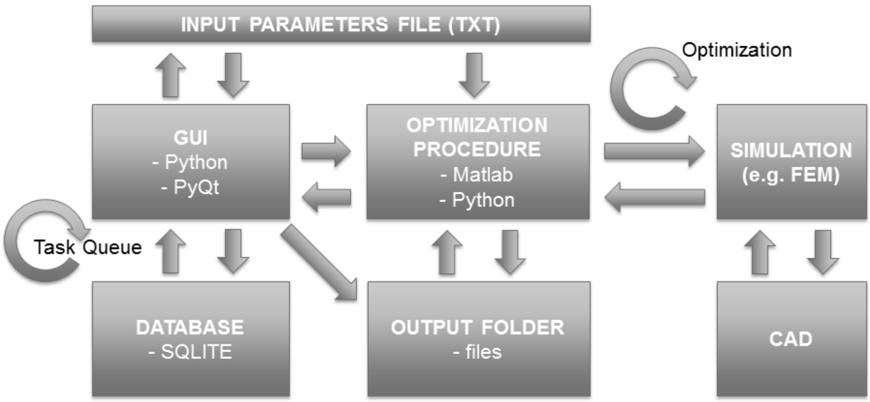

Figure 11. Interfaces and the work flow of the SimPro platform.

7.3 Results and research highlights

The platform was a vital part of the project, so that all the existing optimisation algorithms could be adopted to our use. Adding the Techila HPC feature in the platform made it competitive even against commercial products. The platform was applied to one ongoing research project, and the results gained worldwide interest and were reported in the high-end simulation software ANSYS customer magazine [89]. The associated M.Sc. thesis was also awarded by Pirkanmaan Teknologiateollisuus due to its merits in bringing academic research results to industrial use. The platform was adopted successfully in the design cases of guide rails [2] and telescopic booms [90]. The project results were also reported in [91, 92] to different audiences. The guide rail design case was a typical mass minimisation problem, in which the design variables were the guide rail cross-section and supporting structure dimensions, while the deflections of the rail were forced below a certain level. Multiobjective methods were also used for the problem. The main results of the task were the optimal configuration for various cases and the sensitivity data at the optimal point. In the boom design case, a telescopic boom was designed against given design constraints, as shown in Figure 12.

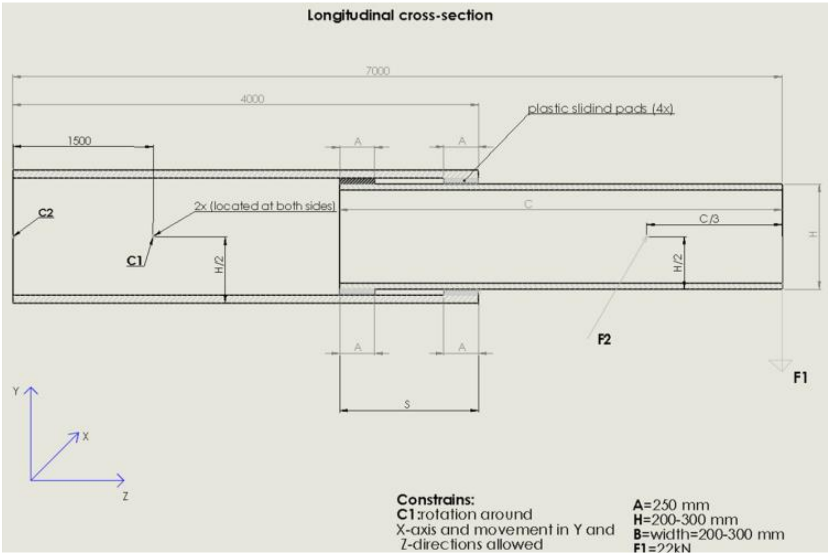

Figure 12. Design constraints for the telescopic boom.

A non-linear FE model of the steel booms and plastic sliding pads was constructed using ANSYS FE software, and the SimPro tool was adopted for the design work. As a result, an optimal configuration was produced with minimal user input.

7.4 Discussion and conclusions

The research subject has proven to be very active both in the academic and especially in the industrial area. A commercialisation project, SORVI, has been active since 1/2015 and can be seen as a continuation of this SIMPRO subproject. Optimisation is a word that has been misused and misunderstood badly during the last decades, but now the industrial players are also beginning to see its ability to speed up and automate the design process. Hence, the SIMPRO subproject has been a success, and we have been able to convince many partners that simulation and optimisation are vital tools in modern design work.

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8. Utilisation of simulation data to support the maintenance of mobile work machines

SIMPRO subproject TUT 2
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8.1 Introduction

Service operations today have a major role in the business of machine manufacturing companies. Many manufacturers of mobile work machines, such as excavators, cranes, and rock crushers, are pursuing increased volume and improved performance from their service departments. Typically, these modern machines contain a lot of automation and control systems that provide measurement data about the operation of the machine through communication buses, but that may also make the localisation of failures time-consuming and the detection of evolving failures difficult. So the main challenge is related to analysing the data masses and forming accurate models for component failures [93–98].

Even though the operating characteristics and condition of an individual component could be accurately defined and modelled in laboratory conditions, reliable diagnostics is far more challenging in field conditions. There, an individual component is just one of hundreds of components in a whole machine, which may operate in a constantly changing environment and under changing loads. The relatively low cost of mobile work machines also restricts the use of sensors and measurement systems for just diagnostic purposes.

Diagnostics of mobile work machines is challenged by:

- limited numbers of sensors due to the relatively low cost of machines
- harsh and highly varying operating conditions
- large variations in the operating principles of owners and operators of machines
- general problems related to data analysis and reasoning.

The use of simulation models and simulators is becoming a necessity in the development of highly automated machines. This is due to the complexity of the automation system and its software. Hardware-in-the-loop (HIL) simulator systems enable the connection of simulation models to real components of a machine, such as control modules and control buses. Simulation models and simulators are typically created during the early development phase of a machine. However, these are not effectively utilised in the later phases of the product life-cycle [99].

The goals for subproject 2 of the Tampere University of Technology (TUT SP2) were to:

1. evaluate the state-of-the-art in using simulators for service and maintenance
2. develop procedures and methods for utilising simulation models and simulators of mobile work machines to support the maintenance personnel in the field
3. develop tools and algorithms for recognition of the machine's state and condition
4. test and evaluate the tools and algorithms with real machines.

8.2 Research methods

TUT SP2 was carried out at the Department of Intelligent Hydraulics and Automation at Tampere University of Technology. The project team was: researcher Jukka-Pekka Hietala, post-doctoral researcher Tomi Krogerus, project manager Mika Hyvönen, senior research fellow Petteri Multanen, and Professor Kalevi Huhtala. The research work was implemented according to the schedule and tasks presented in Figure 13.

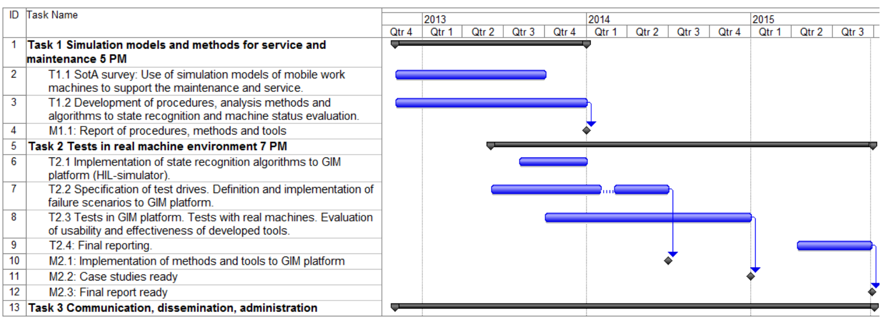

Figure 13. Tasks and schedule of TUT SP2.

In task 1 of the subproject, "simulation models and methods for service and maintenance":

a) The scientific and commercial background of the research area was surveyed. This was based on reviews of literature and articles from scientific databases, and web searches. In addition, one Bachelor of Science thesis was completed in this task.

b) The initial procedure and analysis algorithms were defined for utilising simulators to support the service operations of machines in the field. The analysis algorithms included tools for feature recognition, segmentation, clustering, classification, and, for example, statistical correlation-based data analysis. The initial procedure, analysis methods, and tools were reported in the SIMPRO project research report [100]. The refined versions of these are presented in the following results chapter and the corresponding conference articles.

In task 2 of the subproject, “tests in a real machine environment”:

a) The procedure and analysis tools were tested with the existing IHA’s mobile work machines and their simulators. The simulators were developed in the GIM project (Generic Intelligent Machines), which was the centre of excellence in research by the Academy of Finland between 2008 and 2013.
b) In the first development phase, the effectiveness of analysis tools was tested purely in the simulator environment. After that, an artificial malfunction was caused in one of work machines for real field tests. The simulator environment and the mobile work machines used in this research are presented in the following subchapters.

In task 3 of the subproject, the following activities were carried out:

a) Communication and networking with research and industrial partners
b) Dissemination of project content and results by writing scientific articles and by publishing web content
c) Internal administrative and financial issues of TUT.

8.2.1 Autonomous mobile work machines and simulator environment

The mobile work machines used in this research were autonomous machines, which were developed in earlier projects at IHA. The machines were the GIM machine, which is a modified version of Avant Tecno Oy’s multipurpose wheel loader, and the IHA machine, which is a modified version of the Wille wheel loader (see Figure 14).

Figure 14. The autonomous GIM machine and IHA machine used for the testing of the developed tools and algorithms.

The frames of the machines are original, but the control system, sensors, electronics, and hydraulics have been changed and optimised for autonomous and remote controlled operation. More technical details of the machines are presented in the references [101–103].

The HIL simulator environment developed in IHA is presented in Figure 15.

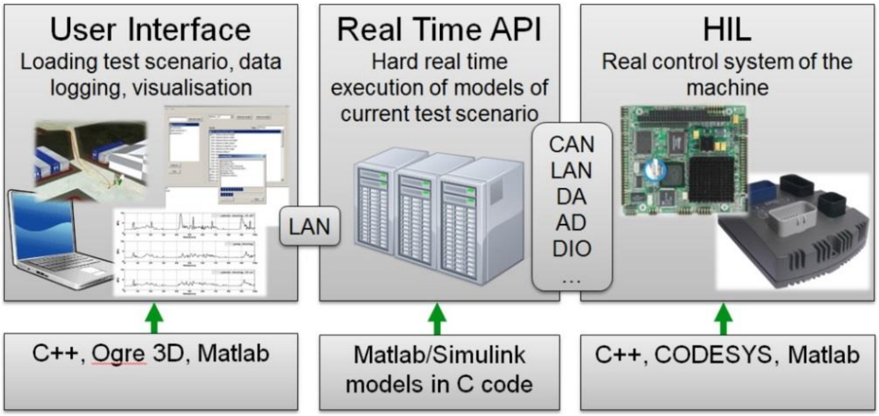

Figure 15. The HIL simulator environment at IHA.

The middle part of Figure 15 is the core of the simulator, consisting of several PCs running an xPC Target hard real-time kernel. The dynamic simulation models of the machines and their operating environment are executed on these computers. They are connected through a local area network. Several computers are used to increase the computing power for the simulation.

The simulator includes several control units and on-board computers, which are identical to the components of real machines. Control units are connected to each other and to one of the simulation PCs through CAN buses. On the left-hand side is a computer for controlling the test setup, loading models for the real-time computers, visualisation of the machine at the terrain, and collection of data.

The simulation models include the following parts and properties of mobile work machines:

- mechanics, machine body, and tyre-road interaction
- hydrostatic drive
- work hydraulics and fluid characteristics
- dynamic friction models
- diesel engine
- numerous sensors.

Models have been verified using several laboratory and field measurements. An example of a modelled part is the hydrostatic drive. Its hydraulic circuit is presented in Figure 16.

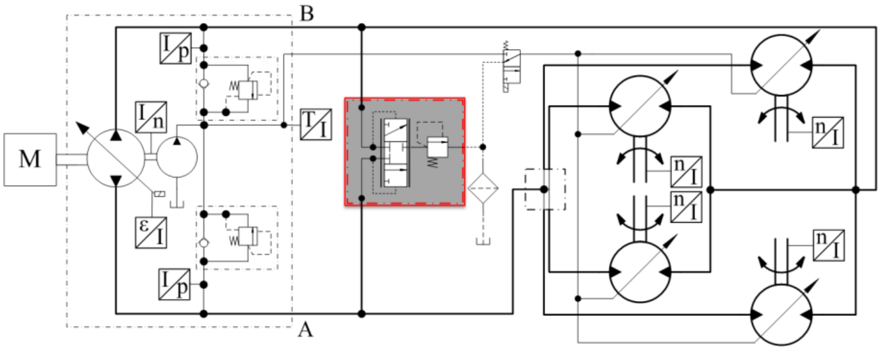

Figure 16. The hydraulic circuit of the wheel loader's hydrostatic drive and flushing valve (grey) [101].

The operation and condition of this hydrostatic drive was one of the test cases used for the testing of analysis algorithms. A deliberate malfunction was caused in the transmission of the real machine during the field test, by jamming the flushing valve presented in Figure 16.

8.3 Results and research highlights

The main results and research highlights of the SIMPRO TUT2 subproject are:

- A maintenance procedure in which HIL simulators are utilised to support the diagnostics and service of machines.
- Development of analysis methods and implementation of statistical data analysis algorithms for the evaluation of machine condition.
- Experiments with real work machines – both undamaged and malfunctioning.

8.3.1 Maintenance procedure utilising HIL simulators

The process flow and main tasks of the developed maintenance procedure are presented in Figure 17.

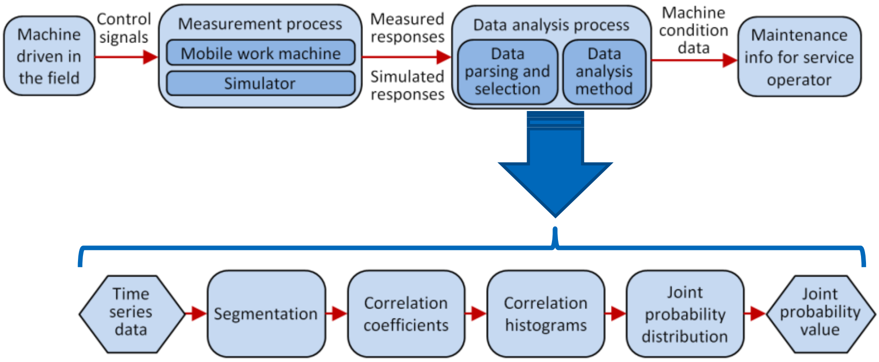

Figure 17. A maintenance procedure utilising HIL simulators and analysis of time series data using the joint probability method [104].

The procedure has two main parts: the measurement phase and the analysis phase. At first, the control signals and corresponding output signals are measured from the real machine. This can be performed manually by service personnel or automatically using a remote monitoring system. In the case of mobile work machines, the control signals may represent, for example, the acceleration and speed of the machine and the use of auxiliary equipment, like a boom and shovel. The measured control signals are used as input in the HIL simulator and the corresponding outputs are saved (measured) as for real measurements. The measured and simulated outputs are then transferred for analysis.

In the analysis, the use of joint probability distribution is proposed. The main idea is to model the behaviour of the system with probability density functions of the correlation coefficients using histograms, and to test how well the future behaviour fits the model. When the correlation coefficients of the segmented multivariate data belong to sections of histograms where the probability is very low, then it is treated as a rare occasion and the probability of an anomaly is high. Again, if the correlation coefficients belong to sections where the probability is high, this is treated as normal behaviour [105]. The principle and tasks of the analysis process are described in more detail in the following.

8.3.2 Experiments

In the following experiment, the IHA machine (Figure 14) was used to test the data analysis algorithms. Only four variables from the machine were selected for the analysis. These were:

- diesel engine rotational speed
- displacement of the hydraulic pump in the hydrostatic drive
- hydraulic pressure A (see Figure 16)
- hydraulic pressure B (see Figure 16).

The recorded control references of the real machine were speed and steering commands. An example of the drive path of the tested machine is presented in Figure 18.

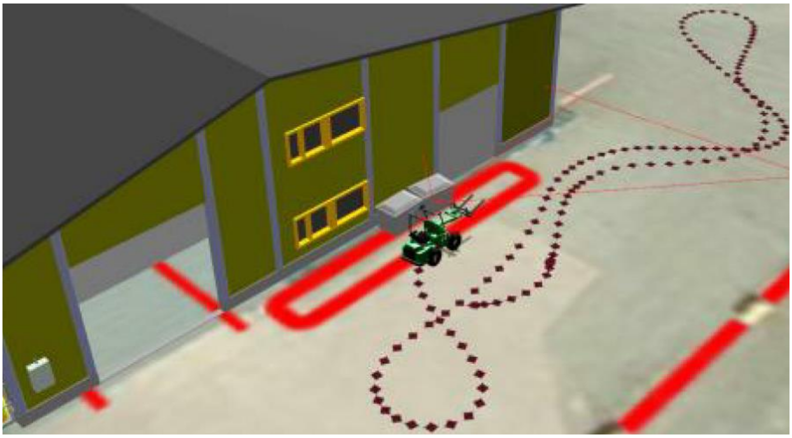

Figure 18. An example of the drive path visualisation in the simulator environment.

The test series included 41 test drives; 20 drives were used in the training phase, for statistical model generation, and 21 drives were used in the actual testing phase.

8.3.3 Segmentation

In the analysis process, the measured data sets are first segmented (i.e. divided) into equal lengths where the segments are overlapping. This divides the time series data into smaller groups of data sets that describe the patterns of the measured variables. Segmentation enables the allocation of the segments, which generates anomalies. Figure 19 shows an example of segmentation, where each data set has a length of 100 data points with 50 overlapping data points. This was used in the data analysis, the results of which are presented in Figure 20.

The length of the segments was chosen to be long enough to capture transient periods that contain the most relevant data with regard to anomaly detection and diagnostics of machine condition. If the segments selected are too long, the effect of the important phenomena on the correlation coefficients decreases.

Figure 19 shows just an example of segmentation using constant segment length. Another option is to select the length based on the information that the measured data presents. An example of this would be a comparison of the acceleration and deceleration phases, regardless of their length. To ease this kind of analysis, automatic feature recognition was also studied in the SIMPRO project.

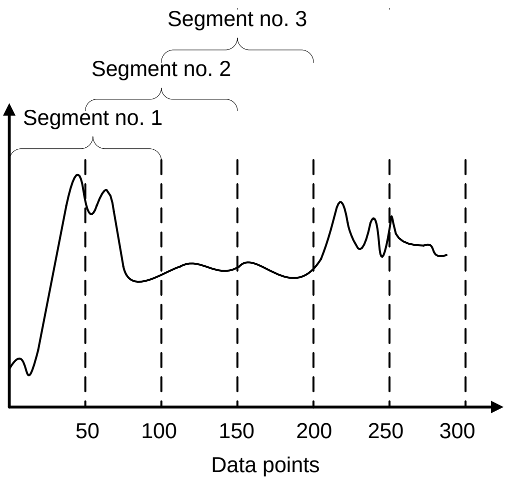

Figure 19. An example of the segmentation of time series data.

8.3.4 Correlation coefficients

In machines, the measured signals are mostly dependent of each other, and in an undamaged machine these dependencies follow certain patterns. These dependencies are represented using statistical models. These models are used to discriminate faulty machines by detecting when the correlations deviate from the statistical models of an undamaged machine. Pearson's correlation coefficients [106] are used to represent the correlations between all measured signals.

These correlation coefficients are treated as random variables and they are modelled using probability density functions. This is done using histogram calculation. The first interval [−1…1] is divided into bins. In this case, the number of bins was 21. The number of bins affects the resolution of the analysis results. More details of the theoretical background are presented in reference [101].

8.3.5 Joint probability distribution

After the statistical model of an undamaged machine is built, the measured signals of the real machine can be evaluated against the model. The same signals are measured for a period of one segment, and correlation coefficients are calculated as described in the previous chapter. Now the probability of the outcome can be evaluated. Further, we can calculate how probable this segment is, using joint probability of all the correlation coefficients in one data segment. More details of this theoretical background are also presented in reference [101].

Figure 20 shows an example of the joint probability distributions from the experiments. The results present mean values of the distributions from the training phase and from tests with both undamaged and damaged mobile work machines.

In the case of the damaged machine, the fault was a jammed flushing valve in hydrostatic transmission, as mentioned before (see Figure 16).

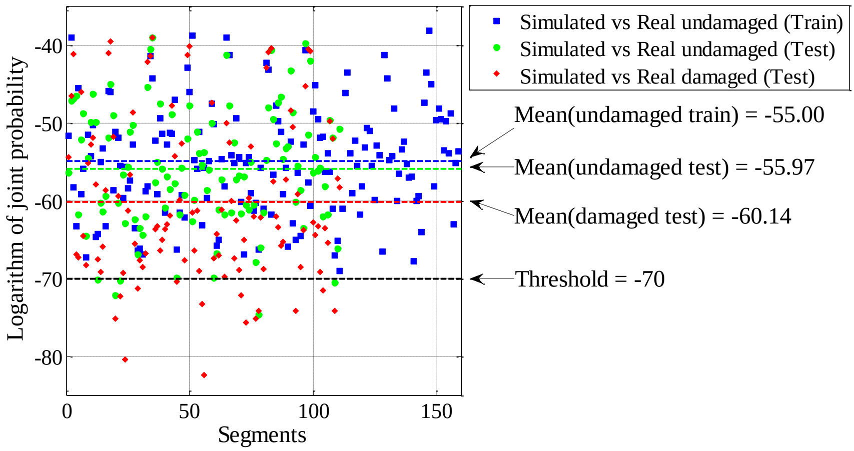

Figure 20. Joint probability distributions of training and actual testing data [101].

In the training phase (blue square dots), the statistical model of the studied machine is generated. In reality, this could take place, for example, at the machine manufacturing factory when the first machines come off the production line and their responses are compared to the simulated responses. The actual tests with undamaged and damaged machines would then take place later, with different individual machines.

The static threshold in Figure 20 is defined for anomaly detection based on the results of the training phase. The differences between the undamaged and the damaged machines can be clearly seen from the mean values.

8.3.6 Subproject deliverables

The following research reports, articles, and thesis were published in the SIMPRO TUT 2 subproject:

- Utilization of R&D simulation models at the maintenance of mobile machines (In Finnish). B.Sc. thesis. C. Oksman. 2013/8.
- Report on methods, procedures and analysis tools. SIMPRO project report, TUT Research report. J-P. Hietala et al. 2014/1.
- Anomaly Detection and Diagnostics of a Wheel Loader Using Dynamic Mathematical Model and Joint Probability Distributions. Conference article. T. Krogerus et al. The 14th Scandinavian International Conference on Fluid Power. May 20–22, 2015, Tampere, Finland. 14 p.
- Novel Procedure for Supporting Maintenance of Mobile Work Machines Using R&D Simulators. Conference article. J-P. Hietala et al. The 11th Int.

Conf. on Condition Monitoring and Machinery Failure Prevention Technologies, 10–12 June 2014, Manchester, UK. 9 p.

- Joint probability distributions of correlation coefficients in the diagnostics of mobile work machines. Journal article in review. T. Krogerus et al. Elsevier's Journal of Mechatronics, the Science of Intelligent Machines.
- Diagnostics of Mobile Work Machines Using Dynamic Mathematical Models and Joint Probability Distributions. Seminar poster. P. Multanen et al. SIMPRO final seminar 2015.
- Utilization of Simulation Data to Support the Maintenance of Mobile Work Machines. Research report, part of the SIMPRO final report. P. Multanen et al. 2015/10.

8.4 Discussion and conclusions

TUT SP2 developed a procedure for using simulators and simulation models for the diagnostics of machines, and to support the service and maintenance work in the field. An essential part of the development work was the selection and testing of analysis tools for the recognition of a machine’s condition.

In the analysis method, the responses of a real undamaged machine and the dynamic mathematical model of the machine are first compared from a stochastic point of view based on probabilities. At this stage, a statistical model, describing the behaviour of the machine, is built. Later, the future behaviour of the machine is checked against this model. In the proposed joint probability distribution method, the probabilities of multiple correlation coefficients for machine signals are compared instead of comparing the measured signals or even the correlations directly. This enables the detection of anomalies, rare situations with low probabilities, from which one can conclude whether there is something wrong in the system. The simultaneous examination of several variables also enables a more generic approach to data analysis and makes it possible to apply it to different types of machines.

The analysis method was applied to the diagnostics of autonomous mobile work machines. A jammed flush valve in the hydrostatic drive of the wheel loader was used as a test case for the damaged machine. The results showed clearly lower probability values for the test drives where the fault was present. In these experiments, the detection of anomalies for diagnostics was presented using a combination of a static threshold and a threshold based on the arithmetic mean of the joint probability distribution. This enables the detection of both single segments with low probability values, indicating anomalies, and also of changing trends in the system. These mean, in practice, a capability for the identification of: 1) sudden critical faults, and 2) slowly evolving failures.

In the presented case studies, the machines were autonomous hydraulically driven mobile work machines, and their operating behaviour was compared to the responses of a hardware-in-the-loop simulator. However, the utilisation of the presented methods is not limited to those. The use of a maintenance procedure and the analysis algorithms are applicable to many other machine systems and environments. The generation of simulation data does not require real-time simulation or the use of any hardware components of machines, as long as the simulated responses correspond sufficiently to the behaviour of real machine.

TUT's work on this field of research has already continued in other Finnish national research projects. In the preparation of these, the results of TUT SP2 were a valuable contribution. Currently, new activities in this field of research are also under preparation on an international level, related to theme of dynamic data-driven application systems (www.DDDAS.org).

8.5 References

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9. Computational methods in mechanical engineering product development

SIMPRO subproject VTT
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9.1 Introduction

The everlasting search for new ways to gain a competitive advantage in business drives product development in companies to balance the contradicting objectives: technically innovative and advanced products should be designed in a continuously shortening time and with decreasing overall costs. Companies that can balance this multi-objective optimisation challenge and have the right product, at the right time, and do successful marketing have a great asset in the business. The computational approach has proven to be a great tool, especially in engineering and design, but also in other areas in business, for making a balanced compromise in the above-mentioned optimisation challenge. Computational methods, including modelling, simulation, and analysis, have become standard tools of research and product development in industry worldwide, and many companies in Finland have applied them already for several decades. In scientific research, the application of computational methods alongside traditional theoretical and experimental research has gained general acceptance [107, 108] and, in practice, the computational approach has enabled cost efficient and fast implementation of research.

Nowadays, there are hardly any doubts about the usefulness of computational methods in research and product development, but this does not mean they are applied efficiently and effectively. The computational approach in research and development (R&D) is a complex concept and contains several separate fields and layers. Getting the most out of it requires adequate mastery of the fields and layers, and an optimal balance of the efforts and investments. Knowledge and know-how about the large concepts and information about the achievable advantages are the necessary building blocks for making strategic decisions in organisations about the main processes and investments, both in the competencies and in the infrastructure.

The SIMPRO VTT subproject covered all four main topics of the SIMPRO research project:

- high-performance computing in mechanical engineering
- optimisation, design studies, and analyses
- requirement- and customer-based product development
- modelling and results data management.

The research methods, results and highlights, and conclusions are discussed in more detail below. The detailed research results for each of the research tasks in the SIMPRO VTT subproject are covered in separate research and technical reports that are all referenced in the text.

9.2 Research methods

The SIMPRO VTT subproject had a clear applied research focus, and the general method of doing the research has been to implement relatively compact research tasks using case examples and following a simple process:

- *Pre-study:* A brief pre-study was done to illustrate the state-of-the-art of the topic, to provide a good basis for the case study, and to prioritise the phases and to concretise the prerequisites for of the case study.
- *Main study with a case example:* The main research work and a concrete study or demonstration to implement a small case for the topic. The objective of the case studies was to test and pilot, in practice, the concepts of the task and to concretise the technology.
- *Conclusions and documentation:* The task work and results were analysed and the conclusions of the work were documented either in a research report or a scientific publication. The objective was to process the new knowledge and know-how into a form that can be utilised further, both in research and in industry.

The research work in the SIMPRO VTT subproject had different levels when it came to the details and scope in the simulation-based product process. Tasks 1 (high-performance computing in mechanical engineering) and 2 (optimisation, design studies, and analyses) focused on computational applications, utilities, and systems, while tasks 3 (requirement- and customer-driven design) and 4 (modelling and results data management) focused on the simulation-based product process, either from the product development or the overall product life-cycle point of view. Mostly, these topics are addressed independently to the whole simulation-based product process. The magazine kind of approach in the project provides concrete and useful new knowledge and generates the necessary building blocks for developing further the big vision of the simulation-based product process.

9.2.1 High-performance computing in mechanical engineering

VTT subproject task 1 concerned HPC in mechanical engineering, meaning the computation technologies, including hardware and software. The main objective was to lower the threshold for design and research engineers to utilise HPC in their everyday work. Five different typical challenges of HPC were raised, as for five different subtasks in task 1.

Subtask 1.1 discussed computation management systems, meaning software tools to make the utilisation of computation resources more efficient and easier for the user. These systems aim to optimise the computational load balancing and resource availability for the users, letting users focus on the actual challenge at hand. Massive computations are run efficiently in different hardware environments, such as workstations, networks of workstations, servers, clusters, and supercomputers. The computation management systems are aiming for a user interface layer, which makes the usage independent of the computation hardware in use. Four different computation management systems were tested with different use scenarios.

Effective use of an HPC environment often requires the utilisation of scripting languages, which was studied in subtask 1.2. Modelling work often includes solutions to a variety of models, such as with different mechanical dimensions or material parameters, making the modelling a tedious and slow procedure. With scripting, we can automate this kind of modelling and develop users' own routines, which can speed up the modelling and analysis time enormously. In addition, scripting enables integration between different software applications in an efficient way. Here, Python scripting was studied with the product design optimisation, structural analysis, and visualisation test cases.

Subtask 1.3 dealt with the multi-physics simulations for electrical machine (i.e. motor and generator) development. Computational research on electrical machines has recently become more attractive due to the fast development of simulation software and the increase in computational power. HPC has not been widely utilised before with electrical machine electromagnetic simulations, due to limitations of commercial electromagnetic finite element method (FEM) software tools. For massively parallel environments, software products licensed under open source licences are very attractive, and actually are the only option in electrical machine analysis. In this subtask, a pre-study was made about the open source software applications Elmer and GetDP, and 3D electrical simulation case studies were done with Elmer. Additionally, the optimisation of electrical machines with an analytical model was studied.

Co-simulation and parallelisation in fluid-structure interaction (FSI) was studied in subtask 1.4. In FSI, two demanding computational analysis domains are coupled to simulate interaction between fluid flow and structural dynamics, such as hydrodynamics and structural phenomena of propulsion systems. The goal of the study was to demonstrate two-way FSI co-simulation utilising weak coupling with the MpCCI technology from Fraunhofer-Gesellschaft. Commercial computational tools for structural FEM, and computational fluid dynamics (CFD) were coupled to model and simulate the multi-physical phenomena.

Subtask 1.5 combined two subtasks originally planned for the VTT subproject's tasks 1 and 2: the large-scale visualisation and open source tools in technical computations and optimisation. The amount of data produced by the simulations is continuously increasing, making the post-processing and visualisation of the results a more challenging task. Here, an HPC point of view for visualisation was taken. A survey of technologies for large-scale post-processing and visualisation was done, and selected tools and practices were tested in case studies. The optimisation case study was performed with the OpenFOAM CFD software environment and the Dakota optimisation tool, both available as open source solutions.

9.2.2 Optimisation, design studies and analyses

The work in VTT subproject task 2 was divided into four different subtasks: parameter optimisation [109–111], topology optimisation [112, 113], utilising a discrete element method with optimised structures [114, 115], and acoustic simulation in a cloud environment [116, 117]. The research work was done by utilising illustrative real-world case examples, which had direct links to industrial needs and relevance.

Subtask 2.1 included parameter optimisation applied using the finite element method (FEM) structural analysis and multibody system (MBS) simulation models. In reality, a number of parameters usually exist that affect the dynamic behaviour of the system. Some parameters have more influence on the system than others, and based on an engineer's judgement, some of these correlations are already known, but there can be correlations that are not commonly known. A sensitivity analysis can be utilised for selecting only the parameters that have an actual effect on the system. This also reduces the size of the optimisation problem to a practical level, which then can be utilised efficiently during the product development process. In the case of the parameter optimisation subtask, a set of process parameters were originally introduced and used in the optimisation process. One of the task objectives was to explore different optimisation tools and to test the efficiency of different optimisation algorithms available in selected tools. In addition, different types and levels of analysis models were introduced in order to illustrate the effect of the target model content on the results.

Subtask 2.2 included topology optimisation applied to a parameter variation process. Conventionally, topology optimisation has been used separately, mainly for new concept studies or for the optimisation of the shape of a new component to be manufactured using certain processes, like casting or additive manufacturing (such as 3D printing). In this study, topology optimisation was applied to an upper-level design of experiment (DOE) process. The aim of the study was to find out how design space variation affects the topology optimisation results. In addition, the use of an HPC environment was explored in order to automate some of the early steps in the design process.

Subtask 2.3 included the discrete element method applied to the parameter optimisation process. The discrete element method (DEM) was applied to be in interaction with a structural component and was utilised in an optimisation process. The objective was to gather experience of how effective the open source and commercial tools are regarding the handling of numerous interacting particles and the structure. The selected study case was a particle damper, which can be used for damping high vibration levels in a harmonically excited structure. Due to the nonlinear nature of the damper behaviour, the simulation has to be performed in the time domain, which is computationally very expensive and therefore presents challenges for the optimisation process.

Subtask 2.5 included the comparison of acoustic simulations between FEM and boundary element method (BEM) based tools. Acoustic simulations were performed using cloud computing services and compared to conventional FEM-based simulations. The acoustic simulation test case was performed using Kuava Oy's software application Waveller Cloud. This uses the CompA solver, which is based on BEM to solve the acoustic wave equation in the frequency domain. In this case, an industrial-level case study, the interior of a tractor cabin, was conducted.

9.2.3 Requirement- and simulation-driven design

The key success factors in the development of complex systems are among the following:

1. systematic processes and life-cycle models, such as ISO/IEC/IEEE 15288 [118] and its daughter standards
2. a systematic model for the engineering artefacts and their relations, such as documents, computer-aided design (CAD) models and pieces of information
3. an effective organisation model:
    - well-defined roles, such as systems engineer and requirements engineer and
    - a well-defined collaboration model (to facilitate a consistent view in all involved organisations of the goal, data, and state of development)
4. well-planned use of project management and systems engineering tools:
    - a good selection of tools (model-based tools advocated) and
    - a flexible tool integration model (to allow integration of various tools used by the collaboration partners)
5. a tool to orchestrate all the above, such as a product life-cycle (PLM) tool.

The work in VTT subproject task 3 targeted the second success factor, a systematic model for engineering artefacts. Traceability of the engineering artefacts in simulation-oriented systems development was the more focused target of the research. The goal was to integrate the artefacts (like simulation results) produced by the simulation engineers and their software tools with the other artefacts of the development processes; current practices easily leave simulation engineers on their distinct islands, without knowing the original stakeholder requirements, the consequent system requirements, and the specific rationale for a specific simulation task.

Engineering artefacts include, among other things, requirement specifications, system functions specifications, system architecture descriptions, and verification and validation artefacts, with simulation-related artefacts being among the verification and validation artefacts. In complex systems, arrangements for traceability and impact analysis play an important role in managing iterative system development. To provide the traceability of engineering artefacts, the following factors need to be provided by the organisation carrying out the systems engineering:

- traceability information model (TIM)
- a tool to restore and trace the engineering artefacts according to the TIM. The tool should provide an integration model to facilitate the integration of different kinds of engineering tools.

The work done in this task provides a systems engineering artefacts model (that was titled SEAModel) to facilitate the creation of traceability information models. Some possible tools to implement SEAModel were evaluated, and finally a demonstration was done to ensure the feasibility of SEAModel in a simulation-driven demonstration case.

9.2.4 Modelling and results data management

Companies are constantly required to provide products with innovative and powerful features. As integrating functions from various disciplines is a major source of innovation, the product and design processes are getting ever more complex. At the same time, in today's highly competitive market, industries are looking to decrease the product development cost and time-to-market. This means developing more complex systems while decreasing the number of physical prototypes. Consequently, this increased use of digital tools leads to an increased amount and diversity of data. A multitude of data is generated across different teams, sometimes even spread worldwide. Often the data of different teams and tools are rather isolated from each other, since the tools used are generally specialised. Consequently, those simulations require the collection of data from various fields, in various formats, and therefore an efficient data management process is essential for running an efficient product development process.

Simulation life-cycle management (SLM) tools promise the seamless combination of design and simulation tools within the same formalised process. The use of SLM tools can reduce the risk of design errors early in the design, and enable the utilisation of design data in later stages of the product life-cycle. As shown in Figure 21, SLM mainly focuses on the virtual world of the product life-cycle. It manages simulations in narrow collaboration with product life-cycle management (PLM) and likewise integrates the capabilities of simulation data management (SDM). SLM offers clearer visibility for simulation data, and enables engineers and scientists to collaborate on the same simulation platform.

Figure 21. Product and simulation data management throughout the system life-cycle.

Task 4.1 [119] of the project was dedicated to studying the current state of the art of data management in modelling and simulation. The task also aimed to provide a better understanding of the major issues currently faced in the Finnish industry concerning modelling and simulation. Meetings and discussions with industrial partners were organised to share their experiences and discuss ways of improvement. It was highlighted by the SIMPRO industrial partners that the companies use a wide range of simulation tools, and the range is getting wider with their sub-contractors, which might use some other tools as well. Currently, companies do not have well-developed tools and processes for managing data especially related to simulation outputs for reuse. Management and traceability of measurements were also highlighted as a possible area in need of improvement.

9.3 Research results and highlights

The SIMPRO VTT subproject implemented several case studies and produced several publications and other deliverables. The main research and highlights for the four focus areas are presented below. The detailed research results are documented in the separate research reports or scientific publications, referenced in the text.

9.3.1 High-performance computing in mechanical engineering

VTT subproject task 1 included seven case studies from five challenging main topics, reported in five subtask reports [120–124] and three scientific publications [125–127]. Below, the results are discussed for each subtask.

In subtask 1.1, different distributed resource management systems (DRMS) were reviewed [120]. Different tools were found to be optimal for different hardware. There are different tools to utilise office laptop and desktop computers' idle resources, dedicated computer clusters, grids of heterogeneous computational hardware, and cloud computing resources. Some DRMSs can deal with several use scenarios, but none of them can handle all the scenarios well, and thus there is multitude of different workable systems. Use experiences are covered for the selected tools: Grid Engine, SLURM, HTCondor, and Techila. Of these, Grid Engine and SLURM are designed for cluster computation, meaning for systems from small to vast collections of dedicated computers connected with a special network. SLURM was found to be more user-friendly with more effort put into the development. HTCondor's and Techila's strengths are in workstation grids, meaning the utilisation of idle computational resources of the workstations and laptops in a heterogeneous computer network, or cloud computing resources. HTCondor was found to be the most versatile DRMS tool, but even it does not fit every use scenario.

One of the most popular present scripting languages is Python. Utilisation of Python in product design optimisation, structural analysis, and visualisation was studied in subtask 1.2 [121, 128]. Python is the scripting language of most computation software tools, making it very suitable for integration between different software. As a case study, Python was utilised in scripting of model updating in structural vibration problems. Python was used between Dakota, Abaqus, and the modal assurance criterion (MAC) method for model updating. The MAC method itself was implemented using a NumPy Python extension. Further, Python was also successfully utilised in scripting ParaView visualisation.

In subtask 1.3, different open source FEM tools for multi-physical electrical machine computation were evaluated [122, 129]. It was found that the only available open source options for 3D simulations are Elmer and GetDP. Both have limitations, but Elmer has developed hugely during the project, and presently even exceeds commercial counterparts in several features. Figure 22 shows one model of the 3D electrical machine case study. Two publications [125, 126] were made from the Elmer development and parallelisation tests; the results show several tenfold higher utilisation of parallel computation compared to the commercial FEM tools. Additionally, optimisation of electrical machines was studied. An analytical model implemented in MATLAB was used to represent an electrical machine in the optimisation process. Both single and multi-objective algorithms were tested in the Dakota optimisation tool. The model was also used in the SIMPRO subproject

Aalto 2 and SIMPRO subproject JYU, and a publication was written in co-operation with JYU [130].

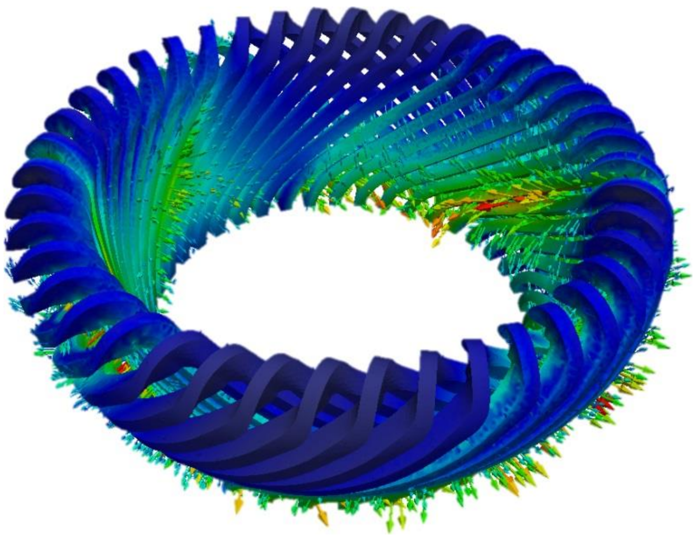

Figure 22. Elmer electrical motor end-winding model, visualised with ParaView.

In subtask 1.4, the two-way fluid-structure interaction (FSI) co-simulation was applied successfully to a case study utilising MpCCI with Fluent CFD software and the Abaqus structural FEM tool [123, 131]. In an FSI simulation, a structure deforms due to forces caused by a fluid flow, while the deformation changes the fluid boundary. So-called weak coupling was used, meaning that each problem is solved separately, and during each time step some variables are exchanged between the two problems. The MpCCI tool handles the connection between the two commercial software applications in use. The case study was to model the interaction of a rotating propeller and a non-rotating cylinder located in the wake of the propeller (see Figure 23).

Subtask 1.5 studied both large case visualisation and optimisation with open source tools. For both, fluid mechanical case studies with OpenFOAM CFD computation were utilised. Post-processing and visualisation possibilities utilising parallel processing were studied with ParaView. Further, the ParaView visualisation was rendered with Blender as photorealistic figures. For example, Figure 24 represents the air flow streamlines rendered using Blender [127]. The results show that Salome platform – OpenFOAM – ParaView – Blender is a very capable open source tool chain, which can produce photorealistic results to be used, for example, in advertising material. Further, demonstration video of the visualisation was produced [132]. All the tools utilised in this subtask are available as open source.

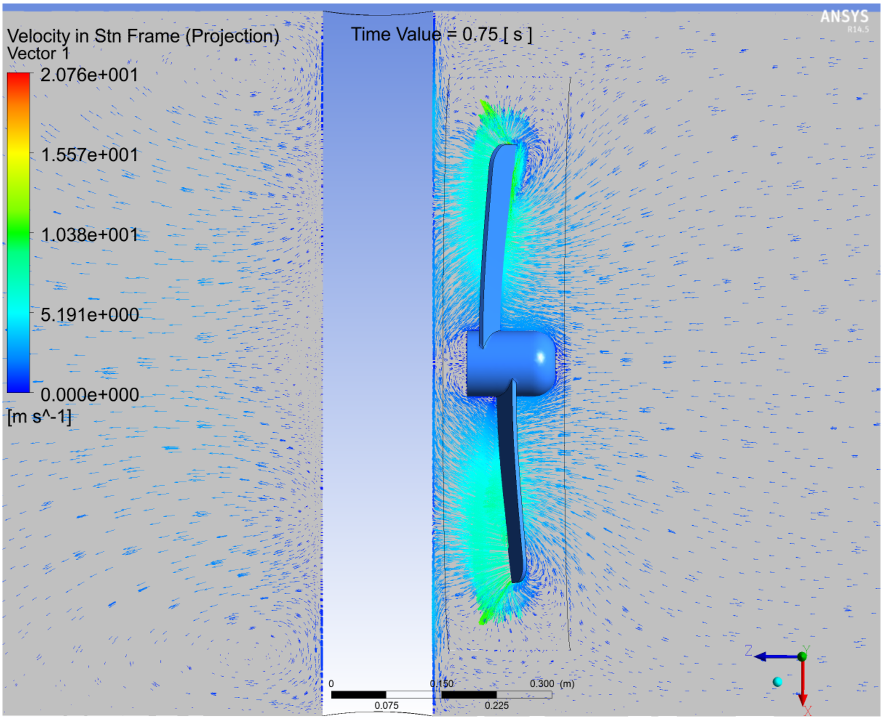

Figure 23. The velocity of the flow and the deformation of the propeller blades in the FSI co-simulation case study.

Further, surrogate optimisation was utilised in the case of a drag minimisation of the airfoil when the minimum lift is given as a constraint [124]. As optimisation software, Dakota was utilised, whereas the objective function is calculated using OpenFOAM. The number of necessary objective function evaluations was quite high, but substantially lower than in the genetic algorithms beneficial for simulation-based optimisation.

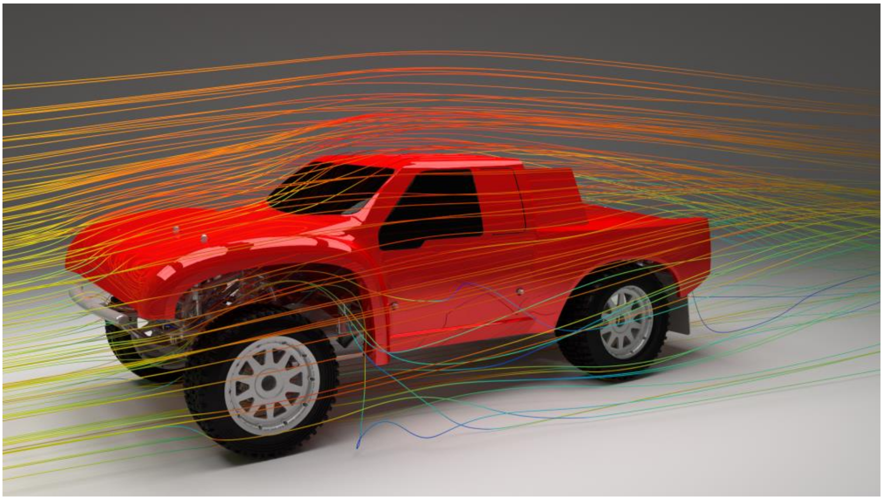

Figure 24. Computed air-flow streamlines coloured by velocity magnitude and rendered using Blender.

9.3.2 Optimisation, design studies, and analyses

All the case studies of VTT subproject task 2 were completed successfully but with different experiences. Especially, parameter optimisation applied to multibody simulation, and topology optimisation applied to a DOE process were completed with good results and corresponding conclusions. In addition, acoustic simulations were successful, and relatively good results were received. There were some case study-related challenges with parameter optimisation applied to the structural analysis FEM models, in which some unnecessary iterations were needed before the complete optimisation problem was properly formulated. In addition, in the subtask related to DEM-based simulation, utilising the selected open source software application, LIGGGHTS, experienced unexpected difficulties, and finally the commercial FE software application Abaqus was selected as the DEM tool to be used in the simulation. VTT subproject task 2 case studies were reported in seven subtask research reports [109–112, 114, 116, 133] and in three seminar posters [113, 115, 117].

The case studies for parameter optimisation applied to a multibody simulation were successful. Two different case studies were defined and run with two different optimisation tools. Both case studies were run with the default parameter values of the optimisation methods. Optimisation tools and the mathematical algorithms inside them were found to be capable and robust for parameter optimisation of multibody models without extensive prior knowledge of optimisation. One of the main results of the case studies is the importance of understanding the actual optimisation case that is being studied. If the optimisation problem is not described with necessary understanding, it could produce an erroneous interpretation of the optimised case or it could even be impossible to get any meaningful result. The core of the optimisation process is the algorithm that manages the iterative process. In the used optimisation tools, HEEDS, MDO, and Dakota, there are several algorithms available, which are suitable for different types of systems. In the case of a multibody model, optimisation of a non-linear system is needed. When using multibody models, the gradient is not available, unless it is approximated somehow and thus gradient-free methods need to be used. In Figure 25, optimisation process progression is presented.

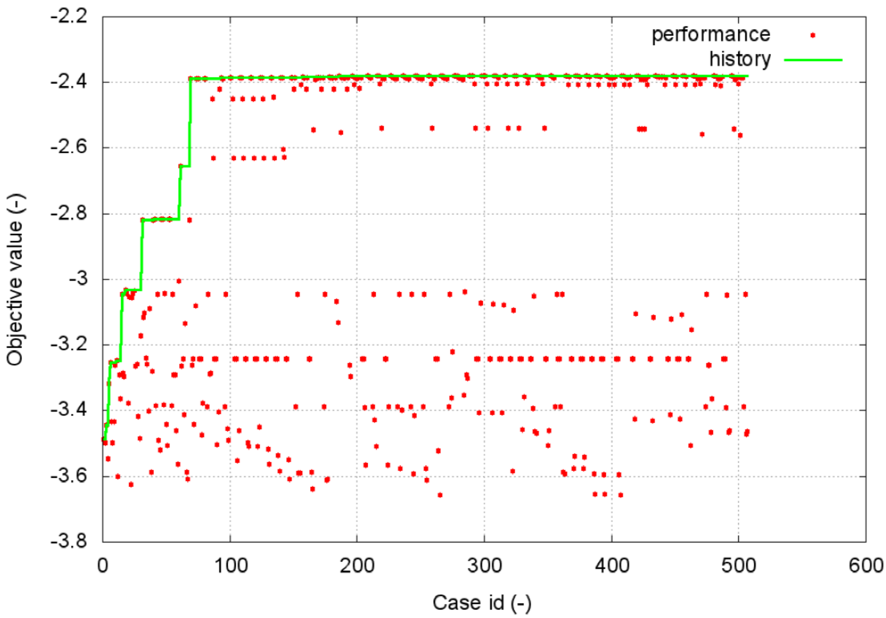

Figure 25. Objective function values of the optimisation case as a function of design ID.

An extra subtask was conducted related to automatic analysis systems connected to parameter variation and the optimisation process (Figure 26). Automatic calculation systems can give clear benefits in modifying existing products or during the design process of new products. Modern and flexible analysis software, combined with effective computer hardware and connected with sophisticated scripting languages, makes it possible to develop completely automatic, effective, and reliable calculation processes. In the case of the utilisation of open source analysis codes, cost benefit can also be included. These processes can then be integrated within the optimisation algorithms, thus enabling product optimisation and control of the inevitable uncertainty in model parameters. In this subtask, three different algorithms – parameter variation, diving rectangles optimisation, and the evolutionary optimisation algorithm – were tested in a generating set study case. The optimisation software Dakota was used for controlling the process in which the mass of the complete set was minimised and overall vibration response levels were controlled. There were a strong resonance close to the nominal operating point, and with all the studied methods the resonance can be moved away from running frequencies. With simple parameter study, as well as with the dividing rectangles (DIRECT) algorithm, the mass remained unchanged. In this case, the evolutionary algorithm delivered the best result. When performing all analyses in an HPC environment, all necessary analyses were completed within a practical time. Depending on the case, the calculation effort can be decreased by using reduced FEM analysis models.

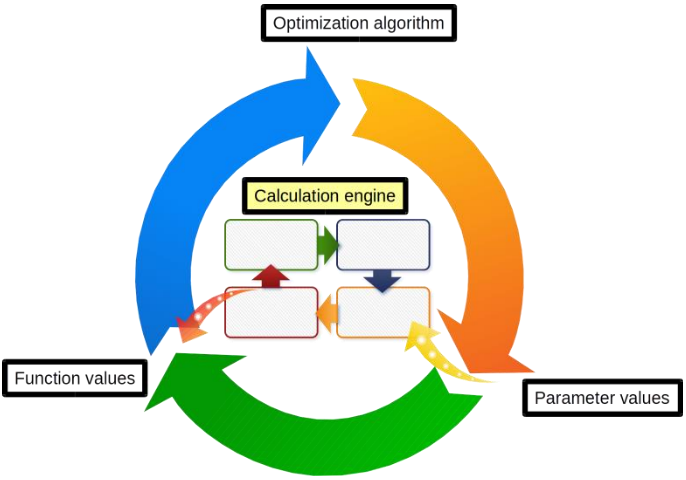

Figure 26. Automatic calculation engine within optimisation [133].

Topology optimisation connected to the parameter variation process gave very valuable information relating to the importance of the optimisation case definition. It was noticed that by varying the initial design space, there can be significant changes to the resulting optimised topology. The main phases included creation of a finite element model of the chosen case study, usage model reduction techniques for connected components, preparation of a topology optimisation model, generation shape variables that altered the length, width, and height of the design space, and the launch of design experiments on a computing cluster so that tens of different variations of the case were run. The basic idea of the study process is presented in Figure 27. The results of the reanalysis were automatically tabulated for easy comparison of designs.

In particular, the phase that automatically processed material distribution results for the geometry, including valid surfaces, for further analysis, gave substantial effectiveness to the complete process. It was seen that without the possibility of automating this phase, the efficiency of the process is substantially compromised.

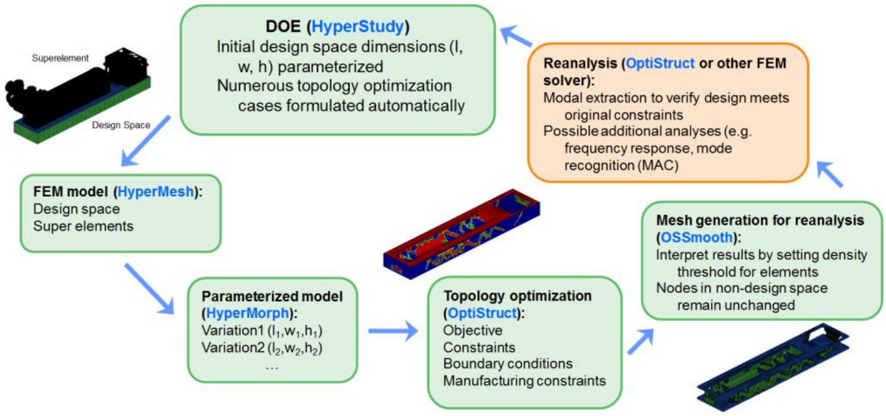

Figure 27. The basic idea of topology optimisation connected to the DOE process.

An acoustic simulation test case was performed using Kuava Oy's software application Waveller Cloud. This uses a CompA algorithm, which is based on BEM to solve the acoustic wave equation in the frequency domain. BEM is mostly used and most applicable to exterior problems, and in this context it was used for interior problems, where it is not as efficient as the finite element method (FEM). The case study, Valtra cabin T888M, was concentrated on the sound field distributions produced by an acoustic point source in the interior of a tractor cabin, and simulation of material utilisation in three inner roof elements, for which calculated results exist based on FEM simulations in the NOVI project [134]. When comparing results from both simulations, some similarities were noticed, but distinct differences were also detected, as seen in Figure 28. True fluid-structure interaction and propagating waves in structures cannot be modelled using only BEM, as they can using coupled vibro-acoustic FEM, as only locally reacting boundary conditions (impedance) for acoustic fields can be associated with the boundary structures. This may cause errors with individual, strongly coupled nearby surface parts, especially if the individual surface properties deviate much from each other.

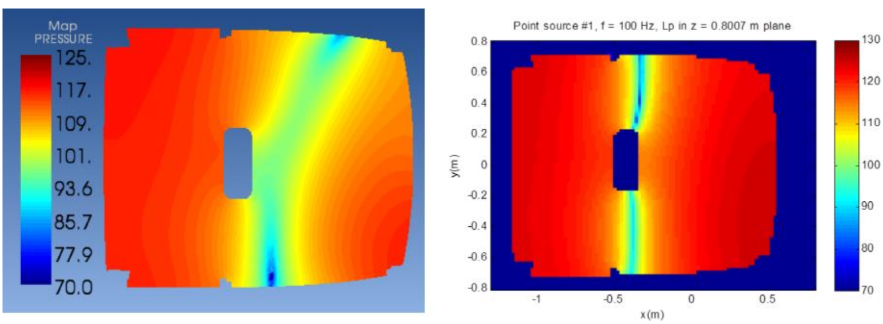

Figure 28. Sound pressure level distributions on three surfaces in the cabin at 100 Hz; left: Actran results, right: Waveller Cloud results; inner roof 3.

9.3.3 Requirement- and simulation-driven design

The Systems Engineering Artefact Model (SEAModel) [135, 136] created in the SIMPRO VTT subproject provides the models for creating and implementing a traceability information model (TIM). The ultimate goal was to provide the framework for tracing simulation artefacts with requirements and design artefacts. An example TIM is provided in Figure 29.

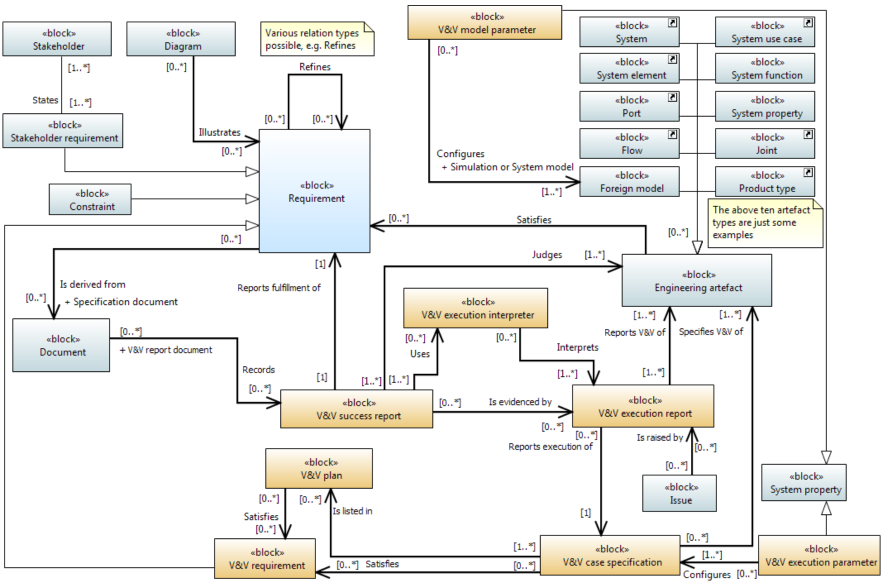

Figure 29. Traceability Information Model for requirements, design, and validation and verification (V&V) artefacts.

The ‘blocks’ in the TIM in Figure 29 represent the artefact types produced during the development process, and the arrowed links represent the traces between the artefacts, with the trace direction from the younger information to the older. Each artefact can be thought of as a model element and implemented as a database object, XML, or similarly structured object. SEAModel provides thus the model for the project data. The consequence is that the project data is not stored in documents but in a structured data repository; documents can, nevertheless, be used, but in most cases their role is to present information, not store or transfer it. The consequence of a structured data repository is that all the data has a single source, although it is presented in several documents. This facilitates the automatic generation of documents using document templates that are populated by the data from the data repository.

The structured data repository can be implemented in several ways. We found that the data repository should feature the following:

- a structured artefact repository, in which relations between the artefacts can be created and maintained
- artefact traceability with impact analysis
- version control of artefacts and of a set of artefacts (with the "baselines" feature)
- modification control
- automatic or semi-automatic document generation
- document management (or seamless integration to an existing document management system)
- the possibility of integration with systems engineering tools, such as requirement management tools, CAD tools, and software programming tools
- concurrent engineering capabilities
- collaboration features including wiki pages, task lists, discussion boards, and announcements
- metrics of various systems engineering issues, such as how many of the system requirements are covered by the design artefacts.

Besides the above features, the following issues need to be considered when selecting the tool:

- cost
- responsiveness (especially important when using traceability features)
- usability and user experience.

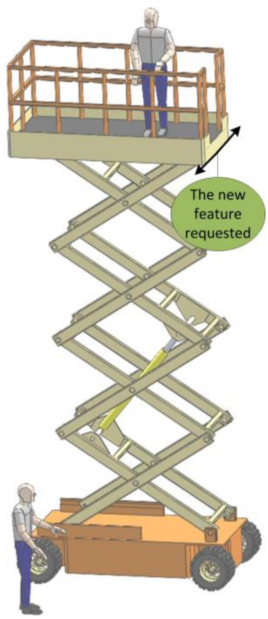

Figure 30. The demonstration case for the traceability information model.

Examples of tools to implement SEAModel are PLM tools, such as CATIA/ENOVIA by Dassault Systèmes, Teamcenter by Siemens, PTC Windchill, or ARAS PLM, but one might not be able to tailor the tools so that SEAModel is completely followed. Such PLM tools, however, provide good integration with a selected set of CAD and simulation tools. With a random set of systems engineering software tool brands, like the 3D CAD tool, simulation tool, and requirements engineering tool brands, a tailored approach might be needed. We evaluated the possibility to implement the data repository with tools such as Microsoft SharePoint (using SharePoint lists as the structured data repository), the Simantics platform (the VTT-created simulation tool integration platform), ModelBus, and Traceino by the Fraunhofer Institute for Open Communication Systems FOKUS (ModelBus is now commercialised by Ingrano Solutions GmbH). ModelBus is an integration platform, a 'communication bus' between software tools from different vendors. Finally, we demonstrated the traceability information model presented in Figure 29, using the IBM Rational DOORS requirements management tool. The demonstration dealt with an imaginary scissors platform machine that was enhanced according to a feature request ('capability to move the platform horizontally sideways') by an imaginary customer (see Figure 30). The demonstration involved the following set of tools:

- IBM® Rational® DOORS® requirements management tool
- Papyrus SysML tool for modelling the initial mechanical architecture
- SOLIDWORKS® (by Dassault Systèmes SolidWorks Corp.) for creating the 3D CAD mechanical model
- Simulink® (MathWorks®) for the simulation.

The Rational DOORS was also used as the integration and traceability platform. The integration was accomplished by adopting the so-called surrogate object method, in which model files are represented as surrogate objects within the DOORS tool. Impact analysis was gained by a script that touches the surrogate object if the linked model file is updated. It was noted that by the surrogate object method, file-level traceability and impact analysis can be arranged, but in cases in which the model elements produced by the engineering tools are compacted into a single file, the granularity of the traceability is coarse. Furthermore, the visibility of data between the tools cannot be provided using the surrogate object method. See more about the demonstration in [136–138].

We also tested the ReqIF [139] requirement interchange format to transfer requirements from a requirements management tool to the Simantics platform [140]. See more in [141].

9.3.4 Modelling and results data management

Task 4.2 [142] identified the challenges and problems faced by the design engineers during the modelling and simulation phase of the product development and design process. Exchanging data among different computational tools is a challenging task, especially when dealing with complex products. From this perspective, some simulation life-cycle management (SLM) tools were surveyed and reviewed. The tools were selected for further study in order to identify the existing gaps between the needs of the industry and the capabilities of commercially available SLM tools in managing the modelling and simulation data throughout the product life-cycle. To illustrate the research work, various product development processes were described, which require the combination of multidisciplinary simulations along with the processes and simulation tools. Data exchange possibilities and mechanisms between various simulation tools, and middleware that plays an important role in the transfer of data, were investigated.

The objective of task 4.3 [143, 144] was to utilise case studies to practically implement and test the data exchange between simulation tools. Commercially available SLM solutions were used to conduct the case studies. The case studies focused on accessibility and exchange of data among teams and between tools. The case studies were defined together with the industrial partners of SIMPRO, to ensure the industrial relevance of the project results.

The first case study consists of performing a short simulation process (Figure 31) that involves various common tools, from CAD software to a knowledge management tool. This process is implemented in ANSYS Workbench and ANSYS EKM.

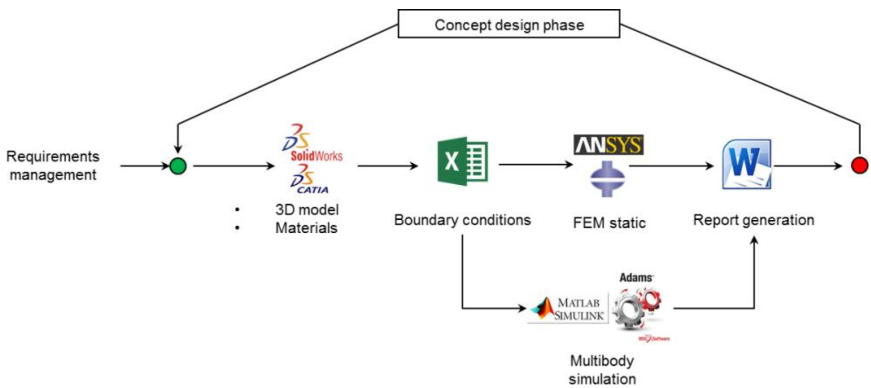

Figure 31. Simulation process defined for the case study.

The process starts by listing the requirements of the case study, creating the model using CAD software (SolidWorks), and listing the boundary conditions in an Excel file, which is then used as input for the FEA performed under ANSYS or Abaqus, and which finally generates a report in Microsoft Word format. In parallel to the FEA analysis, interoperability and data exchange with other tools, such as MATLAB Simulink and Adams, was also studied. The process represents a generalised design iteration in the industry, and the tools are commonly used for performing dynamic and multi-body simulations.

The second case study consists of studying the management of large simulation files, which are becoming increasingly common nowadays in the engineering field. The companies pointed out that with more computational power available, more accurate and more complex simulations can be carried out nowadays. This results in ever larger amounts of simulation data, combined with multidisciplinary simulation, leading to exponential growth in file size. Transferring the data from one computer to another, from one specialist to another, and between different teams is a demanding task and requires very high network bandwidth and storage capacity. An Abaqus ODB file of 1 terabyte (Figure 32) with simulation results was used for the case study in the Dassault Systèmes Simulia environment.

Product life-cycle management was discussed, and the use of open source software applications and systems was studied [145]. In addition, the article introduced a data model architecture for product process data, utilising a semantic data management approach.

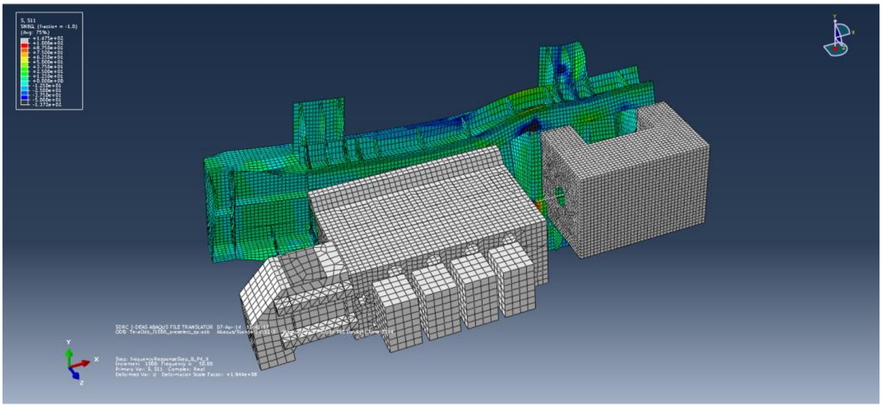

Figure 32. Visualisation of simulation results for the ODB file with Abaqus.

9.4 Discussion and conclusions

The research in the SIMPRO project and the work done in the VTT subproject have shown that the overall concept of the simulation-based product process, either from the strict industrial or wider R&D point of view, is complex and has several layers. Detailed technologies, methods, tools, and systems are needed to implement the next layers in the big vision, and knowledge and know-how of the details are needed to estimate the efforts required for implementing the processes and doing more R&D in these areas. The next fast-paced focus areas in the computational approach are the large computational studies, such as optimisation, design studies, and sensitivity analyses. Successful implementation of these large studies requires fluent mastery of their building blocks, meaning the computational methods, tools, and systems for computational infrastructure, and the necessary know-how for using them. Implementing the computational approach in the industrial product process is far from straightforward. When designing complex products in a heterogeneous operating environment with geographically distributed organisations and layered subcontracting, changing the operating processes and practices requires careful planning and investments in the implementation of the changes. Systems engineering (SE) [118] is a formal methodology for managing the overall process complexity. The more recent flavours of the systems engineering concept, model-based systems engineering (MBSE) and simulation-based systems engineering (SBSE), are interesting attempts to improve the basic concepts of the already relatively old systems engineering approach. The concretisation of using modelling and simulation in the systems engineering process has been started and there are already some commercial solutions, such as the Dassault Systèmes CATIA v6 environment, that implement the fundamental concepts. The remaining challenges in this topic are still the interoperability of the modelling and simulation tools, the data and enterprise processes management systems, and the overall processes and their planning and implementation in organisations.

The research done in the SIMPRO VTT subproject has shown that solutions already exist for implementing most of the areas of the simulation-based product process. In many cases, there are well-productised commercial solutions and open source counterparts for the same need, and these options can be considered based on the organisation's own preferences. Many areas of technical computing require detailed know-how, which may be challenging to create and maintain in the organisation. This know-how, together with technical solutions, can be bought as a service from service and solution providers. When research is taken into this chain, new technologies and future trends and development are taken into account, and can be utilised by both the end-user organisations and the service and solution provider. This was one of the major outcomes of the research in the SIMPRO project: to boost the development and solution offering in Finland for computational R&D, a balanced ecosystem is needed. The ecosystem contains representatives from end-user organisations, service and solutions providers, and basic and applied research. In a balanced ecosystem, all the members benefit from being members of the ecosystem and, on the other hand, benefit the other members of the ecosystem. Like any other system, an ecosystem like this needs fruitful soil and some energy to germinate and grow.

Open source tools were found to have potential for co-utilisation with or even to replace commercial computation software tools. The open source nature also brings many benefits, like the possibility to tailor the tools for the designer's or researcher's point of view, and to better control computation. As multi-physics simulation is becoming a more and more common approach, numerically very efficient tools are needed. Presently, numerical efficiency means high utilisation of massive parallel computation, where open source tools like OpenFOAM, Elmer, Dakota, and ParaView have their strong points. These benefits are not only due to a lack of licensing fees, but also due to a greater number of built-in parallelisation solutions. HPC computation can, in certain situations, make the computation hardware more cumbersome to utilise. However, there are also open source solutions for that, the so-called computation management systems. They hide the complicated hardware from the user and make the usage of the HPC hardware more user-friendly.

However, the commercial tools are still very much needed. They have friendlier user interfaces and they are officially guaranteed to provide accurate solutions. Hence, both commercial and open source tools are seen to have their role in the future, with open source more in optimisation or other massive computation, and commercial for initial tests and confirming the results of open source tools. For this reason, in the future, more effort should be put into improving the co-utilisation of different tools. Furthermore, open source tools often produce their own ecosystem, with support and solution providers and possible cloud services. Hence, open source should be seen as a possibility for the Finnish computation-related enterprise sector.

While different kinds of optimisation methods are nowadays provided by many commercial tools, a definite need exists for understanding how these tools are used appropriately and in such a way that they indeed support the product development process. Easy-to-use tools are available on the market, and there seems to be a trend that less user interaction will be needed or even allowed during the process. It was found during the project that there could be risks related to utilising semi-automatic tools without actually knowing what is done during the process. This also applies to the definition of an optimisation case, as it has to be ensured that enough effort and thought are addressed to a proper definition of the process objective, parameters, and constraints; in other words, the formulation of the optimisation problem is the key to any successful optimisation task. Especially, due to very easy-to-use commercial tools, this phase can often be too limited.

With the Systems Engineering Artefacts Model (SEAModel) developed in task 3 of the VTT subproject, requirements engineering can be extended to cover simulation artefacts. SEAModel supports well at least the basic needs for simulation artefact tracing. SEAModel is implementable with different kinds of database-oriented software platforms, and thus it fits even small- and medium-sized companies. However, the implementation work varies a lot, depending on the chosen platform. An optimal solution is very difficult to find. Traceability of artefacts from a set of heterogeneous modelling tools is difficult to arrange with optimal granularity and full visibility of data. However, file-level granularity of model elements may provide a satisfactory solution for traceability, and is a step forward from neglecting requirement traceability.

The greatest obstacle in requirement-aware simulation engineering is still in the attitudes of the engineers. SEAModel tries to facilitate the creation of data repository and traceability tools so that simulation engineers feel more comfortable with clear boxes for the artefacts they need as the input for their work, and boxes for the artefacts that they and their tools produce. As the awareness and application of model-based systems engineering increases, such a structured data repository is a more natural approach than a conventional document-based repository of systems engineering data.

SLM tools hold the promise to enable the seamless combination of design and simulation tools within the same formalised process. This can significantly reduce the design errors in the early stages of product development, thus reducing the design cost and time to market. This can also enable companies to utilise the design data in later stages of the product life-cycle.

In task 4 of the SIMPRO project, several industrially relevant case studies were conducted using two state-of-the-art commercially available tools. The first case study consisted of performing a simulation process that involved a widely and frequently used CAD and knowledge management tool. This process was implemented in ANSYS Workbench and ANSYS EKM. The second case study consisted of studying the management of large simulation files that is nowadays very common in the engineering field. An Abaqus ODB file of 1 terabyte with simulation results was used for the case study in the Dassault Systèmes Simulia environment. The third case study focused on testing how the Abaqus data can be stored in the ANSYS EKM data management system and extracted.

9.4.1 Future work

As co-utilisation of different commercial and open source tools in numerical computation and simulations seems likely to become more common in the future, different workflows, combining various commercial and open source tools, will be needed. The work has already started in VTT subproject task 1, where Python was utilised to integrate different software. Some kind of standardised interface for different tools would be beneficial. Users should be free to utilise whatever pre-processing, solver, and post-processing tools they wish, and there should be a standard interface between different solver tools and various pre- and post-processing software. Then, the same models could be used for different solution tools, and the results from those different solvers should be imported to a single user-selected post-processing and visualisation tool. Further, this would enable wider utilisation of HPC hardware and vast usage optimisation with open source software. This would require the standardisation of data formats for pre-processors, solvers, and post-processors. The ISO 103030 (STEP) standardisation effort is working on this, but the work may take a long time. The next step after standardisation is to get software vendors to adopt the new standards. When standardised or widely accepted open data specifications exist, the implementation of a functional integration prototype is mainly software development and implementation.

The SIMPRO project showed that optimisation is coming to design and engineering, and that there are excellent software tools, both as open source and as commercial solutions, together with support services. Still, more research work is needed to make the utilisation of optimisation in a design and engineering process robust and efficient for the average design engineer. Topology optimisation, as a special form of optimisation, was found to be a very promising approach. The same challenges apply to topology optimisation – the optimisation process and software applications still require further research and development before the method can be utilised in a design and engineering process as a common tool.

Combining topology optimisation with material engineering and additive manufacturing technologies, such as 3D printing, has been found to be a very interesting approach. It opens new possibilities to tailor the three main areas of a component, meaning the material properties, detailed and overall design, and manufacturing, in such a way that the performance and properties of the component are optimised with fewer compromises. This design chain requires more research, together with method and software application development. The research work on this topic has already started at VTT and in several universities.

The research work done in task 3 (requirement- and customer-driven design) of the VTT subproject identified the need to promote the model-based systems engineering approach in Finland to better manage requirements, design artefacts, and V&V artefacts of complex systems. There is a lot of work to do to make heterogeneous systems engineering tools work on shared data, instead of isolated snapshots of the same information on each tool. Simantics provides one interesting platform for this purpose. With the traceability information model according to SEAModel, the Simantics platform would offer SMEs an affordable solution for integrated systems development.

Another future research topic is the collaboration model to improve communications and data sharing between contractors and their sub-contractors. This is especially important in the development of safety-relevant systems, to ensure a consistent and actual set of safety requirements from contractors to their subcontractors, and the transfer of evidence of fulfilling the requirements from subcontractors to the main contractors. SEAModel can be used as the basis for the data-sharing model.

The SLM tools hold the promise to provide a single product development platform. The process automation activity is a very promising feature, but it still requires quite a large amount of effort for implementation. Creating connectors for various simulation tools to exchange data is not an easy task. Some applications were found to be extremely challenging to implement and required deep expert knowledge. However, when the implementation is made possible, the entire simulation process is executed and the progress can be monitored and design decisions can be made based on meaningful results.

The results from the case studies showed that the integration of simulation tools and the data exchange between the tools requires further development work for better transparency. Integration of proprietary design and simulation tools remains a major challenge. With current tools, the implementation of a simulation process is nonflexible, cumbersome, and requires significant expertise. As a result, after initial investment, companies continuously remain dependent on the tools' suppliers. This can be a significant bottleneck, particularly for SMEs, whose competitiveness depends on continuous innovation and small production batches.

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10. Summary

SIMPRO research project
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The SIMPRO research project covered a wide set of research topics. This section summarises and discusses the main outcomes and makes conclusions about the results and findings. In addition, ideas and proposals for future research topics are presented and discussed.

10.1 Discussion

The SIMPRO project covered many aspects of the overall product life-cycle, starting from the concept phase design and requirements assessment, and reaching to the later product life-cycle phases, when the product is already in use. The product life-cycle as a concept itself is very large, and each organisation and even each product line defines and implements it in a different way, so no single truth can be found and no single best practice for a task can be defined. The form of a good product life-cycle is a combination of meaningful processes and good practices, tools and systems that support the processes and practices, and skilled and motivated people that implement the processes and keep developing the product life-cycle process continuously. Utilising computational methods, including simulation and analyses, in many phases of the product life-cycle process has been shown to be a good general approach, especially with complex systems and products, but it does not make a whole if the other elements in the equation, namely the processes, practices, and people, are not all in balance.

The SIMPRO research project has shown that there is still great and only partially exploited potential in the computational approach in the product life-cycle process for Finnish industry. In many technology companies, for example, optimisation is utilised too seldom in daily design, and engineering tasks or large design analyses, such as design of experiments (DOE) or design and analysis of computer experiments (DACE), are not utilised systemically for new designs. The technology and tools for these already exist and are not even very expensive. Some good tools are available even as open source solutions, which should lower the threshold for adopting new tools and techniques. On the other hand, the SIMPRO project has shown that moving from the traditional product design and engineering culture to a fluent and efficient simulation-based product process is more complicated than just adopting new software tools and systems. One added value of using a computational approach is to speed up the product process for getting the products to the markets faster and, naturally, to lower the design and engineering costs. This is done practically by increasing the process efficiency and especially by utilising concurrent design and engineering. This, on the other hand, brings new challenges to managing the process, including solving technical conflicts, validating and verifying decisions, and communicating the necessary information to relevant parties. This is where systems engineering [146] is providing a toolbox of useful concepts. In the modernised variants of the original systems engineering concept, meaning model-based systems engineering (MBSE) and simulation-based systems engineering (SBSE), the modern computational methods and tools are utilised and integrated with the main concepts of system engineering. In MBSE, the main focus is on utilising models as the design and engineering artefacts, instead of written textual documents. This is to improve the efficiency in the compressed design and engineering process, where keeping all the design and engineering documentation up-to-date is becoming a bottleneck in the process. In SBSE, the main focus is on improving the iterative design and engineering validation and verification process, and naturally on providing efficient means for high-quality R&D. More unrevealed potential lies in utilising the design and engineering models and simulation results in the later phases of the product life-cycle process. The simulation-based product life-cycle process can provide great opportunities for improving, for example, maintenance and service business, and can even open totally new business potential for companies.

In the sections below, some general conclusions about the topics covered in the SIMPRO project are presented. More detailed information is available in the SIMPRO subprojects' deliverables documents and directly from the project participants.

10.2 Conclusions

10.2.1 Concept design, formal methods, and information capture

Formal management of data, information, and knowledge in different phases of the product life-cycle is becoming increasingly important. The pace of the product life-cycle process keeps increasing, and the one who is able to utilise all the existing information and get the most out of it has a strong advantage in the markets. The most important decisions concerning a product are usually made in the early phases of the product process, especially in the concept design phase. Utilising all the existing information in this phase can improve the overall design of the product and prevent bad design decisions. Testing the concepts, for example with computer simulations and analyses, can save time and money many times during the later phases of the product process. Evaluating the possible design options in the concept design phase, using formal methods and optimisation, can reveal totally new ways of fulfilling the design requirements. The studied formal design concept analysis and evaluation methods, and developed prototype tools for the methods, showed great potential. The topic is an essential part of the product life-cycle process and systems engineering, and its integration into the process, both from the process and from the data and software applications point of view, is necessary for revealing its full potential. The concept phase design and its formal methods and information capture were the focuses of the SIMPRO subproject Aalto 1.

10.2.2 Optimisation, method development

Optimisation has high unleashed potential in design and computational engineering. Even though there is still room for method research and development, numerous well-tested methods exist for single- and multiobjective optimisation, and the offering for dedicated optimisation software tools is already wide. In addition, there is good expertise available in Finland for applying advanced optimisation in R&D, both in research and in industrial applications.

The efficiency of an optimisation process is strongly dependent on the optimisation target system. If the target system responses are smooth, the optimisation process itself can be fast and efficient. In the case of a varying and noisy system response, more effort is needed for the optimisation, and the process may require both time and computational effort. So far, there is no explicit way to identify the system's response without having either extensive experimental or computational data about the system's responses. This means that the best algorithms and implementation of the optimisation process have to be tried and learned. At the same time, more research is needed to find and develop new and robust techniques, such as nature-inspired computing (NIC) methods, to improve the efficiency of the optimisation process.

Optimisation at its best is an approach that combines efficient algorithms and software applications with the process of applying optimisation. A typical optimisation process requires a large number of so-called objective function evaluations, which often means, in a case of engineering optimisation, running a computer simulation and analysis. These simulations or analyses produce a large amount of valuable information even though they do not necessarily provide optimal results. In other words, the optimisation process may be equally useful as its result. This is especially the case if the target of the optimisation is not clear and explicit. Running optimisation with computationally expensive cases may require a long time or may require excessive computing power. Interactive optimisation involving multiple conflicting objectives, which combines efficient optimisation algorithms and the user into an integrated process, provides promising opportunities for product design and engineering. This approach again integrates computational methods and tools with the process itself, and thus contains the potential to become an integral part of the overall simulation-based product process.

Optimisation was studied or involved in several subprojects in the SIMPRO research project, including subprojects Aalto 2, JYU, TUT 1, and VTT. This indicates that there is a great interest in optimisation in general, but also that broad expertise exists in this area in Finland.

The subproject JYU is an example of method development. In this subproject, methods applicable for computationally expensive multiobjective optimisation involving multiple conflicting objectives were surveyed and developed. Attention was paid to demonstrating the potential of interactive methods in which a human decision-maker directs the solution process with their own preference information, and is supported in finding the best balance from among the objectives and in being convinced of the goodness of the eventual solution.

The increased interest in the applications of optimisation in the product process has also been seen in the activity to productise new technologies and innovations. Two parallel and separate productising projects with the SIMPRO project were started to develop the optimisation concepts and tools further. These Tekes-funded “new knowledge and business from research ideas” type of projects focused on evaluating the business potential, and on productising (1) the structural analysis-specific methods and tools chain for machine design, and (2) the application of interactive optimisation in the product process.

10.2.3 Real-time simulation in product design and engineering

The steadily continuing fast development of computer technology and increasing computing power enable large and complex computer simulations to be run in R&D. Another direction in which to utilise the increasing computer power is to run simulations faster and thus enable designers and engineers to get immediate feedback from the simulations. A good example of this is the use of real-time simulation in designers’ daily work, meaning the use of real-time design simulators. These simulators provide accurate enough simulation results, but run in real time. The designers can virtually run and test the design and get information, for example about the structural loads and general performance of the product under development. This enables a fast and intelligent design process and fits well with the simulation-based systems engineering process. The same computational technologies that are used in real-time simulation can be used for improving the computational performance of offline simulation. This has particular value when used in large computational studies, such as optimisation, in which a large number of individual simulations are needed.

The research and development in the subproject LUT was a good example of utilising new scientific information for the benefit of productised computational tools. The best methods for describing structural flexibility in real-time multibody system simulation were studied and reported, and the research results are to be used in the development of real-time multibody system simulation in design simulators.

10.2.4 Method development for faster and more accurate computations

Utilisation of computational methods in the product process is a combination of several aspects. Accurate computational methods are useless in an industrial context if the methods are too slow or resource intensive. An example of this is the direct numerical simulation (DNS) approach in computational fluid dynamics (CFD). In DNS, no simplified models are used for describing the fluid-flow phenomena, but the flow field is computed based on the fundamental physics models. This leads to a very large number of computational cells and further to very short time steps in computing, which means that the computational times for even a simple computational case are very long. DNS is mainly used for studying fundamental flow phenomena, such as turbulence. For industrial applications, simplified but much faster computational methods are needed. Fast and accurate enough methods enable evaluation of several design options and, for example, the use of optimisation in the design process. The development of the CompA software in subproject Aalto 3 was a good example of method development that was immediately utilised in commercial tools and thus made available as a productised solution for industrial cases.

The fast but steady progress in computational technology encourages investment in computationally resource-intensive methods in areas where there is clear added value to achieve. One such area is the simulation of electro-magnetic phenomena in electrical machines. The simulations that now run for several weeks will, after five years, be run in just days or even hours.

Even though the computing times for the electro-magnetic phenomena in industrial cases are now very long, beginning to study the applications of the computational methods prepares us to utilise these tools and methods efficiently when the computational power has improved enough. The research work done in the SIMPRO subproject VTT for developing a parallelising software application, Elmer, for electro-magnetic simulations is part of a larger R&D effort in this field. The work has been done in several projects, and it will continue after the SIMPRO project. The development of the Elmer software is a good example of an eco-system, in which research, software development, and end users are involved and work towards the common goal.

10.2.5 Development of a simulation-based product process

Computational tools and systems alone are not the solution for an efficient product process. The process itself also has to be developed and improved. In systems engineering (SE), the so-called V-model has gained popularity as a formal model for the process of the development of complex products [146]. The roots of the systems engineering approach are in the 1940s, so the fundamental idea of having formal processes and means to implement a complex product process is not new. There are more recent flavours of the systems engineering approach, namely model-based systems engineering (MBSE) and simulation-based systems engineering (SBSE). Using a formal information and knowledge management approach and utilising modelling and simulation in the right phases of the product process can improve the overall efficiency and quality of the process. The concept phase design and the definition of the primary design requirements are part of this approach. Management of the requirements and tracing the verification and validation data in the process are other means to guarantee the quality of the product process.

The different detailed aspects of the systems engineering process were studied in the SIMPRO subprojects Aalto 1 and VTT. The research and development work in the SE area will take more time and effort to cover the SE concept and to provide general solutions and tools for industrial use.

10.2.6 Utilising simulation in later phases of the product process

Simulation can provide remarkable added value in the later phases of the product life-cycle process. Simulation is a valuable tool in product and system condition monitoring and maintenance. Using simulation for analysing the condition of the product or system can improve the monitoring efficiency, or simulation can be used to either increase the monitoring accuracy and resolution or to decrease the use of expensive and prone-to-damage sensors in products that are used in harsh conditions. These so-called soft sensors are an especially attractive alternative if simulation models already exist for the product or process. The use of simulation in work machine condition monitoring was successfully studied in the TUT 2 subproject. More extensive and efficient utilisation of simulation in the later phases of the product life-cycle process will require improvements in product design and engineering, as well as maintenance and monitoring data management.

10.2.7 Computational utilities and systems for computational product process

Successful application of the computational product process approach requires that all the aspects of the process are mastered well enough. To get a good understanding of the existing utilities and solutions for improving the efficiency of the computational process, a set of utilities and solutions were studied and tested in the project. The result showed that there are excellent solutions for many areas of the computational product process, such as distributed computational resource management systems, scripting solutions and tools for script development, high-quality open source computational tools, and post-processing and data visualisation tools for demanding cases. As discussed in the Introduction section of this report, the computational tool technologies are already relatively mature, and faster progress can be achieved in other areas than just developing the tools. Designing the engineering process carefully and utilising the existing tools and systems in right phases of the process can lead to remarkable improvements in the overall process. The existing computational tools and systems were studied in several SIMPRO subprojects, including subprojects Aalto 2, JYU, TUT 1, and VTT.

10.2.8 Efficient data management

The increasing application of the computational approach, together with increasing computational power, will irrevocably lead to an explosion in the amount of data. Managing and tracing data takes an increasing amount of time in the product process and requires development both of tools and systems and of the process itself. As an example, the computational fluid dynamics case done in VTT subproject task 1.5, "large-scale visualisation and open source tools in technical computations", produced 8.7 TB of data just for one simulation case. This is already so much data that transferring it from a computational cluster system to a local workstation requires a long time and the data transfer has to be planned before implementation. In addition, nowadays few workstations have such a large disk space that this amount of data can be transferred. This means that the overall concept of managing, accessing, and using the computational data in the simulation-based product process has to be reconsidered. At this point, a new concept of "*computational big data*" is introduced, combining the concepts of "*big data*" and "*computational data*". The same challenges and solutions than exist in "*big data*" could be selectively applied to "*computational data*" and the challenges in data management.

In computer and information sciences, data, information, and knowledge are concepts that illustrate the value and meaning of the information to humans. Roughly speaking, data becomes information when a way exists to interpret the data into something meaningful. Further, information becomes knowledge when there is human experience involved in the interpretation or use of the information. In the current offering of solutions for design and engineering, the emphasis is on managing data. Product data management (PDM) systems, which in most cases are document based and do not take the content of the data into consideration, are still used by many companies. Solutions exist for product life-cycle management (PLM) and dedicated solutions for simulation life-cycle management (SLM), but most them focus on data and its relatively low-level management. The meaning of the data is still bound to the people involved in the process. This may be due to the fact that the concepts of formal information and especially knowledge management are still not clear and mature enough. While there is no exact demand for an information and knowledge management solution in business and industry, there is no wide solution offering for it.

The concepts of design, engineering, and simulation data management were studied in the SIMPRO subproject VTT. Some of the existing commercial solutions for PLM and SLM were studied, and knowledge about the concepts and the solutions were shared among the participating project organisations.

10.3 Future work

All the levels of the computational product process are equally important and needed (Figure 33): computational methods and numerical computing details, utilities and support systems, computational tools, knowledge and know-how in how to use the tools and systems, understanding of the systems engineering process, managing data, information and knowledge, and mastery of the product life-cycle process. Below are some larger research topics that have arisen from the implementation and results of the SIMPRO research project.

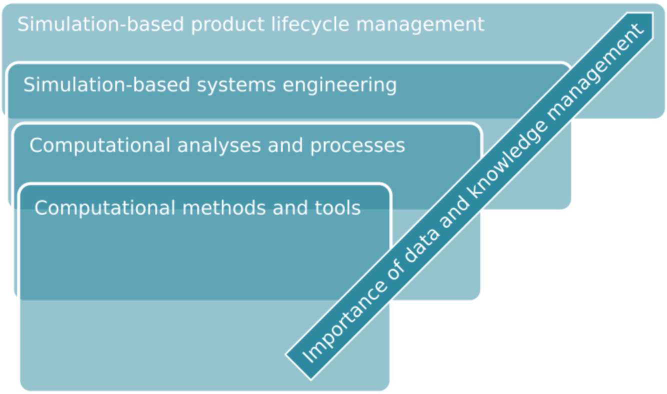

Figure 33. Four different levels of the simulation-based product process.

10.3.1 Improving simulation process efficiency

Computational methods and tools are just part of the computational engineering process, and the process itself has a remarkable role. A typical simulation process contains the pre-processing, simulation, and post-processing phases. In the pre-processing phase, the computational model is created and the case parameters are defined. Depending on the computational case and the method used, this phase can take from 50% to even 80% of the overall simulation process time. Where the overall efficiency of the computational process is concerned, the pre-processing phase looks like a potential starting point. The means that improving the pre-processing phase includes, among other things, integration of software applications and data, meaning the fluent co-use of software applications and data exchanges between them, and improved data management. Automating the process as much as possible enables improving the process and also serves the use of optimisation and large design analyses in the product process. There is a clear need for research and development in this topic.

10.3.2 Systematic validation of virtual models

The correlation of a virtual model with experimental measurements plays an important role when estimating the virtual model's capability to perform realistically. Model validation methods have been used to systematically identify the level of correlation and, if necessary, to update the model parameters to improve the match with real-world behaviour. Currently, the complete model validation process requires an extensive experimental effort to handle large and complex models properly. In practical industrial projects, this is not always possible, due to the time or resource constraints.

Model validation methods are usually based on different kinds of optimisation techniques and, in the case of large models, certain challenges can be expected. There is a clear need for more robust model validation for practical use, and the validation process, software tools, and data integration require further development. In addition, the ability to partially validate and update large models with relevant information within statistical certainty limits requires more research and development.

10.3.3 From single simulations to large computational studies

Using modelling and simulation to run single simulations is already mature technology, and there are many efficient solutions for this. The obvious next step in the simulation-based product process is to utilise computer optimisation and large design analyses, such as DOE and DACE, in design and engineering. One interesting direction is to move from “the one case truth”, meaning running only a few computer simulations or analyses, to statistically comprehensive computational studies. The technology for implementing this approach already exists, but the methods and tools for computer-aided inferring of the results still needs more research.

10.3.4 Data, information, and knowledge management

The previous concept, namely moving from running single simulations to running large design studies, obviously leads to challenges in data management. One efficient way to compress data is to process it into information and knowledge. Formal knowledge engineering (KE) and knowledge management are research topics that have a long history in the research of artificial intelligence (AI). This research has produced solutions for many areas of formal knowledge engineering that could be utilised in the product process. There are still unresolved research challenges in KE, such as performance issues with large data and efficient reasoning of complex knowledge. On the other hand, the research in KE has mainly focused on general knowledge, which means that the techniques and solutions must tackle wide-ranging and sometimes ill-formatted information. In design and engineering, most of the information is relatively explicit and well-formatted, and thus well-suited for machine interpretation. This is an area of research where cross-technological co-operation is needed and could lead to new breakthroughs.

An intermediate development step for high-level knowledge could be the use of product models in the product life-cycle process. The concept of a product model has been studied in detail in the building sector, and there is even standardisation for the data models and formats in the form of Industrial Foundation Classes (IFC) [147]. A similar concept to the IFC could be utilised for machines and other systems. The same design and engineering data, and the same models and simulation results, could be used in the different phases of the product life-cycle. The data and information is managed in one place only, to avoid the use of incorrect information. In a wider application of the concept, the data and information from product life-cycle phases other than design and engineering could be included and made available for the process. The concept requires extensive work on standardisation, research in methods and solutions for many areas of the concept, and large investments in the implementation of software systems and applications. On the other hand, the benefits from such solutions could be remarkable.

10.3.5 Building a Finnish ecosystem for virtual design and engineering

Improving progress in applying the simulation-based product process in Finnish industry requires active and vivid communication between all the stakeholders in the process. One of the major discoveries in the SIMPRO project was the need for a vigorous eco-system for the simulation-based product process in Finland. The eco-system should include all the major parties in the process, meaning the end users in industry and business, the software and solution providers, and the research parties. The SIMPRO project provided a good starting point for further development of such an eco-system, and the concept of a Forum of Virtual Design was discussed during the project. Such a forum was running actively from the late 1990s to 2007, but ceased due to a lack of relevant activities. The active operation of such an eco-system requires active participants and the will to make success happen. Activity and will are the driving forces and do not directly require money or concrete resources. If there is the will, there are usually ways to proceed and make things happen.

10.4 References

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Title	**Towards a simulation-based product process** SIMPRO research project final report
Author(s)	Jarmo Alanen, Ezral Baharudin, Eric Coatanea, Xiao-Zhi Gao, Jukka-Pekka Hietala, Kalevi Huhtala, Mika Hyvönen, Seppo Järvenpää, Janne Keränen, Juha Kortelainen, Tomi Krogerus, Marko Matikainen, Kaisa Miettinen, Aki Mikkola, Faisal Mokammel, Ali Muhammad, Petteri Multanen, Sami Pajunen, Karthik Sindhya, Juha Virtanen, Pasi Ylä-Oijala & Kai Zenger
Abstract	Computer-aided design (CAD) and computer-aided engineering (CAE) are daily tools for designers, engineers, and researchers both in Finland and worldwide, but there is still unleashed potential in the computational approach. The mainly Tekes-funded 'public research networked with companies' type of research project, SIMPRO, focused on the efficient application of a computational approach in the whole product life-cycle process, from the concept phase design until the simulation-based condition monitoring of machines and simulation life-cycle management. The computational approach was studied on four different levels: 1) from the computational methods, tools, and systems point of view, 2) from the optimisation and computational analysis point of view, 3) from the simulation-based product design and engineering process point of view, and 4) from the simulation-based product life-cycle point of view. The research in the SIMPRO project was implemented from a practical point of view, applying the studied methods and tools to selected case studies. This approach provided valuable knowledge about the practical utilisation of the tools and methods and concretised the new knowledge. The objective of the project was to produce new research knowledge and to develop the existing and new knowledge into an easily exploitable form in industry. The main conclusion of the project was that the computational methods and available tools are already mature. The bottleneck for fast progress in industry is in the application of these methods and tools, which would require further development and renewal of the processes. The potential for improving the product process using a computational approach is still remarkable.
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Nimeke	**Kohti simulointipohjaista tuoteprosessia** SIMPRO-tutkimusprojektin loppuraportti
Tekijä(t)	Jarmo Alanen, Ezral Baharudin, Eric Coatanea, Xiao-Zhi Gao, Jukka-Pekka Hietala, Kalevi Huhtala, Mika Hyvönen, Seppo Järvenpää, Janne Keränen, Juha Kortelainen, Tomi Krogerus, Marko Matikainen, Kaisa Miettinen, Aki Mikkola, Faisal Mokammel, Ali Muhammad, Petteri Multanen, Sami Pajunen, Karthik Sindhya, Juha Virtanen, Pasi Ylä-Oijala & Kai Zenger
Tiivistelmä	Tietokoneavusteinen suunnittelu (CAD) sekä erilaiset simulointi- ja analyysimenetelmät (CAE) ovat suunnittelijoiden, tuotekehitysinsinöörien sekä tutkijoiden päivittäisiä työkaluja niin Suomessa kuin maailmallakin, mutta näiden menetelmien ja työkalujen hyödyntämisessä on edelleen paljon käyttämätöntä potentiaalia. Tekesin pääosin rahoittama, elinkeinoelämän kanssa verkottunut tutkimusprojekti SIMPRO keskittyi laskennallisten menetelmien tehokkaaseen soveltamiseen. Tarkastelu kattoi koko tuotteen elinkaariprosessin konseptivaiheen suunnittelusta aina simuloinnin soveltamiseen koneiden kunnonhallinnassa sekä simulointitiedon elinkaaren hallintaan. Projektissa laskennallisten menetelmien soveltamista tarkasteltiin neljässä tasossa: 1) laskennalliset menetelmät, työkalut ja tietojärjestelmät, 2) optimointi, laajat laskennalliset analyysit ja laskentaprosessi, 3) simulointi tuotekehityksessä ja suunnittelussa sekä 4) simulointi osana tuotteen elinkaariprosessia. SIMPRO-projektissa tutkimus pyrittiin toteuttamaan käytäntölähtöisesti niin, että tutkittuja menetelmiä ja tekniikoita sovellettiin valittuihin esimerkkitapauksiin. Näin uusien menetelmien ja tekniikoiden käytännön sovellettavuudesta saatiin arvokasta tietoa ja saatu uusi tieto saatiin konkretisoitua. Tutkimusprojektin tavoitteena oli sekä tuottaa uutta tutkimustietoa että jalostaa olemassa olevaa ja uutta tuotettua tietoa teollisuudessa helposti sovellettavaan muotoon. Projektin keskeinen yleinen johtopäätös on, että laskennalliset menetelmät sekä tarjolla olevat laskentaohjelmistot ja laskennan tukiohjelmistot ja -järjestelmät ovat jo nyt pitkälle kehittyneitä. Nopean kehityksen pullonkaulana on menetelmien tehokas soveltaminen tutkimuksessa ja tuotekehityksessä, mikä vaatii toimintaprosessien kehittämistä sekä uudistamista. Laskennallisen tuoteprosessin tehokkaalla soveltamisella on saavutettavissa merkittäviä etuja tutkimuksessa ja tuotekehityksessä.
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Towards a simulation-based product process
SIMPRO research project final report

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